Institution: University of Oxford		
Unit of Assessment: 12 – Engineering		
Title of case study: Practical and Economic Benefits of Improved Offshore Wind Turbine Monopile Foundations		
Period when the underpinning research was undertaken: Aug 2013 – July 2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Byron Byrne	RAEng / Ørsted Professor of Advanced Geotechnical Design (PI)	2001 - present
Prof. Harvey Burd	Associate Professor (Co-I)	1987 - present
Prof. Guy Houlsby	Professor of Civil Engineering (Co-I)	1980 - 2020
Prof. Chris Martin	Professorial Research Fellow (Co-I)	2000 - present
Prof. Ross McAdam	PDRA, then Associate Professor (Co-I)	2013 - present
Period when the claimed impact occurred: 2018 - Dec 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The offshore wind industry is central to the UK's energy plans, and this project was directed entirely towards enhancing the economic viability of offshore wind through improved engineering design. The Joint Industry Pile Soil Analysis (PISA) research project created new engineering design methods for the "monopile" foundations that support offshore wind turbines. The new methods reduce risk, address design conservatism and reduce associated costs. By optimisation of turbine foundation for specific geographic locations, accounting for the complex offshore ground conditions, the methods developed have contributed to lower overall costs for wind energy, and have influenced standards for the design of offshore wind farms. Applying the method, Ørsted optimised 50% of the foundations for Hornsea 1 (1.2GW, 174 turbines), the largest operational windfarm in the world, and Borssele 1&2 (752MW, 94 turbines), both constructed, leading to [text removed for publication] of savings on steel, and de-risking the design. The PISA design methods have been applied to RWE's Triton Knoll windfarm (0.86GW, 90 foundations), under construction, Equinor's operational Dudgeon windfarm (0.4 GW, 67 foundations), and Equinor / SSE's Dogger Bank windfarm (3.6GW, 300 foundations) currently in design.

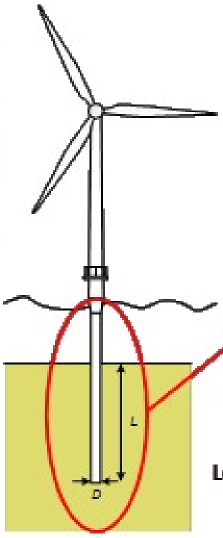
2. Underpinning research

The research was completed during the PISA project (between Aug 2013 and Jul 2018), funded through the Carbon Trust's Offshore Wind Accelerator, led by Ørsted, and with a further 10 industry partners comprising the key European wind farm developers (responsible for over 75% of European installed wind capacity). The scientific work was led by the University of Oxford (Byrne as Principal Investigator, Houlsby, Burd, Martin, McAdam), collaborating with Imperial College London (Zdravković, Jardine, Potts, Taborda) and University College Dublin (Gavin). Oxford provided the scientific and strategic leadership for the work, collaborating closely with the industrial partners, and took responsibility for the delivery of new design methods, including theoretical developments and all scientific aspects of the extensive field pile-testing campaign. Imperial College led on the three-dimensional finite element modelling and site characterisation activities. University College Dublin provided support to the field-testing activities. The close involvement of industry partners in the research allowed rapid uptake of the results by the industry, even as the research was being developed.

During the project, the scientific team developed new design methods to allow optimisation of the monopile foundations that support offshore wind turbines. Monopiles are large diameter steel tubes (see Figure on next page), impact driven into the seafloor, typically 8m to 10m in diameter, 30m to 50m long, and weighing up to 1000t. Optimisation is central to wind farm economics and long-term wind turbine performance. The key research achievement was to capture accurately the detailed monopile soil-structure interaction for each wind farm site, ensuring site-specific and turbine-specific optimisation to save on steel costs. This insight was developed from a range of connected and carefully planned activities: (a) site investigation and laboratory element testing, (b) numerical modelling, including sophisticated three-dimensional finite element analysis, (c) theoretical developments, including development of simplified design procedures, and (d) a comprehensive medium-scale field pile testing campaign to validate the new design methods.

