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Research paper

Legal barriers to the development of onshore wind power plants and the design of wind turbine tower pile foundation

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Abstract: Even the best project of a wind power plant (WPP) can fail if there are not favourable legal regulations for its completion. Most of the research has dealt with identification of various obstacles to implement WPP (political, social, legal, environmental). Analyses of legal barriers (LBs) have been usually made at a high degree of generality. This paper offers a thorough overview of LBs for localization of WPPs in Poland. This is the country where restrictive regulations have blocked the possibility of implementing such projects in many areas. Unfriendly law may persuade investors to choose worse wind turbines foundation conditions. In our research we focus on a problem little dealt in scientific studies, i.e. on the localization of WPP in difficult geotechnical conditions. The article presents the analytical engineering method, which includes the mutual influence between foundation piles in carrying on the construction load on a subsoil. The paper presents the geotechnical parameters responsible for calculation outcomes, the theoretical basis of the curve analysis method of settlement of a single pile and of the calculation of piles settlement working in a group and fastened with a stiff head. It also shows the effect of pile arrangement in a foundation and a load distribution of in-dividual piles, as well as a settlement and leaning of foundation of wind power turbine towers. The method enables a more precise, safer and optimal design of a wind turbine foundation.

Keywords: foundation, legal barriers, wind power plant, pile arrangement

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1. Introduction

It is a worldwide trend to develop the wind power among other renewable energy sources (RES). According to Renewable Status Global Report [1] ca. 28% of global production of energy comes from RES. At the European level the conditions for the development of wind energy production is determined by the Directive 2009/28/WE of the European Parliament and of the Council of April 23, 2009 on promotion of using energy from renewable sources [2] (presently Directive (EU) 2018/2001 [3]). The first of these documents assumed that the share of energy from RES in the final usage of gross energy in 2020 in each EU country should achieve the goal foreseen for it. Poland as one of few member states did not accomplish the national aim on time (Fig. 1). Latest data show that the 2030 target may also be difficult for Poland to achieve (21–23%).

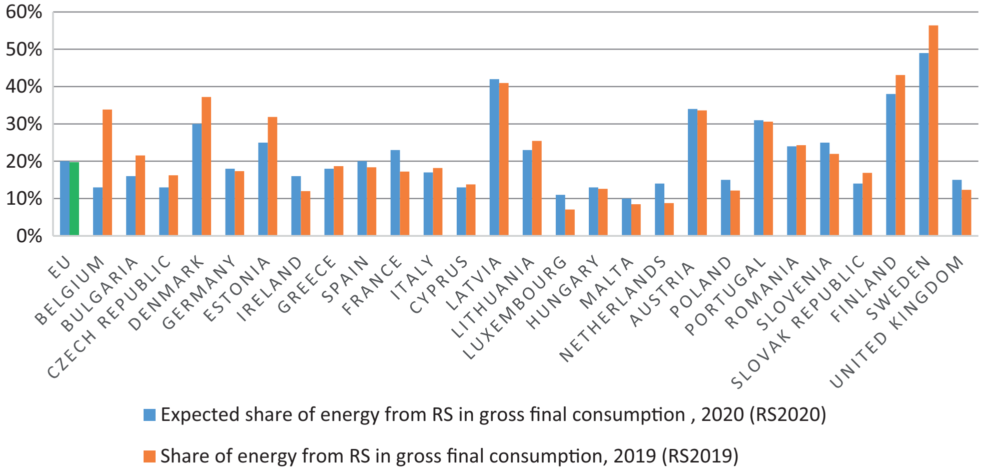


Fig. 1. Share of RES in gross final consumption of energy in the EU countries in 2019 and 2020

These fears were confirmed in 2016 when the development of wind power plants (WPPs) has been stopped because of the insufficient legal safety of such projects. Without consequent state politics towards RES, and among them the wind power, it can be also impossible for Poland to achieve the aim as determined in the directive (UE) 2018/2001 [2]. According to this goal by 2030 at least 32% of the final energy used in the EU should come from RES [3]. In the case of Poland this share should stand at 23% (PEP40 [4, 5]), of which 30% to 50% energy ought to be generated by WPPs [6].

There are very few studies on the present legal barriers (LBs) for localization of WPPs. The research [7–9] and report [10] are focused on 2016 (coming in force of LBs) and previous years. The analytical period covered in this research does not include the full range of changes made in the legal system. In the research [11] significant special conditions were determined and their influence on localization of WPPs in a chosen self-government unit – the Great Poland province (at present there are 16 provinces in Poland). In study [7, 11–13] different barriers of the development of WPPs were analyzed. The analysis of LBs they present are thus more general than this made in our article. Many studies pertain to offshore WPPs [14–16]. Maritime wind energy production is one of the fastest developing technologies of RES in Europe. It is gaining popularity also in Asia and North America. Offshore WPPs, however, have different localization requirements. Investments in the Polish offshore sector are still at the design stage [16]. Apart from that the data of Wind Europe implies that in the period of 2021–2025 over 70% of new wind farms in Europe will constitute land ones [17]. Defining of LBs for localization of WPPs is a great significance for supporting future decision making.

The awareness of existence e.g. distance buffers may lead to a choice of wind farms localization in worse geotechnical conditions. The problem of determining the optimal localization of WPPs in disadvantageous ground conditions is a subject of numerous publications. The importance of geotechnical setting conditions issues from the characteristics of foundation operation of a WPP tower. WPPs foundations are characterized by the type of load, namely a large overturning moment and inclination of the structure, which generates negative pressures, i.e. lifting of a part of the foundation with an increasing moment and eccentricity.

