New design methods for large diameter piles under lateral loading for offshore wind applications

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ABSTRACT: Offshore wind turbines are typically founded on single large diameter piles, termed monopiles. Pile diameters of between 5m and 6m are routinely used, with diameters of up to 10m, or more, being considered for future designs. There are concerns that current design approaches, such as the *p-y* method, which were developed for piles with a relatively large length to diameter ratio, may not be appropriate for large diameter monopiles. A joint industry project, PISA (PIle Soil Analysis), has been established to develop new design methods for large diameter monopiles under lateral loading. The project involves three strands of work; (i) numerical modelling; (ii) development of a new design method; (iii) field testing. This paper describes the framework on which the new design method is based. Analyses conducted using the new design method are compared with methods used in current practice.

1 INTRODUCTION

More than 1000 offshore wind turbines have been installed around European coastlines; further installations are planned for the next decade. These turbines are typically founded on single, large diameter, driven piles, termed monopiles. Early designs were based on monopiles with a diameter in the region of 4m. In more recent installations the typical diameter is in the region of 6m; future designs are likely to be based on monopiles with diameters of up to 10m or more. These piles are subjected to substantial overturning moments from the action of the wind on the turbine and tower, as well as wave loading on the monopile and transition piece. The method normally used to design the piles under these lateral and overturning loads is based on a Winkler modelling approach, commonly termed the *p-y* method. This approach, recommended in many of the offshore design codes (*e.g.* DNV, 2014; API, 2010), assumes that the pile acts as a beam supported by a series of uncoupled springs, each of which represents the local soil reaction. These springs are normally described by non-linear functions (*p-y* curves) to define the soil reaction, *p*, at a given depth, as a function of the lateral movement, *y*. There is a long history to the development of the *p-y* method, dating back to the 1950s and 1960s, when it was first applied to pile design for offshore oil and gas structures. The original *p-y* curves were based on the results of field tests on long slender piles, with

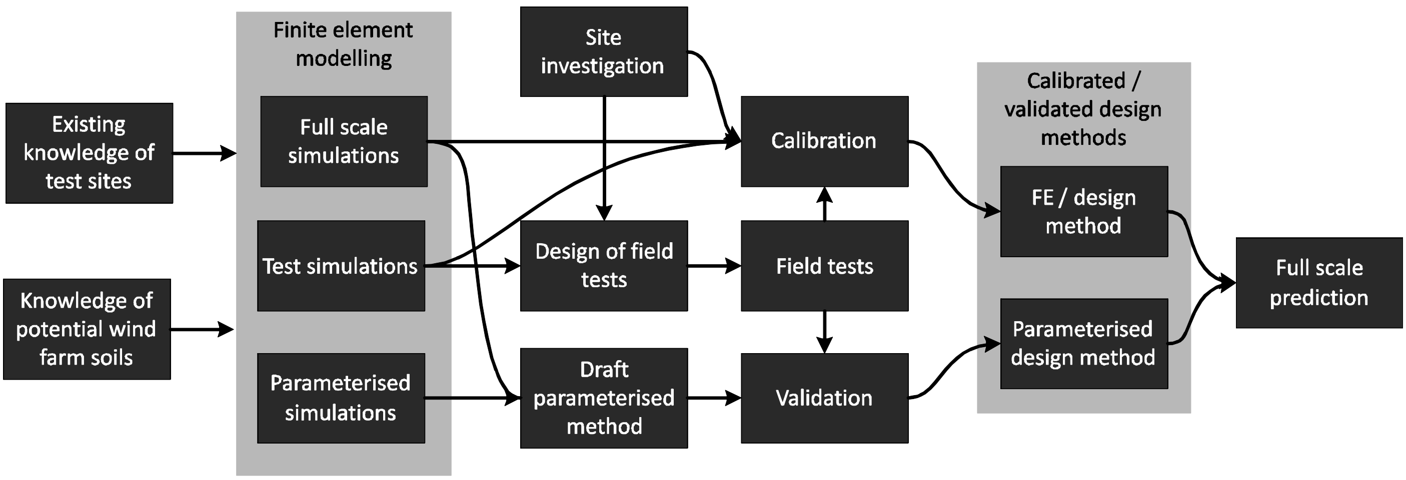

Figure 1. PISA Academic Work Group approach to the development of new design methods for laterally loaded piles.

diameters around 610mm and a length to diameter ratio of 34.