Key outputs of the PISA design method include generic design procedures for wind farm designers, as well as bespoke design equations. These enable simplified calculations to be completed, which have the fidelity of more complex finite element calculations, but computed in a fraction of the time, covering a wide range of design conditions. The procedures specifically address the computational requirements for the engineering design team, where many load cases and design scenarios must be considered in a short period of time during the design phase of a project.

Above: Monopile supported offshore wind turbines at Burbo Bank UK



Left: Schematic showing layout of monopile foundation supported wind turbine

Below: 7.5 m diameter monopile foundation (Gode Wind Offshore Wind Farm, 2015)

The procedures have been developed for a wide range of common soil types found in the offshore environment, and account for layered soil profiles typically encountered. The procedures can be applied at concept design stage or for more detailed design and can be adapted for specific sites, depending on the amount of site investigation data available to the design team. Importantly, the procedures allow the design calculation to be optimised for each individual turbine location, accounting for the wide range of geological profiles found across very large wind farm sites (often covering hundreds of square kilometres). The research outputs have been reported in the leading journal *Géotechnique* **[R1], [R2], [R3], [R4], [R5], [R6]** (all Open Access) and are also embodied in commercially available software (MoDeTo) developed collaboratively with the geotechnical software provider PLAXIS.

The research has produced a new engineering design method (the PISA design model) for offshore wind turbine monopile foundations, described in outputs **[R1]** and **[R2]** (led by Oxford). The research initially explored geological conditions relevant to UK offshore wind farms, and was validated by an ambitious programme of field testing, described in outputs **[R3]** and **[R4]** (led by Oxford). The basis for the numerical modelling that underpins the simplified design calculation procedures (developed in **[R1]** and **[R2]**) is described in outputs **[R5]** and **[R6]** (led by Imperial College). The work was then further developed to include a wider range of soil profiles relevant to offshore UK, as well as across Europe and internationally. The application of the new PISA design model to layered soils routinely encountered offshore (led by Oxford) was also addressed.

To achieve maximum impact, a comprehensive and planned dissemination programme was central to the project. The dissemination programme was led by Oxford, and included:

- 10 confidential reports for the industrial sponsors (between 2013 and 2018);
- 8 confidential workshops for the PISA Project Industry Partners (>50 attendees each time);
- to reach a wider audience, 38 invited lectures / presentations at academic and industry focused conferences, including at the Institution of Civil Engineers, at industry workshops, at universities (UK, US, Australia), and at national Geotechnical Societies (British, Danish, French), some of which were also recorded for web-viewing;
- 7 conference papers, including an invited keynote paper for an international industry conference, all involving oral presentations;

- 10 journal papers (9 Open Access) to provide a permanent record of the scientific work.

The excellence of the management of the PISA Project was recognised by the British Geotechnical Association's Fleming Award, 2017, for "excellence in the practical application of geotechnics in a project", the only time the award has been made to a research project.

3. References to the research (Oxford authors in bold)

[R1] Byrne, B.W., **Houlsby, G.T.**, **Burd, H.J.**, Gavin, K., Igoe, D., Jardine, R.J., **Martin, C.M.**, **McAdam, R.A.**, Potts, D.M., Taborda, D.M.G. and Zdravković, L. (2020). "PISA design model for monopiles for offshore wind turbines: application to a stiff glacial clay till." *Géotechnique*, Vol. 70, No. 11, pp 1030-1047, doi.org/10.1680/jgeot.18.p.255 (Journal Article)

[R2] Burd, H.J., Taborda, D.M.G., Zdravković, L., Abadie, C.N., **Byrne, B.W.**, Gavin, K., **Houlsby, G.T.**, Igoe, D., Jardine, R.J., **Martin, C.M.**, **McAdam, R.A.**, Pedro, A.M.G. and Potts, D.M. (2020). "PISA design model for monopiles for offshore wind turbines: application to a marine sand." *Géotechnique*, Vol. 70, No. 11, pp 1048-1066, doi.org/10.1680/jgeot.18.p.277 (Journal Article)

