Institution: Imperial College London

Unit of Assessment: 14-Civil and Construction Engineering

Title of case study: 1: New design methods from piling research that improve the foundation safety and economy of offshore structures

1. Summary of the impact

The Imperial College Pile 'ICP' effective-stress pile design approaches for offshore foundations offer much better design reliability than conventional methods. Their use delivers substantial economies in many hydrocarbon and renewable energy projects, better safety and confidence in developing adventurous structures in others. The ICP has enabled production in otherwise unviable marginal hydrocarbon fields, new options in high-value deep-water projects and helped eliminate installation failures that can cost hundreds of £million. We present evidence that the research delivered direct benefits exceeding £400m since 2008 in projects known to us, with larger worldwide benefits through project risk reduction and independent exploitation.

2. Underpinning research

The deep foundations required for offshore structures comprise a crucial and costly part of their build. Research into such foundations has been led by Prof Jardine at the Department of Civil and Environmental Engineering of Imperial College London since the early 1990s. We highlight specific research findings since 1993 that have had a substantial impact on engineering practice.

(A) Research co-funded by EPSRC [7] and Industry running up to 1997 investigated the fundamental effective-stress behaviour of displacement piles. Extensive field experiments at four UK clay and two French sand sites with novel highly instrumented piles, supported by laboratory/theoretical studies, identified the key mechanisms that control the stress system set up by pile driving and the parameters that control both shaft and base stiffness and ultimate resistance, which differ radically from those assumed conventionally. The research underpinned an improved ability to understand, allow for and exploit in design the influence of factors such pile slenderness, tip conditions, varying responses in different clay types and the crucial importance of sand state as revealed by local CPT tests. Three PhDs that all won Imperial College Prizes were completed under the supervision of Prof Jardine and new paradigms established to capture the principal physical features in completely new design procedures [1,2,3,4,5]

(B) New simplified design rules that captured the key physical principles were developed and tested against a verification database of over 130 industrial pile tests assembled by the Imperial College team. The study demonstrated greatly improved predictive reliability for piles driven in a broad range of geomaterials. The standard errors of conventional capacity predictions (around 65%) were reduced to 20-30%. A practical design book was produced in 1996 and short courses run for leading companies, including Shell - who awarded a Technology Prize in 1997.

(C) Comprehensive investigation took place over 1998-2005 into multiple new factors. One post-doctoral study explored unexpectedly marked beneficial pile ageing and previously neglected cyclic loading degradation through full scale tests and supporting studies funded by EU and Health and Safety Executive (HSE); industrial application was demonstrated through advanced analysis with Atkins. Another PhD study investigated response to seismic loading, considering 'anomalous' Gulf of Mexico (USA) and Mexican clays [4]. An HSE supported programme in conjunction with Trinity College Dublin demonstrated previously unappreciated negative pile group effects with industrial-scale piles under static and cyclic loading. Further projects, some involving BP, Shell and Norwegian Geotechnical Institute, investigated pile behaviour under a wide variety of driving and loading conditions. 'Problematic' calcareous, diatomaceous, weathered-residual, silt-dominated and sensitive natural deposits were considered as well as 'standard' North Sea soils. New insights were gained into all of these topics leading to seven Journal (and multiple Conference) papers, e.g., [2,4]. An updated Design Booklet [G] was published in 2005 by ICE's Thomas Telford Limited that delivered practical guidance on all of these new aspects.

(D) New research over 2005-2013 included joint investigations with Professor Pierre Foray and

his team at Institut National Polytechnique de Grenoble (INPG) into pile ageing and cyclic loading, working with their intensively instrumented calibration chamber and a new Imperial College instrumented model pile, engaging a post-doctoral and doctoral PhD team [6]. The research led to Jardine taking an advisory role in the French national programme of centrifuge, laboratory, theoretical and field research into pile cyclic loading.

New theoretical research is underway with UPC (Catalan Polytechnic University) Barcelona and new journal papers will be published later in 2013/14 with co-workers from Sydney and Zhejiang (China) that test advanced theoretical analyses against the recent model and field test data. The on-going research is underpinning new Journal papers, International Keynotes (including two at the 2013 Paris ICSMGE), grant proposals and updating/extension of the ICP design approach.

3. References to the research * References that best indicate quality of underpinning research.

The research led to dozens of journal and conference papers between 1993 and 2013, as well as reports published by HSE and design manuals. Six journal paper examples are given below. Recognition of the extended research programme led to awards for Jardine of the British Geotechnical Association Prize in 1996, the Shell Technology Award in 1997 and a Royal Academy of Engineering Medal in 1998. Papers 1, 5 and 6 are arguably the best. Paper 5 was awarded the ICE's Geotechnical Research Medal in 2007.

