# WSTĘPNA ANALIZA ZAKRESU BADAŃ GEOLOGICZNO-INŻYNIERSKICH I PROBLEMÓW ZWIĄZANYCH Z POSADOWIENIEM TURBIN WIATROWYCH NA ZWAŁOWISKACH NADKŁADU KOPALŃ ODKRYWKOWYCH WĘGLA BRUNATNEGO – PRZEGLĄD LITERATURY

# PRELIMINARY ANALYSIS OF THE SCOPE OF GEOLOGICAL-ENGINEERING INVESTIGATIONS AND PROBLEMS CONNECTED WITH OF WIND TURBINES FOUNDATION ON THE SPOIL DUMPS SOILS IN LIGNITE OPEN-PIT MINES - LITERATURE REVIEW

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*W artykule przedstawiono wstępny przegląd pozycji literaturowych związanych z badaniami geologiczno-inżynierskimi dla celów posadowienia turbin wiatrowych z uwzględnieniem ich lokalizacji na gruntach zwałowych kopalni węgla brunatnego. Pracę zrealizowano w ramach projektu SUMAD „Zrównoważone wykorzystanie zwałowisk górniczych" finansowanego ze środków Funduszu Badawczego Węgla i Stali UE współfinansowanego przez Ministerstwo Edukacji i Nauki. W polskim prawie budowlanym brak jest norm dotyczących badań podłoża dla turbin wiatrowe. Są one tam określane, jako budowle nietypowe, niezależnie od złożoności warunków gruntowych, których wykonanie lub użytkowanie może stanowić poważne zagrożenie dla użytkowników lub konstrukcje zawierające nowe rozwiązania techniczne niewystępujące w przepisach i niesprawdzone w praktyce krajowej. Obiekty tak scharakteryzowane zaliczane są wg Prawa Geologicznego i Górniczego do trzeciej kategorii geotechnicznej, która wymaga szczegółowych badań geotechnicznych, dokumentacji geologiczno-inżynierskiej oraz projektowania geotechnicznego według norm PN-EN1997-1 EUROKOD 7 i PN-83/B-03020. Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z 2012 r. [11] przedstawia ogólny zakres badań geotechnicznych, które muszą być wykonywane przy projektowaniu fundamentów, w tym turbin wiatrowych. Warunkiem koniecznym tego typu posadowienia jest odpowiednia nośność podłoża, jego stateczność oraz zdolność do przyjmowania różnorodnych obciążeń statycznych i dynamicznych. Duże znaczenie ma również ograniczenie możliwości generowania geozagrożeń i negatywnego wpływu na środowisko. Zwałowiska kopalń odkrywkowych węgla brunatnego są zbudowane z gruntów antropogenicznych cechujących się dużą niejednorodnością i zmienną litologią. Są one zbudowane w przewadze z gruntów ilastych o niskiej wytrzymałości, a grunty piaszczyste o korzystnych parametrach występują podrzędnie. Grunty zwałowe posiadają domieszki substancji organicznych, są podatne na duże osiadanie i mają wysokie ryzyko generowania osuwisk i przemieszczeń, nawet przy małych obciążeniach. Grunty zwałowe o niskiej wytrzymałości nie nadają się do posadowienia turbin wiatrowych. Dlatego duże znaczenie mają reprezentatywne badania geologiczno-inżynierskie zawierające badania terenowe i laboratoryjne w tym testy in-situ i modelowanie, oraz ich korelacja i analiza przez inżyniera geotechnika i projektanta fundamentów w celu sprawdzenie możliwości posadowienia turbiny w określonym miejscu. Typowe badania powinny obejmować 1-2 otwory, około 20-50 m głębokości (w zależności od wysokości turbiny wiatrowej), 1-3 sondowania in-situ w celu określenia parametrów wytrzymałościowych gruntu CPTU, DMT, badanie presjometrem Menarda, sondowanie dynamiczne (w przypadku gruntów niespoistych), badania wytrzymałości na ścinanie, badania in-situ w celu określenia sztywności gruntów w przypadku małych odkształceń (SCPTU, SDMT); pobieranie próbek NNS do badań laboratoryjnych (testy podstawowych parametrów fizycznych gruntu, edometryczne, trójosiowe). Zaawansowane analizy stateczności powinny uwzględniać reprezentatywne parametry wytrzymałościowe gruntu oraz działające na niego siły. Kompleksowe analizy geotechniczne wymagają uwzględnienia geometrii konstrukcji, zmienności przekazywanych naprężeń w czasie, etapów procesu budowlanego oraz wieloaspektowego zachowania się gruntu. Złożoność konstrukcji turbiny wiatrowej i jej praca pod obciążeniami cyklicznymi wymaga przyjęcia reprezentatywnego modelu geotechnicznego gruntu o wiarygodnych parametrach. Przyjęte do analizy fundamentu parametry mechaniczne i odkształceniowe gruntu powinny realistycznie odzwierciedlać jego zachowanie przy zmiennych obciążeniach. Oszacowanie nośności gruntu powinno uwzględniać teorię równowagi granicznej. Znacznie bardziej skomplikowana analiza przemieszczeń konstrukcji turbiny wiatrowej wymaga zastosowania zaawansowanych metod modelowania. Podstawowym problemem projektanta posadowienia jest złożoność interakcji sił cyklicznych i dynamicznych przenoszonych przez fundament na podłoże gruntowe. Właściwie zaprojektowanie przez konstruktora fundamentu lub wzmocnienia podłoża gruntowego powinno gwarantować bezpieczne i ekonomiczne posadowienie. W każdym przypadku należy dokładnie rozważyć możliwość konkretnej lokalizacji w celu eliminacji niebezpiecznych miejsc.*