The use of the *p-y* approach for oil and gas structures, for which design is principally concerned with avoiding ultimate collapse, is considered routine practice. The pile diameters that are typically used are of the same order as the field tests from which the *p-y* method was originally developed; this provides some confidence in the reliability of the method. However, the *p-y* approach has increasingly been used, in recent years, for the design of offshore wind turbine monopiles, for which the pile diameters (and diameter to length ratios) are significantly larger than those on which the *p-y* method is based. Questions arise as to whether extrapolating the *p-y* method to large diameter monopiles is justified. Moreover, the design conditions that are relevant to offshore monopiles depart significantly from those that are typically applied in the design of the relatively slender piles used for oil and gas structures. For example, although the ultimate capacity of monopiles is important, the fatigue design and assessment of the dynamic performance of the system (turbine, tower and foundation) is also critical. In addition, a wind farm typically includes between 50 and 200 turbines. It is essential that the design of each of the turbines and support structures is optimised. Using design methods typically employed for the foundations of jacket structures for the oil and gas industries may not be appropriate. This is now recognised in a recent update (F2.4.1) to the DNV guidance on the design of monopiles (DNV, 2014).

Approach adopted in the PISA Project

A joint industry project, PISA (PIle Soil Analysis), has been established to develop new design methods specifically tailored for offshore wind turbine monopiles. The project involves: (i) numerical modelling using 3D finite element analysis; (ii) the development of a new design method, and (iii) field testing at two separate sites. The 3D modelling is described in a companion paper to this conference by Zdravkovic *et al.* (2015). The results of the field tests will be used to calibrate the proposed design method. The design of the field tests, to be conducted in late 2014 / early 2015, is described in Byrne *et al.* (2015). This research is being conducted by an Academic Work Group (AWG), comprising the current authors, supported by the larger PISA industrial consortium. The AWG began work in August 2013, on the basis of the project plan shown in Figure 1.

One variation of the new design method being developed by the AWG is based on an extension of the existing *p-y* approach, in which additional soil reaction terms are included. These extensions follow previous work by Davidson (1982), Lam and Martin (1986) and Lam (2013) for the design of piles, principally for onshore applications. In the conventional *p-y* method, the interaction between the pile and the ground is limited to modelling the lateral forces developed between the pile and the soil. It seems plausible, however, that other significant interaction mechanisms exist, especially for short, large diameter, monopiles. Four separate components of soil reaction (termed ‘soil reaction curves’) are included in the proposed design model (see Figures 2 and 3) as follows:

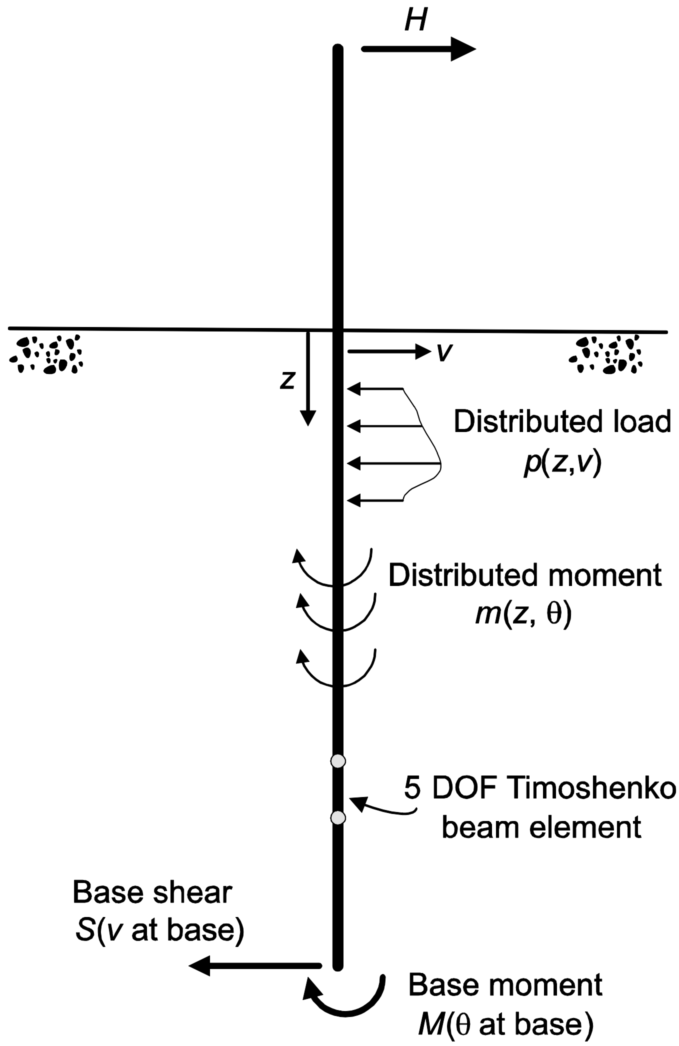

Figure 2. Framework for the proposed 1D finite model for monopile foundations.

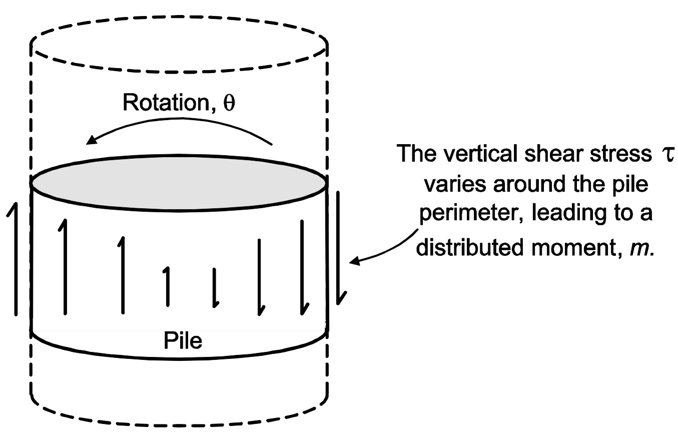

Figure 3. A distributed moment is induced by vertical shear stresses acting on the outside of the pile.

- Distributed load curve. This defines the relationship between the distributed lateral load, p, applied to the pile and lateral pile displacement v. The distributed load curve has the same function as a conventional p-y curve;
- Distributed moment curve. This defines the relationship between the distributed moment applied to the pile, m, and the pile cross-section rotation, θ. This distributed moment is associated with the vertical shear stresses, τ, developed on the pile shaft (Figure 3);
- Base shear curve. This defines the relationship between the base shear force, S, and the lateral displacement of the pile toe; and
- Base moment curve. This defines the relationship between the base moment, M, and the rotation of the pile toe.

This design model is implemented in the 1D finite element framework shown in Figure 2. The pile is modelled using Timoshenko beam theory (to include shear strain effects). The soil adjacent to the pile conforms to the same interpolated displacements that are assumed for the pile. (Note that for consistency with the nomenclature commonly used in solid mechanics, lateral displacement is denoted v in Figure 2 rather than y).

In conventional p-y approaches, standard forms of p-y curve are given in guidance notes or design standards. The curves are expressed in a mathematical form with parameters to be specified on the basis of local soil conditions. It is anticipated that the current work will lead to the development of new standard forms of soil reaction curve. However, the possibility of an alternative approach, in which soil reaction curves are established on a site-specific basis, is also being explored. In this second approach, a limited number of bespoke 3D finite element monopile models would be developed for a particular site. Data on the stresses induced at the pile/soil interface would be extracted from the numerical results and used to establish site-specific soil reaction curves. These curves would then be used in the 1D model (Figure 2) to conduct the detailed design.