*[1] Bond, A.J. and Jardine, R.J. (1995) 'Shaft capacity of displacement piles in a high OCR clay', *Geotechnique*, **45**(1) pp. 3-23, doi:10.1680/geot.1995.45.1.3

[2] Jardine, R.J. , Overy, R.F. and Chow, F.C. (1998) 'Axial capacity of offshore piles in dense North Sea sands', *ASCE, JGE*, **124**(2) pp.171-178, doi:10.1061/(ASCE)1090-0241(1998)124:2(171)

[3] Jardine, R.J., Chow F.C., Matsumoto, T. and Lehane, B.M. (1998) 'A new design procedure for driven piles and its application to two Japanese clays', *Soils and Foundations*, **38**(1), pp. 207-219. http://dx.doi.org/10.3208/sandf.38.207

[4] Saldivar, E.E. and Jardine, R.J. (2005) 'Application of an effective stress design method to concrete piles driven in Mexico City clay', *Canadian Geotechnical Journal*, **42**(6), pp. 1495-1508, doi:10.1139/T05-062

*[5] 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*, **56**(4), pp. 227-244, doi:10.1680/geot.2006.56.4.227

*[6] Yang, Z.X., Jardine R.J., Zhu, B.T., Foray, P. and Tsuha, C.H.C. (2010) 'Sand grain crushing and interface shearing during displacement pile installation in sand', Géotechnique, **60**(6), pp. 469-482, doi:10.1680/geot.2010.60.6.469

Grant Information (note: matching funding provided by Amoco UK, HSE and Shell UK)

[7] EPSRC Reference: GR/H49719/01, Title: The Behaviour Of Offshore Piles, Value: £109,972 (Pre-FEC), Starts: 01 September 1992 Ends: 31 December 1995.

4. Details of the impact

The research outlined in section 2 led to Jardine's invitation onto the principal International Industry (API, ISO, SUT and ISSMGE) Committees and engagement in multiple major practical projects. Critical to the reach and depth of impact was the production of a widely read and used design book [H], developed through engagement with Industrial partners (Amoco, BP, HSE, Shell) and Consultants and published through the ICE's publishers, Thomas Telford. Additional web-based practical guidance was produced with HSE, who endorsed and funded the work. Other steps included the organisation of CPD courses and keynotes delivered to over 1000 engineers in 14 countries. Examples of effective knowledge transfer include work with, among others, Atkins, BP, Fugro, GCG, Noble Denton, Shell, as noted in our supporting evidence. Also critical was direct engagement in practice, as outlined under A to D below. Taken together, these steps led to ICP's adoption in Industry Standard American Petroleum Industry (API-2011) and ISO design guidance, leading to beneficial impacts on a regular basis. It has been used by Shell as their main design method for all new platforms since 1996 [B].

4.1 BP and Premier Oil

The 'ICP' research was critical to BP's development of the large, exceptionally difficult, Atlantic Frontier Clair field [A and E]. Applying (over 2010-13) ICP to the new Clair Ridge structures (£4.5bn value) allowed driving failure risks to be reduced with low L/D piles that were shown to be satisfactory after accounting for negative cyclic loading and pile group effects (which are ignored routinely). The foundation costs (around £100m) were reduced greatly and the piles installed without difficulty in June 2013 [A]. ICP was also applied with Senergy (over 2012-2013) to Premier Oil's nearby dual-structure SOLAN development [E].

Similar benefits are being realised offshore Angola, where BP's deepwater projects each cost around £10bn. While piles can be driven at 2km depths to anchor large floating facilities, the 'unusual' Angolan sediments fall outside prior piling experience. Applications of the more fundamental ICP (2011-2012) linked to field trials allowed piles to be used more confidently. Foundations cost around £70m per installation; ICP optimisation offers scope for savings in tens of £m each and, more importantly, a wider range of secure development options [A]

4.2 Shell

Shell have applied ICP to all their North Sea projects over the survey period and in other regions including Brunei and Doha [B]. In another example, Shell authors describe in [H] how the ICP allowed adventurous platform designs at Skiff and later Brigantine that enabled marginal fields to be developed, achieving 30 to 50% construction cost savings [F]. Peak production from these micro-platforms' ran at over £100m/year (based on 15.10^8 m^3/year and \$120 per $1000m^3$ five-year price); their production revenues remained at tens of £m/yr over the 2008-2013 review period.

4.3 Renewable Energy

ICP also delivers benefits for tripod or jacket-based offshore wind-turbines. The method was used in the biggest offshore development in Germany; Borkum-West-II in 2010/11. This project has a 1bn Euro construction cost where foundations comprise 30% of costs; 120 large piles were driven in hard conditions without failure [H]. The ICP design procedures took into account potentially negative storm loading, horizontal and axial cyclic interactions, system reliability and potential driving problems. The Technical Director of Offshore Wind Consultants (OWC) has made a detailed assessment of the material and installation cost savings made, which amounted to 18 million euros [C]. Employing the ICP probably avoided far larger installation problem costs; ICP is now being applied in new German projects, including the Gode Wind development by Danish Oil & Natural Gas (DONG) [E]. UK projects are also benefitting. Atkins are applying ICP in the Beatrice, Rampion and Galloper projects where more than 1600 large offshore piles will be driven with anticipated material and installation costs around £500m. Preliminary analyses by Atkins indicate that ICP will save up to £100m and substantially reduce both project risks and pile driving impact on marine mammals [D]. Similar benefits may be taken in many other developments, including the major East Anglia Offshore Wind (EAOW) project where the ICP is being applied by Geotechnical Consulting Group (GCG) and Offshore Wind Consultants (OWC) [C].