*W innych konieczne może być podjęcie specjalnych działań w zakresie specjalnych metod posadowienia, wzmocnienia gruntu różnymi technikami lub usunięcia gruntu o niskich parametrach.*

**Słowa kluczowe:** *badania geologiczno-inżynierskie, geotechnika, turbiny wiatrowe*

*The article presents a list of available literature items related to geological-engineering investigations for the foundation of wind turbines, taking into account their foundation on the spoil dumps after lignite mining. The work was carried out on order within the EU project RFCS SUMAD agreement 847227. The work was performed under the SUMAD project entitled: "Sustainable Use of Mining Waste Dumps" financed within Research Found for Coal and Steel and co-financed by Ministry of Education and Research. In Polish Construction Law there are no standards for geological engineering investigations for this type of facility. Wind turbines are referred there as atypical structures, regardless of the complexity of ground conditions, whose construction or use may pose a serious threat to users or structures containing new technical solutions not present in the regulations and not proven in national practice. The objects so characterized are classified, according to the Geological and Mining Law, in the third geotechnical category, which requires detailed geotechnical tests, geological-engineering documentation, and geotechnical design according to the standards PN-EN1997-1 EUROKOD 7 and PN - 83/B – 03020 [4-7]. The Regulation of the Minister of Transport, Construction and Maritime Economy of 2012 [11] presents the general scope of geotechnical tests that must be performed when designing foundations, including wind turbines. The necessary condition for this type of foundation is the representative bearing load capacity of the ground, its stability, and ability to take various static and dynamic loads, limiting the possibility of generating geo-hazards together with a negative impact on the environment. Lignite opencast mine spoil heaps are characterized by high heterogeneity and variable lithology. Apart from the sandy soils with favorable strength parameters, they are mostly built of low strength clayey soils. These soils are prone to high subsidence and have a high risk of generating displacement, even at low loads. Organic low-strength clayey soils are not suitable for the foundation of wind turbines. Therefore, representative geological-engineering studies, field and laboratory tests, and correlation of the obtained test results are very important to check the possibility of its foundation in the specified place. This is required by a geotechnical engineer and foundation designer. Typical investigations should include 1-2 boreholes, approximately 20-50 m depth (depending on the wind turbine height), 1-3 in-situ sounding to determine the strength and stiffness parameters of the soil (CPTU, DMT), dynamic sounding (for non-cohesive soils), vane undrained shear strength tests, in-situ testing to determine the stiffness of soils for small deformations (SCPTU, SDMT); NNS sampling for laboratory testing (index, oedometer, triaxial). Advanced stability analyses should take into account the representative strength parameters of the soil and the forces acting on it from the wind turbine. Complex geotechnical engineering analyses require taking into account the geometry of the structure, variability of transmitted stresses in time, stages of the construction process, and multi-aspect behaviour of the soil. The complexity of the wind turbine structure and its operation under cyclic loads requires the adoption of a representative geotechnical model of the ground with reliable soil parameters. The parameters describing the mechanical and deformation properties of the soil, adopted for the analysis of the foundation, should realistically reflect the behaviour of the soil during variable structural loading. The estimation of the bearing capacity of the soil by analytical methods is performed by civil engineer constructor according to the limit equilibrium theory as a standard. A much more complicated analysis of the wind turbine structure displacement requires the use of advanced modelling methods. The basic designer problem is the complexity of the interaction of cyclic and dynamic forces transmitted by the foundation to the subsoil. Properly designed reinforcement of the subsoil should guarantee the safe and economic foundation of the wind turbines. In each case, the possibility of a specific location should be carefully considered to eliminate dangerous sites. In other cases, it may be necessary to take special measures in terms of special methods of foundation, reinforcement of the soil with various techniques, or removal of soil dump soil with low parameters.*

**Keywords:** *geological-engineering investigations, geotechnical engineering, wind turbines*

## General conditions for geotechnical engineering investigations for wind turbine foundation

Designing a safe foundation for wind turbines is one of the most difficult engineering tasks. Its foundation requires free from geological hazard, stable geotechnical conditions. Stresses generated by wind turbines have a complex nature and are changing constantly. This includes the horizontal stresses due to wind, the lateral ground pressures, the vertical loads, and the loads connected with generated vibrations (Fig. 1). The foundation design should safeguard it and minimize the costs. Shallow foundations are found in regions with strong soils and they transmit the loads to the nearest soil layer. The foundation's weight ensures the stability of the structure and transfers the loads to the ground. A deep foundation is used in difficult soil conditions and transmit the applied loads to stronger bedrock layers. The static diagram of a power plant tie is a cantilever in the form of a thick-walled steel pipe anchored in the foundation of the power plant and transferring the loads to a monolithic foundation which is a plate footing or pile support. The bearing capacity of the foundation is reduced due to the cyclic loads. The wind turbine foundation must be supported by the ground beneath it. It must remain stable even if any geological problem in the soil will occur [2].

