Office of Emerging Technologies Program Briefing Paper

Project Start Date: 9/18/13
Project Title: *"Design of Wind Turbine Monopiles for Lateral Loads"*
Contract Number: E13PC00017
Project Completion: 9/18/15
Contractor: University of Texas at Austin

Purpose:
The objective of this research was to evaluate the suitability of API RP 2A/2GEO for the design of wind turbine monopiles and to provide recommendations for improving the design method for these types of foundations.

Scope of Work:
The Final Report for this study included the results of the research for the four tasks outlined in the contract:

1. Lateral Load Test Database – A database of lateral load tests, with a particular focus on large diameter and low slenderness, was compiled. Currently it includes a total of 76 tests and includes both field and laboratory tests.
2. Lateral Load Tests on Model Monopile – The tests in the database was supplemented with model tests conducted on monopiles that ranged from 1-in to 4-in in diameter. Tests were carried out under 1-g condition and in several different clay test beds.
3. Numerical Analyses –Numerical analyses were performed using the Ensoft Inc. finite-difference program LPILE and using the general purpose finite-element program ABAQUS.
4. Design Guidelines – Results from the laboratory and numerical tests were synthesized in to recommended design guidelines for wind turbine monopiles.

Conclusions and Recommendations:
The following conclusions about laterally loaded monopiles in clay were drawn based on the University of Texas at Austin's analysis of the laboratory, numerical modeling, and field test results:

1. Numerical modeling and model-scale testing with rigid piles of different diameters indicate that the form of the Matlock (1970) p-y curves, in which the lateral displacement is normalized by pile diameter and lateral soil resistance is normalized by the ultimate resistance, appropriately captures the effect of pile diameter. For very small L/D ratios (say less than one), the p-y curves near the tip may be affected by interaction with the soil resistance mobilized around the tip.
2. Field and model testing indicate that the Matlock (1970) p-y models consistently underestimate the lateral resistance when used to analyze laterally loaded piles in

normally to moderately overconsolidated clays. This observation applies to small (2 inch) and large (54 inch) diameter piles. It even applies to the Sabine River tests (Matlock and Tucker 1961) that formed the basis of the Matlock (1970) p-y models.

3. An approximate version of the Jeanjean (2009) p-y model, in which the Matlock (1970) p-y curves are scaled by p-multipliers calculated at various depths, generally provides a reasonable match to measured lateral displacements at the pile head when a relatively large strain at one-half the undrained shear strength is assumed, i.e., ε_{50}= 0.02. This result applies both to small scale model tests in kaolinite and large-scale field tests in high-plasticity clay provided that a gap does not form behind the pile.
4. The creation of a gap on the backside of the pile can lead to a reduction in the stiffness of the pile response and the ultimate lateral capacity. The creation of a gap is related both to the overconsolidation ratio and the magnitude of lateral displacement; as the overconsolidation ratio near the ground surface increases and the magnitude of lateral displacement increases, the potential for a gap increases. The Matlock (1970) p-y models provide a lower bound estimate for the response of a laterally loaded pile if a gap forms.
5. Field and model testing show that cyclic loading causes the secant stiffness of the lateral pile-soil response to degrade by up to 20 to 30 percent when the cyclic load amplitudes are 50 to 90 percent of the ultimate lateral capacity. The stiffness degradation occurs within the first 100 cycles, after which the stiffness is reasonably constant. Smaller or no degradation may occur if the lateral loading is a smaller percentage of the ultimate lateral capacity.
6. Model testing shows that the ultimate lateral capacity of the pile is not significantly affected by the previous cyclic loading.

For design of laterally loaded monopiles in clay, it is recommended that the following guidance be provided:

1. The form of the p-y curves for static loading in API RP 2GEO be adjusted using a bearing capacity factor of 8 versus 3 at the mudline and 12 versus 9 at depth for a normally consolidated to moderately overconsolidated clay (i.e., one in which a gap is not likely to form).
2. For cyclic loading in normally consolidated and overconsolidated clay, the currently recommended reduction in stiffness in API RP 2GEO (2011) be applied to the adjusted static p-y curves.
3. For lateral capacity checks under extreme environmental loading conditions after cyclic loading, the ultimate lateral resistance be represented by the ultimate lateral resistance for the adjusted static p-y curves.
4. The design of wind turbine structures be checked by both increasing and decreasing lateral stiffness of the soil that is predicted by the p-y curves in order to account for possible variations in the natural frequency of the structure.