
**Soil-Structure Interaction for
Non-Slender, Large-Diameter
Offshore Monopiles**

Soil-Structure Interaction for Non-Slender, Large-Diameter Offshore Monopiles

Volume 1

PhD Thesis by

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Preface

This thesis is submitted as one of the requirements for obtaining the degree of Ph.D. according to the regulations put forward by The Doctoral School of Engineering and Science at Aalborg University, Denmark.

The thesis concerns the interaction between soil and pile for monopile foundations for offshore wind turbines. The thesis is divided into two volumes. The first volume presents the overall outcome of the Ph.D. fellowship. Further, the first volume is divided into four parts which cover research areas that have been investigated during the Ph.D. fellowship:

- **Part I – Review of laterally loaded piles in sand** – This part presents a review concerning the design of laterally loaded piles used as the foundation for offshore wind turbines. The Winkler approach and the p - y curve formulation for piles in sand, currently adopted by design regulations of the American Petroleum Institute, the International Organization for Standardization and Det Norske Veritas, are assessed thoroughly. The review highlights and assesses several limitations and uncertainties in the current design methodology.
- **Part II – Physical modelling of laterally loaded, non-slender piles in sand** – This part deals with physical modelling of laterally loaded non-slender piles. A new test set-up for small-scale tests on laterally loaded piles has been developed and validated. The test set-up facilitates the application of an overburden pressure to the soil such that the soil properties for the small-scale tests are similar to the soil properties for sand around full-scale foundations. Tests have been conducted on both statically loaded and cyclically loaded piles. A scaling law is presented and validated against the small-scale tests.
- **Part III – Numerical assessment of the initial part of p - y curves for piles in sand** – This part presents a parametric study on the initial part of p - y curves for piles in sand. The parametric study is conducted through numerical modelling by means of the three-dimensional finite difference program *FLAC*^{3D}. A new expression for the initial slope of p - y curves is determined so

as to accurately capture the behaviour of piles exposed to serviceability limit state loads.

- **Part IV – Design of offshore monopiles unprotected against scour**
– This part deals with the design of offshore monopiles that are unprotected against the development of local scour. The time scale of the backfilling process as well as the relative density of the backfilled soil material is assessed through large-scale physical modelling. The significance of the results from the physical modelling on the design of foundations for offshore wind turbines is elucidated through a desk study.

The second volume of the thesis presents the test results from the physical modelling of laterally loaded non-slender piles in sand (Part II).

The Ph.D. thesis is based on the following collection of scientific papers and reports written by the author of the present thesis and in cooperation with other authors:

* Sørensen, S.P.H., Augustesen, A.H. & Ibsen, L.B. (2012). Revised expression for the static initial part of p - y curves for piles in sand. *Submitted for publication.*

* Sørensen, S.P.H., Ibsen, L.B. & Foglia, A. (2012). Testing of Laterally Loaded Rigid Piles with Applied Overburden Pressure. *Submitted for publication.*

* Sørensen, S.P.H. & Ibsen, L.B. (2012). Assessment of Scour Design for Offshore Monopiles Unprotected Against Scour. *Submitted for publication.*

Sørensen, S.P.H., Ibsen, L.B. & Frigaard, P. (2012). Relative Density of Backfilled Soil Material around Monopiles for Offshore Wind Turbines. *Accepted at the 22nd International Ocean and Polar Engineering Conference, XXII ISOPE, Rhodes, Greece.*

* Sørensen, S.P.H. & Ibsen, L.B. (2012). Experimental Comparison of Non-Slender Piles under Static Loading and under Cyclic Loading in Sand. *Accepted at the 22nd International Ocean and Polar Engineering Conference, XXII ISOPE, Rhodes, Greece.*

Leth, C.T., Sørensen, S.P.H., Klinkvort, R.T., Augustesen, A.H., Ibsen, L.B. & Hededal, O. (2012). A snapshot of present research at AAU and DTU on large-diameter piles in coarse-grained materials. *Proceedings of the Nordic Geotechnical Meeting, XVI NGM, Copenhagen, Denmark.*

Sørensen, S.P.H. & Ibsen, L.B. (2012). Small-scale testing of laterally loaded non-slender piles in a pressure tank. *Proceedings of the Nordic Geotechnical Meeting, XVI NGM, Copenhagen, Denmark.*

Roesen, H.R., Thomassen, K., Sørensen, S.P.H. & Ibsen, L.B. (2011). Evaluation of Small-Scale Laterally Loaded Monopiles in Sand. *Symposium Proceedings: 64th Canadian Geotechnical Conference and 14th Pan-American Conference on Soil Mechanics and Engineering, 5th Pan-American Conference on Teaching and Learning of Geotechnical Engineering, Toronto, Ontario, Canada: Pan-AM CGS Geotechnical Conference.*

Thomassen, K., Roesen, H.R., Sørensen, S.P.H. & Ibsen, L.B. (2011). Small-scale testing of laterally loaded monopiles in sand. *Symposium Proceedings: 64th Canadian Geotechnical Conference and 14th Pan-American Conference on Soil Mechanics and Engineering, 5th Pan-American Conference on Teaching and Learning of Geotechnical Engineering, Toronto, Ontario, Canada: Pan-AM CGS Geotechnical Conference.*

Brødbæk, K.T., Augustesen, A.H., Møller, M. & Sørensen, S.P.H. (2011). Physical modelling of large diameter piles in coarse-grained soil. *Proceedings of the 21st European Young Geotechnical Engineers' Conference, XXI EYGEC, 4-7. September, Rotterdam, The Netherlands.*

* Sørensen, S.P.H., Ibsen, L.B. & Frigaard, P. (2010). Experimental Evaluation of Backfill in Scour Holes around Offshore Monopiles. *Proceedings of the 2nd International Symposium on Frontiers in Offshore Geotechnics, II ISFOG, Perth, Australia, 8-10 November 2010. Balkema Publishers, A.A. / Taylor & Francis, The Netherlands, 2010, pp. 617-622.*

Frigaard, P. Lykke, T. Rodriguez, J.R.R., Sørensen, S.P.H., Martinelli, L., Lamberti, A., Troch, P., de Vos, L., Kisacik, D., Stratigaki, V., Zou, Q., Monk, K., Vandamme, J., Damsgaard, M.L. & Graversen, H. (2010). Loads on Entrance Platforms for Offshore Wind Turbines. *Proceedings of the HYDRALAB III Joint Transnational Access User Meeting, Hannover, February 2010. Red. /Joachim Grüne, Mark Klein Breteier. Hannover: Forschungszentrum Küste FZK (Coastal Research Center), 2010, pp. 25-28.*

Augustesen, A.H., Sørensen, S.P.H., Ibsen, L.B., Andersen, L., Møller, M. & Brødbæk K.T. (2010). Comparison of calculation approaches for monopiles for offshore wind turbines. *In Proceedings of the 7th European Conference on Numerical Methods in Geotechnical Engineering, VII NUMGE, (eds. Benz and Nordal), 2.-4. June, Trondheim, Norway, CRC Press, Taylor & Francis Group, 901-906.*

Sørensen, S.P.H., Ibsen, L.B. & Augustesen, A.H. (2010). Effects of diameter on initial stiffness of p-y curves for large-diameter piles in sand. *In Proceedings of the 7th European Conference on Numerical Methods in Geotechnical Engineering, VII NUMGE, (eds. Benz and Nordal), 2.-4. June, Trondheim, Norway, CRC Press, Taylor & Francis Group, 907-912.*

Augustesen, A.H., Brødbæk, K.T., Møller, M., Sørensen, S.P.H., Ibsen, L.B., Pedersen, T.S. & Andersen, L. (2009). Numerical Modelling of Large-Diameter Steel Piles at Horns Rev. *In Proceedings of the 12th International Conference on Civil, Structural and Environmental Engineering Computing (eds. Topping, Costa Neves and Barros), 1.-4. September, Madeira, Portugal, Civil-Comp Press, Dun Eaglais, Kippen, UK, Paper 239.*