Therefore, the research [18, 19] emphasizes the role of the scope and quality of geotechnical work which precede laying foundations for wind turbines. In the study [20] different technologies of strengthening a foundation subsoil are analyzed. Available publications also indicate the commonness of using complicated numerical models (e.g. finite element method [21]) for analyzing different foundation variants. In-depth analyzes pertain mainly to the prediction of displacement since wind turbines have very strict requirements on stiffness of setting (limitation of settlement and especially of inclination). Some studies [22] deal with the dynamic character of loads, which entails the possibility of occurrence of resonance phenomena and the necessity to consider the dynamic parameters of the subsoil and foundation impedance. The authors claim that in comparison to a shallow foundation, the pile foundation considerably improves the resonance characteristics of the entire structure of WPP. In [23] the analysis of the effect of the soil shear strength parameters on the results of the design calculation for piled-raft foundations to support tall wind turbines in clayey and sandy soilbase is presented. It was found the differential settlement controlled the final design and was considered as the response of concern in the optimization procedure for the pile foundation structure. In the design methods, depending on a chosen type of foundation, the subsoil itself is being modelled or the subsoil with vertical reinforcing elements [24]. In the case of occurrence of geological layers with a susceptibility to deformation and low carrying capacity (organic soils, cohesive plastic soils and soft plastic soils) the safest method of setting is a pile foundation. We believe that although these problems have been thoroughly studied, especially for rigid slab foundations, yet the issue of calculation of designed piles in a group loaded with a foundation of a wind power stations tower has not been comprehensively discussed. The reason for it are the difficulties in realistic mapping of foundation piles behavior working in a group in the condition of a layered subsoil. The aim of our study is to present a proposal for an effective method of settlement calculation and an assessment of distribution of the forces transmitted to individual foundation piles.

2. Materials and methods

The research has been done in two basic parts. In the first one a complex overview of literature was conducted on legal conditions of localization of WPPs in Poland and WPPs foundation in difficult geotechnical conditions. A methodical analysis of the overview (Figure 2) was carried out on the basis of official documents and articles from the databases of Thomson Reuters Web of Science Core Collection and Google Scholar using the following combination: LBs for localization of WPPs; WPP foundation in difficult geotechnical conditions. The presented research attempts to answer the questions: (1) What LBs stopped the development of WPPs in Poland since 2016? (2) In what research fields it is considered to WPPs foundation in difficult subsoil conditions? (3) What method of settlement calculation and an assessment of forces distribution transmitted to individual piles in foundation of a wind power station is effective? The research method used was verified in the study [25]. In the second part of the research the analytical method of settlement calculation of pile groups was presented, in which the mutual reaction between foundation piles in the transmission process of loads from the structure to the subsoil. The effect of an interaction between foundation piles placed in a multi-layered the published results.

3. LBs for localization of wpps in Poland

Wind energy is the most exploited one worldwide [9, 13, 16]. This trend is not quite true for Poland. According to the GUS data [28–31], in the period of 2015–2019 energy from RES was obtained mainly from solid biofuels. As late as in 2011 Poland ranked 10 in the world in respect of investment attractiveness in the sector of wind energy production. It was a very good result considering the area of our country and the countries which outpaced us technologically. The entry into force the Act from June 16, 2016 on investments in WPPs introduced restrictions in terms of localization of land WPPs which hinder the development of this sector.

Figure 3 presents a preliminary overview of these LBs which will be discussed in more detail in this section. In the Polish legal system there is no rule which comprehensively regulates the issue of localization of WPPs (B1). The Parliamentary act of May 20, 2016 on investment in WPPs (the “Wind Farm Act”) [32] has a key significance and it determines general principles of their localization and construction. This act introduced three changes to the previous one to the Parliamentary Act of July 7, 1994 on building law [33] (which regulates the issues of designing, construction and maintenance of all building objects). The first change is a deletion of the rule which introduces a division of wind power plant in a building and non-building part. The second change consists in pointing to a voivode as an architectural and constructional administrative body proper to issue a decision on building permission of a wind power station (in opinion of the law-giver the voivode office (a second-level body on issuing building permits) are better prepared to perform the function than district officials). The third change pertains to the conclusion that a wind power station belongs to the XXIX category of building objects, thus it requires obtaining a use permit. The scope of these changes influenced enormously a multifold increase of WPPs taxation with a real estate tax (the issues of taxation of buildings

