Institution:	Imperial College London
Unit of Assessment:	12 Engineering
Title of case study:	Optimising the Delivery of Offshore Structures through New Design Methods for Safe and Economic Foundations

Period when the underpinning research was undertaken: January 2000 - December 2020

Details of staff conducting the underpinning research from the submitting unit

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
Prof Richard Jardine	Professor of Geomechanics	2000 – present
Prof David Potts	GCG Professor of Geotechnical Engineering	2000 – present
Prof Lidija Zdravkovic	Professor of Computational Geomechanics	2000 – present
Dr Stavroula Kontoe	Reader in Soil Dynamics	2006 – present
Dr David Taborda	Senior Lecturer	2012 – present

Period when the claimed impact occurred: 1 August 2013 – 31 December 2020

Is this case study continued from a case study submitted in 2014? Yes

1. Summary of the impact

Integrated programmes of geotechnical research led by Profs. Jardine, Potts and Zdravkovic, in collaboration with industry, delivered substantial benefits to offshore energy sector since 2014, including:

- I1. new axial, lateral, monotonic and cyclic offshore pile design technologies, endorsed by a widespread use in Industry;
- I2. critical design solutions to fossil and renewable offshore energy projects that have enabled multi-million GBP developments to progress safely in deeper waters and more challenging environmental and/or ground conditions;
- I3. piling cost reductions up to 30% over codified methods, delivering UK benefits rising to approximately GBP300,000,000 per year by 2018;
- I4. greenhouse gas emission reductions and other environmental benefits following the two-third reduction achieved in offshore-wind electricity prices and its growth of a one-third share of UK supply, allowing developers to switch to principally offshore-wind production.

2. Underpinning research

Research streams explained below underpinned the development of new, robust and accurate, field-validated, design technologies for axially and laterally-loaded offshore piles through: (i) advanced laboratory experiments, Imperial College Pile (ICP) and other field testing campaigns with new technologies, integrated with (ii) advanced numerical modelling developments and their applications with the bespoke geotechnical Imperial College Finite Element Program (ICFEP).

1. **Axial pile loading research in clays and sands [R1-2]:** Investigations since 2000, led by Jardine, funded by French Government (CNRS), EPSRC, Health & Safety Executive (HSE), Royal Society, Shell, Total and others included: extensive laboratory research; development/application of new highly instrumented pile models [R2]; and field pile testing at Dunkirk [R1]. Identifying the fundamental mechanisms governing the ageing and damage of piles under axial cyclic loading enabled new, field-verified, “ICP” design methods for clays and sand. Dissemination through papers, keynotes, honour lectures, design booklets, engagement in offshore projects led to widespread application and

inclusion in American Petroleum Institute (API), HSE and International Organisation for Standardisation (ISO) guidance [R3].

2. **Axial and lateral monotonic and cyclic loading of piles in chalk [R3]:** Chalk, which is encountered widely offshore Northern Europe can lose strength dramatically during pile driving and give uncontrollable pile free-falls into the seabed. The 2014-17 UK-Innovate project with Iberdrola and Geotechnical Consulting Group (GCG), led by Jardine and Kontoe, applied novel sea-bed static and dynamic pile testing technologies in unique field measurements at the new Wikinger Baltic windfarm [R3]. Together with instrumented onshore experiments, the research identified the piles' governing installation, ageing and cyclic-loading processes, identified why installation problems may occur, and showed how to overcome the difficulties through new "ICP-Chalk" design methods that avoid unnecessary over-conservatism. Jardine and Kontoe led further chalk research with the ALPACA and ALPACA Plus (2019-20) Joint Industry Projects (JIPs) with Oxford University, eight offshore developers and four Consultants. Novel dynamic fibre-optic sensors and physio-chemical investigations delivered detailed guidance on axial-and-lateral, static-and-cyclic design analysis for chalk sites [R3].
3. **Numerical modelling of soil-structure interaction [R4-6]:** Numerical analysis of foundation problems is challenging because of soils' highly non-linear and multi-phase nature. Research since 2000, led by Potts and Zdravkovic, funded by EPSRC, Portuguese Government, GCG, Crossrail and HSE, delivered ICFEP's unique monotonic and cyclic soil modelling capabilities, enabling realistic predictions of small-strain [R5] and failure [R4] behaviour of soils for a wide range of loading and ground conditions. Together with novel structural shell element formulation and modelling approaches for submerged soil-structure interfaces, these advances enabled the first accurate analyses of laterally-loaded offshore piles [R6] and identified the primary mechanisms governing the soil response to such loading.
4. **PISA design method [R6]:** Field-monitoring of monopile wind-turbine foundations by Ørsted identified costly over-conservatism in monopile design processes adopted in industry. The 2013-18 PISA & PISA2 JIP projects funded by Carbon Trust and ten offshore developers, delivered substantially more efficient design for laterally-loaded piles than existing codified methods, by applying advanced three-dimensional (3D) predictive ICFEP modelling approach, soil laboratory testing and comprehensive large-scale field pile testing. Zdravkovic, Jardine, Potts and Taborda worked with Prof Byrne's team at Oxford to design and model large instrumented pile tests at sites in UK and France. Excellent agreement between ICFEP predictions and subsequent field observations unlocked paths to more economical 3D numerical [R6] and 1D design methods. The PISA research outputs found immediate and widespread application through engagement in the sponsors' projects and through a suite of Géotechnique papers, including [R6], endorsed by the Industry and UK Carbon Trust: https://www.carbontrust.com/news-and-events/news/new-design-methods-for-offshore-wind-monopiles-to-create-cost-savings-for. New research under the EPSRC/ORE Supergen ALPHA project has extended ICFEP design analyses for lateral pile loading to include challenging (brittle and sensitive) chalk ground conditions.