Sørensen, S.P.H., Brødbæk, K.T., Møller, M., Augustesen, A.H. & Ibsen, L.B. (2009). Evaluation of the Load-Displacement Relationships for Large-Diameter Piles in Sand. *In Proceedings of the 12th International Conference on Civil, Structural and Environmental Engineering Computing, (eds. Topping, Costa Neves and Barros), 1.-4. September, Madeira, Portugal, Civil-Comp Press, Dun Eaglais, Kippen, UK, Paper 244.*

* Sørensen, S.P.H., Brødbæk, K.T., Møller, M. & Augustesen, A.H. (2012). Review of laterally loaded monopiles employed as the foundation for offshore wind turbines. *DCE Technical Reports, No. 137, Department of Civil Engineering, Aalborg University, Aalborg, Denmark.*

+ Sørensen, S.P.H. & Ibsen, L.B. (2011). Small-scale cyclic tests on non-slender piles situated in sand - Test results. *DCE Technical Reports, No. 118, Department of Civil Engineering, Aalborg University, Aalborg, Denmark.*

+ Sørensen, S.P.H. & Ibsen, L.B. (2011). Small-scale quasi-static tests on non-slender piles situated in sand - Test results. *DCE Technical Reports, No. 112, Department of Civil Engineering, Aalborg University, Aalborg, Denmark.*

Copies of the publications marked with "*" are enclosed in the back of Vol. 1 of the thesis, while publications marked with "+" are enclosed in Vol. 2 of the thesis.

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During the Ph.D. fellowship, I spent four months at the Centre for Offshore Foundation Systems (COFS), University of Western Australia, Perth, Western Australia, Australia, under the supervision of Professor Mark Randolph. At COFS, my work was concentrated on numerical modelling of the behaviour of non-slender laterally loaded piles. Further, Mark Randolph also provided me with great insight within the scope of physical modelling including practical use of dimensional analysis with

respect to laterally loaded piles. I would like to express gratitude to Professor Mark Randolph for his assistance and supervision during the time I spent at the University of Western Australia.

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Aalborg, May 2012

Søren Peder Hyldal Sørensen

Summary in English

Strong political and industrial forces, especially in Northern Europe, support the development of new technologies as well as improvements of existing technologies within the field of renewable energy. Offshore wind power is a domestic, sustainable and largely untapped energy resource. Today, the modern offshore wind turbine offers competitive production prices compared to other sources of renewable energy. Therefore, it is a key technology in breaking the dependence on fossil fuels and in achieving the energy and climate goals of the future.

For offshore wind turbines, the costs of foundation typically constitutes 20-30 % of the total costs. Hence, improved methods for the design of foundations for offshore wind turbines can increase the competitiveness of offshore wind energy significantly. The monopile foundation concept has been employed as the foundation for the majority of the currently installed offshore wind turbines.

The overall aim of the present thesis is to enable low-cost and low-risk foundations to be designed for future offshore wind farms. Therefore, the soil-pile interaction for non-slender, large-diameter offshore piles has been investigated.

A review of current design methods for laterally loaded piles is presented. The review focuses on the Winkler approach in which the pile is considered as a beam on an elastic foundation. The elastic foundation consists of a series of uncoupled springs with stiffnesses governed by means of p - y curves. The p - y curve formulation for piles in sand, which is currently adopted in design regulations of organisations such as the American Petroleum Institute, the International Organization for Standardization and Det Norske Veritas, is presented in detail. Limitations to the Winkler approach as well as limitations to the p - y curve formulation currently adopted by design regulations have been presented. The following uncertainties/limitations have been addressed in detail: shearing force between soil layers; ultimate soil resistance; influence of vertical loading on the lateral soil response; effect of pile flexibility; initial stiffness of p - y curves; choice of horizontal earth pressure coefficient; shearing force at the pile toe; shape of p - y curves; effect of soil layering; long-term cyclic loading; effect of scour/backfilling on the soil-pile interaction. Through the literature study several limitations have been identified for the p - y curve formulation

currently recommended in the design regulation. These limitations need to be addressed in order to enable design of low-cost and low-risk monopile foundations for offshore wind turbines.

The behaviour of laterally loaded piles can be investigated by means of small-scale testing, large-scale testing, numerical modelling and by means of analytical methods. A new test set-up for the small-scale testing of laterally loaded piles has been developed. The test set-up enables the application of an overburden pressure to the soil. Hereby, traditional uncertainties for the soil parameters for small-scale tests have been avoided. These traditional uncertainties include very high friction angles and very low Young's modulus of elasticity in comparison with soil properties for full-scale foundations. Both a series of static tests and a series of cyclic tests have been conducted. A scaling law that includes an applied overburden pressure has been proposed. The scaling law has been validated against the small-scale tests. The pile rotation at failure depends on the applied overburden pressure such that the rotation at failure increases with increasing overburden pressure. This finding is similar to the increase of the strain at failure for increasing confining pressure which can be found for conventional drained triaxial tests on cohesionless materials. Cyclic tests have illustrated another significant difference between tests with and without overburden pressure applied: for the tests without overburden pressure, the cyclic loading caused a part of the soil volume to cave-in and a part of the soil volume to gap; for the tests with overburden pressure applied, no soil cave-in was observed.

A parametric study on the initial part of p - y curves has been conducted. In the parametric study, the influence of a broad spectre of parameters have been addressed. These parameters include: the pile diameter, the Young's modulus of elasticity for the soil, the friction angle, the pile flexibility, the loading eccentricity, and the depth below seabed. The parametric study has been conducted by means of *FLAC^{3D}* which is a commercial, three-dimensional finite difference program. It has been concluded that the initial part of the p - y curves depends on the pile diameter, the Young's modulus of elasticity for the soil and the depth below seabed, while the friction angle, the loading eccentricity and the pile flexibility do not have any significant effect on the initial part of the p - y curves. Based on the findings from the numerical study, a modified expression for the initial stiffness of p - y curves has been proposed so the behaviour of piles exposed to serviceability limit state loads can be captured accurately.

A large-scale test on backfill around piles in waves has been conducted at the large wave flume (GWK) at the Coastal Research Centre (FZK) in Hannover. The time scale of the backfilling process has been found to be significantly smaller than what can be expected on the basis of previously published small-scale tests on the backfilling process. This illustrates that more research is needed regarding the time scale of backfilling in waves and that the scaling laws for the time scale of backfilling need further investigation. The relative density of the backfilled soil material has been measured to vary from 65 % to 80 %. Hereby, the backfilled soil material can be

categorised as medium dense to very dense and therefore the backfilled soil material can be expected to be rather stiff and to have a significant strength. Through a desk study, the significance of accounting for the time variation of scour/backfilling in the fatigue and ultimate limit state design has been elucidated.

The Ph.D. research project has lead to an improved understanding of the interaction between soil and pile for offshore pile foundations. Hereby, the research contributes to the design of low-cost and low-risk foundations for offshore wind turbines.

Resumé (Summary in Danish)

Udviklingen af nye teknologier samt forbedringer af eksisterende teknologier inden for vedvarende energi bliver støttet af indflydelsesrige politikere, økonomisk stærke virksomheder og fonde. Denne politiske og industrielle støtte er især udbredt i Nordeuropa. Offshore vindenergi er en bæredygtig energiform og en i høj grad uudnyttet energiressource. Produktionspriserne for nye havvindmøller har efterhånden nået et niveau, hvor offshore vindenergi er konkurrencedygtig i forhold til andre former for vedvarende energi. Optimering af teknologien inden for offshore vindenergi er derfor særdeles vigtig, for at bryde afhængigheden af fossile brændstoffer samt for at møde fremtidens energi- og klimamål.

Omkostningerne forbundet med funderingen af havvindmøller udgør typisk 20-30 % af de samlede omkostninger for havvindmøller. Dermed kan forbedringer af de nuværende designmetoder for funderingen af havvindmøller være med til at øge konkurrenceevnen for offshore vindenergi væsentligt. Den mest anvendte funderingstype for offshore vindmøller er monopæle.