[R3] Byrne, B.W., **McAdam, R.A.**, **Burd, H.J.**, Beuckelaers, W.J.A.P., Gavin, K., **Houlsby, G.T.**, Igoe, D., Jardine, R.J., **Martin, C.M.**, Muir Wood, A., Potts, D.M., Skov Gretlund, J., Taborda, D.M.G. and Zdravković, L. (2020). "Monotonic laterally loaded pile testing in a stiff glacial clay till at Cowden." *Géotechnique*, Vol. 70, No. 11, pp 970-985, doi.org/10.1680/jgeot.18.pisa.003 (Journal Article)

[R4] McAdam, R.A., **Byrne, B.W.**, **Houlsby, G.T.**, Beuckelaers, W.J.A.P., **Burd, H.J.**, Gavin, K., Igoe, D., Jardine, R.J., **Martin, C.M.**, Muir Wood, A., Potts, D.M., Skov Gretlund, J., Taborda, D.M.G. and Zdravković, L. (2020). "Monotonic laterally loaded pile testing in a dense marine sand at Dunkirk." *Géotechnique*, Vol. 70, No. 11, pp 986-998, doi.org/10.1680/jgeot.18.pisa.004 (Journal Article)

[R5] Zdravković, L., Taborda, D.M.G., Potts, D.M., Abadias, D., **Burd, H.J.**, **Byrne, B.W.**, Gavin, K., **Houlsby, G.T.**, Jardine, R.J., **Martin, C.M.**, **McAdam, R.A.** and Ushev, E. (2020). "Finite element modelling of laterally loaded piles in a stiff glacial clay till at Cowden." *Géotechnique*, Vol. 70, No. 11, pp 999-1013, doi.org/10.1680/jgeot.18.pisa.005 (Journal Article)

[R6] Taborda, D.M.G., Zdravković, Potts, D.M., **Burd, H.J.**, **Byrne, B.W.**, Gavin, K., **Houlsby, G.T.**, Jardine, R.J., Liu, T., **Martin, C.M.** and **McAdam, R.A.** (2020). "Finite element modelling of laterally loaded piles in a dense marine sand at Dunkirk." *Géotechnique*, Vol. 70, No. 11, pp 1014-1029, doi.org/10.1680/jgeot.18.pisa.006 (Journal Article)

Grants – G7 was won through a competitive tender process through the Carbon Trust Offshore Wind Accelerator. G8 and G9 were follow-on awards.

[G7] Byrne, B.W., **Houlsby, G.T.**, **Burd, H.J.**, **Martin, C.M**., Zdravkovic, L., Potts, D.M., Jardine, R.J., Taborda, D.M. and Gavin, K. (2013 - 2016). "PISA – Pile Soil Analysis – Academic Work Group package" Sponsor: Ørsted and Carbon Trust Offshore Wind Accelerator. Overall project value approximately GBP3,500,000 with the Academic Work Group sub-contract GBP815,000. Oxford sub-contracted contributions from Imperial College and University College Dublin. Value to Oxford GBP494,500.

[G8] Byrne, B.W., **Houlsby, G.T.**, **Burd, H.J.**, **Martin, C.M.**, **McAdam, R.A.**, Zdravkovic, L., Taborda, D.M., Potts, D.M. and Jardine, R.J. (2017 - 2018). "PISA2 – Layered Soils Extension – Academic Work Group package" Sponsor: Ørsted and Carbon Trust Offshore Wind Accelerator. Overall project value GBP380,000. Oxford sub-contracted contributions form Imperial College. Value to Oxford GBP165,000.

[G9] Burd, H.J., **McAdam, R.A.** and **Byrne, B.W.** (2018). Development of "Advanced Monopile Design Tool" under licence to Plaxis. Sponsor: Plaxis. Value: GBP100,000.