Wind power plants with a capacity of 2-2.5 MW are usually approx. 100 m high and have foundations of variable thickness in the shape of an octagon described on a 20 m diameter circle. There are several types of wind turbine foundations solutions. Its types are based on soil geotechnical properties and acting loads. method is based on several factors. First, the most important is the engineering geology conditions in the area of planned investment. The next is the size of the wind farm, costs, and the experience of the designer. Wind turbine foundation cost could vary significantly from country to country due to the variation of construction cost. Usually, the foundation cost range depends on soil properties, the foundation type, and dimensions. According to Danish resources the octagonal raft foundation range from \$ 100,000 to \$ 200,000 depending on dimensions [3]. A cost-benefit study showed that the foundation on good quality soil without piling makes up 3-7% of the total costs of the wind turbine. Deep foundations on the other hand come at a much higher up to 28% costs and take longer to construct. However in the occurrence of low strength soils, if they reach stiff bedrock they provide good performance for settlement and tilting, and the decision process the chosen foundation solution should provide a balance cost, speed of construction, quality, and performance.

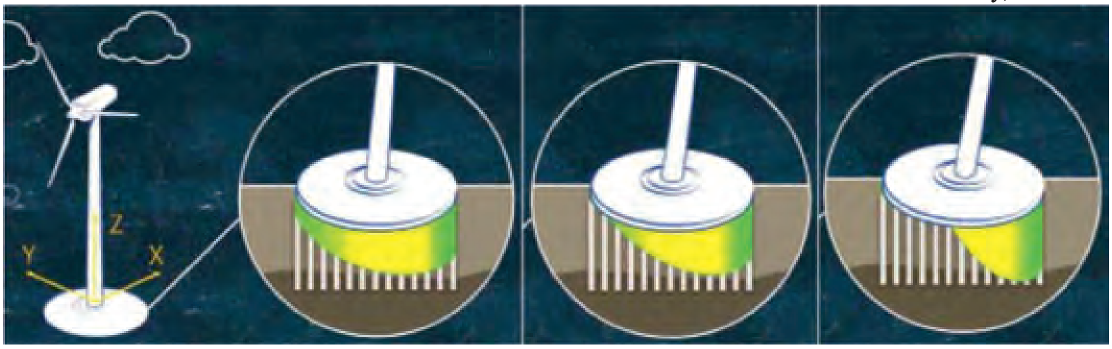


Fig. 1. Diagram of stress change under the foundation of the wind turbine [3]
Rys. 1. Schemat zmian stanu naprężeń pod fundamentem turbiny wiatrowej [3]

A very important factor affecting foundation stability is the presence or absence of groundwater. Foundations subjected to the hydrostatic buoyancy may differ from each other by 30%. With this in mind, before the investment, it is recommended to monitor water conditions with piezometers and analyze available archival material from at least the last 20 years [3]. Analysis of the morphology of a given area in the context of groundwater accumulation and existing streams may also be helpful. When weak soils are occurring up to a depth of 10-15 m below ground level, it could be cheaper to reinforce the soil. The most popular solutions include concrete columns CMC (Controlled Modulus Columns), creating soil and concrete columns composite, BMC (Bi-Modulus Column Method), is a kind of complement to the CMC technology, DPS (Deep Soil Mixing Columns) in drilling holes by improving soil properties by mixing them with cement. Rigid concrete columns are topped with a gravel head that improves the stress distribution. SC columns (Menard Susceptible / Supple Column) are also available as an advanced variant of gravel and injection columns. At greater depths, piling is most often used. The foundation reinforced by soil columns and the pile foundation differ from each other in the type of soil-structure cooperation. The foundation using the columns is separated by a so-called transmission layer (40-100 mm) which makes them work independently (in case of very weak soils it should be reinforced with geosynthetics). The piles are connected rigidly to the foundation through reinforcement. Due to the nature of observed loads, the parameters of the subsoil need to be checked in terms of load-bearing capacity and instability that include settlement and susceptibility to dynamic loads. According to Eurocode 7 (ENV 1997: 1:1994) [5], the eccentricity of the resultant vertical force causing the gap between the ground and the base of the foundation cannot exceed 0.6 radius of the eaves inscribed in the octagon of the base of the foundation. These include maintaining the conditions of dynamic rotational stiffness of the ground, specified by the manufacturer of wind turbines by parameter $k_{jdyn}$ [Nm/rad]. Non-fulfilment of the conditions of dynamic stiffness of the ground often forces the reinforcement of the ground. In most cases, during the construction of a wind farm, several locations require soil reinforcement. The choice of the reinforcement

Anthropogenic spoil dump soils from lignite open-pit mines are often built from low strength clayey soils, of high heterogeneity and variable lithological content. These soils are prone to high settlement and have a high risk of subsidence or collapse, even under low loads. Soft and organic soils are not suitable for any type of foundation. In every case possibility of specific localization of wind turbines should be carefully considered. In difficult soil conditions, the safe location of these types of infrastructure could be impossible or special measures may have to be adopted for the foundation including special ground improvement. In general, in such conditions, the most usual solution is to support the construction on piles transferring the loads to the resistant bedrock sub-stratum below the spoil dump, taking into account the negative skin friction which spoil dump soils could produce. Another option is soil reinforcement by different techniques as CMC, DSM, BMC, or SC columns [17]. If the low strength spoil dump is not very thick the best solution could be its removal.