Det overordnede mål med denne afhandling er at optimere de nuværende designmetoder for monopæle fundamenter, således at konkurrenceevnen for offshore vindmøller kan forbedres. Derfor er interaktionen mellem jord og pæl blevet undersøgt for stive offshore pæle.

Et litteraturstudie af de nuværende designmetoder for horisontalt belastede pæle præsenteres. Litteraturstudiet fokuserer på Winkler metoden, hvori pælen modelleres som en bjælke på et elastisk fundament. Det elastiske fundament består af en række ukoblede elastiske fjedre, hvoraf fjederstivhederne bestemmes ved brug af p - y kurver. p - y kurve formuleringen for sand, der i dag er inkorporeret i standarder fra the American Petroleum Institute, the International Organization for Standardization og Det Norske Veritas, præsenteres og analyseres. Begrænsninger både i forbindelse med Winkler metoden og i forbindelse med den nuværende p - y kurve formulering præsenteres. De følgende usikkerheder/begrænsninger analyseres og vurderes: forskydning mellem jordlag; ultimativ jordtryk; indflydelse af vertikal belastning på det horisontale jordtryk; betydningen af en pæls fleksibilitet; initialstivheden af p - y kurver; valg af horisontal jordtrykskoefficient; forskydning ved pælespidsen;

p - y kurvernes form; betydningen af lagdelt jord; betydningen af cyklisk belastning; betydningen af scour/backfill på interaktionen mellem jord og pæl. For at optimere designet af offshore pæle og hermed øge konkurrenceevnen for offshore vindenergi er det nødvendigt at undersøge de ovennævnte usikkerheder/begrænsninger.

Interaktionen mellem jord og pæl for horisontalt belastede pæle kan undersøges ved småskala forsøg, storskala forsøg, numerisk modellering og ved analytiske beregninger. En ny forsøgsopstilling for småskala forsøg af horisontalt belastede pæle er blevet udviklet. Forsøgsopstillingen muliggør påførslen af et overlejringstryk. Idet et overlejringstryk påføres, kan de traditionelle usikkerheder i forbindelse med bestemmelsen af jordens egenskaber ved småskala forsøg undgås/formindskes. For traditionelle småskala forsøg udført ved normalt spændingsniveau vil jorden have en meget stor friktionsvinkel samt en meget lille stivhed sammenlignet med egenskaberne for jorden omkring fuldskala pæle. Der er både udført en forsøgsserie med statisk og cyklisk belastning. En skaleringslov, der inkluderer det påførte overlejringstryk, er blevet udledt. Skaleringsloven er blevet valideret i forhold til forsøgsserien på stive pæle udsat for statisk belastning. Ud fra forsøgsserien hvor en statisk belastning er påsat er det erfaret, at pælens rotation ved brud stiger ved stigende overlejringstryk. Denne sammenhæng mellem pælens rotation og overlejringstrykket tilsvarende sammenhængen mellem brudtøjning og den mindste hovedspænding ved drænedede triaksialforsøg. Ved de cykliske forsøg kunne det observeres, at der dannes et 'hul' (gap) bag pælen idet denne belastes. Udviklingen af dette 'hul' afhænger dog af om der er påført et overlejringstryk eller ej: for forsøgene uden overlejringstryk blev 'hullet' delvist tilbagefyldt (cave-in); for forsøgene med overlejringstryk blev tilbagefyldning af sandmateriale (cave-in) ikke observeret.

Et parametrisk studie vedrørende den initiale del af p - y kurver er udført. Betydningen af følgende parametre er undersøgt i det parametriske studie: pælens diameter; jordens elasticitetsmodul; jordens friktionsvinkel; pælens fleksibilitet; lastens excentricitet; samt dybden under havbunden. Det parametriske studie er udført ved brug af det kommercielle finite difference program $FLAC^{3D}$. Gennem det parametriske studie erfarer det, at den initiale del af p - y kurverne afhænger af pælens diameter, jordens elasticitetsmodul samt dybden under havbunden, hvorimod friktionsvinklen, lastens excentricitet samt pælens fleksibilitet ikke har nogen signifikant betydning for den initiale del af p - y kurverne. Et modificeret udtryk for initialstivheden af p - y kurver for pæle i sand er blevet præsenteret baseret på det numeriske studie. Det modificerede udtryk er fremkommet således, at den initiale del af p - y kurverne for pæle i sand tilnærmes med god nøjagtighed.

I den store bølgerende (GWK) ved Coastal Research Centre (FZK) i Hannover er der udført et storskala forsøg på backfill omkring pæle i bølger. Tidsskalaen for backfill-processen var betydeligt mindre end hvad der kan forventes baseret på publicerede småskala forsøg omhandlende backfill. Dette tydeliggør nødvendigheden af udvidet forskning indenfor backfilling i bølger samt at de nuværende skaleringslove for tidsskalaen af backfill kræver yderligere validering. I storskala forsøget blev den

relative lejringsstæthed fundet til 65-80 %, hvormed det kan konkluderes, at det tilbagefyldte sand-materiale har en høj stivhed og styrke. Betydningen af at tage højde for den tidlige variation i scour-dybde ved undersøgelse af udmattelses- og brudgrænsetilstanden er blevet belyst.

Ph.D.-projektet har ført til en øget forståelse af interaktionen mellem jord og pæl for offshore pælefundamenter. Ph.D.-projektet bidrager dermed til en øget konkurrenceevne for offshore vindenergi.

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Foundations for offshore wind turbines

Wind energy is a competitive and promising source of renewable energy, and hereby wind energy plays an important role when trying to break the dependence on fossil fuels and when trying to reduce carbon emissions. Wind energy is a sustainable source of energy. Today, the majority of the installed wind turbines are positioned onshore. However, in countries with dense populations and vast coastlines, offshore wind energy is an alternative to onshore wind energy. Placing wind turbines offshore offers advantages such as: higher wind speeds; less turbulent wind; less or no visual impact; and no human neighbours. However, both construction costs and maintenance costs are significantly higher for offshore wind turbines than for onshore wind turbines. To minimise the construction and maintenance costs, offshore wind turbines should preferably be placed near shore and at low water depths.

The first offshore wind farm was erected in Vindeby, Denmark, and consisted of 11 wind turbines with capacities of 450 kW. The first large-scale offshore wind farm was erected in 2003 at Horns Rev, Denmark. Horns Rev Offshore Wind Farm consists of 80 wind turbines, and it has a total capacity of 160 MW. In 2009, the capacity of offshore wind energy in Europe was approximately 2 GW. The European Wind Energy Association (EWEA) has set targets for the offshore wind energy capacities in Europe. By 2020 and 2030, the European offshore wind energy capacity should reach 40 GW and 150 GW, respectively. The installation of offshore wind energy is expected primarily to take place in Northern Europe. (www.ewea.org)

For offshore wind turbines, the costs of foundation typically constitutes of 20-30 % of the total costs. Therefore, it is of high interest to optimise the foundation design. This can be accomplished either by improving existing technologies or by developing new technologies.

Today, the majority of the installed offshore wind turbines have capacities up to

3.6 MW, are positioned within a distance of 10 km from shore and are located at positions with water depths less than 20 m. However, the installation of several offshore wind turbines with capacities of up to 7 MW, distances to shore of up to 100 km and water depths of up to 60 m have been consented/planned.

1.1 Loads acting on foundations for offshore wind turbines

Offshore wind turbines are exposed to environmental loads from waves, wind and currents. The foundations for offshore wind turbines are therefore exposed to large lateral loads as well as large overturning moments. The vertical loading originates from the selfweight of the wind turbine and of the foundation. Therefore, the vertical loading is rather small. The loading from wind and waves are cyclic. So, resonance between the loading frequency and the natural frequencies of the offshore wind turbine structure should be avoided. Further, the deformation/rotation of the foundation, due to long-term cyclic loading as well as the fatigue-life of the steel material of both the foundation and the wind turbine, should be investigated.