4.4 Sustainability and other new-build hydrocarbon projects

Extending existing UK energy supplies is vital. 'ICP-based' investigations and re-analyses have shown that foundation capacities may be higher in some cases than anticipated, and so allow platforms to carry additional plant or new wells. Research into installation techniques, cyclic loading, group-action and well-drilling effects have been crucial. North Sea platforms analysed in conjunction with Atkins and GCG include: Indefatigable 49/23AC (2009-2010), Auk (2010-2011), Montrose and Claymore (2013) [D]. Dr Rob May, the Head of Energy Geotechnics at Atkins states that "The ICP based methodology has provided robust and reliable assessments of foundation capacities and has, in many cases, enabled enhanced capacities to be demonstrated. The benefits to the producers and UK economy *…is to..* extend production at these ageing facilities while avoiding expensive (tens to hundreds of millions of pounds) platform replacements or early decommissioning of assets" [D]. The value of such developments was confirmed by BP's CEO Bob Dudley who is quoted on the company's website as saying that the redevelopment of BP's Valhall field, which involved applying the ICP to some of BP's existing structures [see A and E] "is one of BP's most complex field expansion developments and gives Valhall a further 40-year design life

with the capacity to handle 120,000 barrels of oil and 143 million cubic feet of gas per day", with daily production values easily exceeding £10m.

The ICP has also been applied to assist a wide range of other new-build oil and gas projects, including EdF's major new Cygnus multi-structure North Sea gas project, providing major savings for several new platforms [E].

4.5 Financial assessment of impacts

While accurate assessment is difficult, we have evidence [A-D] of substantial benefits to 20 projects that involved direct ICP input through Jardine since 2008 (Clair, Clair Ridge, Solan, Angola, Ormen Lange, Skiff, Brigantine, Borkum-West, Beatrice, Rampion, Galloper, Indefatigable, Auk, Claymore, Montrose, EAOW, Gode Wind, Cygnus, Valhall) The ICP is being used independently by other designers and Lloyds Register confirms its use in an additional 20 cases since 2008. Several other Independent Verification Bodies operate internationally and some producers self-certify, so the worldwide total is certainly higher. The ICP research has also led other groups to modernise their procedures leading to beneficial impacts from the research even in cases where the ICP is not adopted as the formal design method.

Detailed data provided by OWC, Atkins and Senergy [C] to [E] attest to savings of £18m to £100m in individual projects. Assuming a modest £10m average benefit per project and estimating at least 40 project applications indicates an overall impact exceeding £400m since 2008. Larger but unknown, additional benefits accrued through the confidence given to develop more adventurous designs worldwide, exploit marginal fields, avoid unnecessary costs, improve safety and eliminate/reduce installation failures.

5. Sources to corroborate the impact

[A] Letter of corroboration from Senior Geotechnical Engineer, BP Exploration Operating Co. Ltd. to confirm the use and the subsequent finical impact of ICP within BP

[B] Letter of corroboration from Principal Geotechnical Engineer, Shell UK Ltd. to confirm the use and the subsequent finical impact of ICP within Shell

[C] Letter of corroboration from Technical Director, Offshore Wind Consultants Ltd. to confirm the use and the subsequent finical impact of ICP within their industrial sector

[D] Letter of corroboration from Head of Energy Geotechnics, Atkins Ltd. to confirm the use and the subsequent finical impact of ICP within their industrial sector

[E] Letter of corroboration from Director, Senergy Survey and Engineering Ltd. to confirm the use and the subsequent finical impact of ICP within their industrial sector

[F] http://www.offshore-technology.com/projects/brigantine Archived at https://www.imperial.ac.uk/ref/webarchive/tsf

[G] R.J. Jardine, F.C. Chow, R.F. Overy, J.R. Standing, "ICP design methods for driven piles in sands and clays", Thomas Telford Services Ltd, London, pp. 105, (2005) ISBN: 9780727732729 http://www.thomastelford.com/books/bookshop_main.asp?ISBN=9780727732729

[H] Merritt, A., Schroeder, F., Jardine, R., Stuyts, B., Cathie, D., Cleverly, W. (2012) Development of pile design methodology for an offshore wind farm in the North Sea. Proc 7th Int. Conf. on Offshore Site Investigations and Geotechnics, SUT London, pp 439-448. Summary available here. Archived https://www.imperial.ac.uk/ref/webarchive/51f on 01/11/2013

[I] R.F. Overy, P. Sayer, "The use of ICP design methods as a predictor of conductor drill-drive installation", Proc. 6th Int Conf on Offshore Site Investigations, SUT London, pp. 333-340, (2007) Document ID: OSIG-07-333, ISBN: 0 906940 49 4. Summary available here. Archived https://www.imperial.ac.uk/ref/webarchive/m8f on 19/11/2013