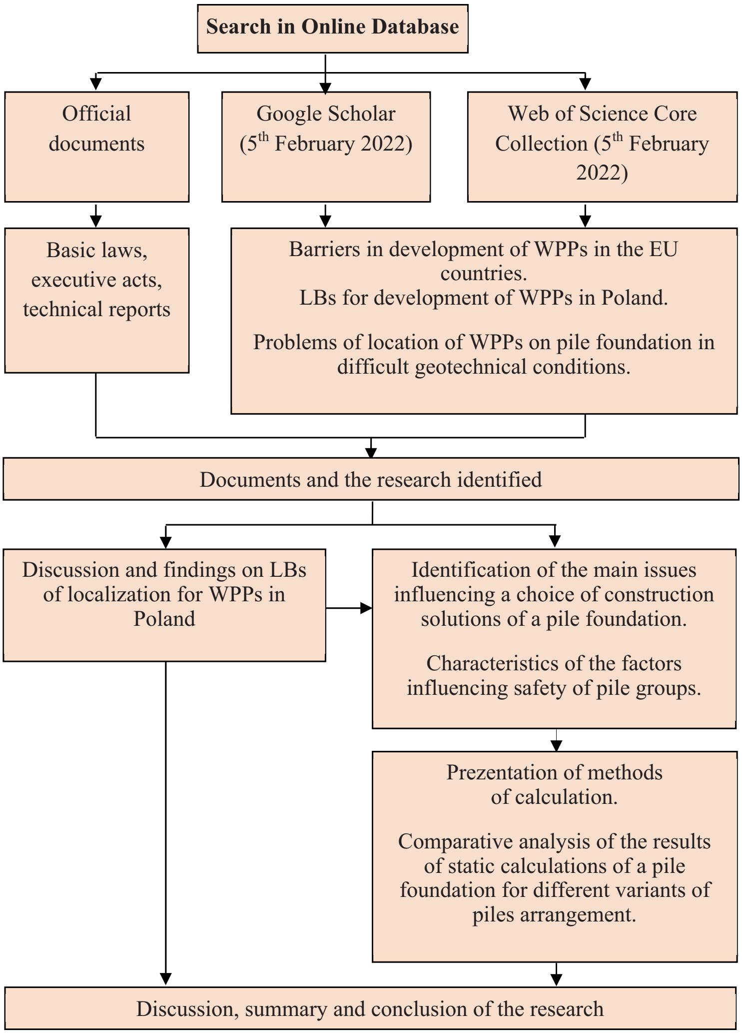


Fig. 2. Procedure of the research

and their parts are regulated by the Parliamentary act of January 12, 1991 on taxes and local payments [34]). The Parliamentary act of March 27, 2004 on local land management [35] determines the principles of making and introducing changes in the local plans in communes which should clearly demarcate plots which are allocated for building WPPs.

The Wind Farm Act (the WFA) [32] gave to WPPs the status of non-public goal investments (the principles of localization of public goal investments are less strict than private ones). The Parliamentary act of October 3, 2008 on access to information about the environment and its protection, social participation in environment protection and in assessment of an impact on the environment [36] divides investments in wind farms into requiring and non-requiring

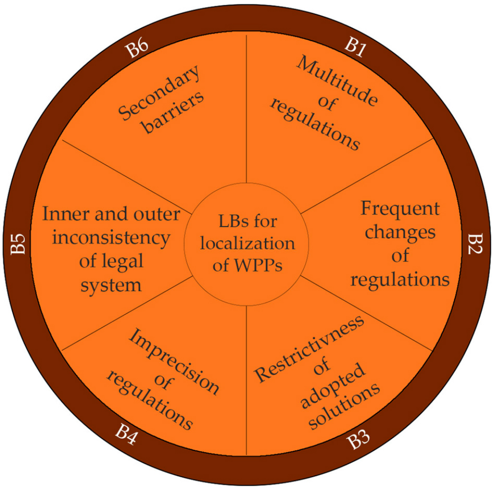


Fig. 3. Overview of LBs for localization of WPPs in Poland

an environmental report in which a localization variant is decided, optimal for the natural environment). The Parliamentary act from April 16, 2004 on environment protection [37] introduced a ban on localization of WPPs within the area of national parks and nature reserves. Within landscape parks and areas of protected landscape such investments are possible, if the procedures of environment impact assessments showed a lack of negative impact on the environment and the evaluation of a voivode (a director of a landscape park) were positive. Building WPP may require a rezoning of agricultural or sylvan land into non-agricultural or non-sylvan. The change of land use is subject to restrictions as stated in the Parliamentary act of February 3, 1995 on protection of agricultural and sylvan land [38].

The decree of the Minister of the Environment from November 4, 2008 on requirements for making measurements of the amount of emission and of water taken [39] determines the principles and guidelines of making noise measurements in the environment as defined in the so-called Reference Methodology of conducting periodical noise measurements in the environment originated from installations or devices except impulsive noise. The multitude of legal regulations (B1) makes Polish investors, designers and clerks confused. The Polish legal system on localization of WPPs is subject to frequent changes (B2) which considerably violates the principle of legal safety. The Parliamentary act on investments in wind power stations (the WFA) [32] was thoroughly changed (2018, 2019, 2021). In its original version the act foresaw a minimal distance from wind turbines to human dwelling places at 10 H (H = the total height of a wind turbine with a blade in its full rise), a lack of the possibility of modernizing or repairing a power plant and the increase of real estate taxes calculated from the value of all parts of wind turbines. Localization of WPP became possible only on the basis of the local area management plan. Such a plan had to meet specific requirements. Firstly, it had to determine the maximal total height of a wind power station. Secondly, it should be made in such a way as to show the terrain on which WPP is allowed and its impact area, constituting an area of the tenfold height of WPP. The introduction of this principle of localization made the investment process much more difficult because in 2016 the percentile of the coverage by local development plans did not exceed 30% of the national area of Poland [40] (in the previous legal standing, due to the lack of the local development plans, investors building WPPs might apply for a planning permission and on this basis apply for a building permit). Respecting the rule of optionality of passing such plans and due to its long time of preparation, some communes reluctantly take work on such plans for the need of wind energetics. An amendment to the act from 2018 returned to the previous tax rules of wind power stations. It prolonged its validity (from three to five years) and introduced the possibility of changing permits for advanced projects of wind power stations (in the first version of the act there was not such a possibility). It determined though, complicated principles of calculation of a public support (and especially its cumulation), which led to resignation of wind energy producers in auctions. Liberalization of the distance in the WFA [32] should take place this year. In the Polish legal system there are no unequivocal solutions for official financing of local development plans. The concept of a landscape dominant, which are surely tall WPPs, has not been also introduced, and which would strengthen protection of landscape attractive areas. Imprecision of law (B3) may lead to evading it. The restrictions on the distance of wind turbines from residential buildings passed in 2016 constitute a Parliamentary act obligation and they are one of the strictest in Europe (B4). Globally the localization recommendations vary widely and they have different status and different basis. Most often the acceptable distances are defined as [10,41]: 1. Stated distance buffors (e.g. 500 m – France, Ireland, Portugal, most Spanish regions, some German federal states – in the range of 300÷1000 m, most often 500 m; Sweden – 400÷1000 m; Greece – depending on a type of building development, from 500 to 1500 m in the case of ancient monuments; England – 350 m; from non-European countries – some provinces of Canada 500÷550 m); 2. Multiple value of the turbine height (e.g. Denmark – 4× the total height of a turbine [law-abiding]; the Netherlands, 4x the height of a mast [recommendation]; Bavaria – 10× the height of a turbine [recommendation, but with the possibility of exceptions in accordance with a given local development documentation]; outside Europe, among others.: chosen provinces of Canada [e.g. New Brunswick 5× the height of a turbine, Prince Edward Island 3x the height of a turbine] and states and counties of the USA – usually a distance of 1,5 the total height of a turbine]); 3. others, e.g. in Switzerland – 300 m from the end of a rotor's blade or in Northern Ireland a recommendation of the total distance – the total height of a turbine+10%. Before the entry of the distance Parliamentary act, investments of building WPPs assumed the use of wind turbine models of the total height of 150–200 meters and more. The 10h rule impelled to keep a distance of 1.5÷2 km (and more) from the nearest buildings, chosen protected areas and Forest Promotion Complexes. According to the estimation of the Polish Association of Wind Energetics the distance Parliamentary act excludes almost 99 per cent of the country form wind investments.