3. References to the research

R1 was awarded the Institution of Civil Engineer's 2007 Geotechnical Research Medal, R2 was included in the Editor's list of six best 2014 papers, R3 was invited for presentation to 35 audiences in 25 countries (over 2016-18), while R6 covers research on the PISA project, which won the British Geotechnical Association's 2017 Fleming Award for "*excellence in geotechnical design and construction*".

R1. **Jardine, R.J**, Standing, J.R and Chow, F.C. (2006). Some observations of the effects of time on the capacity of piles driven in sand. *Geotechnique* 55 (4), pp 227-244. https://www.icevirtuallibrary.com/doi/10.1680/geot.2006.56.4.227

R2. **Jardine R.J**, Zhu, B.T., Foray, P. and Yang, Z.X. (2013). Measurement of stresses around closed-ended displacement piles in sand. Geotechnique 63 (1), 1–17. https://www.icevirtuallibrary.com/doi/full/10.1680/geot.9.P.137

R3. **Jardine, R.J**. (2020). Geotechnics, Energy and Climate Change. 56th Rankine Lecture, *Géotechnique,* 70, (1), pp 3-59. https://www.icevirtuallibrary.com/doi/full/10.1680/jgeot.18.RL.001

R4. Tsiampousi, A., **Zdravkovic, L**. and **Potts, D.M**. (2013). A new Hvorslev surface for critical state type unsaturated and saturated constitutive models. *Computers and Geotechnics* 48, pp 156-166; https://doi.org/10.1016/j.compgeo.2012.09.010

R5. **Taborda, DMG., Potts, D.M.** and **Zdravkovic, L**. (2016). On the assessment of energy dissipated through hysteresis in finite element analysis. *Computers and Geotechnics* 71, 180-194; https://doi.org/10.1016/j.compgeo.2015.09.001

R6. **Zdravkovic, 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. (2019). Finite element modelling of laterally loaded piles in a stiff glacial clay till at Cowden. *Geotechnique*, https://doi.org/10.1680/jgeot.18.pisa.005

4. Details of the impact

I1. **New pile design paradigms:** The 'ICP' axial cyclic loading and ageing design approaches for sands and clays, [R1, R2], have been applied in many £multi-billion North Sea oil/gas and wind-energy projects since 2014, enabling better safety and economy in foundation design, as detailed in publications [S1-S5] co-authored with industry. Iberdrola group, lead industrial partners on East Anglia One (EAONE) wind farm, report that [S2b]:

> "*the ICP-05 method is considered highly reliable for North Sea sands and clays and will be continuously considered where relevant on future developments within the Iberdrola offshore renewables ever growing portfolio*".

The new ICP-Chalk axial loading and ageing methodology applied on SPR's GPB1,200,000,000 Wikinger Baltic windfarm, [R3], enabled material and risk reduction project benefits valued at [S5]:

> "*tens of millions of Euros in supply and fabrication costs and several further million Euros of savings in [pile] installation costs".*

Comparable benefits from 'ICP' design approaches apply to new Chalk projects, including SPR's GBP1,000,000,000 Baltic Eagle and LEMS' 496MW Le Tréport projects whose developers maintain close links with the Imperial team, including investing in ALPACA JIP. Ørsted applied the team's novel field-testing technologies in GBP40,000,000 pile experiments conducted offshore Taiwan in 2019.