4. Details of the impact

The impact of the work is derived from reducing the direct and indirect costs for the foundations that support offshore wind turbines, leading to improved economic viability generally for offshore wind, and for specific offshore wind farm developments. The industry funding partners for the PISA project consisted of 11 of Europe's main offshore wind developers, collectively responsible for more than 75% of Europe's installed offshore wind capacity (Ørsted, E.ON, EDF, GE Renewable Energy, Iberdrola, Innogy (now RWE), SSE, Statkraft, Equinor, Van Oord and Vattenfall), and also involved in offshore wind development outside Europe (e.g., USA, Taiwan). They each had access to the research outputs at an early stage and were therefore able to implement the recommendations through their engineering teams as the results became available **[S1, S2, S3]**. This close collaboration, with the work focusing on soil profiles relevant to UK / European wind farm sites, ensured that the new methods were applied rapidly to design of new wind farm developments. Specific impacts include:

Economic Impact - savings to design and construction for industry partners

The PISA design method was initially delivered to industry partners between 2014 and 2016. Ørsted have seen **direct savings of** [text removed for publication] in reduced steel costs for the monopile foundations now constructed at Hornsea 1 (1.2GW, PISA applied to 87 of the 174 foundations) and Borssele 1&2 (0.7GW, PISA applied to all 94 foundations). Anticipated savings have been factored into costing of bids to develop future sites, playing an important role in the success of these bids: Ørsted have estimated **further direct savings of** [text removed for publication] **over the next 5 years** for wind farms currently in design and construction (e.g. Hornsea 2 - 1.4GW, 165 foundations; Skipjack – 0.12GW; Ocean Wind – 1.1GW, Godewind 3 – 0.24GW, Borkum Riffgrund 3 – 0.9GW). The PISA design method is fully implemented into Ørsted's design process for these and future wind farms **[S1]**. RWE's Triton Knoll wind farm, currently under construction with foundations now installed (0.86GW, 90 foundations), RWE's Sofia wind farm (1.4GW, 100 foundations) and the Dogger Bank wind farm (3.6GW, 300 foundations) to be developed jointly by Equinor and SSE, have all adopted the PISA design model **[S2, S3]**. PISA was first applied to Equinor's Dudgeon Wind Farm (0.4GW, 67 foundations) in 2015/16, providing confirmation that the original American Petroleum Institute (API) design and methods were conservative **[S3]**.

A paper authored by parties entirely independent from the PISA project, from the consulting engineers Atkins, verifies that 30% savings by mass of the monopile foundation can be delivered in commercial design (note that *D* below refers to diameter of foundation, which identifies the length of pile reduction achieved):

> *"Whilst monopiles have been the dominant foundation type for offshore wind, the soil response which plays such a significant role in their design has historically been modelled using either inadequate or poorly calibrated representations. The recently completed PISA JIP which involved large scale lateral pile load tests at two sites and state of the art finite element analysis offers recommendations to better model the soil response. It considers four components of resistance and recommends that formulations for the non-linear soil reaction springs be derived from 3-D numerical models (calibrated to pile load test results).*
>
> *The PISA JIP recommendations have successfully been implemented for the design of an offshore wind farm in the UK North Sea and some of the practical aspects of the implementation have been presented. The improved soil response modelling has resulted in significant monopile embedment reductions (1 to 2 D) and mass reductions (in excess of 30%) compared to traditional design approaches.*
>
> *The implementation of the PISA JIP improved soil response modelling approach leads to significant CAPEX reductions and also enables monopiles to be considered in deeper waters and for larger turbines than previously considered."* **[S4]**.

The paper refers to Triton Knoll wind farm as the subject, for which Atkins were the foundation designer **[S2, S4]**. Offshore construction began in Q1 2020, with the 90 monopile foundations installed by August 2020. RWE **[S2]** states that "*The weight of the installed foundations was c.600 tonnes [600t] – had they not been designed by PISA they would have been substantially heavier and costlier.*" First power is expected in early 2021.