The Polish legal system in its part pertaining to localization of WPPs is characterized by inner and outer inconsistency (B5), which transgress the rule of clarity and transparency of law. An amendment to the Parliamentary act on RES and some others, which defined differently notions of "a building" and "a wind power station" and contributed to the relaxation of the taxation rules of wind power stations levied with a real estate tax was passed in mid-2018.

Yet the taxation changes came into force starting from January 1, 2018. The decision of a retrograde entry into force led to a loss of tax revenue levied by self-government and a refund of overpaid real estate especially in small communes. Thus communes were not interested in preparation of local development plans for the need of wind energetics. The law was declared by the Constitutional Tribunal as inconsistent with the rule of law non-reactivity stated in the Constitution of the Republic of Poland. The limitation in completion of new wind power stations was also arbitrated on the European stage. The case of Eco-Wind Construction, C-727/1 was brought before the Court of Justice of the EU [42]. The verdict of the CJEU provided a basis to challenge the 10H principle. Polish courts were to verify whether the regulations violated the EU law, and in the case they affected the principle of proportionality, they were to be declared non-applicable.

Liberalization of the “10 H rule” has been essential to make the law more friendly to WPPs’ development. It has also been necessary for reaching one of the milestones for Poland to obtain funds from the National Recovery Plan. In response to those needs the government draft amendment of the WFA appeared in July 2022. This draft maintained the principle of locating a new WPP on the basis of a local plan. However, the obligation to prepare such a plan or to amend it for the purposes of the planned investment was to be applied to the area of the projected impact of the wind farm, and not to the entire area designated in accordance with the “10H rule”. The local plan could determine a different distance from the wind farm to any residential building than the one determined by the “10H rule”, taking into account the range of the wind farm’s impact, but keeping the minimum distance of 500 meters. The basis for determining the minimum distance of the wind farm from residential buildings should be the results of the prognosis of environmental impact assessment carried out as part of the strategic environmental assessment (SEA). It was also established that the commune authorities cannot withdraw from making the SEA for the draft local plan, which foresees the location of the wind farm. The requirement to respect the “10 H rule” has been retained in the case of national parks, and of nature reserves – the limit of 500 meters. However, the proceeding of the government amendment draft of the WFA was postponed to 2023. Consultations on this draft took place at the beginning of March with the intention of introducing a minimum distance of 500 m from buildings to WPPs. On March 14, the act in this form was signed by the President of the Republic of Poland. The change introduced in the WFA, increasing the minimum distance of a WPP from 500 to 700 meters to residential buildings may in practice lead to problems in further development of WPPs in Poland. The current LBs for localization of WPPs may persuade investors to choose worse foundation conditions and make the process of designing foundation more complicated.

4. The design calculation of WPP’s pile foundation

Designing foundations of WPP includes particular issues related to the characteristics of load, geometrical shape of the foundation part and the occurrence of unfavourable geotechnical conditions in the site of a wind farm. In this case the most advantageous choice may be the use of a pile foundation.

In general, the process of designing a large pile foundation consists in:

- load distribution among all piles in foundation;
- design of piles (technology, size, number);
- settlement of piles in group;
- settlements, bending moments and shear forces in spread or raft foundation (and/or superstructure).

All these stages are corelated. For instance, an arrangement and the magnitude of piles load depend on their number, the value of settlement. On the other hand, settlement depends among others on geotechnical conditions, the type of piles, their dimension, number and arrangement, etc. Therefore, the above-mentioned designing stages should be carried out in an iterative way assuming a slab foundation based on elastic supports, which stiffness depends on settlement of individual foundation piles, Fig. 4.