Depending on local conditions sometimes fills (or spoil dumps) can be treated additionally by grouting, grouting, dynamic compaction (for non-cohesive soils), preloading, and other additional techniques including chemical and biological remediation but these techniques couldn't be recommended as a main for ground improvement.

The type and dimensions of every foundation will depend on the strength parameters of the ground and the load types. The basic condition for the safe and economic operation of this type of power plant is a properly designed foundation [12, 13]. Its design must meet the following conditions:

1. Foundation must be stable and have an adequate factor of safety (the ratio between different types of static and dynamic loads on the ground and the ultimate shear strength of the ground).
2. The elasticity or deformability of the ground must be acceptable, i.e. that displacement such as settlement, horizontal movements, or rotation, caused by the deformation of the ground due to the stresses transmitted by the foundation will be limited to tolerated by the structure of wind turbine and permit it to function as it was designed.
3. Foundation of wind turbines must not affect nearby infrastructure, the effects of foundation on the ground must be tolerable outside limits of the structure under construction. This means ensuring that they do not have any negative effects on other infrastructure outside them. It is also important that it will be impossible that nearby infrastructure will affect the wind turbine foundation.
4. It must be durable to ensure that the above conditions will last throughout the intended life of the wind turbine.

This means considering the possible change of the initial conditions to [3]:

1. Changes in the volume of the ground due to the collapse of poorly compacted landfills (low strength spoil dump soils) or naturally collapse soils such as loess or silts.
2. Changes in the volume of the ground due to changes in the moisture content of potentially expansive clayey soils.
3. Undermining in river beds and banks.
4. Soil erosion from broken sewers or other water pipes.
5. Deterioration of the concrete used for the foundations from contact with aggressive soil or groundwater.
6. Fluctuations in the water table, which may cause changes in effective stresses or the strength and deformability of the soil.
7. Landslides, if the construction is considered on an unstable slope.

Geotechnical problems for foundations or its failure tend to occur in the following situations:

1. Lithological heterogeneity, where the material of different strength occurring in the same area under the foundation.
2. Low strength soils under foundation, when deep competent stratum is below foundation level, which may require deeper and more expensive foundations (Fig. 2).
3. Adverse geotechnical factors such as high groundwater table, intensive seepage processes steeply sloping ground, aggressive water, and materials.
4. Anthropogenic fills and spoil dumps with very high compressibility, contamination, gas generation, and erratic geometry.
5. Solutions cavities and soft, expansive, organic collapsible, or soluble soils.

In the case of points, no 1-3 foundations should include piles, rafts, dewatering. In the case of points, 4-5 that representing most of the lignite spoil dump soils besides the techniques listed above will require additional special measures and ground improvement. The most frequent engineering geology problems for foundations were observed in expansive and swelling clays, collapsible soils, karst cavities, soft and organic soils, and anthropogenic fills. Every wind turbine foundation should be designed in stages. These stages are described below.

Fig. 2. Failure of wind turbine foundation [1]
Rys. 2. Katastrofa fundamentu turbiny wiatrowej [1]

1. Collecting data connected with wind turbine structure and the loads envisaged and their distribution. Loads generated by wind turbines have a very complex nature, the horizontal due to wind, the lateral ground pressures, the vertical loads, and the loads connected with generated vibrations.
2. Geotechnical site reports should pay particular attention to ground shear strength and deformability. Strength is expressed as the angle of internal friction and cohesion, or the undrained shear strength in the case of clayey soils. Deformability is expressed as the deformation modulus or compression index and where long-term settlement is predicted as the coefficient of consolidation. The non-uniformity or heterogeneity of the ground should also be considered as the differential settlement may occur if a foundation covers ground that has different properties (or include organic material).
3. Defining the ultimate shear strength of the soil and applying a factor of safety, to obtain the allowable pressures. Deformation or settlement from the loads applied to the ground has to be estimated and analyzed to determine if the structure of the wind turbine will be safe and tolerant.
4. Designing the foundation, its dimensions, shape, and needed reinforcement.
5. Comprehensive recognition of soil strength conditions is basic for foundation design.

These data together with the factors described above could define the need and the type in the reinforcement of the soil.

**Methods of the geotechnical analysis of the wind turbine foundation**

The soil under the foundation is exposed to an approximate triangular stress distribution due to the overturning moment

M=H x h, where H is the resultant horizontal force from the wind and h is the vertical distance between the line of action of the resulting horizontal force and the tower base (Fig. 3). Soil can't carry any tension stresses at the interface between the foundation and the soil. Therefore the effective contact between the foundation and the soil is expected to be decreased as the overturning moment from the wind load increases. The effective foundation area is the centrally loaded area. The effective foundation area depends on the value of the load eccentricity and the foundation radius and is is elliptic.

The design of wind turbine foundations needs the following requirements [2]:

***a) check of the foundation for bearing capacity***

Shallow wind turbine foundations have to be designed to keep the maximum imposed concerning the allowable bearing capacity of the soil. There are two expressions relate to the bearing capacity of the soil: ultimate bearing capacity $q_u$ which is theoretical maximal pressure that could be supported without causing shear failure and allowable bearing capacity which is equal ultimate bearing capacity divided by the factor of safety $f_s$. The allowable bearing capacity should be used in the geotechnical design.

