# Geotechnical Exploration for Wind Energy Projects

## Compagnes géotechniques destinées aux parcs éoliens

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ABSTRACT: Wind energy projects are often fast-paced and cover large terrains. Such conditions result in increased geotechnical risks and require specially adapted geotechnical exploration and data analysis techniques that are designed to manage risks at different stages of project development. Use of geophysical methods, in addition to the traditional subsurface exploration methods, is generally required to collect design critical data. During the early stages of project development, using quick qualitative geophysical methods can prove advantageous for finalization of wind farm layout and preliminary foundation design. However, as project plans progress, a more thorough geotechnical investigation is required. At all stages of a project, an understanding of the available geotechnical tools, along with their associated risks and cost implications is essential to minimize the likelihood of design changes that result in cost over runs. This paper presents geotechnical exploration methods used at different stages of project development and discusses key geotechnical parameters for wind turbine foundation design, available geotechnical tools, and the degree of confidence associated with these tools. The paper makes an attempt to present an exploration approach that is optimized for efficiency and risk.

RÉSUMÉ : Les projets d'énergie éolienne sont souvent réalisés dans un contexte d'exécution rapide et couvrent des terrains de grandes envergures. Ces conditions présentent des risques géotechniques accrus et nécessitent des compagnes d'exploration géotechnique et des techniques d'analyse de données spécialement bien adaptées pour gérer les risques à différentes étapes du projet. Le recours à des techniques géophysiques en plus des méthodes d'exploration traditionnelle est généralement requis pour obtenir les données critiques. Durant les premières étapes du projet, le recours à des méthodes géophysiques qualitatives et rapides peut s'avérer plus avantageux pour établir " la faisabilité du projet, " le plan d'implantation du projet et la conception préliminaire des fondations. Toutefois, dans les étapes plus avancées, une étude géotechnique plus poussée doit être réalisée. A toute étape, une connaissance adéquate des méthodes géotechniques disponibles, des risques et coûts qui leurs sont associés est essentielle pour minimiser l'éventualité de changements à la conception résultant en dépassement de coûts. Cet article est un essai de présenter une approche d'exploration optimisant l'efficacité et le risque.

KEYWORDS: geotechnical exploration, risk management, wind energy, efficiency.

## 1 INTRODUCTION

The period leading up to an operational wind energy plant starts several years before construction and can be divided into three overlapping phases: project development, engineering design, and project construction (Figure 1). During the development phase, various risk types and sources are evaluated and decisions are made to maintain, modify, or abandon the project. During the engineering design phase, decisions are made to refine the design while maintaining acceptable levels of risk. Any subsequent changes to the design typically result in additional cost. This paper focuses on geotechnical risks, particularly how such risks are being addressed currently and how this process may be improved. The objective is to assess risks and catch flaws as early as possible in the project development phase while there are still opportunities to make changes before significant development funds are spent. As in all large expenditure projects, early decisions have the greatest impact on financial performance. The motivation of this paper is to minimize the cost of civil infrastructure related to wind energy projects (turbine foundations, access roads and facilities such as the substation and the operation and maintenance building) through a rational redistribution of the geotechnical exploration effort. It has been estimated that civil infrastructure accounts for 4 to 10% of the total wind energy project cost. Given the thin profit margins of wind energy projects, a 2% saving can make the difference between whether a project goes ahead or is shelved.

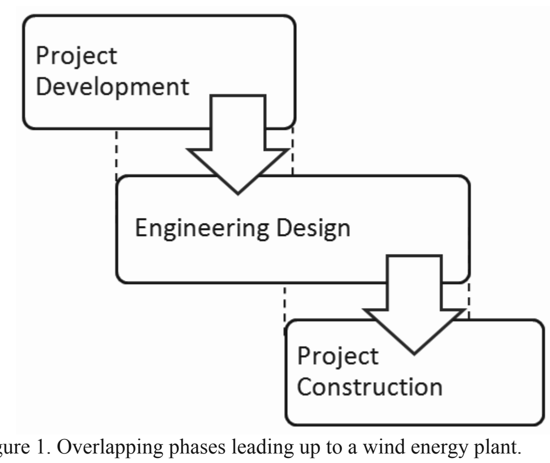


Figure 1. Overlapping phases leading up to a wind energy plant.

## 1 PROJECT REALISATION PHASES

All three project phases (development, design, and construction) involve some level of geotechnical risk assessment and management, with most of this effort currently focused at the engineering design phase. Current and proposed activities related to geotechnical risk assessment for each phase are described below.