2 SOIL CONDITIONS

The PISA project is focussed on the development of design methods that can be applied to any profile of sand and clay soil. To simplify the parameter space, for the purpose of developing the new design concept, current work is concerned with two reference soil profiles. Given that a number of current and future offshore wind projects are situated in the North Sea Quaternary deposits, the focus of the current work is on stiff to very stiff over-consolidated ductile Quaternary clay and dense to very dense marine Pleistocene sands. These materials are typically surface strata and therefore have a particular influence on the design of laterally loaded piles. Two on-shore sites, representative of these materials, have been chosen for the field testing phase; (a) Cowden, a clay site in north-east England, and, (b) Dunkirk, a sand site in northern France. These sites represent the typical soil conditions found at many North Sea wind farm sites. Both sites have been used for previous pile testing activities and, as a consequence, various field and laboratory soil data are available. This makes them ideal reference sites for the development of the new design methods. Details of the soil profiles are given in Zdravković *et al.* (2015).

3 NUMERICAL SIMULATIONS

Detailed 3D finite element parametric studies have been conducted (Zdravković *et al.* 2015) to provide the data that are needed to establish appropriate soil reaction curves for use in the 1D model. The soil reaction curves described in the current paper have all been determined from finite element analyses conducted on the idealised profiles described in Section 4.3 and Figures 4 and 5 of Zdravković *et al.* (2015). These parametric studies have been conducted for a range of geometries and loads (Table 1), intended to represent future offshore wind installations.

Table 1: Parameters explored in PISA numerical study.

Parameter	Range Simulated
Diameter, D (m)	5 – 10
Lateral load eccentricity, M/HD	5 – 15
Aspect ratio, L/D	2 – 6
Thickness ratio, D/t	60 – 110

Two specific pile geometries have been selected from the parametric study for detailed discussion. One geometry is referred to as 'long pile' (D = 10m, L/D = 6, M/HD = 5, D/t = 100). The other is referred to as 'short pile' (D = 10m, L/D = 2, M/HD = 5, D/t = 100).

Procedures to determine the soil reaction curves from the 3D finite element results were implemented in post-processing routines as follows. The computed normal and vertical shear stresses in the interface elements between the pile and the soil were integrated around the pile circumference to determine the local lateral load, p, and the distributed moment, m. These data were related to the local pile displacement, v, and the local cross-section rotation, θ. Computed nodal forces at the base of the soil plug, together with nodal forces computed at the base of

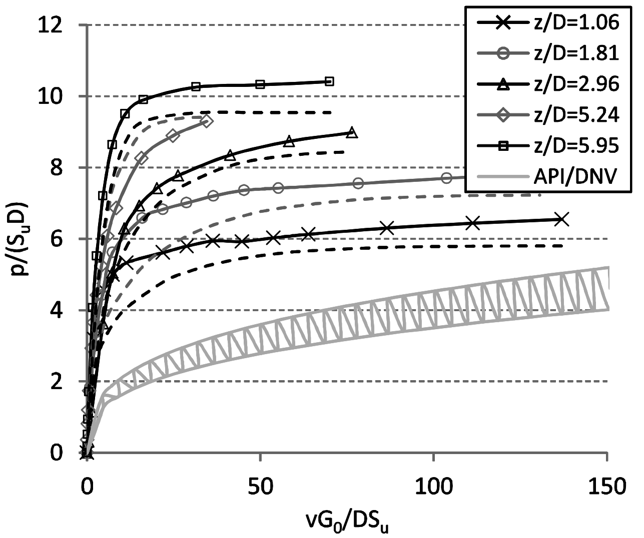

Figure 4. Numerical (solid lines) and parameterised (dashed lines) distributed load curves for the long pile in clay, plotted in dimensionless form. The region bounded by the API/DNV *p-y* curves is also indicated.