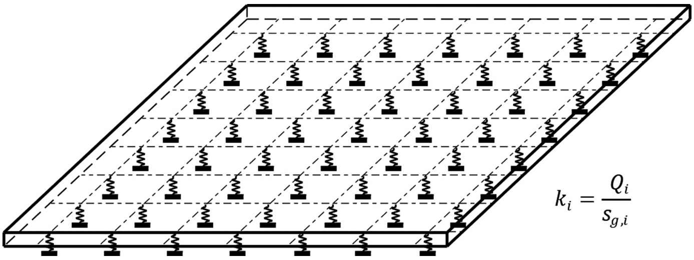


Fig. 4. Scheme of the consideration of the raft (slab) stiffness

Efficient settlement calculation method can be used for structural design with consideration of the raft (slab) stiffness according to procedure:

(I) calculation of pile group settlement $s_{g,i}$ for specified pile loads Q_i, flexible slab;

(II) static calculations for stiff slab on linear spring bearing instead of piles – k_i from step (I);

(III) calculation of pile group settlement $s_{g,i}$ for pile loads Q_i as the response of spring bearing evaluated in step (II);

(IV) static calculations for stiff slab on linear spring bearing instead of piles – k_i from step (III).

The settlement of the group of piles is much larger than for a single pile at the same conditions. The settlement of the pile group may reach a magnitude of several centimetres. According to EC 7 "for piles that undergo significant settlements, ultimate limit states may occur in supported structures before the resistance of the piles is fully mobilised. In these cases, a cautious estimate of the possible range of the settlements shall be adopted in design". Factors influencing magnitude and distribution of pile settlement in group are:

- magnitude and distribution of load;
- layout and variability of soil layers;
- inhomogeneity of subsoil;
- mechanical characteristic of soil;
- stiffness of the foundation and superstructure.

Mechanical properties of the soil are not constant but depend on the stress state in the soil. After all, the settlement of piles and the distribution of loads depend on the stiffness of the foundation and the entire superstructure. It should be remembered that displacement is an action that can generate significant internal forces in the structural system. This fact is often ignored in common design practice.

The most important geotechnical parameter in the settlement calculations is related to the magnitude of soil deformation modulus, which vary with both stress and strain state. We can't define constant value of modulus for specific soil layer. Modulus is non-lineary variable (Fig. 5).

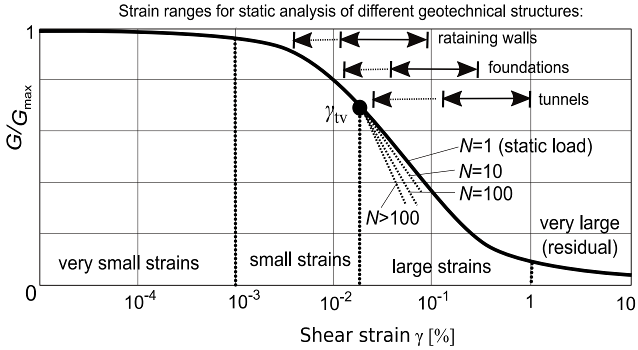


Fig. 5. Scheme of G modulus degradation with ranges of strains for different geotechnical structures (adapted from [43] and [44])

The non-linearity of soil stiffness and capability of its determination in laboratory tests were described in [45]. We can determine initial value of modulus for very small strains, as $E_{\max}$ or $G_{\max}$. We should take into account the degradation of soil modulus. Determination of shear modulus of soil and its degradation for designing wind power plant foundations was presented in [46]. On Fig. 5 we can see different ranges of strains, in which individual structures work. The non-linearity is caused by both a characteristics of the subsoil work as well as the phenomena occurring within the contact zone between the pile and the soil. One can observe a change of shear modulus of the soil with the change of stress-strain state.

5. The method for pile group settlement calculation

There exist a lot of various approaches for calculation of pile foundation settlements, from very simple ones to very complex, which make use of numerical codes. All the analysed methods are based on various simplifications and assumptions.

The presented method of settlement assessment is based on the hybrid approach according to [47]. Some additional solutions have been introduced, as equation for non-linear behaviour of single pile and interaction between piles for low-strain shear modulus and includes mode of nonlinear modulus degradation [48]. Non-linear characteristic of pile work has been described by function representing the change of shear modulus G as a function of mobilised soil resistance or strain.

The degradation of the modulus G can be described by means of a hyperbolic function depicting the relations between the current value of the modulus G and the value τ of the tangent component of the stress state or the magnitude of the current level of strain γ, see Fig. 6. The example for a such relation is a function used in the hypo-elastic constitutive model presented by Duncan and Chang [49]:

$$\tau = \frac{1}{\frac{1}{G_{\max}} + \frac{\gamma}{\tau_{\max}}} \tag{5.1}$$

where: τ – current tangent stress, γ – current shear strain, $G_{\max}$ – initial shear strain modulus (for very small deformations), $\tau_{\max}$ – maximum shear stress at failure.

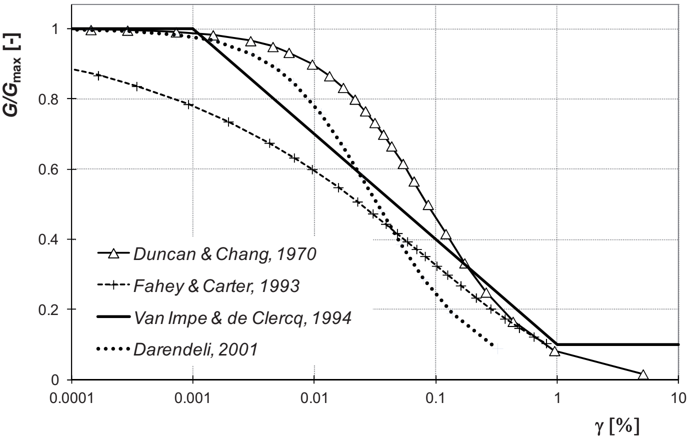


Fig. 6. Comparison of models of soil modulus degradation used in the method

This equation may be also presented as the function of the change of shear stress:

$$G = G_{\max}\left(1 - \frac{\tau}{\tau_{\max}}\right) \tag{5.2}$$

In the above-presented degradation model of the modulus G in accordance with the hyperbolic function a constant Poisson's coefficient is assumed, and the value of the modulus G is represented by a secant modulus.