### 1.1 *Project Development Phase*

During the project development phase, the developer is usually focused on wind resource assessment, land agreements, power purchase agreements, and identifying potential investors. The geotechnical aspect is secondary and is typically limited to site visits and reporting of surficial characteristics such as terrain topography, accessibility, proximity to bodies of water, etc. The initial environmental permitting effort presents an opportunity to identify geotechnical conditions that carry cost implications as most environmental permitting efforts include an evaluation of geo-environmental conditions. However, the development phase of a wind project rarely includes geotechnical field investigation activities. However, the development phase is the most opportune time to identify significant geotechnical risks. The findings of a preliminary geotechnical investigation conducted during the development phase rarely render the project non-pursuable. However, preliminary geotechnical investigations are critical to proper planning and allocation of risks to the appropriate stakeholders. The achievement of the benefits of this proposed shift can be formalized through techniques such as geostatistics, Bayesian updating, statistical inference and neural networks (Christian et al. 2006 and Lin and Hung 2011). An immediate benefit of a more holistic development phase exploration is to focus the detailed exploration effort on the critical issues or portions of the project area. In addition to desk studies, recommended development phase exploration techniques include:

- Geophysical surveys using seismic methods such as Multi-Analysis of Surface Waves (MASW) at all proposed turbine locations, possibly excluding locations where rock is at the surface. An MASW survey provides depth profiles of shear and compression wave velocities. The information is used to gain an insight into site stratigraphy and to estimate elastic moduli needed to verify foundation stiffness requirements. The MASW survey, conducted at the project development phase, helps to identify soft locations or locations with potential difficulties as an aid to micrositing of turbines. This exercise lessens the likelihood of needing very large foundations or performing costly ground modifications at soft sites. MASW surveys are also quick and relatively low cost, making them the ideal qualitative tool that is suited for the development phase.
- Preliminary geotechnical exploration borings using a limited number of traditional SPT, SCPT, CPT, or DMT borings spread over different portions of the project area. Exploration pits may also be used along planned access road alignments. Information obtained through site visits and review of available published information and online maps can be used to decide on the locations of the preliminary borings so that the captured range of variability is as wide as possible. Information from the preliminary exploration is used to assess the type and range of variability of site geomaterials, to identify potential foundation types and to plan the full investigation. For example, if a gravity base (shallow) foundation is deemed feasible, an effort should made at the project development stage to assess the depth range of the stationary groundwater table in order to decide if buoyancy will be a design consideration. If soft materials are encountered requiring consideration of deep foundations, the depth of borings during the full investigation can be adjusted.
- The preliminary geotechnical exploration should also include electrical and thermal resistivity testing as this input is critical to sizing the electrical collection system which is associated with a significant share of project cost.

### 1.2 *Engineering Design Phase*

During this phase, a full geotechnical investigation must be carried out to finalize the design. The full geotechnical study is designed to complete the investigation and to fill the gaps remaining after the preliminary exploration. The full investigation should confirm and refine the assessment of the risks identified during the preliminary investigation and should assess any additional risks that may be uncovered. At a minimum, standard practice includes at least one exploratory boring at every turbine location extending to a depth of interest not less than the largest base dimension of the structure (DNV/Risø 2002, GL 2010). For a typical shallow foundation used to support wind turbines, the explored depth is 1 to 1.5 times the foundation diameter. Common current practice is to perform geophysical testing during the full investigation phase at a limited subset (approximately 10%) of turbine locations. In the proposed redistribution of effort, a more extensive geophysical survey is recommended at the development phase. A non-exhaustive list of risks that should be assessed as early as possible during the development and preliminary design phases (but prior to the final design phase) is shown in Table 1. Geotechnical exploration activities help in identifying these risks but are not the sole resource.

Table 1. Non-exhaustive list of potential wind farm geotechnical and geo-environmental risks (in no particular order).