The frequency range of extreme waves is typically in the range of 0.07-0.14 Hz while the energy rich wind turbulence typically is below 0.1 Hz. The rotor of modern offshore wind turbines typically undergoes 10-20 revolutions per minute corresponding to a frequency of 0.17-0.33 Hz. This frequency is denoted the rotor frequency, 1P. Due to aerodynamic imbalances or imbalances in the mass distribution, minor excitations can take place with a frequency of 1P. The rotor blades pass the tower with a frequency of 3P, 0.5-1 Hz. Large excitations take place with this frequency due to the impulse-like excitation from blades passing the tower. Today, most foundations for offshore wind turbines are designed such that the first natural frequency of the wind turbine including foundation lies within 1P and 3P. The natural frequencies of offshore wind turbines depends on both the stiffness of the foundation and tower structure as well as on the stiffness of the interaction between soil and foundation. The stiffness of the material used for the tower and foundation can be predicted with high accuracy. However, determination of the stiffness of the interaction between the soil and the foundation is complicated. Furthermore, the cyclic loading might change this stiffness since cyclic loading can lead to possible softening/hardening of the soil. Furthermore, erosion of seabed material causes the stiffness of the interaction between soil and foundation to vary with time and sea conditions.

For offshore wind turbines, the permanent rotation of the foundation arising from installation as well as from long-term loading is typically required to be less than 0.5° . Therefore, an accurate prediction of the long-term variation of the stiffness of the interaction between soil and foundation is needed. An accurate prediction of this stiffness is also important when designing the steel material in the foundation

and tower against fatigue damage.

Besides loading from wind and waves, offshore wind turbine foundations are also loaded from currents. In comparison with wave loading, the loading from currents is rather small. Both currents and waves induce shear stresses on the seabed, and therefore they can cause erosion of seabed material near to the foundations. To avoid erosion of the seabed around offshore foundations, scour protection consisting of rock infill can be positioned.

For offshore wind turbines located in cold waters, drifting ice can induce major loads on the foundation. In order to minimise the loading arising from drifting ice, foundations for offshore wind turbines located in cold waters are typically designed with either an upward breaking cone or a downward breaking cone in the height of the mean water level.

1.2 Types of foundation for offshore wind turbines

Several types of foundation concepts can be employed as the foundation for offshore wind turbines, for instance the monopile foundation concept, the gravity based foundation concept, the bucket foundation concept, the jacket foundation concept and the tripod foundation concept. The majority of these concepts have originally been developed for the foundation of offshore structures for the oil and gas sector. Offshore structures used for the oil and gas sector, typically, have significant masses. Therefore, both the vertical and the lateral loading on the foundation are significant for foundations used in the offshore oil and gas sector. In contrast, the lateral loads and overturning moments are dominant for foundations used for offshore wind turbines. The choice of foundation depends on several factors: the water depth, the sea conditions, the soil conditions, the wind turbine size, etc.

1.2.1 The monopile foundation concept

The monopile foundation concept is presently the most used type of foundation for offshore wind turbines. Monopiles are typically hollow steel piles driven or drilled into the seabed. The pile diameter is typically 4-6 m, and the embedded pile length ranges from approximately 15 to 35 m. Until today, monopiles have been used for water depths up to approximately 25 m.

For monopiles, the loading is primarily transferred to the ground by means of lateral bedding as the vertical loading is small in comparison with the lateral loads and overturning moments. The upper soil layers of the bedding are therefore important for the load transfer.

To connect the monopile with the wind turbine tower, so-called transition pieces are used. The space between the transition pieces and the monopiles is typically grouted. In fig. 1, a monopile as well as a transition piece are shown.



Figure 1: Monopile foundation being loaded on board a vessel. The yellow pillar at the rear is a transition piece. www.dongenergy.com

After the lifetime of an offshore wind turbine, the monopile foundation is typically cut-off several meters below the seabed. This is a costly process and one of the downsides of the monopile foundation concept. Another disadvantage is the environmental concerns regarding the installation when pile driving is employed.

1.2.2 The gravity based foundation concept

Gravity based foundations employed in the offshore sector typically consist of caissons made of reinforced concrete, steel or composite material (see fig. 2). Caissons with a cellular design, so they can be floated to the site, are often used. As ballasting, sand, gravel, concrete, etc. can be employed. For gravity based foundations, the loads are transferred to the seabed by means of normal shear stresses at the base of the foundation. Hence, a large base as well as a large ballast are necessary to withstand the overturning moments. The hydrodynamic loads are generally large on gravity based foundations. For gravity based foundations, the subsoil close to the seabed surface needs to have a sufficient bearing capacity. Any soft top layers need to be removed prior to installation. Further, the seabed needs to be levelled and a course base layer should be placed prior to installation. The gravity based

foundations erected up till now are primarily erected at locations with water depths of up to 10 m. For larger water depths, the hydrodynamic loads will be very large, and subsequently the costs of foundation would be very large.



Figure 2: Gravity based foundation to be used as foundation at the Nysted Offshore Wind Farm. The gravity based foundation has been designed with a downward breaking ice cone. www.no-tiree-array.org.uk.

1.2.3 The bucket foundation concept

The bucket foundation concept is a rather new foundation concept for offshore wind turbines. The foundation type originates from the oil and gas sector in which suction anchors have been used for the anchoring of floating structures. A bucket foundation comprises of a steel cylinder closed at the top. The bearing behaviour of bucket foundations are similar to the classical foundation concept. Bucket foundations are installed into the seabed by creating a vacuum inside the pile. Initially, when a bucket foundation is to be installed, the selfweight of the structure will cause the bucket to sink a certain depth into the soil. Afterwards, the installation is continued by pumping out water from inside the bucket. This creates suction inside the bucket. Further, for cohesionless soils, the applied suction causes a flow of water from outside the bucket. This loosens the soil and therefore reduces the shaft resistance inside the

bucket and the base resistance. After the lifetime of the offshore wind turbine, the bucket foundation can be uninstalled by means of pumping water into the bucket. Hereby, a pressure will build up inside the bucket causing uplift.

In 2002, a bucket foundation was installed as foundation for a 3 MW wind turbine in an embanked area at Frederikshavn harbour, Frederikshavn, Denmark (see fig. 3). The bucket foundation concept has, furthermore, been employed for a met mast at Horns Rev 2. The bucket foundation concept is a promising foundation concept. However, it still needs to be proven that the concept can be used for a range of soil conditions and that the foundation can be handled during transport and installation in rough sea conditions.



Figure 3: Bucket foundation for a 3 MW wind turbine in Frederikshavn, Denmark. www.hornsrev.dk.

1.2.4 The tripod and jacket foundation concept

For water depths larger than approximately 30 m, the costs of foundation for the monopile foundation concept and the gravity based foundation concept are very large. For such water depths, use of the tripod or the jacket foundation concepts will typically be optimal. These two concepts can both be considered as steel frame structures. They are typically prefabricated and piles are typically used for the anchoring of the steel frames. Moreover, suction buckets can also be employed for the anchoring. The tripod foundation concept consists of a main pipe with three legs, while jacket foundations typically consists of a steel frame with four legs. For

the Alpha Ventus offshore wind farm, both the tripod and the jacket foundation concept have been used. The wind farm is located in the North Sea, approximately 45 km north of the German coastline. Both types of foundation support six 5 MW wind turbines. The tripod and the jacket foundations installed at Alpha Ventus are illustrated in fig. 4 and fig. 5, respectively.



Figure 4: Tripod foundation for a 5 MW wind turbine at the Alpha Ventus offshore wind farm, Germany. www.owt.de.

For steel frame structures such as the tripod or the jacket foundation concepts, the vertical loading as well as the overturning moments give rise to alternating tensile and compressive forces in the piles or suction buckets used to anchor the steel frame into the seabed. In order to minimise the tensile loading, which often is critical, additional ballasting can be employed. The lateral loading is carried by either lateral bedding or by the use of piles that are inclined.