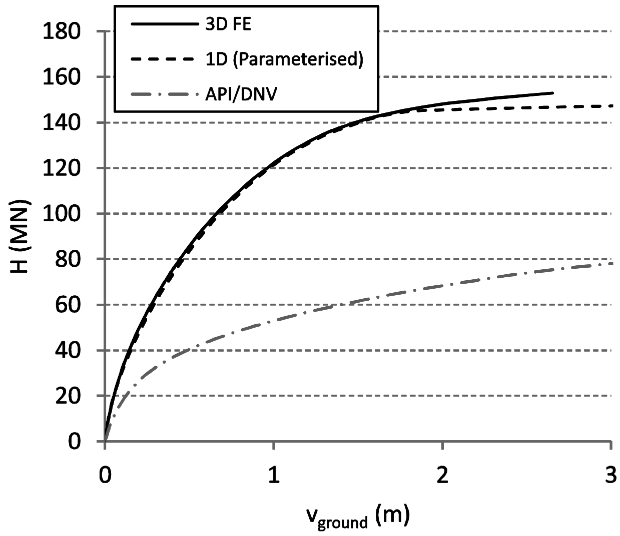

Figure 5. Long pile response in clay

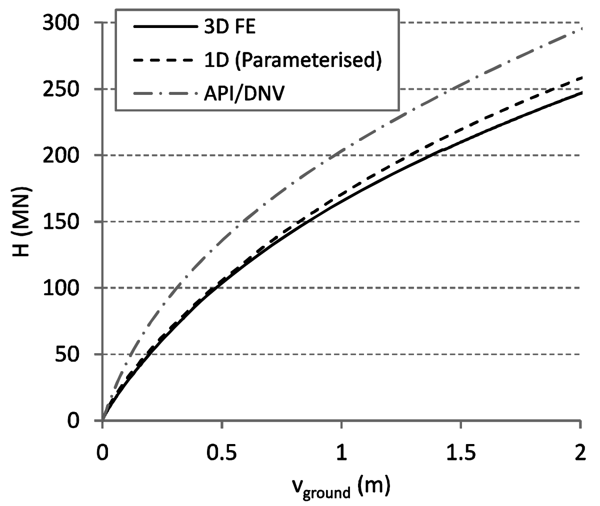

Figure 6. Long pile response in sand

the pile wall, were used to compute the moment, M, and shear force, S, developed at the base of the pile.

Two types of soil reaction curve have been determined. The raw numerical data extracted from the 3D analysis are implemented as 'numerical soil reaction curves'. Additionally, the numerical data are used to calibrate appropriate mathematical functions to represent the soil reaction curves. This latter method is referred to in this paper as the 'parameterised approach'. An important feature of the parameterised approach is that all 3D results for a particular site are represented by a single set of parameters (*i.e.* the parameters do not depend on the pile geometry).

Numerical and parameterised distributed load curves for the long pile, for an analysis conducted using the idealised clay till profile, are plotted in Figrue 4. The lateral displacement, v, and the distributed load, p, are normalised using values of S_u and G_0 determined from the 'idealised clay till profile' in Figures 4 and 5 of Zdravković *et al.* 2015. Also shown on Figure 4 are the *p-y* curves determined from API/DNV (API 2010 Section 6.8).

Parameterised soil reaction curves have been determined for all four components of the model for both the clay and the sand idealised profiles. Using these parameterised curves in the 1D model, the response of piles within the parameter space of Table 1, and in similar soils, may be predicted. Figure 5 shows the response of the long pile in clay computed using the 3D finite element model, the response computed using the 1D model based on the parameterised curves and the response computed using the *p-y* approach based on the API/DNV approach. The 1D (parameterised) method agrees well with the 3D results. The method based on the API/DNV *p-y* curves, however, significantly under predicts the stiffness and ultimate capacity of the pile. Figure 6 shows the computed results for the long pile in sand, where it can be seen that the API/DNV approach provides a more accurate, if slightly higher, prediction than is the case with the clay. The API/DNV calculation assumes a soil friction angle of 39.5 degrees, which is appropriate based on the soil profile adopted for the numerical model.