| *No.* | *Risk* | *Identification tools* |
|---|---|---|
| 1 | High groundwater | Drilling, excavation pits, monitoring wells and permeability testing. |
| 2 | Flooding, storm surge, tsunami | Records, maps |
| 3 | Shallow bedrock / blasting | Visual, drilling, MASW |
| 4 | Slope stability & landslides | Visual, geologic study |
| 5 | Mine subsidence | Records, LiDAR, maps |
| 6 | Coal seams | Drilling, records |
| 7 | Karst subsidence, caves & voids | Records, drilling, LiDAR, maps, type of underlying rock, groundwater regime |
| 8 | Shrink/swell (expansive) soils | Laboratory testing |
| 9 | Frost heave | Records, climatic data |
| 10 | Permafrost | Records, climatic data |
| 11 | Freeze-thaw | Climatic records |
| 12 | Collapsible soils | Laboratory testing |
| 13 | Excessive consolidation / tilt | Laboratory testing |
| 14 | Aggressive environments: high sulfates, high salinity, corrosion | Laboratory testing |
| 15 | Alkali-Silica Reaction (ASR) | Testing, local information |
| 16 | Peat bogs and soft grounds | Visual, drilling, MASW |
| 17 | High seismicity / liquefaction | Exploration, design codes |
| 18 | Hurricanes | Records, design codes |
| 19 | Volcanic activity | Records, geologic study |
| 20 | Scarcity of gravel / road base | Visual, local information |
| 21 | Buried pipelines & infrastructure | Records |
| 22 | Forest logging roads | Drilling, excavation pits |
| 23 | Drifting sands | Visual, local information |
| 24 | High soil electrical resistivity | Field and lab testing |
| 25 | High soil thermal resistivity | Field and lab testing |

### 1.3 *Project Construction Phase*

During the construction phase, geotechnical activity is typically limited to quality assurance testing which serves to confirm and ensure that the design assumptions remain valid. This is the phase where risks missed during the earlier phases may become apparent with the potential for project cost overruns.

Rarely would geotechnical input in this phase result in cost savings. However, *value engineering* where the balance of plant (BOP) contractor is provided an opportunity to redesign is becoming more popular. Value engineering often occurs shortly before construction or as the BOP contractor is mobilizing to construct the project. Ironically, the likely reason for value engineering is the tendency of the original designer to err on the conservative side because of compressed schedules and/or lack of substantive geotechnical basis of design at the end of the development phase, creating opportunities for the BOP contractor to cut costs at the last minute.

### 1.4 *Summary of Current and Proposed Practice*

Table 2 shows a summary of current and proposed practice. The essence of the proposed redistribution of the geotechnical exploration effort is to advance the geophysical survey and the preliminary investigation to the development phase (P1). Details of the geotechnical activities for the proposed redistribution are shown in Table 3.

Table 2. Common and proposed geotechnical effort.

| | Common | | | Proposed | | |
|---|---|---|---|---|---|---|
| Phase | P1 | P2 | P3 | P1 | P2 | P3 |
| Desk study | X | | | X | | |
| Geophysical survey | | X | | X | | |
| Preliminary investigation | | X | | X | | |
| Full investigation | | X | | | X | |
| Assurance & validation | | | X | | | X |

Phases: P1 = Development, P2 = Design, P3 = Construction

Table 3. Wind farm realization phases and proposed geotechnical activities.

| *Phase* | *Proposed minimum geotechnical activities* |
|---|---|
| Development | • Desk study:<br>○ Often required for permitting but can be useful in planning preliminary investigation<br>• Geophysical Survey<br>○ All turbine locations except possibly sites where rock is at the surface<br>○ Useful for micrositing<br>• Preliminary Investigation<br>○ Drilling at a subset of turbine locations distributed strategically to capture maximum variability<br>○ Excavation pits along potential access road alignment<br>○ Electrical and thermal resistivity testing<br>○ Limited laboratory testing |
| Design | • Full Investigation<br>○ Drilling at all turbine locations<br>○ Extensive laboratory testing<br>○ Fill all gaps to form design basis |
| Construction | • Construction QA/QC<br>○ Confirm validity of design assumptions<br>○ Ensure compliance with design requirements |

## 2 SOURCES OF UNCERTAINITY

Wind energy projects differ from most traditional projects in that they cover large terrains. Wind turbines are typically placed 5 to 10 rotor diameters apart to optimize energy extraction (Denholm et al. 2009). Nowadays, typical rotor diameter for large wind turbine generators is around 120 meters, signifying turbine spacing of 0.5 to 1 kilometer just for energy extraction efficiency. Therefore, wind turbines are too far apart to consider any relationship between ground conditions from one turbine location to another. This is separate from regional or larger scale characteristics which may be applicable to the project area or portions of it, such as those related to different geologic settings or terrains. Turbine structures themselves are also unique due to the nature of loading they impart to foundations and supporting soils in terms of type, magnitude and variation. Thus, in addition to increased uncertainty due to essentially independent conditions at turbine locations, these projects also require parameters unique to these structures such as those needed to ensure adequate foundation stiffness.