If piles are used for the anchoring of the steel frames, these should be cut-off several meters below the seabed at removal.



Figure 5: Jacket foundations for the 5 MW wind turbines at the Alpha Ventus offshore wind farm, Germany. www.panoramio.com.

1.2.5 Floating foundations

For very large water depths, floating foundation concepts might be optimal. Floating type foundations have been used successfully in the offshore oil and gas industry. Until today, floating foundations have, however, only been employed for one full-scale offshore wind turbine, the so-called Hywind, which has been installed approximately 10 km southwest of Karmøy, Norway. This floating foundation supports a 2.3 MW turbine and the water depth at the location is approximately 220 m. A ballast stabilised floating foundation has been employed at Hywind. A ballast stabilised floating foundation consists of a hollow steel cylinder filled with ballast consisting of water and rocks. The foundation is attached to the seabed by means of mooring lines.

Aims of thesis and specific objectives

Offshore wind energy is a sustainable and largely untapped energy resource. For offshore wind turbines, the costs related to the foundation typically comprises of 20-30 % of the total costs. Hence, reduction in the costs of the foundation for offshore wind turbines can increase the competitiveness of offshore wind energy significantly. Reductions can be obtained by for instance:

- optimisation of existing types of foundations for offshore wind turbines.
- improvement of the design guidelines for existing types of foundations for offshore wind turbines such that the foundation behaviour can be predicted more accurately.
- development of new foundation concepts for offshore wind turbines.

The overall aims and specific objectives of the present Ph.D. research programme concern the monopile foundation concept, and they are within the field of geotechnical engineering. One of the specific objectives concerns coastal engineering as well as geotechnical engineering.

2.1 Overall aim

The overall aim was to improve the knowledge regarding the behaviour for laterally loaded, non-slender piles situated in the offshore environment and hereby to enable the construction of low-risk and low-cost monopile foundations for offshore wind turbines.

2.2 Specific objectives

The specific objectives were:

- to review the current knowledge regarding the behaviour of laterally loaded, non-slender piles in sand and further to identify, analyse and assess limitations in the current design guidelines for laterally loaded offshore piles.
- to develop a new test set-up for the small-scale testing of laterally loaded, non-slender piles. The new test set-up should enable the application of an overburden pressure to the soil such that the traditional uncertainties for small-scale testing related to small effective stresses in the soil can be avoided. The new test set-up should be proven through a test series on statically loaded and cyclically loaded piles.
- to investigate the stiffness of the interaction between pile and soil through numerical modelling and to establish a new formulation for the initial slope of p - y curves for piles in sand such that the pile behaviour for piles exposed to serviceability limit state loads can be captured accurately.
- to investigate the time scale of backfill in waves and further to investigate the relative density of backfilled soil material. Further, the effect of scour/backfilling on the design of offshore monopile foundations should be assessed.

CHAPTER 3

The research project

The research conducted in connection with the Ph.D. fellowship has, as previously mentioned, been divided into four parts. Part I presents a review of the current design methodology for offshore monopile foundations. Further, in Part I, uncertainties and limitations related to the current design methodology is presented and assessed. Two of these uncertainties and limitations have been investigated further in Part III and Part IV. In Part II, a new and innovative test set-up for laterally loaded piles is presented and validated against a large test series on laterally loaded piles.

In this chapter, the contents of the four research parts are presented. Further, an overview of the contents of the six publications, attached at the back of the present Ph.D. thesis, is presented. The overview includes background information, rationale, objectives and methods.

3.1 Part I – Review of laterally loaded piles in sand

Various design approaches exist for laterally loaded offshore monopiles. Organisations such as the American Petroleum Institute, the International Organization for Standardization and Det Norske Veritas (API, 2000; ISO, 2007; and DNV, 2010) recommend the use of the Winkler approach (Winkler, 1867) for the design of offshore monopiles exposed to lateral loading. This part of the research project consists of the scientific publication "Review of laterally loaded monopiles employed as the foundation for offshore wind turbines". The paper presents a review of the design approaches for offshore monopiles. The review focuses on the Winkler approach in which the interaction between soil and pile is addressed by means of p - y curves.

The p - y curve formulation for piles in sand currently adopted in API (2000), ISO (2007) and DNV (2010) is primarily based on the research presented in Cox et al. (1974), Reese et al. (1974), O'Neill and Murchison (1983), and Murchison and O'Neill (1984). The outline of the paper is as follows:

- **Introduction** – The monopile foundation concept for offshore wind turbines is presented. Furthermore, various design approaches for offshore monopiles are briefly described.
- **p - y curves and Winkler approach** – The Winkler approach is presented in detail. The presentation includes a historic timeline of the development of the Winkler approach as well as the development of p - y curve formulations for piles in sand.
- **Formulations of p - y curves for piles in sand** – The p - y curve formulation originally suggested by O'Neill and Murchison (1983) and currently adopted in design regulations such as API (2000), ISO (2007) and DNV (2010) is presented in detail. Both the analytical derivations/assumptions and the field tests that form the basis of the p - y curve formulation are presented.
- **Limitations of p - y curves** – Based on a review of published literature concerning the behaviour of laterally loaded offshore monopiles, the uncertainties and limitations of the currently adopted p - y curve formulation for piles in sand is addressed in detail. Alternative p - y curve formulations as well as alternative design approaches for the design of offshore monopiles are assessed. The following uncertainties/limitations have been addressed: the shearing force between soil layers; the ultimate soil resistance; the influence of vertical pile load on the lateral soil response; the effect of soil-pile interaction; the effect of diameter on the initial stiffness of p - y curves; the choice of horizontal earth pressure coefficient; the shearing force at the pile-toe; the shape of p - y curves; the effect of layered soil; the effect of long-term cyclic loading; and the effect of scour on the soil-pile interaction.

This part of the thesis highlights uncertainties and limitations in the Winkler approach as well as in the currently used p - y curve formulation for piles in sand. Hereby, Part I of the thesis constitutes a basis for Parts II-IV.

3.2 Part II – Physical modelling of laterally loaded, non-slender piles

The behaviour of laterally loaded piles can be examined by means of, for instance, small-scale testing, large-scale testing, numerical modelling and analytical methods.

Since large-scale testing is expensive and time-consuming, small-scale testing is a useful tool for analysis of the behaviour of laterally loaded piles. Further, small-scale tests can be used for validation of numerical models. When conducting traditional small-scale tests on laterally loaded piles, the low effective stresses in the soil cause significant uncertainties regarding the soil properties. This part of the Ph.D. research project has concerned the development of a new and innovative test set-up for the small-scale testing of laterally loaded piles. The new test set-up has been developed and validated at the Geotechnical Laboratory at Aalborg University, Denmark.

Many researchers have published results from physical modelling on the behaviour of laterally loaded piles. For example, Mansur et al. (1964), Cox et al. (1974) and Bhushan et al. (1981) have investigated the behaviour of flexible piles in sand through physical modelling. The behaviour of non-slender piles has been investigated by, for instance, LeBlanc et al. (2010a) and Peralta and Achmus (2010). Their investigations were based on small-scale tests conducted at 1-g.