Figure 7 shows that, for the short pile in clay, the 1D (parameterised) method matches the 3D finite element results well. However, the API/DNV approach is less accurate than is the case for the long pile. Figure 8 shows the split of the response between the four different soil response components. (Note that for the data in Figure 8, the 1D model was based on the numerical soil reaction curves determined directly from the 3D model). Figure 8 demonstrates that the distributed load curves alone are insufficient to compute the pile response accurately. It is clear that, in this case, the other three soil reaction components need to be included. Each additional component is seen to offer approximately equal contributions to the computed lateral load, H.

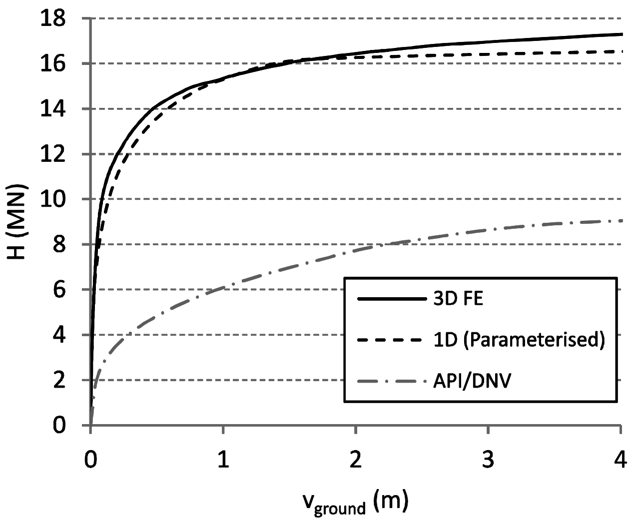

Figure 7. Short pile response in clay.

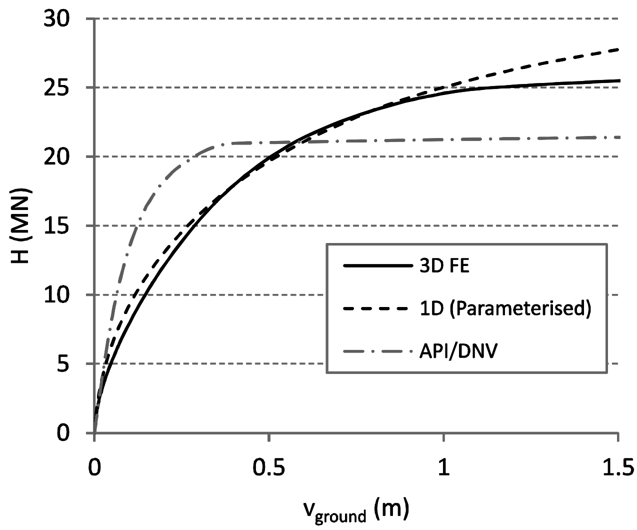

Figure 9. Short pile response in sand.

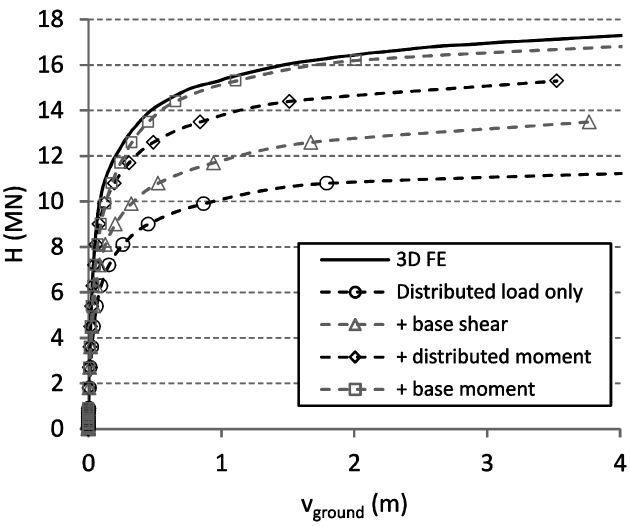

Figure 8. Cumulative component breakdown in clay computed using the 1D model with numerical soil reaction curves.