The modified form of the hyperbolic function of the modulus G degradation was initially used to project the settlement curves of piles loaded with an axial force introducing an additional parameter controlling the shape of the function according to Kraft et all. [50]:

$$G = G_{\max}\left(1 - \frac{R_f \cdot \tau}{\tau_{\max}}\right) \tag{5.3}$$

where the constant of the hyperbolic curve $R_f = 0.5 \div 0.9$.

According to Van Impe and De Clercq [51, 52] for the piles loaded with a axial force proposed a relations, in which the linear characteristics of modulus G change was assumed in the function $\log(\gamma)$ in the define range of shear deformations.

Fahey and Carter [53] proposed in 1993 other hyperbolic function of shear modulus degradation in the generalized form:

$$G = G_{\max}\left(1 - \left(\frac{\tau}{\tau_{\max}}\right)^{g}\right) \tag{5.4}$$

where the exponent $g = 0.3 \div 0.7$.

Darendeli [54] proposed function assuming reference strain γ_r as shear strain corresponding to shear stress value, in which $G/G_{\max} = 0.5$ ($\gamma_r = \gamma_{0.5}$):

$$G = G_{\max}\frac{1}{1 + \left(\frac{\gamma}{\gamma_r}\right)^{\alpha}} \tag{5.5}$$

where: α – an exponent which Darendeli [54] took as $\alpha = 0.92$.

Some models of soil modulus degradation have been comparised on Fig. 6. The model of degradation affects the shape of the predicted load-settlement curve for single pile. In the presented example, for prefabricated reinforced concrete driven piles, function (5.2) was assumed for the shaft and (5.4) for the base.

Using the function of the degradation of the stiffness soil modulus of G and making use of numerical codes the pile, being treated as elastic medium is digitised by small elements with elastic supports in its nodes. For pile in-group, additional movement caused by interaction of other piles is determined using Mindlin's solution of Elasticity Theory for the force acting inside uniform, isotropic, elastic half-space [48]. After division of the piles' system onto small elements the rigidity matrix is constructed. The settlements of nodes are a solution of global set of equations:

$$\{Q\} = [K]\{s\} \tag{5.6}$$

where: $[K]$ – rigidity matrix is a sum of respective stiffness matrices of the soil $[K_s]$ and the piles $[K_p]$, $[K_s] = [F]^{-1}$, $[F]$ – flexibility matrix of soil, $\{Q\}$ – vector of external loads of system nodes, $\{s\}$ – vector of searched nodal settlements.

The elementary stiffness matrix of the i-th pile element has the following form:

$$\left[k_p\right]_i = \frac{E_p A_i}{l_i}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{5.7}$$

where: E_p – Young's modulus for pile material, $A_{p,i}$ – cross-sectional area of element i, l_i – length of element i.

The total stiffness matrix of a pile k_p is created by combining all individual element stiffness matrices.

The calculations are conducted for following load increments with next new value of soil modulus G calculated with adopted scheme of degradation of modulus [55].

The numerical procedure enables the determination of load-settlement curve for a single pile as well as for an arbitrary pile in the group for wide range of loads, complex soil conditions and arbitrary system of piles.

6. Comparison of calculation for pile foundation with different arrangement of piles

An analysis of the results of calculations for the foundation of WPP on a pile foundation is presented in this section. The subsoil is made of geotechnical layers (see Fig. 7), which are characterized by the parameters presented in Table 1.

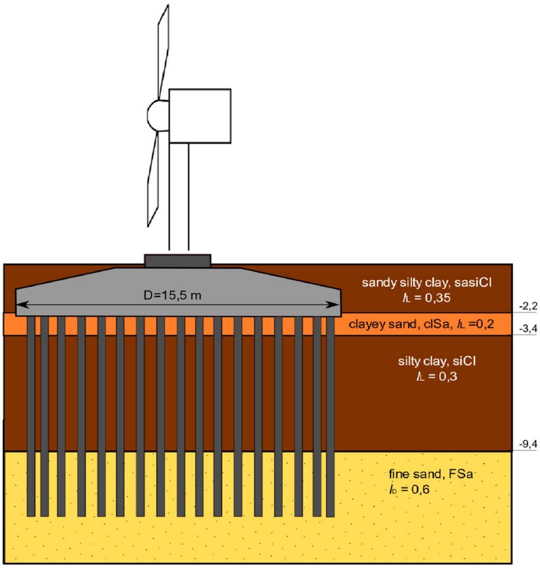


Fig. 7. Assumed geotechnical profile for the analysed pile foundations

Pile foundation characteristics:

- number of piles: 48;
- type of piles: driven prefabricated, reinforced concrete;
- dimensions: 40/40 cm, legth $L = 10$ or 13 m.

Loads:

- overturning moment: $M = 63\,000$ kNm;
- vertical load: $V = 3600$ kN;
- average uniform load (with dead weight): $q = 59.8$ kPa.