The new test set-up enables the application of an overburden pressure to the soil. By application of an overburden pressure to the soil, the traditional uncertainties related to the determination of the friction angle and the Young's modulus of elasticity for the soil can be overcome. Further, these parameters will be almost constant with depth when an overburden pressure is applied to the soil. However, the application of overburden pressure also causes the effective stresses to vary trapezoidally along the pile length instead of triangularly. For laterally loaded piles several researchers have proposed scaling laws, for instance, Gudehus and Hettler (1983), Peralta and Achmus (2010), and LeBlanc et al. (2010a). However, these scaling laws do not account for the overburden pressure applied to the soil. A new scaling law has therefore been developed so that small-scale tests on laterally loaded, non-slender piles with overburden pressure applied to the soil can be compared to small- and full-scale tests on laterally loaded, non-slender piles with no overburden pressure applied. This scaling law is presented in the paper "Testing of laterally loaded rigid piles with applied overburden pressure". The scaling law is validated against a series of static tests on laterally loaded, non-slender piles with and without overburden pressure applied to the soil. The outline of the paper is as follows:

- **Introduction** – The background for the test series on laterally loaded non-slender piles is presented. Further, the purpose of applying an overburden pressure to the soil during tests on laterally loaded piles is detailed.
- **Test set-up** – The test set-up is presented in detail. The description of the test set-up includes a description of the soil preparation, the soil properties, the pile properties, the measuring system and the method in which an overburden pressure has been applied to the soil.
- **Dimensional analysis** – A scaling law that enables the scaling of tests on laterally loaded piles with applied overburden pressure is presented.

- **Load-displacement relationships** – The test results are presented and the proposed scaling law is validated against the small-scale tests. Furthermore, a discussion on the advantages/disadvantages of applying an overburden pressure to the soil, when conducting small-scale tests on laterally loaded piles, is presented.
- **Potential implication for design** – The scaling law is used for the scaling of the small-scale tests to full-scale foundations.

In "Experimental Comparison of Non-Slender Piles under Static Loading and under Cyclic Loading in Sand", the pile behaviour of laterally loaded, non-slender piles exposed to static and cyclic loading are evaluated. The evaluation is based on a test series on small-scale piles in which an overburden pressure has been applied to the soil. In the paper, the advantages/disadvantages of applying an overburden pressure to the soil when conducting small-scale tests on laterally loaded piles exposed to static loading and cyclic loading are discussed. The paper outline is as follows:

- **Introduction** – The background for the test series on laterally loaded piles is presented.
- **p - y curve formulation** – The p - y curve formulation suggested by O'Neill and Murchison (1983) is briefly presented.
- **Delimitations concerning the current p - y curve formulation** – Delimitations concerning the p - y curve formulation proposed by O'Neill and Murchison (1983) is addressed. Especially the effect of flexible/rigid pile behaviour on the soil-pile interaction is discussed.
- **Test set-up** – The test set-up and the test programme is presented.
- **Results** – The test results are presented. The effect of overburden pressure on the static and cyclic pile behaviour is addressed in detail. The advantages/disadvantages of applying an overburden pressure to the soil when conducting small-scale tests on laterally loaded piles are evaluated based on the test results.

3.3 Part III – Numerical assessment of the initial part of p - y curves for piles in sand

For offshore monopiles employed as the foundation for offshore wind turbines, the sum of the rotation due to installation and of the rotation due to long-term loading is typically required to be less than 0.5° . Further, the first natural frequency of the wind turbine including foundation is designed to be within a narrow range so

fatigue damage to the steel material used for the foundation and for the wind turbine tower is minimised. Therefore, accurate prediction of the foundation stiffness and hereby also of the initial slope of the p - y curves is of high importance. In the p - y curve formulation suggested by O'Neill and Murchison (1983), the initial slope of the p - y curves depends only on the depth below seabed and the friction angle. Various researchers have investigated the initial slope of p - y curves for piles in sand, however, with contradictory conclusions: Terzaghi (1955), Vesic (1961), Ashford and Juirnarongrit (2005), and Fan and Long (2005) indicated that the initial slope of p - y curves for piles in sand should be independent of the pile diameter; Carter (1984) and Ling (1988) proposed a p - y curve formulation in which the initial slope of the p - y curves is linearly proportional with the pile diameter; Lesny and Wiemann (2006) suggested that the initial slope of p - y curves for piles in sand increases non-linearly with the depth below seabed. In this part of the thesis, the initial slope of p - y curves for piles in sand has been investigated by means of numerical modelling. A parametric study has been conducted with use of the commercial finite difference program *FLAC^{3D}*. The numerical study is presented in the scientific paper "Revised expression for the static initial part of p - y curves for piles in sand". The outline of the paper is as follows:

- **p - y curve formulation** – Briefly, the p - y curve formulation proposed by O'Neill and Murchison (1983) is presented. The validity of the formulation with respect to non-slender, large-diameter piles is discussed. Especially, the validity/accurateness of the initial slope of the p - y curves for non-slender large-diameter piles is addressed.
- **Numerical modelling** – A numerical model established in the commercial finite difference program *FLAC^{3D}* is presented in detail. The numerical model is validated against the small-scale tests on laterally loaded, non-slender piles presented in Part II of the thesis.
- **Results** – A parametric study on the initial slope of p - y curves for piles in sand is presented. The parametric study is conducted by means of the numerical model. Based on the parametric study, a modified expression for the initial slope of p - y curves for piles in sand is presented. The modified expression aims at improving the prediction of the behaviour of monopiles exposed to serviceability limit state (SLS) loads. Although the modified expression has been determined so the pile behaviour can be predicted accurately for SLS-loads, the procedure used for the determination of the modified expression can with minor changes be used for the determination of a modified expression suitable for other limit states.
- **Example – Horns Rev 1** – The predicted pile behaviour when employing the modified expression for the initial slope of p - y curves and the initial slope of p - y curves as suggested by O'Neill and Murchison (1983), respectively, are

compared. Further, these predictions are compared with the results from three-dimensional analysis in *FLAC^{3D}*. The comparison is made for a monopile employed as the foundation for an offshore wind turbine at the Horns Rev 1 Offshore Wind Farm.

3.4 Part IV – Design of offshore monopiles unprotected against scour

Local erosion can take place around monopile foundations in the offshore environment. Hence, local scour holes can be formed causing decreased stiffness and capacity of the foundation. Scouring is especially an issue when the upper layers of the seabed consists of sandy or silty soils. The scour phenomena has been investigated by several researchers, for instance, Breuser et al. (1977), Sumer et al. (1992a), Sumer et al. (1992b) and Sumer et al. (1993). Local scouring can lead to scour depths of up to approximately $2.0D$. Hence, local scouring significantly decreases the stiffness and capacity of the foundation. Offshore monopiles can therefore be designed either with or without scour protection. If an offshore monopile is designed without scour protection, the monopile needs extra embedded length to account for the decrease in stiffness and capacity caused by the local scouring.

The local scour depth around monopiles unprotected against the development of scour depends on factors such as the pile diameter, the water depth, the sea conditions and the soil properties. Further, the scour depth does not change momentarily. Therefore, the scour depth depends on the variation with time of the current velocity, the water depth and the wave height. An equilibrium scour depth exists for a given sea condition. Generally, the equilibrium scour depth is large when currents are dominating and small when waves are dominating. The process in which the scour hole decreases is denoted backfilling. The knowledge regarding the backfilling process is currently rather limited. Hartvig et al. (2010) studied the time scale of backfilling and the shape of the scour hole during the backfilling process through small-scale testing. This part of the Ph.D. thesis consists of two scientific publications: the paper "Experimental Evaluation of Backfill in Scour Holes around Offshore Monopiles" and the paper "Assessment of scour design for offshore monopiles unprotected against scour". The paper, "Experimental Evaluation of Backfill in Scour Holes around Offshore Monopiles", presents a large-scale tests on the backfilling process around a vertical pile in waves. Both the time scale of backfilling as well as the properties of the backfilled soil material is evaluated through the large-scale test. An overview of the paper is given below:

- **Introduction** – The background for the paper is briefly stated.
- **Scour phenomenon** – A short review of the present knowledge regarding scour/backfilling around vertical offshore piles is presented.

- **Test set-up** – The test set-up employed for the backfill test at the large wave flume (GWK) at the coastal research centre (FZK) in Hannover, Germany is presented. The presentation includes the preparation of the initial scour hole, the water led-in, the wave generation as well as information concerning the taken soil samples and the conducted cone penetration tests.
- **Results** – The test results regarding the time-scale of backfilling for piles in waves and the relative density of the backfilled soil material are presented. Further, the impact of the test results on the design of offshore monopiles unprotected against the development of scour is shortly discussed.