The PISA research [R6] led to paradigm changes in numerical modelling methods of offshore piles, as detailed in publications co-authored with industry [S6, S8, S9], which deliver significantly more accurate and efficient designs for laterally-loaded monopiles. Ørsted [S10a] refer to the work as:

> "*a flagship in the offshore wind industry, an extremely successful joint-industry project that has had a direct and indisputable effect on the ability of offshore wind to become cost-effective and in turn be able to compete with other energy sources*", reporting that "*PISA methods provided cost savings in excess of £10m as compared to conventional design methods*" for the Hornsey-01 windfarm.

I2. **Critical design solutions to offshore developments:** The static and cyclic axial ICP design methods' [R1-R2] contributions to major projects since 2014 include: (i) assuring safety in difficult ground conditions in BP's GBP4,500,000,000 West-of-Shetland Clair Ridge (the UK's largest oil project), where production commenced in 2018 under extreme metocean conditions, [S1]; (ii) Gaz de France's GBP1,400,000,000 2016 Cygnus project, which is the UK's largest gas field and supplies 1.5M UK homes; and (iii) EAOOne, a GBP2,300,000,000 SPR/Vattenfall windfarm that adds 800MW to UK capacity [S2a], whose developers attested in 2018 after completing the foundations for 102 jacket-supported wind-turbines that [S2b]:

> *"the use of the ICP-05 design methodology played a very significant part in its success",* achieving "*estimated £11m steel cost savings"* while dynamic load tests *"proved the required capacity*".

Similar contributions were made to Chevron's Captain Enhanced Oil Recovery project [S3], Premier Oil's Solan West-of-Shetland development and German North Sea jacket-supported structures, including Orsted's Borkum Riffgrund [S4].

The Imperial team has also worked with GCG to apply ICFEP's predictive modelling approach and advanced capabilities [R4-R5] in several major offshore wind projects. Source [S10b] testifies:

> "*ICFEP has been instrumental in enabling a step-change in the design of monopiles as foundations for offshore wind turbine generators*", documenting particular benefits in "*enabling Ørsted's foundation design to meet certification body standards*" and achieving "*some of the major landmarks in Ørsted's offshore wind development*": *(i) Burbo Bank Extension, operational since 2017, the world's first to use currently largest 8MW turbines; (ii) Walney Extension, at 659 MW the world's largest wind-farm when commissioned in 2018; (iii) Hornsea-01, world's first to exceed 1 GW capacit*y with 174 turbines (in 2020) and (iv) Hornsea-02, currently under design, to deliver 1.386 GW, adding to Ørsted's capacity to power 5.5M UK homes by 2022.

Similar ICFEP-supported design contributions were made to Ørsted's German Gode-Wind (2014, [S6]), UK Race Bank (2015) and German Borkum Riffgrund 02 (2016) projects and Innogy's UK Triton Knoll, where the next generation 9.5 MW turbines will deliver 855 MW from 2021, [S8].

I3. **More economical foundations:** Examples of the multi-million British Pound savings enabled by the ICP static and cyclic axial offshore design procedures, [R1-R3], at clay, sand and chalk 'jacket' sites are detailed in [S2b], [S3] and [S5]: savings up to 30% in foundation costs were achieved over routine codified methods.

The PISA design guidance for lateral loading, [R6], has been applied in multiple projects since 2015 and PISA-based tools (MoDeTo) were implemented for general use, https://www.bentley.com/en/products/product-line/geotechnical-engineering-software/plaxis-modeto, in the leading commercial software Plaxis since 2018. Independent consultants, [S7], working with PISA-based tools, report savings for the Triton Knoll UK windfarm:

> "*in excess of 30% compared to traditional design approaches*".

Ørsted [S10b] testifies to PISA design methods being:

> "*central to increased efficiency of foundation design and reduced cost of foundations, which accounts for around 20% of the total capital (CAPEX) expenditure*".

CAPEX reductions of 6% were achieved from the foundations research in the 17 major offshore projects cited above, and in many others, through the new approaches' widespread UK and international use. Noting that the CAPEX value of UK offshore wind projects commissioned in 2018 exceeded six billion GBP, widespread use of the new methods may have led to UK savings exceeding GBP300,000,000, plus further international benefits.