The calculations were made for two cases of pile arrangement, see Fig. 8:

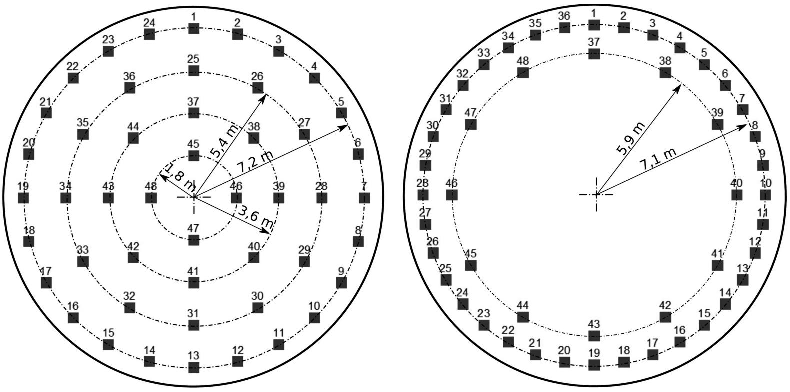
- case 1: piles spaced under the entire foundation;
- case 2: piles located under the perimeter of the foundation.

Calculations were made for two variants of load:

- variant “A” – individual piles loaded with the same average vertical forces $Q = 310$ kN (settlement results in Fig. 9);
- variant B” – foundation loaded with a vertical force and overturning moment (settlement results in Fig. 10).

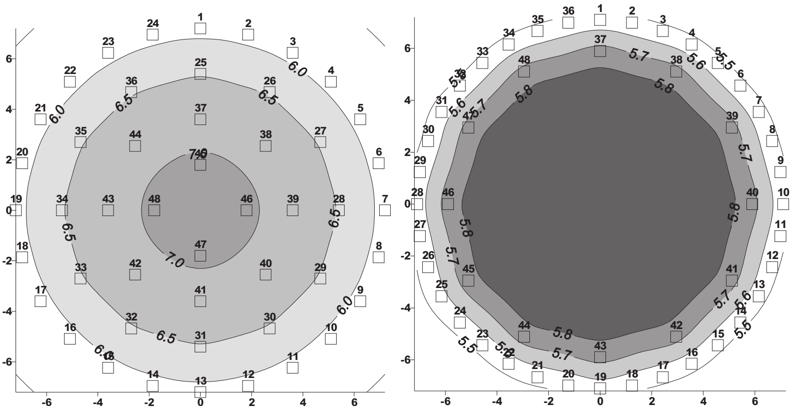
Table 1. Geotechnical conditions under a foundation of WPP

No. of layer	Soil	Thickness [m]	ρ [g/cm^3]	I_D [–]	I_L [–]	τ_f [kPa]	q_f [kPa]	$G_{\max}$ [MPa]
1	sasiCl	2.2	1.85	–	0.35	–	–	–
2	clSa	1.2	1.90	–	0.20	25	–	22,5
3	siCl	6.0	1.95	–	0.30	42	–	36
4	FSa	8.0	1.75	0.60	–	66	2500	85



(a) (b)

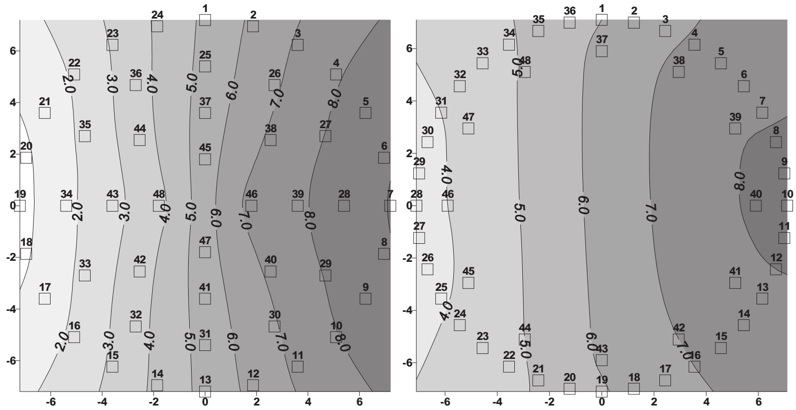
Fig. 8. Pile arrangement in a foundation: a) case 1, b) case 2



(a) (b)

Fig. 9. Calculation results of settlement in millimeters of pile foundation for load variant "A": a) case 1, b) case 2

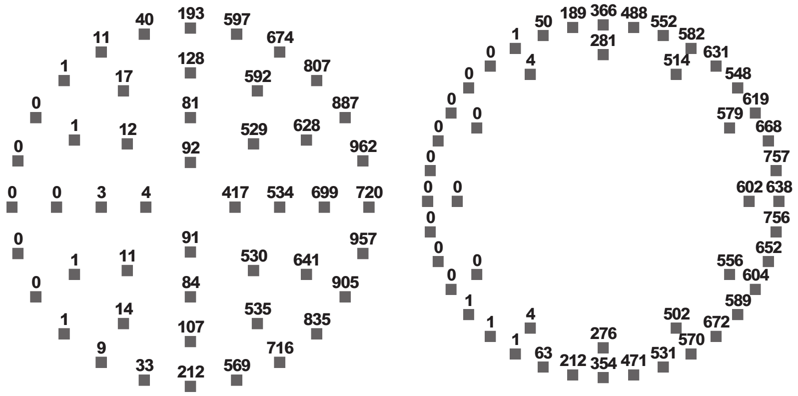
For load variant “B” in arrangement case 1 the settlement is 1 to 9 millimetres, in case 2 differential settlement is smaller (settlement equals 3.5 to 8.5 millimetres), see Fig. 10.