The paper, "Assessment of scour design for offshore monopiles unprotected against scour", presents an adaptive scour design approach in which the variation of scour depth with time and sea conditions is considered. It should be emphasised that further research concerning the backfill process is needed before the adaptive scour design approach can be put into practice. The purpose of the adaptive scour design approach is merely to illustrate the potential savings that can be obtained by accounting for the variation in scour depth with time when designing monopile foundations that are unprotected against scour development. The outline of the paper is as follows:

- **Introduction** – The design of monopiles for offshore wind turbines and the scour/backfilling phenomena around vertical piles in waves is described.
- **Review of the scour/backfilling phenomena** – A review of the scour and backfilling phenomena for vertical piles in the offshore environment is presented. The review considers the equilibrium scour depth, the prediction of the variation of scour depth with time, and the properties of the backfilled soil material.
- **Adaptive scour design** – An adaptive scour design approach is presented. The design approach takes the variation of scour depth with time and the properties of the backfilled soil material into account.
- **Example – Design of monopile foundations for offshore wind turbines based on revised scour adaptive approach** – The fatigue limit state design and the ultimate limit state design of a monopile foundation for an offshore wind turbine is assessed for varying assumptions regarding the scour/backfilling conditions. The Horns Rev 1 Offshore Wind Farm has been employed as example.

Conclusions

Offshore wind energy is a competitive and a largely untapped source of renewable energy. Hence, offshore wind energy plays a major role in the attempt to break the dependence on fossil fuels and in trying to reduce the human-induced carbon emission. The present Ph.D. thesis aims at improving the knowledge regarding the behaviour of laterally loaded, non-slender piles situated in the offshore environment. This can enable the construction of low-risk and low-cost monopile foundations for offshore wind turbines and hereby contribute to improved competitiveness for offshore wind energy. The Ph.D. thesis has been divided into four parts. Three of these parts deal with topics within the field of geotechnical engineering. The fourth research topic concerns both geotechnical engineering and coastal engineering.

In this chapter, the major contributions and main conclusions from the Ph.D. research project are summarised.

4.1 Part I – Review of laterally loaded piles in sand

In this part of the Ph.D. thesis, a literature review of the present knowledge regarding the behaviour of laterally loaded piles has been presented. In the review, the Winkler approach and the p - y curve formulation originally proposed by O'Neill and Murchison (1983) have been used as reference points. The p - y curve formulation proposed by O'Neill and Murchison (1983) are based primarily on physical modelling on flexible piles. The monopiles used for the foundation of today's offshore wind turbines are non-slender, and therefore the applicability of the p - y curve formulation by O'Neill and Murchison (1983) can be questioned. Several limitations/uncertainties concerning the p - y curve formulation proposed by O'Neill and Murchison (1983)

were found and addressed: the shearing force between soil layers; the ultimate soil resistance; the influence of vertical pile load on the lateral soil response; the effect of soil-pile interaction; the effect of diameter on the initial stiffness of p - y curves; the choice of horizontal earth pressure coefficient; the shearing force at the pile-toe; the shape of p - y curves; the effect of layered soil; the effect of long-term cyclic loading; and the effect of scour on the soil-pile interaction. Of these uncertainties and limitations, especially the effect of diameter on the initial stiffness of p - y curves, the effect of long-term cyclic loading on the accumulated pile rotation and on the foundation stiffness, and the effect of scour on the soil-pile interaction are important for the design of monopile foundations for offshore wind turbines.

For offshore wind turbines, it is of great interest to enable accurate predictions of the foundation stiffness, so the rotation of the foundation and the natural frequencies of the wind turbine can be predicted accurately. Therefore, it is also important to be able to determine the initial stiffness of p - y curves for laterally loaded piles in sand with high accuracy. The initial stiffness of p - y curves for laterally loaded piles in sand has been investigated by several researchers. Terzaghi (1955), Vesic (1961), Reese et al. (1974), Ashford and Juirnarongrit (2005) concluded that the initial stiffness is independent of the pile diameter. In contrast, Carter (1984) and Ling (1988) found that the the initial stiffness is linearly proportional to the pile diameter. Further, both a linear and a non-linear effect of the depth below seabed on the initial stiffness has been suggested. Hence, more research is needed to enable accurate predictions of the stiffness of monopile foundations in sand.

Offshore wind turbines are exposed to long-term cyclic loading due to primarily wind and waves. It is therefore important to include the effect of long-term cyclic loading on the soil-pile interaction. This has been investigated by several researchers by means of either small-scale testing or by implementing results from cyclic triaxial tests in three-dimensional numerical models.

For monopile foundations for offshore wind turbines, the pile behaviour for long-term cyclic loading is of great interest when determining the accumulated tilt of the foundation and when predicting the time variation of the first natural frequency of the structure. Cyclic loading is only in a very simplified manner incorporated in the p - y curve formulations proposed by O'Neill and Murchison (1983). The accumulation of pile deflection due to long-term cyclic loading have been investigated by means of both numerical modelling and small-scale tests. Most researchers conclude that the pile deflection accumulates exponentially with the number of cycles. Further, factors such as the relative density, the ratio between the cyclic load amplitude and the static capacity as well as the ratio between the maximum and minimum load during a load cycle affect the accumulated rotation.

For random cyclic loading, contradicting conclusions have been presented. For instance, LeBlanc et al. (2010b) found that the accumulated pile rotation is independent of the loading sequency, while Peralta and Achmus (2010) concluded that the

loading sequence influences the accumulated pile rotation.

Only a limited number of researchers have investigated the variation of the stiffness of the soil-pile interaction with cyclic loading. LeBlanc et al. (2010a) suggested that the stiffness increases logarithmically with the number of cycles independently of the relative density of the soil. However, they only considered piles in loose to medium dense sand. Hence, further research is needed to enable a better prediction of the pile behaviour for long-term cyclic loading. Especially full-scale tests could lead to a better understanding of this topic.

Both global and local scour will take place for offshore piles installed without scour protection. The scour depth will depend on the sea conditions and therefore the scour depth will vary with time. The presence of global and local scouring around offshore monopiles lead to decreased stiffnesses and capacities of monopile foundations. Design regulations such as ISO (2007) and API (2010) suggest a simplified method for modification of p - y curves due to scouring. However, the method relies on empirical consideration and needs to be validated. Lin et al. (2010) pointed out that the soil becomes overconsolidated when scouring takes place. Hence, the coefficient of horizontal earth pressure and the friction angle of the soil increases. Lin et al. (2010) present a method in which the p - y curves can be modified so that the overconsolidation of the soil is taken into account.

Due to changing sea conditions, the depth of the scour holes around unprotected offshore piles will vary with time. Knowledge is needed regarding the properties of backfilled soil material. Such knowledge can be essential for optimising the fatigue design of monopiles that are designed unprotected against scour development.