***b) check for overturning***

To prevent overturning, the loads must be balanced by loads from the ground acting on the bottom surface of the foundation. Wind turbines could be subjected to high horizontal loads. These loads could cause overturning or sliding failure (Fig. 3).

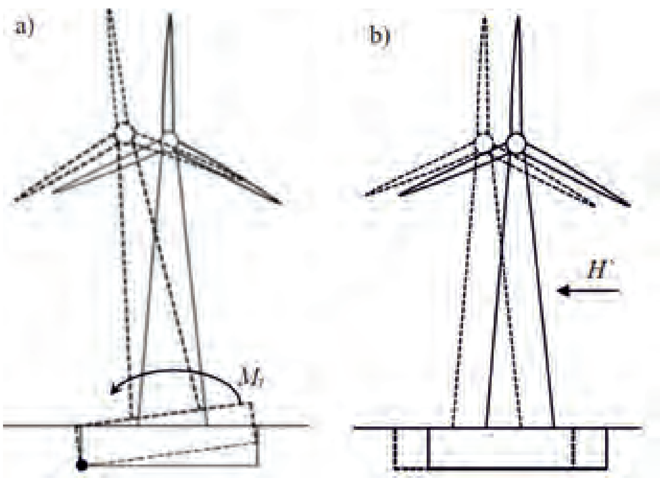


Fig. 3. Failure of wind turbine a) overturning, b) sliding, $M_t$ – total overturning moment $H$ – horizontal force [2]
Rys. 3. Katastrofa turbiny wiatrowej a) przewrócenie się, b) poślizg, $M_t$ – całkowity moment siły przewracającej, $H$ – siła pozioma [2]

***c) check for settlement and tilting***

Provided that shear failure, overturning, and sliding are prevented, settlements and tilting are considered serious problems for shallow wind turbine foundations that rest on week soils, especially spoil dump. To calculate maximum settlement and tilting for this type of soil numerical modelling using finite element software is usually used. The maximum settlement for any type of shallow foundation should not exceed allowable settlement. These allowable values depend on the foundation type and the soil type, for example, the allowable settlement is 12 cm for the raft foundation according to Eurocode 7. The allowable settlement for the same foundation is 10 cm for sand and 15 cm for clay. For anthropogenic spoil dumps soils observed settlements could reach extremely high values even to several meters. The check for bearing capacity, sliding resistance, and overturning resistance is used to compare the foundation solutions, check the properties of foundation options, calculate the required raft diameter, and find the appropriate choice.

Depending on the complexity of the soil conditions, implemented in-situ tests, three methods of analysis for the foundation of wind turbine foundations could be performed [16, 17].

They could be based on:

- type A - empirical patterns,
- type B - standard engineering programs that provide the analysis of the structure, characterizing the soil as a resilient bedrock,
- type C - finite element method – 2 D or 3D numerical analyses of the interaction between soil and wind turbine foundation.

A-type analysis

The verification of the bearing capacity of the foundation must be carried out under the official standards. This method is taking into account the reduction of the bearing capacity due to cyclic loads.

Since the first boundary condition is in most situations not a dimensional condition, basic calculation programs used for the calculation of standard foundations can be used for its estimation. In the case of the insufficient load-bearing capacity of the soil, it is not necessary to analyze the movements of the foundation on the unreinforced ground. The next step in method A is the analysis of the condition of acceptable differential settlements of the foundation. In most cases, the canting criteria to be met by the foundation are determined by the manufacturer of the turbine, while the extent of tearing off should be adopted according to the applicable national guidelines and engineering practices. It should be stressed here that the A method displacement analysis for eccentrically loaded wind turbine foundations gives inaccurate results. The manufacturers of turbines in most cases give acceptable differential settlements of wind turbine foundations equal to S < 3.0 mm/m. Due to the uneven load distribution, the dimensioning of differential settlements using the analytical method may be inaccurate [2]. Differences in the settlement are a critical condition for the displacement of the structure. The condition of maximum settlement is an element that is not dimensional when designing this type of structure.

- A-type analysis for the foundation in the reinforced substrate

Where the soil load-bearing capacity is insufficient or its deformability is too high, the special reinforcement of the soil under the foundation is recommended. An alternative to the reinforcement is piles connected with the foundation. This solution is more expensive and also less safe due to the cyclical load acting on piles. Depending on the adopted soil reinforcement technology two types of analysis could be performed. If the reinforcement is characterized by high rigidity, e.g. CMC columns, the analysis could be based on rigid support theory. The external resistance and the length of the columns should be determined under applicable standards and guidelines. Substrate reinforcement in susceptible technologies (e.g. SC, BSM, or DSM columns) can be analyzed like a foundation founded on a homogeneous medium with averaged parameters.

- B type analysis

This type of analysis is recommended for estimating displacements for simple and complex ground conditions. To estimate the cooperation of the reinforcement with the soil substrate, the stresses between the soil and the piles should be estimated. The estimation of this parameter is based on the thickness of the layer and the modulus of deformation. This type of analysis consider the elastic substrate, otherwise known as the Winkler substrate.