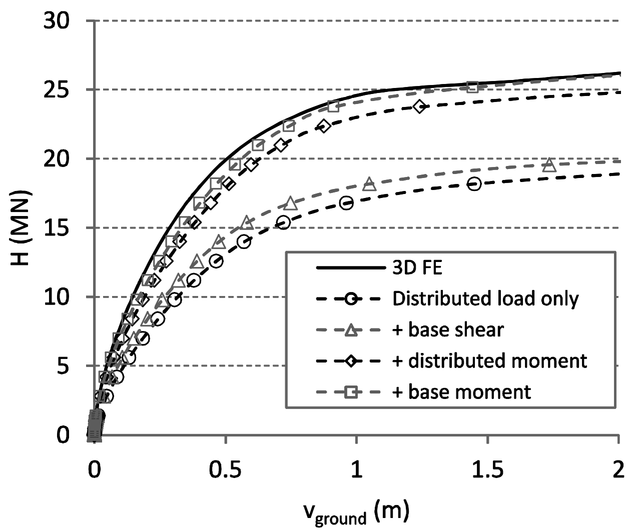

Figure 10. Cumulative component breakdown in sand computed using the 1D model with numerical soil reaction curves.

Figure 9 shows a comparison between the 1D (parameterised) approach and results obtained from the 3D analysis for the short pile in sand. The 1D method represents the response well, although there is a divergence at large displacement. This divergence could be addressed by using different weighting functions when fitting the curves to the soil reactions, or by adopting a different reference curve for the fitting. The figure shows that the API/DNV approach provides a reasonable prediction of the ultimate load, but a poor representation of the response shape. The individual soil reaction components are cumulatively applied to the short pile in sand, using the numerical soil reaction curves, as shown in Figure 10. As is the case for the clay analyses, an analysis limited to the distributed load curves will not provide an accurate prediction of the pile response in sand. The results indicate that, after the distributed load curves, the distributed moments have the most significant effect on pile response, with smaller contributions from base shear and moment components.

The 1D (parameterised) model provides a good fit with the 3D finite element data for all of the parameters investigated in the parametric study (Table 1). This suggests that the design method is capable of operating over the full range of geometries shown in Figure 11. Studies conducted using the 1D model typically indicate that, for long piles, the influence of the distributed moment, the base shear and base moment terms are relatively small. For short piles, however, these terms (not included in the traditional *p-y* method) become more significant. The results suggest that for piles with a large diameter to length ratio there is a 'diameter' effect associated with the increased influence of the distributed moment, base shear and base moment on the overall response.

4 APPLICATION TO DESIGN

There are two ways in which the proposed design method could be applied in practice. The first way would be as a 'rule-base method', likely to be used

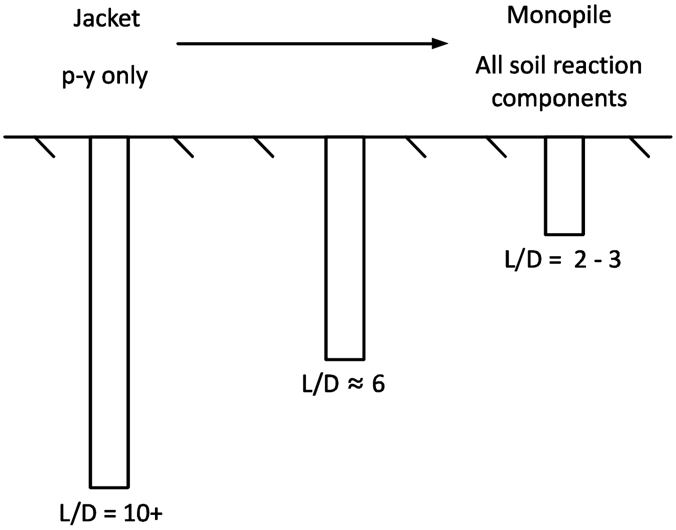

Figure 11. Application of design method to different pile geometries.