4.2 Part II – Physical modelling of laterally loaded, non-slender piles

A new and innovative test set-up for the small-scale testing of laterally loaded piles has been developed. The new test set-up for laterally loaded piles enables the application of an overburden pressure to the soil. Traditionally, when conducting small-scale tests at normal stress level, the friction angle will be high and the Young's modulus of elasticity for the soil will be low due to low effective stresses. Furthermore, accurate determination of these parameters is very difficult for small-scale tests, since triaxial tests at confining pressures less than 5-10 kPa are subject to large uncertainties. When an overburden pressure is applied to the soil, the uncertainties mentioned above can be avoided. The new test set-up has been validated based on a large test series on laterally loaded piles. Small-scale tests with and without overburden pressure applied to the soil have been conducted for both statically loaded and cyclically loaded, non-slender piles. The main findings of the physical modelling were as follows:

- The test set-up worked as planned. Generally, the uncertainties related to the test set-up was found to decrease when overburden pressure was applied to the soil.
- Rather similar load-displacement relationships was found for tests on open-ended and closed-ended piles, respectively. Therefore, the shear and normal stresses acting on the pile toe only slightly affected the behaviour of the test piles.
- The pile stiffness and the pile capacity increases significantly when applying an overburden pressure to the soil.
- A scaling law has been proposed for the behaviour of non-slender, laterally loaded piles. The scaling law captures the behaviour of piles with overburden pressure applied to the soil. The scaling law was validated against the small-scale tests for loading eccentricities of $0.74 L_p$ to $1.54 L_p$ and slenderness ratios of 3 to 6.
- In a normalised plot of the moment-rotation relationship, the tests with overburden pressure generally has a lower stiffness than the tests without overburden pressure applied to the soil. Further, the pile rotation at failure was found to increase for increasing value of the overburden pressure. These findings is analogue to the relationship between the strain at failure and the confining stress in triaxial tests.
- For the tests on cyclically loaded piles, the formation of a gap behind the pile was found to depend on whether overburden pressure has been applied to the soil. The gap was significantly more pronounced for the tests with overburden pressure applied to the soil than for the tests without overburden pressure applied to the soil. The reason for this observation needs further examination. Further, the presence of a gap behind large-scale piles installed in cohesionless soils needs to be investigated.
- During unloading for the cyclic tests, friction along the sides of the pile was observed. The friction, however, only had a moderate value. This indicates that the pile capacity is governed primarily by frontal resistance.
- Comparison of the load-displacement relationships for static and cyclic loading indicated that the accumulated pile displacement is primarily governed by the largest applied loading. Similarly, LeBlanc et al. (2010b) also concluded that the accumulated pile displacement depends primarily on the largest applied loading.

4.3 Part III – Numerical assessment of the initial part of p – y curves for piles in sand

In the literature review presented in Part I of the thesis, it was pointed out that several researchers have investigated the initial stiffness of p – y curves for piles in sand, however, with contradictory conclusions. For offshore wind turbines, it is a major concern to enable accurate estimations of the foundation stiffness. Therefore, accurate predictions of the initial stiffness of p – y curves for piles in sand is similarly a major concern. In the present part of the thesis, a numerical study on the initial slope of p – y curves for piles in sand has been presented. The aim of the numerical study has been to investigate which parameters affect the initial slope of the p – y curves for piles in sand. The commercial three-dimensional finite difference program *FLAC^{3D}* was employed for the numerical study. The numerical model was successfully calibrated/validated against the experimental tests on laterally loaded piles presented in Part II of the thesis.

The initial slope of p – y curves for piles in sand was found to depend on the depth below seabed, the pile diameter and the Young's modulus of elasticity for the soil. The friction angle, the loading eccentricity and the pile flexibility were found not to affect the initial slope of the p – y curves. A modified expression for the initial slope of p – y curves for piles in sand was fitted to the numerical simulations so that accurate predictions of the pile behaviour for piles exposed to serviceability limit state loads has been enabled. The modified expression is not expected to be well-suited when investigating the first natural frequency of an offshore wind turbine. However, by implementation of an associative model capturing the small strain behaviour of soil, a similar method can be used to determine values for the initial slope of p – y curves which should be employed for accurate determination of the first natural frequency.

4.4 Part IV – Design of offshore monopiles unprotected against scour

Around offshore piles situated in cohesionless soils, currents and waves can lead to the development of scour holes. The size of these scour holes will vary with time given that the sea conditions affect the equilibrium scour depth. Much research has been conducted so far on the equilibrium scour depth for varying sea conditions. Furthermore, the time scale of the process in which the scour depth increases has similarly been studied intensively. However, little knowledge exists regarding the time scale of the process in which the scour depth decreases (backfilling). Furthermore, no knowledge exists regarding the relative density of backfilled soil material. The variation of scour depth with time as well as the relative density of the back-filled soil material have a significant influence on the stiffness and capacity of offshore

pile foundations. A large-scale test on backfilling around piles in waves has been conducted at the large wave flume (GWK) at the coastal research centre (FZK) in Hannover, Germany. Both the time scale and the relative density of the backfilled soil material has been investigated. Due to limited time available at the large wave flume, it has only been possible to conduct one test on the backfill around piles in waves. Therefore, the conclusions of the study on the backfilling process for piles in waves are only indicative and further research is needed to validate the findings. The following results were observed:

- The normalised time scale of backfilling determined in the large-scale test was significantly smaller than the normalised time scale of backfilling for the small-scale tests reported by Hartvig et al. (2010). The Shields parameter and the Keulegan-Carpenter number for the small- and large-scale tests were of similar values. Therefore, the dependency of the time scale on these parameters cannot explain the significant difference in the normalised time scale. The large-scale test hereby demonstrates that more research is needed regarding the time-scale of backfilling around piles in waves. Further, the scaling of the time scale of backfilling needs further investigation.
- The relative density of the backfilled soil material was found to be approximately 80 % at the new soil surface and decreasing with depth to 65 % at the bottom of the original scour hole. The relative density was determined after the waves were stopped. Therefore, the variation of the relative density with time has not been investigated. Further, it is not known whether the backfilled soil material underwent liquefaction during the backfilling process. Further research is needed regarding the influence of the Shields parameter, the Keulegan-Carpenter number and time on the backfilling process.
- The backfilling process around piles in combined waves and current needs to be investigated.
- Since, the findings of Hartvig et al. (2010) contradicts the results of the large-scale test, the backfilling process around piles needs to be investigated through a combination of small- and large-scale tests.

A desk study has been conducted concerning the influence of the time variation of scour depth and the relative density of backfilled soil material on the design of monopiles for offshore wind turbines. The soil profile, foundation geometry and wind turbine geometry of the Horns Rev 1 Offshore Wind Farm has been employed in the desk study. From the desk study, the variation of the scour depth with time as well as the properties of the backfilled soil material were shown to have a major impact on especially the fatigue life of an offshore wind turbine. Several assumptions have been employed in the desk study. Therefore, the desk study should only be seen as indicative. However, based on the desk study, it can be concluded that accounting

for the time variation of scour depth in the design can reduce the foundation costs significantly. It is emphasised that further research is needed regarding the time scale of backfill around piles and regarding the properties of backfilled soil in order to enable a more optimised foundation design.

4.5 Concluding remarks

The research project in the present Ph.D. thesis was aimed at improving the design of offshore monopiles used as the foundation for offshore wind turbines. The behaviour of offshore non-slender, large-diameter offshore piles were studied through a combination of physical and numerical modelling. The outcome of the research has lead to an improved understanding of the behaviour of offshore piles and hence the research contributes to an improved economic feasibility of offshore wind energy.

CHAPTER 5

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CHAPTER 6

Enclosed scientific papers

Sørensen, S.P.H., Brødbæk, K.T., Møller, M. & Augustesen, A.H. (2012). Review of laterally loaded monopiles employed as the foundation for offshore wind turbines. *DCE Technical Reports, No. 137, Department of Civil Engineering, Aalborg University, Aalborg, Denmark.*

Sørensen, S.P.H., Ibsen, L.B. & Foglia, A. (2012). Testing of Laterally Loaded Rigid Piles with Applied Overburden Pressure. *Submitted for publication.*

Sørensen, S.P.H. & Ibsen, L.B. (2012). Experimental Comparison of Non-Slender Piles under Static Loading and under Cyclic Loading in Sand. *Proceedings of the 22nd International Ocean and Polar Engineering Conference, XXII ISOPE, Rhodes, Greece.*

Sørensen, S.P.H., Augustesen, A.H. & Ibsen, L.B. (2012). Revised expression for the static initial part of p - y curves for piles in sand. *Submitted for publication.*

Sørensen, S.P.H., Ibsen, L.B. & Frigaard, P. (2010). Experimental Evaluation of Backfill in Scour Holes around Offshore Monopiles. *Proceedings of the 2nd International Symposium on Frontiers in Offshore Geotechnics, II ISFOG, Perth, Australia, 8-10 November 2010. Balkema Publishers, A.A. / Taylor & Francis, The Netherlands, 2010, pp. 617-622.*

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