- C-type analysis

The C analysis is based on the use of the Finite Element Method, which enables accurate mapping of the stresses in the structure under normal conditions. Analyses could be performed using the following soil models:

- Coulomb-Mohr,
- Hardening Soil,
- Small strain,
- Linear Elastic.

This method not only allows for the accurate implementation of the geometry of the structure but also the soil models, which could reproduce the cooperation of the soil and the reinforcement elements.

**Polish practice of geotechnical investigations for the foundation of wind turbines**

Although the first wind turbines were built in Poland more than 20 years ago until now no official technical standards are dealing in detail with the foundation of this type of facility [15]. Polish engineers usually applying EU standards, or other foreign and Polish regulations.

Under the "Regulation of the Polish Minister of Transport, Civil Engineering and Maritime Economy of 25 April 2012 on establishing geotechnical conditions for the foundation of buildings" § 4. 1 point 3b and 3c [10] and the "Regulation of the Council of Ministers of 9 November 2010 on projects that may have a significant impact on the environment" [10] wind turbines may be described as not typical construction, regardless of the complexity of the ground conditions, the execution or use of which may pose a serious threat to users" or „constructions which contain new technical solutions not found in the regulations and not tested in national practice". Objects so characterized are classified in the third geotechnical category, which requires detailed geotechnical tests, geological-engineering documentation, and geotechnical design under PN-EN1997-1 EUROKOD 7 [4] and PN - 83/B – 03020 [6] standards. The first regulation from 2012 presents the general scope of geotechnical tests that need to be carried out when designing foundations, including wind turbines. The geotechnical design procedure for a shallow foundation consists of four parts. The first involves determining the applied loads on the foundation. The second ceding soil investigations to provide all needed data of the ground properties. These investigations consist of laboratory testing of samples and in-situ testing. The third is a geotechnical design and the final part involves a structural design. The geotechnical design considers many aspects such as determination of required foundation type and dimensions and the required foundation weight to remove the failure probability of the foundation considering soil bearing capacity, sliding, overturning, settlement and tilting. For the installation of wind turbines, it is necessary to perform detailed geological-engineering documentation to check the possibility of its foundation in the specified place by a geotechnical engineer and foundation designer. Advanced stability analyses should take into account the representative strength parameters of the soil and the forces acting on it from the wind turbine. Complex geotechnical engineering analyses require taking into account the geometry of the structure, variability of transmitted stresses in time, stages of the construction process, and multi-aspect behaviour of the soil. The complexity of the wind turbine structure and its operation under cyclic loads requires the adoption of a representative geotechnical model of the ground with reliable soil parameters. The parameters describing the mechanical and deformation properties of the soil, adopted for the analysis of the foundation, should realistically reflect the behaviour of the soil during variable structural loading. The estimation of the bearing capacity of the soil by analytical methods is performed according to the limit equilibrium theory as a standard. A much more complicated analysis of the wind turbine structure displacement requires the use of advanced modelling methods. The basic designer problem is the complexity of the interaction of cyclic and dynamic forces transmitted by the foundation to the subsoil. Properly designed reinforcement of the subsoil should guarantee the safe and economic foundation of the wind turbines. The geotechnical design is about the soil or bedrock involved for the building or the civil engineer work. Normally a construction has got some kind of connection to the ground. The most common situation is that the construction is footed on the ground directly, but piles are also commonly used [9]. These connection elements together with the surrounding soil or bedrock should be design concerning possible deformations and observed the strength of the soil.

When designing wind turbine foundations it is necessary has to consider several possible types of failure ( Eurocode 7) [5]:

- Failure due to the geotechnical capacity in the soil (GEO)
- The impact on structural elements, resulting in the failure in the soil (STR)
- Overall equilibrium in the geostructure (EQU)
- Lost equilibrium caused by hydraulic uplift or other vertical lifting forces (UPL)
- Bottom relaxation or erosion caused by the hydraulic gradient (HYD)

The geotechnical design requires information about soil parameters such as thickness, type, and weight ( unit weight - $\gamma$ ) of the soil layers, the shear strength (effective friction angle - $\varphi_e$, shear stress - $\tau$,), the groundwater level (GWL), the over-consolidation ratio (OCR), and the stiffness properties. To retrieve information on these parameters a ground investigation and laboratory testing are necessary. Due to the shape of the foundation, it is necessary to make at least three core impregnated geological engineering boreholes for each power plant. Their depth should be determined based on the stress influence depth (H), which is estimated from relation H=2B (where b is the diameter of the foundation, it is usually about 25 m). It is recommended to carry out field tests up to a depth of about 1.5 diameters of the foundation. The most frequent drillings are made at a depth of about 25 m [2]. It is very important that at the stage of designing geological-engineering research, people deciding on its scope and methods of the foundation are aware of the very high complexity of cooperation between the wind turbine structure and the ground.

The exemplary field tests, which should be carried out to properly design the foundation of the wind turbine, should include:

a) 3 boreholes, approximately 20-50 m depth (depending on the wind turbine height)
b) 1-3 in-situ sounding to determine the strength and stiffness parameters of the soil:
- CPTU tests,
- DMT tests,
- Menard pressuremeter tests,
- Dynamic sounding (for no-cohesive soils),
- Vane undrained shear strength tests
- In-situ testing to determine the stiffness of soils for small deformations:
- SCPTU tests,
- SDMT tests,
- NNS sampling for laboratory testing.
c) index, oedometer, triaxial CIU, CID tests.