Economic Impact – Indirect savings to industry resulting from the PISA project

Industry partners have noted the many indirect savings arising from the use of the new PISA design methods. These are more difficult to quantify without detailed costing analyses for alternative scenarios. However, Ørsted, for example, states that "*other indirect savings, such as a) reduction of installation risk due to shorter pile lengths, b) continuation of use of monopile as the cheapest foundation concept in deeper waters and with bigger turbines* [text removed for publication] *c) shorter offshore installation time and d) better assessment of foundation fatigue* *life (due to better understanding of foundation initial stiffness response) leading to better quantification of risks have also led to major cost savings for foundation design and construction"* **[S1]**. RWE and Atkins also refer to the indirect savings resulting from PISA **[S2, S4]**.

New commercial software "MoDeTo", produced by PLAXIS, a geotechnical engineering software company, under licence from Oxford, **captured the PISA design method**. This software, released in 2018, allows commercial designers to carry out engineering design calculations incorporating the PISA design method during the design of new offshore wind farms. It is now marketed through Bentley as the "PLAXIS Monopile Designer" **[S5]**.

Economic Impact – reduction to the cost of offshore wind energy

The PISA design method contributes to improved engineering design for offshore wind to **reduce the "levelised cost of energy",** leading to more rapid deployment of offshore wind, with consequent decarbonisation of the electricity system (e.g., each installed 8MW offshore wind turbine displaces approximately 12,000tCO_2/year from fossil fuel generation). The use of the PISA design model directly influences foundation costs, which are approximately 20% of capital costs. PISA has been adopted for the foundation design underpinning Contract for Difference (CfD) bids (all expressed in 2012 prices, date given is of the successful auction) for Hornsea 2 (2017, Ørsted, 1,400 MW, GBP57.50 per MWh), Dogger Bank (2019, Equinor/SSE, 3,600MW, GBP39.65 to GBP41.61 per MWh), Sofia (2019, Innogy, 1,200MW, GBP39.65 per MWh). This compares to 2015 figures for nuclear power of GBP92.50 per MWh and offshore wind of GBP114 to GBP120 per MWh. RWE **[S2]** states that "*The strike price reductions have been achieved through multiple technical advances, including very significant contributions on the foundations component from the PISA project led by Oxford University.*" The PISA design model is actively contributing to offshore wind becoming "subsidy-free" **[S1, S2, S3]**.

Policy Impact – PISA findings being incorporated into international standards

Ørsted **[S1]** states that "*The PISA project has been a **highly successful case of close industry-academia collaboration** and has led to significant improvements in design methodologies of offshore windfarm foundations.*" The work is being incorporated into the **international standards and guidance** used by engineers designing offshore wind farms, and which, if followed, normally allow design certification to be achieved. CFMS, the French society for soil mechanics, first incorporated the method into French guidance notes for offshore wind design in 2018 **[S6]**. Draft guidance is being incorporated into the new revision of ISO 19901-4, the international standard for offshore geotechnical design, due out shortly. It is expected that similar text would be included within API RP 2GEO, the American Petroleum Institute guidance on offshore geotechnical design, in due course through a process that will continue into 2022 **[S7]**.The corroborating letter from Equinor **[S3]** concludes "*In summary, PISA has resulted in a more reliable design with risks better assessed and improved accuracy.*"

5. Sources to corroborate the impact

[S1] Ørsted letter (Jan 2021) corroborating the use of the design method and cost figures.
[S2] RWE letter corroborating use of design method and benefits.
[S3] Equinor letter (Jan 2021) corroborating use of design method and benefits.
[S4] Corroborator 1: Technical Director, Offshore Geotechnics Technical Authority, Atkins may be contacted to confirm information. Details are also corroborated in the conference paper available from onepetro.org: Manceau, S., McLean, R., Sia, A. and Soares, M. (2019). "Application of the findings of the PISA joint industry project in the design of monopile foundations for a North Sea wind farm". Offshore Technology Conference (paper OTC2957), Houston, Texas.
[S5] Product website evidencing software capturing the PISA design method, originally developed by PLAXIS and now part of the Bentley software suite
[S6] Comité Français de Mécanique des Sols et de Géotechnique (CFMS) Guidelines evidencing PISA Project incorporated into French offshore wind farm design guidance notes
[S7] Corroborator 2: Principal Geotechnical Engineer, Lloyd's Register may be contacted to confirm information.