for concept design where detailed constitutive soil behaviour are not available. This approach would rely on determining basic strength and stiffness parameters, either from a desk-study, or from initial site investigation at the proposed site. Soil reaction curves would be based on pre-defined functions, which will depend on the soil type. Further work is needed to determine appropriate soil reaction curves for a range of soils (e.g. softer or more brittle clays and sands of a range of densities) as well as the effects of soil layering. A second more detailed approach, termed the 'numerical-based method', would involve carrying out high quality site investigation and laboratory testing to determine detailed strength and nonlinear stiffness parameters for a particular site. A set of site-specific soil reaction curves would then be determined using 3D finite element analysis of a typical set of laterally loaded monopiles. The particular arrangement analysed would be selected on the basis of the local soil conditions and the particular monopile dimensions being considered for the site. Soil reaction curves would be extracted from the finite element results (*e.g.* using the methods described above). These soil reaction curves would be incorporated within the 1D modelling framework, to allow the selection of array geometries and locations in an efficient manner.

5 LIMITATIONS AND FUTURE WORK

The proposed model has been developed for monotonic loading, with the focus on improving the baseline response model, before considering more complex effects. The model has been developed in such a way that more advanced geotechnical effects such as cyclic behaviour, multidirectional loading, damping, densification, age hardening, installation methods and creep can be incorporated. For example cyclic loading could be incorporated using simple rule based methods such as 'Masing rules' or incorporated through the use of a kinematic hardening plasticity model. Clearly there are aspects of cyclic loading, such as accumulation of deformation and degradation or strengthening of response (as observed by Leblanc *et. al.* 2010), which will need to be incorporated into such models. These more complex models must be consistent with the baseline model, which itself must be a close approximation to full scale behaviour. The modelling described in this paper, and in Zdravković *et al.* (2015), assumes that the piles are 'wished into place'. No consideration is given at this stage to installation effects, including the effects of consolidation and ageing.

6 ACKNOWLEDGMENTS

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7 REFERENCES

API. 2010. RP 2A-WSD - Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms. Washington: American Petroleum Institute.

Byrne, B.W., McAdam, R., Burd, H.J., Houlsby, G.T., Martin, C.M., Gavin, K., Doherty, P., Igoe, D., Zdravković, L., Taborda, D.M.G., Potts, D.M., Jardine, R.J., Sideri, M., Schroeder, F.C., Muir Wood, A., Kallehave, D. and Skov Gretlund, J. 2015. Field testing of large diameter piles under lateral loading for offshore wind applications. Proc 16th European Conference on Soil Mechanics and Geotechnical Engineering (ECSMGE). Edinburgh, UK.

DNV. 2014. DNV-OS-J101 - Design of Offshore Wind Turbine Structures. Oslo: Det Norske Veritas.

Davidson, H.L. 1982. Laterally loaded drilled pier research, Vol 1: Design methodology, Vol. 2: Research documentation. Final Report by GAI Consultants Inc., to Electric Power Research Institute (EPRI).

Lam, I.P.O. and G.R. Martin (1986) Seismic Design of Highway Bridge Foundations. US Department of Transportation Report No. FHWA/RD-86/102

Lam, I.P.O. 2013. Diameter effects on p-y curves. Deep Marine Foundations - A Perspective on the Design and Constrction of Deep Marine Foundations.

Leblanc, C., Houlsby, G.T. and Byrne, B.W. 2010 Response of stiff piles to long term cyclic loading. Géotechnique 60, No 2, pp 79-90.

Zdravković, L., Taborda, D.M.G., Potts, D.M., Jardine, R.J., Sideri, M., Schroeder, F.C., Byrne, B.W., McAdam, R., Burd, H.J., Houlsby, G.T., Martin, C.M., Gavin, K., Doherty, P., Igoe, D., Muir Wood, A., Kallehave, D. and Skov Gretlund, J. 2015. Numerical modelling of large diameter piles under lateral loading for offshore wind applications. Proc 3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015). Oslo, Norway.