Generally, there are three main sources of uncertainty in a geotechnical design property: i) inherent soil variability, ii) measurement error, and iii) transformation error (see Baecher and Christian 2003, Phoon and Kulhawy 1999). Often, a design parameter is not measured directly in-situ or in a laboratory test but is calculated based on other measured properties. Two of the above sources (inherent variability and measurement error) are associated with the measured property. The third source is associated with uncertainty in the selected transformation model, i.e., the empirical or theoretical relationship used to calculate the design property from the measured properties. Point estimates, as well as spatial variability of various shear strength, mechanical and index properties, are available in the literature (e.g., Lee et al. 1983). This information can be used to select the test methods that result in lowest variability depending on the soil type. In this section, uncertainty sources are discussed in more detail as they relate to wind energy projects.

### 2.1 *Uncertainty Due to Inherent Soil Variability*

Inherent soil variability is related to the natural geologic processes that produced the soil and should not include the influence of deterministic trends (e.g., trends due to depth), mixing of soils from different geologic units, or measurement errors. In the case of wind projects, inherent variability should be considered at each individual turbine location.

Another source of uncertainty is related to spatial variability extending vertically and horizontally to dimensions of influence. Uncertainty related to spatial variability is affected by the scale of fluctuation or correlation distance which is an important statistical parameter loosely defined as the distance within which the values of a given parameter are significantly correlated (Fenton and Griffiths 2008). Due to the often layered nature of soils, the correlation distance is typically shorter in the vertical direction than in the horizontal direction. Engineering design practice, including that within the wind energy industry, considers single (or point) variables to represent properties of an entire soil mass. Thus, in designing a shallow foundation for a wind turbine, for example, traditional practice assumes an infinite horizontal correlation length where a single value is assumed for the soil in each layer. Furthermore, while focus is on variation in the vertical direction, geotechnical exploration rarely goes beyond one boring at the center of the foundation unless there is strong reason to believe conditions are non-uniform in the lateral directions, such as in cavitose terrain. Thus, knowledge of the vertical spatial variation is often limited to the line of the boring. On the other hand, knowledge in the horizontal direction is limited to the observation and verification of the exposed foundation bearing surface. This is very limited information but standard practice. This is also why at least two forms of exploration should be carried out at each turbine location: a traditional boring and a seismic survey (MASW).

### 2.2 *Uncertainty Caused by Measurement Error*

Measurement uncertainty is related to the equipment being used, in-situ or laboratory test procedures, and random data scatter. Naturally, measurement error is different for different test procedures. Reported measurement error data have been summarized for various laboratory and field tests by various investigators (e.g. Phoon and Kulhawy 1999). It is worthwhile to note that the highest variability attributed to in-situ test measurement error is that corresponding to the Standard Penetration Test (SPT). The error introduced by sample size is sometimes considered as a measurement error. Normally, the greater the number of data points or sample size, the smaller the error. However, beyond a rather low number of samples, it is more important to capture the full range of variability than to obtain more data points. There are numerous simplified rules to estimate standard deviation and variability based on the range and number of samples (Tippett 1925, Withiam et al. 1997, Whitman 2000 and Foye et al. 2006). For this reason, the effort to capture the full range of variability as early as possible is very important to the early assessment of risks.

### 2.3 *Uncertainty Caused by Transformation Error*

Transformation or model errors are introduced when test measurements are used to calculate the desired design properties using empirical or theoretical relationships. The sources of the error include the fitting errors in the case of empirical equations and the simplification/idealization errors in the case of theoretical relationships. The transformation errors for several design properties (undrained shear strength, effective stress friction angle, Young's modulus, horizontal stress coefficient, etc.) have been compiled (e.g. Phoon and Kulhawy 1999) for various laboratory and in-situ test methods. Noteworthy remarks from these compilations include:

- Higher variability (as expressed in higher coefficients of variation) result for sand properties obtained though correlations with SPT blow counts, especially if "universal" empirical relationships are used; i.e., relationship not calibrated to a specific geology. Hence, "local knowledge" seems to be important for interpretation of SPT results.
- Higher variability is typically obtained for sand properties than for clay properties.

## 3 CONCLUSIONS

Wind energy projects are almost always developed and built under compressed schedules where project realization phases overlap. They also cover large terrains that involve wide variability of geotechnical and geo-environmental conditions. For these reasons, geotechnical risks must be addressed as early as possible during the development phase to avoid overlooking fatal hazards that can shelve or financially devastate the project. This paper proposes to conduct extensive, low cost and quick geophysical surveys during the development phase to help with turbine micrositing and to gain an insight into the variability of the entire project area. The paper lists potential hazards that should be assessed and discusses sources of geotechnical uncertainty and how they relate to wind energy projects.

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