Old layout, new layout - the same geotechnical campaign?

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Fraunhofer IWES develops a technology to quantify geotechnical information on unexplored locations. © *Fraunhofer IWES*

'Measure twice, cut once' as the old proverb goes. And it is true. A thorough geological site investigation campaign is one of the most important sources of data when it comes to designing foundations. Especially in the case of high-risk offshore constructions such as wind turbines. However, what should we do if the style changes even before we start to cut? Or, even worse, climate change forces us to sew a summer dress instead of making a winter coat? Should we measure once again? Moreover, what if the client is far away and does not want to be bothered? Can we deduce the missing values for the new dress pattern from existing measurements?

All of these questions arise if the layout of a wind farm changes after the geotechnical campaign has been completed. It may take several years to develop an offshore wind farm project from the initial desk studies through to the construction phase. During this time, a number of reasons may lead to changes to the original wind farm layout, the position of the wind turbines in relation to each other. One of them is the continuing development of wind turbine technology itself and the availability of ever larger and ever more efficient turbine generations during the planning phase. Another reason results from the geophysical and geotechnical campaign itself. Some locations, although theoretically leading to a high wind yield, may incur high foundation costs due to their geological settings: e.g., glacial channels filled with soft sediments.

However, changes to the turbine layout usually have to be approved by the corresponding authority. The requirements of the different national regulatory authorities can vary greatly. For example, German authorities normally require a

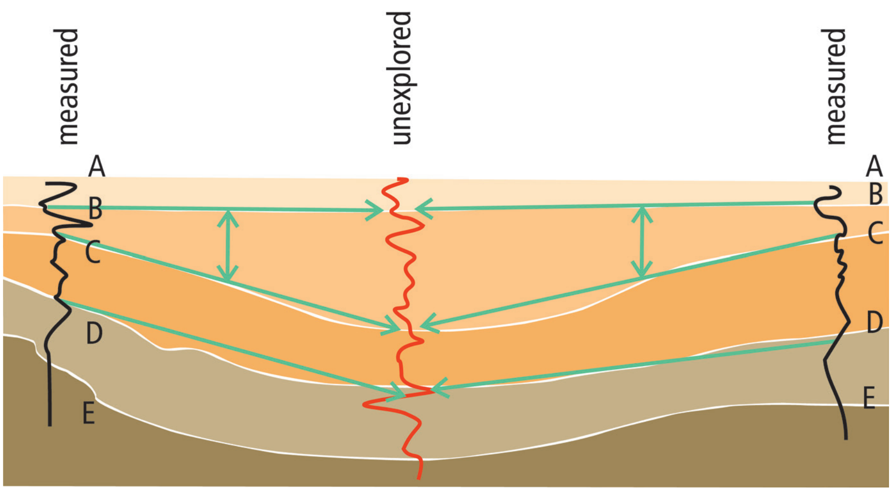
borehole or a cone penetration test at every planned wind turbine location to prove and confirm the proposed foundation design. Consequently, if changes are made to the layout during the project planning phase, a new geotechnical campaign is generally needed. In certain cases, however, regulatory authorities will accept an estimation of the soil properties at unexplored locations based on available data. Nevertheless, the project, including the layout changes and the foundation design, still has to be certified and officially approved.

How are the soil conditions at a geotechnically unexplored site estimated? The key words here are 'synthetic cone penetration test' and 'intelligent ground model'. Intelligent ground models allow the extraction of geotechnical data at any point of the wind farm site based on the interpolation of geotechnical data supported by geophysical data. Thus, the building of intelligent ground models containing geotechnical parameters of interest is currently one of the most important interdisciplinary topics in the endeavor to optimize site characterization efforts for wind farm development. To construct such a model, the available seismic and geotechnical in situ measurements, sometimes also laboratory data, are passed through a sieve of interpolation techniques.

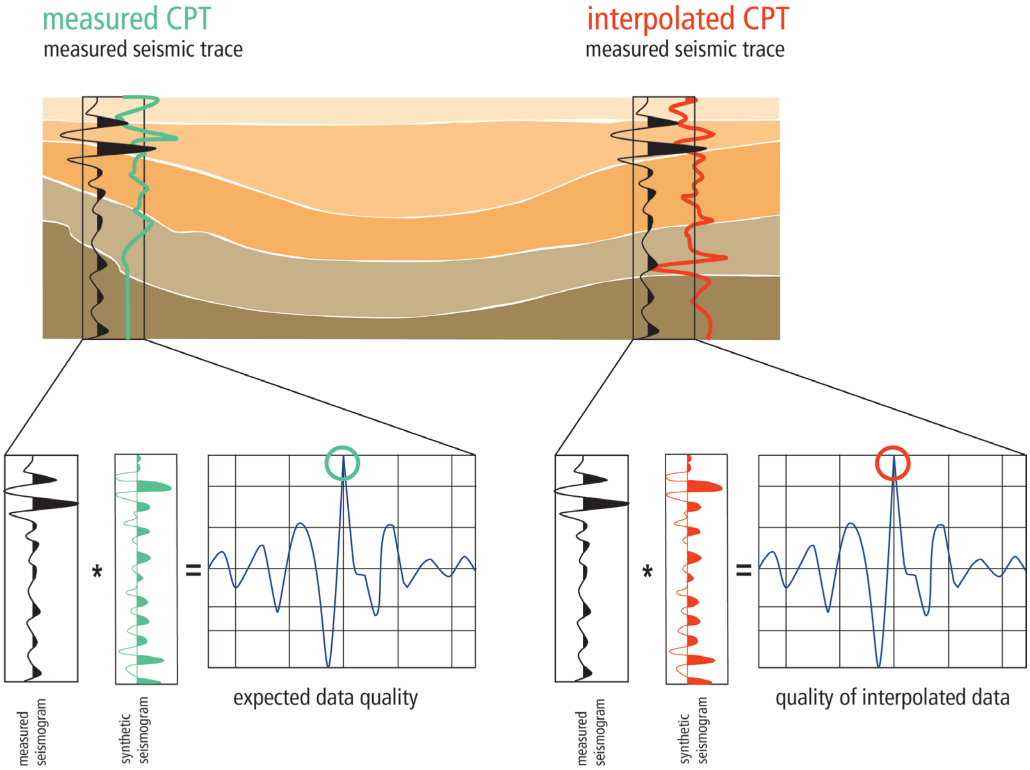
The specific technique is selected based on the availability and quality of the measurements, the project timeline, and the financial constraints. Currently, interpolation methods such as linear regression, inverse weighted distance, radial basis functions, and kriging-based techniques are applied to fill the gaps between the actual data points obtained by measurements. Here the main challenge lies in the nature of the data. They are multivariate, uncertain and unique, sparse, and incomplete, as postulated by modern geostatistics. As the geological conditions may change abruptly between investigated locations, predictions based solely on the proximity of the data points may easily fail and lead to undesirable and sometimes even fatal results in terms of costs.