(a) (b)

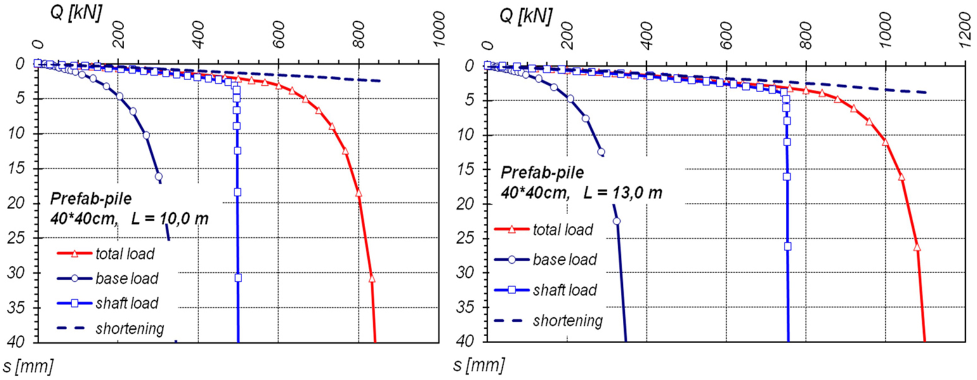
Fig. 10. Calculation results of settlement in millimeters of pile foundation for load variant “B”: a) case 1, b) case 2

The effect of pile arrangement is more visible when we analyze the magnitude of the pile supports reactions, see Fig. 11. For the load variant “B”, the arrangement case 1, the maximum forces are about 960 kN, whereas in the arrangement case 2, the maximum forces are about 760 kN. In case 1, we need piles of greater length on the periphery of the foundation, $L = 13$ m (Fig. 12).



(a) (b)

Fig. 11. Resultant values of forces [kN] on piles for load variant “B”: a) case 1, b) case 2



(a) (b)

Fig. 12. Calculated settlement curves for piles 10 m and 13 m long

7. Conclusions

As a result of our study, it was established that:

1. The Polish legal system regulating the localization of wind power plants (WPPs) is complicated, inconsistent, ambiguous and difficult to apply. The entry into force to it the Wind Farm Act (the WFA) made it necessary for investors to take into account many different legal acts when locating WPPs. It was very onerous not only because of the number of acts, but also because that some of them were mutually contradictory. The WFA not only did not eliminate old problems, but also generated new ones. It introduced the 10H rule, according to which WPPs cannot be located closer than 10 times the total height of the turbine to a residential building (or a building with a mixed function). This shows how enormous influence can have an individual legal regulation on the entire wind energy sector.
2. Due to the restrictive distance requirement Polish investors are forced to choose less advantageous foundation conditions.
3. The ultimate limit state is the basis for geotechnical design of WPPs. In addition to the static analysis, the design of the wind turbine tower foundation should also include the analysis of dynamic and cyclic actions. Although the service ability limit state is not critical, a method of calculating the settlement of piles considering the interaction between the piles (group effect) is required for the static calculations of the pile-plate system. As a result of the interaction of the structure with the entire pile foundation, pile settlements are produced, which constitute additional effects on the structural system and affect the value and distribution of forces transferred to the piles and internal forces in the cross-sections of structural elements.
4. Presented calculation method for the settlement of piles in group enables the selection of the dimensions of piles and their arrangement, providing a safe and economically optimal solution for the wind turbine foundation, especially in unfavourable geotechnical conditions.

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Bariery prawne w rozwoju lądowej energetyki wiatrowej a projektowanie fundamentów wież turbin wiatrowych

Słowa kluczowe: fundament palowy, elektrownia wiatrowa, bariery prawne

Streszczenie:

Nawet najlepiej przygotowany projekt elektrowni wiatrowej może zakończyć się niepowodzeniem, jeżeli zabraknie korzystnych przepisów prawnych dla jego realizacji. Problematyka rozwoju energetyki wiatrowej jest współcześnie niezwykle ważna. Decydujący udziałw dynamice tego rozwoju mają rozwiązania systemowe, w tym również rozwiązania prawne. Od wielu lat toczy się dyskusja dotycząca strategii rozwoju polityki energetycznej uwzględniającej wykorzystanie odnawialnych źródełenergii. W tym kontekście prowadzone są również badania i analizy skoncentrowane na uwarunkowaniach rozwoju energetyki wiatrowej. Spora część z nich identyfikuje różne przeszkody we wdrażaniu i rozwoju energetyki wiatrowej (polityczne, społeczne, prawne, środowiskowe). Analizy barier prawnych są zazwyczaj dokonywane na wysokim poziomie ogólności. Niniejszy artykułzawiera szczegółowy przegląd barier prawnych mających wpływ na lokalizację wież elektrowni wiatrowych w Polsce. Polska to kraj, w którym restrykcyjne przepisy zablokowały możliwość realizacji takich projektów lub skłaniają inwestorów do wyboru lokalizacji, na których występują niekorzystne warunki posadowienia. W naszych badaniach skupiamy się na problemie projektowych konsekwencji lokalizacji elektrowni wiatrowych w trudnych warunkach geotechnicznych. W artykule przedstawiono metodę obliczeniową proponowaną w analizie statycznej fundamentów palowych wież turbin wiatrowych, która uwzględnia wzajemny wpływ pali fundamentowych na przenoszenie obciążeń na podłoże gruntowe. W pracy przedstawiono parametry geotechniczne odpowiedzialne za wyniki obliczeń, teoretyczne podstawy metody analizy osiadania pala pojedynczego oraz obliczania osiadania pali pracujących w grupie i zwieńczonych sztywną głowicą żelbetową. Na podstawie przykładowych obliczeń przedstawiono wpływ rozmieszczenia pali w fundamencie na rozkład obciążenia poszczególnych pali, a także osiadanie i obrót fundamentu wież turbin wiatrowych. Przedstawiona metoda umożliwia dokładniejsze, bezpieczniejsze i bardziej optymalne projektowanie fundamentu lądowej turbiny wiatrowej w niekorzystnych warunkach ich lokalizacji.

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