Based on field and laboratory tests (index tests of basic physical soil parameters, including content of organic material, IL oedometers compressibility tests, and triaxial compression tests) the following parameters should be determined, which are necessary for the correct design of the foundation of the structure:

- Type of soil with division into lithological layers,
- Maximum groundwater table level,
- The leading parameters obtained from the sounding for the individual layers, e.g. resistance of the $q_c$ - cone resistance, $R_f$ - friction ratio, and $u$ - generated pore pressure parameter,
- Effective soil strength parameters,
- Soil strength parameters without drainage,
- Deformation parameters of soil,
- Soil strain modulus E for the strain range ($10^{-2} > E > 10^{-3}$),
- shear modulus G for the deformation range ($10^{-2} > G > 10^{-3}$),
- Poisson's ratio in the drained and undrained conditions.

In spoil dump soils high content of organic material will influence its compressibility. Spoil dump clayey overburden transported by conveyor belt system has usually very low strength especially if it is highly saturated by groundwater. Its index strength and compressibility parameters should be carefully studied on a representative number of samples. The parameters for prediction of possibilities of wind turbines foundation should be based on the in-situ test data calibrated by the laboratory tests.

**Problems in recognition of soil strength parameters for the foundation of wind turbines in the Polish geotechnical practice**

The lack of official standards for geological - engineering documentation for wind turbines in Poland creates several problems. The scope and quality of geotechnical research are crucial for the planned foundation works. In Poland, it often happens that geological-engineering tests are carried out in a quick time and general manner, which contributes to the overestimation of design solutions or exposure to damage to the structure during its use. Bearing this in mind, for this type of foundation global standards should be followed. In Poland, geological-engineering surveys carried out for wind power plants include dynamic soundings of PPL and DPH type when the investigations are performed in non-cohesive soils. For cohesive soils, most often samples are taken and laboratory tests are performed. CPTU tests are also performed, but they are not always correlated with laboratory tests. Sometimes SCPTU seismic cone tests are also used to determine the dynamic strain modules of the soil. Proper calibration and interpretation of in-situ tests are one of the main tools used in the work of the foundation designer, hence the quality of geological-engineering survey and the degree of recognition of the soil influence the further design process. However, some investigators pointed out that, despite the use for this purpose modern in-situ testing methods, the final soil strength parameters are not representative and often determined only based on the simple index tests [2]. This usually includes only the IL degree of plasticity from the previous PB-81/B-03020 Polish standard. These parameters often do not correlate with the results of in-situ field tests. In Poland at the stage of the design project, the type of foundation is determined mostly only by the constructor, who does not always have extensive geotechnical experience. The participation of an authorized geotechnical engineer expert, who will prepare geotechnical opinion and will be participated in the foundation design process, is not required. This leads to erroneous interpretation of soil compressibility parameters where oedometer modules determined using these two methods for the same geotechnical layer were varied by 200%. For example, the analysis of wind turbine foundation subsidence based on the oedometer module calculated from IL degree of plasticity slightly exceeding the soil mechanic limit state by 10%, whereas for the modules determined from CPTU and DMT tests exceeded it by 75%. In the case of not typical building foundations, the determination of soil parameters using the PB-81/B-03020 standard should be abandoned. Soil strength parameters determined based on the degree of compaction and plasticity may lead to serious design errors. It is recommended to perform in-situ tests CPTU or DMT tests and calibrate them carefully through laboratory tests. Data from these tests have a direct impact on the value of the designed wind turbine foundations and its construction. A less danger is the situation when the consequence of poor geotechnical investigations is over the sizing of the foundation. However, it is worse when the foundation is underestimated and there is a risk of its damage. Due to the nature of the construction of wind turbines and its third geotechnical category, it is required to prepare a geotechnical design according to the guidelines of the turbine manufacturer. The shape and size of the foundation should be determined by the structural civil engineer designer and based on static numerical analysis. The dimensional criterion is the lack of tearing off the foundation for characteristic loads from DLCQP (quasi-permanent loads combination) actions. This condition must be met for a direct foundation. For a deep foundation, the absence of pulling forces in piles must be ensured. The guidelines and standards define the range of permissible pulling forces for the other types of foundations. All destabilizing effects (e.g. groundwater influence and displacements) and other factors must be taken into account. The importance of checking the dynamic stiffness condition of the foundation rotation should be stressed. This analysis should aim to exclude the overlapping of the vibrations transmitted from the turbine and the natural frequency of the foundation footing. In this way, the resonance condition could be checked. Failure to meet this criterion leads to a dramatic increase in displacement, which may destroy the foundation structure.

**Examples of wind turbine foundation in Polish opencast mines**

In Poland location of wind turbines at spoil dump soils started in 2001 external spoil heap in Belchatow opencast mine. Another installation of the wind turbines in Adamow mine is now in progress and will be finished in December 2020. The PGE Group wind power plant installed at former external spoil heap in Belchatow mine called "Mount Kamiensk". This remediated area of 1480 ha is an artificial hill with a height of 386 m above sea level was created as an external dump volume of 1350 million m$^3$ at the southern end of the Belchatow Upland. The relative height of the hill is about 195 meters. Its dumping began on 6 June 1977 and was completed in November 1993, when KWB Belchatow was storing the entire overburden on the internal spoil heap. Installed at the top of Mount Kamiensk, 15 wind turbines have a capacity of 2 MW (each). The 40 m long blades give the total capacity of the wind park about 30 MW produces energy for about 6 thousand farms.