To supplement sparse geotechnical data, other data sources should be used to guide interpolation. Such additional data need to be related to the geotechnical parameters. Seismic measurements can be well suited for this purpose. Seismic surveying is usually carried out prior to the geotechnical campaign, providing 2D or even 3D coverage of the whole wind farm area. On the one hand, the seismics can provide the stratigraphic constraints to guide the interpolation along the layer boundaries. On the other hand, recorded seismic signals can also be related to the geotechnical parameters of interest and therefore provide additional control of the interpolated values. Furthermore, seismic measurements are far more cost-effective per location in comparison to the direct measurements and borehole data, as the whole area is covered at once.

Seismic data can guide and justify the interpolation results of the geotechnical information. However, seismic data are acquired in travel-time units below the source and receiver geometry and the geotechnical data are acquired in meters below the seafloor, rendering dependable depth



1 Interpolation of geotechnical information between explored locations taking seismic measurements into account. © *Fraunhofer IWES*



2 Application of the synthetic seismogram for quantification of interpolation quality on unexplored locations. © *Fraunhofer IWES*

conversion of seismic data necessary. The resolution of the cone penetration tests can be as high as 50 measurements per meter. The seismic wave is up to several meters long and cannot provide the same fine details. Careful integration of the two datasets is thus essential for successful site characterization.

Since 2015, the Fraunhofer IWES has been advising wind farm developers on layout changes and helping them to gain regulatory approval in case of changing layouts during ongoing planning phases. To acquire the necessary seismic data to support CPT interpolation, the IWES relies on 2D and 3D seismic acquisition systems developed in-house at the institute. The interpolation results of geotechnical data guided by seismic reflection data are validated using blind tests. For a blind test, one measurement is omitted and compared with the prognosis for this location, resulting in a measure of the interpolation quality. The quantitative assessment of the achieved interpolation quality can be obtained using synthetic seismograms.

Synthetic seismograms are artificial seismic traces derived from a given geological section and an idealized seismic wavelet. In this case, they are created using primarily geotechnical information at the location of interest before being compared to the seismic traces measured in the vicinity of the measurement locations. The comparison of explored locations with the corresponding seismic data provides an overview of the expected correlation quality between geotechnical and seismic measurements (see figure 2 above).

In the next step, synthetic seismograms at the unexplored locations are created using inferred geotechnical information and compared with the seismic traces actually measured (see figure 2 above). A specified measure, for example the coefficient of correlation between the synthetic and the real seismic trace, provides a quantitative assessment of the interpolation quality. In this example, the interpolated geotechnical data is assigned a quantitative parameter describing the quality of the interpolated data, which can then be used for design purposes.

This unique approach has allowed justification of the quality of the interpolated CPTs at unexplored locations, approval of the foundation design, and successful certification of the wind farm project by the TÜV Süd.

Current research and outlook

The interpolation quality itself depends on the quality of the input parameters – both the primary (geotechnical) and the secondary (seismic) information. The quantification of interpolation uncertainty is key to ensuring the optimal usability of the generated data for foundation design. Depending on the sensitivity of the design method, the acceptable uncertainty range of the interpolated data may be broader or narrower. In a current research project, the Fraunhofer IWES and its partners are linking the uncertainties in model building to the design purposes in order to provide wind farm developers with additional quantitative tools for the assessment of project risks and associated costs.

Using the wide range of Fraunhofer IWES activities, we plan to extend this technology to minimize the occurrence of layout changes in later project phases by taking into account both the meteorological and geological information right from the early phases of wind farm planning. The model not only considers the wind direction, wakes, and water depths so as to find the optimum layout, but also includes additional variables such as the costs for foundations and cables. The integration of these inputs into the cost function for the wind farm will provide the most cost-efficient layout.

Conclusion

Synthetic CPTs are the solution for filling the gap between explored geotechnical locations. With additional application of synthetic seismograms, we are not only providing a mean of filling this gap, but also quantifying the interpolation quality in a cost-effective way. Of course, care is required in the interpretation of the results so as to avoid possible pitfalls, but guidance offered by experienced interdisciplinary teams of scientists and engineers can help to find the most suitable solution for the given data, time, and financial constraints.

The journey to successful project certification will lead through comprehensive data analysis, interpretation, and integration. To return to the sewing analogy: we may change the style and adapt the sewing machine, but we do not have to bother the 'client' again. Stop measuring – start sewing!

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