I4. **Cheaper, greener and secure energy:** The team's piling research helped the UK to maintain secure and cost-effective domestic oil & gas supplies since 2014, while reducing offshore wind-energy costs by two-third, down to half new nuclear prices (http://tinyurl.com/y274hvlf).

Developers have been able to shift to low-carbon sources, with Ørsted [S10b] stating that:

"*the share of green energy in Ørsted's power generation has risen from 17%* [in 2006] *to 75%* [in 2018]*, with the number expected to reach 99% in 2025*".

5. Sources to corroborate the impact

We offer three main means to corroborate the impact reported. First, evidence relating to several major industrial projects is given in [R3]. Next, public domain case history papers [S1-2a; S3-9] published in collaboration with industrial developers and consulting companies, demonstrate the research's application in major projects and give evidence of the depth and breadth of the beneficial research impact. Finally, we corroborate the detailed statements made in Sections 2 and 4 with Technical Notes and letters from Scottish Power Renewables (SPR) and Ørsted, two of the largest wind power developers worldwide, which give details of the economic, risk reduction and other benefits they have taken from the research [S2b and S10].

S1 Hampson, K., Evans, T.G., Jardine, R.J., Moran, P., Mackenzie B. and Rattley, M.J. (2017) Clair Ridge: Independent foundation assurance for the capacity of driven piles in very hard soils. Proc 8th Int. Conf. on Offshore Site Investigations and Geotechnics, SUT London. Vol. 2, p. 1299-1306.

S2a Rattley, M.J., Costa, L., Jardine, R.J. and Cleverly, W. (2017). Laboratory test predictions of the cyclic axial resistance of a pile driven in North Sea soils. Proc 8th Int. Conf. on Offshore Site Investigations and Geotechnics, SUT London. Vol. 2, p. 636-643.

S2b Economic Impact of ICP-05 Design Method for East Anglia Offshore wind Project. Technical Note by Scottish Power Renewables. February 2019.

S3 Argiolas, R. and Jardine, R.J. (2017). An Integrated pile foundation re-assessment to support life extension and new build activities for a mature North Sea oil field project. Proc 8th Int. Conf. on Offshore Site Investigations and Geotechnics, SUT London. Vol. 2, p. 695-702.

S4 Jardine, R.J., Thomsen, N.V., Mygind, M., Liingaard, M.A. and Thilsted, C.L. (2015). Axial capacity design practice for North European wind-turbine projects. Proc. Int. Symp. on Frontiers in Offshore Geotechnics, Oslo, CRC Press, London, Vol. 1, pp. 581-586.

S5 Barbosa, P., Geduhn, M., Jardine, R.J. and Schroeder, F.C. (2017). Large Scale Offshore Static Pile Tests – Practicality and Benefits. Proc 8th Int. Conf. on Offshore Site Investigations and Geotechnics, SUT London. Vol. 2, p. 644-651.

S6 Schroeder, F.C., Merritt, A.S., Andersen, K.W., Muir Wood, A., Thilsted, C.L. and Potts, D.M. (2015). Predicting monopile behaviour for the Gode Wind offshore wind farm. Proc. Int. Symp. on Frontiers in Offshore Geotechnics, Oslo, CRC Press, Vol. 1, pp. 735-740.

S7 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. Proc. Offshore Technology Conference, Houston, OTC-29557-MS.

S8 Schroeder, F.C., Grammatikopoulou, A., Barwise, A., Duffy, C, Jardine, R.J. and Potts, D.M. (2020) The use of numerical analysis to aid the design of monopile foundations for a Norh Sear offshore wind farm; Proc. Int. Sym. on Frontiers in Offshore Geotechnics, Austin.

S9 Grammatikopoulou A., Pedone G., Schroeder, F.C., Sorensen T., Taborda D.M.G. and Potts. D.M. (2020); 3D Finite element analysis of monopile foundations and its application in offshore wind farm design; Proc. Int. Sym. on Frontiers in Offshore Geotechnics, Austin.

S10 a) PISA project manager, Ørsted. Letter on the impact of ICFEP in the development of PISA design methodology and impact of PISA design, October 2019.

b) Lead Geotechnical Engineer, Ørsted. Letter on the impact of advanced ICFEP analyses on offshore wind development; August 2019.