The "Przykona" wind farm in the former Adamow opencast mine will be operated by Energa OZE Manufacturing with a capacity of 31 MW [8] (Fig. 4). The turbines will be placed on 117 m high towers. The farm is being built the area of 250 ha remediated after the Adamow open-pit lignite mine closure. The work is proceeding according to the schedule. Recently the foundation for the seventh generator has been completed. Because of the anthropogenic clayey spoil dump soil, i.e. not naturally formed, but as a result of mining activities, it was decided to use DSM columns and KKS. Each of the foundations used about 540 m of concrete and 70 tons of steel of armaments. The installation of complete wind turbines is planned to begin in December 2020. According to the plans, infrastructure will be permitted to work in the second quarter of 2020.

**Summary and conclusions**

Wind turbine foundation design is a complicated issue, especially in low strength spoil dump soils. With the Polish regulation of 27 April 2012 on geotechnical conditions of the foundation of the buildings, wind turbines should be classified in geotechnical category III as „power facilities". The foundation of such objects requires the representative quality of in-situ and laboratory test data for the design. Properly design tests and modelling methods are necessary due to the complexity of static and dynamic loads of the above-mentioned structures. The role of designers and the geotechnical environment is to return investors' comprehensive data connected with geotechnical conditions, soil strength parameters, and all other possible hazards which are the input materials for designing the foundations of the wind turbines. The geotechnical investigation from the site is providing information about the soil layer sequence, the distance to the bedrock, the strength and stiffness parameters of the soil layers, the groundwater level, and its variation. This information is valuable when deciding the foundation level if special methods of foundation or soil improvement are needed. In good soil strength conditions wind turbines could be located at former spoil heaps, as it was done in Belchatow opencast and will be realized in Adamow opencast mine soon. However, it should be noted that not every spoil heap will be proper for such a foundation. In Belchatow mine wind turbines foundations were located in predominately sandy spoil dump soils of relatively good geotechnical parameters. In Adamow mine in low strength, clayey spoil dump special reinforcement and protection techniques will need to be used. The problem of the foundation of wind power plants on the weak ground can be effectively solved provided that several conditions are met, which include the performance of high-quality geological-engineering studies and the application of a well-selected technology for strengthening the ground adapted to the prevailing groundwater conditions. If the soil is strong and stiff and the groundwater level is at great depth a spread foundation is to prefer. This is the simplest wind turbine foundation method in many respects, it is a well-proved foundation that is easy to construct and easy to design. It is generally also a cheap method as no piling work is necessary. In a situation where the soil does not show sufficient bearing capacity, replacing part of the soil could be helpful [3] (cost-justified replacement is about 1.5 m). If the soil parameters are worse the sufficient area of a spread foundation is quite big to keep the ground pressure below the soil's capacity [1, 3]. The required amount of concrete is getting very big as the volume increasing with the squared distance, and another foundation method may be more cost-efficient. There are several possible alternatives besides the spread foundations then. One good solution can be to foot the foundation deeper in the ground. If the capacity of the ground is better at a greater depth, the width of the foundation can be decreased thanks to

Fig. 4. Construction of Przykona wind turbine foundation [8]
Rys. 4. Budowa fundamentu turbiny wiatrowej w Przykonie [8]

the bigger vertical load from the overlying soil. This will result in a smaller eccentricity of the load. The disadvantage of this solution is the major excavation work this requires. If the site is remote and the excavated soil cannot be used as refilling material this may be an expensive method. Compacting the soil, or add some strength to the soil with help of lime/cement columns or grout is another solution for soil improvements. These methods are expensive, but can yet be realistic if the soil quality is poor. If the soil layer sequence shows that a strong and stiff layer is at reasonable depth it can be a good solution to drive piles to this layer. The piles are then functioning as toe-bearing piles, and soil above the strong layer is not carrying any load. To ensure that the piles are not buckling, the sub-grade modulus of the soil cannot be too low [3]. The same is valid for piles driven to the bedrock. A benefit with the bedrock-driven piles is that the piles can be anchored in the bedrock to handle tension forces, though this requires very solid and strong bedrock. If the bedrock is at great depth and the soil hasn't got enough stiffness for a reasonable big spread foundation it can be a good method to install cohesion piles [1]. To reduce the number of piles and the pile length a calculation model which assumes that both the plate and the piles are bearing load, can be of interest. It is then necessary that the designers have highly reliable information about the stiffness parameters of the ground to model this in the right way. Oversized reinforcement can result in too big loads in the piles and a failure can occur. The proper decision for the foundation is not easy and requires high-quality geotechnical data and monitoring. Attention should be paid to the geotechnical risks and costs of the applied soil reinforcement and stabilization solutions. The location of wind turbines on anthropogenic spoil dump soils could be risky therefore it should be carefully chosen and checked by advanced geotechnical in-situ, laboratory, and modelling methods by certified and experienced in wind turbines foundation projects geotechnical and civil engineering experts.

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