Integrated Research into the Foundation Behaviour of Offshore Energy Production Platforms

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ABSTRACT: This paper revisits research undertaken by the Authors with Professor J B Burland in which key contributions were made to the pioneering Magnus Foundation Monitoring Project (FMP), Hutton Tension Leg Platform (TLP) and Gullfaks-C platform oil production platform projects in the North Sea. Close liaison with industry and an integrated approach that combined high quality laboratory and in-situ testing with cutting-edge numerical analysis and accurate observations of full-scale field behaviour were central to the improvements achieved in analysing the foundations of these and similar structures. The paper asserts the central importance of understanding regional geology before reviewing how teams led by John Burland developed new laboratory and field monitoring instruments, as well as experimental and numerical approaches that have had a lasting impact in many areas of geotechnical engineering. Recent developments that sprang from the projects and the associated research programmes are highlighted. Particular attention is given to subsequent improvements to pile design methods whose development started with the first two cited case histories, as these and later developments are now contributing to a worldwide shift towards renewable, low-carbon, wind-energy production.

KEYWORDS: Foundations, Offshore energy, Field monitoring, Advanced laboratory testing

1. INTRODUCTION

This paper revisits three case histories in which research was undertaken with Professor J B Burland in connection with pioneering North Sea oil production projects. John Burland's input included working in tandem with the industry to promote an integrated approach in which high quality laboratory and in-situ testing was applied in combination with cutting-edge numerical analysis and accurate observations of full-scale field behaviour. His contributions included proposals for novel instrument systems for laboratory and field measurements, along with geotechnical and structural engineering insights into the key issues relating to research and practice.

The most common foundation systems for fixed continental shelf oil and gas production platforms comprise driven steel tubular piles, which are also employed in port, bridge and other onshore projects. This paper's first case history concerns BP's fixed, piled, Magnus platform which was, when installed in April 1982, the worlds' largest steel jacket structure. Large tubular piles are also employed in some deeper-water developments, including the novel Tension Leg Platform (TLPs) concept that was tested by Conoco with the Hutton TLP. The latter platform, which was installed in June 1984, is the second case covered in our paper.

Gravity Base Structures have also been installed at multiple North Sea and other offshore sites and we revisit in our third case study work undertaken for one of the largest GBS structures ever installed, the Gullfaks C platform, which was the first deep skirted Gravity Base Structure (GBS) when it was installed offshore Norway in May 1989 by Statoil, now known as Equinor.

In all three of these pioneering cases Professor Burland aimed to encourage advanced laboratory testing research to progress in tandem with developments in numerical analysis, leading to outcomes that have had widely reaching long-term impact in geotechnical engineering. Jardine (2020) summarises how some of the developments reported paved the way for improved site characterisation, design and analysis approaches that have been applied internationally and developed considerably since the 1980s projects described in this paper. For example, the continuous improvements made to pile design methods, which started with the first Magnus case history, are now helping to facilitate a major shift towards renewable offshore wind energy production that is taking place in the North Sea and, increasingly, worldwide.

2. IMPORTANCE OF REGIONAL GEOLOGY

Understanding geology is crucial to successful foundation design in all settings. Davies et al (2011) summarise conditions in the UK North Sea sector, where the Magnus and Hutton TLP projects were sited. Quaternary soils dominate, and the 15 main units mapped in Figure 1 comprise multiple glacial tills combined with marine sand and clay sediments overlying Tertiary, Cretaceous, Jurassic and older bedrocks. The latter are encountered closer to the seabed in the south and older sediments are encountered on the eastern coastline north of Teesside. The northern Quaternary sediments become thicker with distance away from the UK's eastern coastline (see Figure 2) and reach their maximum (800m) in the central North Sea. Davies et al (2011) demonstrate that repeated glaciation took place in the North Sea Basin during the Middle and Late Pleistocene through ice sheets originating in northern Scotland. Sea levels fluctuated greatly between glacial and inter-glacial stages and the submerged glacial geomorphology is highly variable with frequent buried channels, moraines, boulder beds and other pro-glacial features. The sediments vary from very hard clay tills and extremely dense sands through to low Over Consolidation Ratio (OCR), very soft clay buried valley infills. Figure 3 provides, as an example, a schematic of the features identified for the Clair Ridge development West of Shetland by Hampson et al (2017) where the ICP-05 design procedures set out by Jardine et al (2005a), whose development started with the Magnus project described above, have been employed to help assure safe and effective foundation design for a major recent development sited in an extremely harsh North Atlantic wave and wind loading environment.

3. PILED PLATFORM CASE HISTORIES

3.1 Background

Offshore pile design involves making choices for diameters, wall thicknesses and embedded lengths so that the piles can be driven without damage or undue fatigue and fulfil suitable serviceability and ultimate limit state criteria. While the piles' axial, lateral and moment load-displacement responses often need to be assessed in pile design, driveability and axial capacity often tend to be the most critical factors in practice. Predicting the axial capacity of piles driven in clays and sands is therefore central to assessing foundation safety and is usually a more pressing design concern than improving load-displacement analysis.

Database studies by Briaud and Tucker (1988), Tang et al (1990) and others crystallised widespread concerns over the reliability of the

Main Text American Petroleum Institute (API) and linked International Standards Organisation (ISO) design approaches. The latter have evolved from approaches developed initially for Gulf of Mexico projects, where considerable thicknesses of low OCR Quaternary marine clays and sands are often encountered.

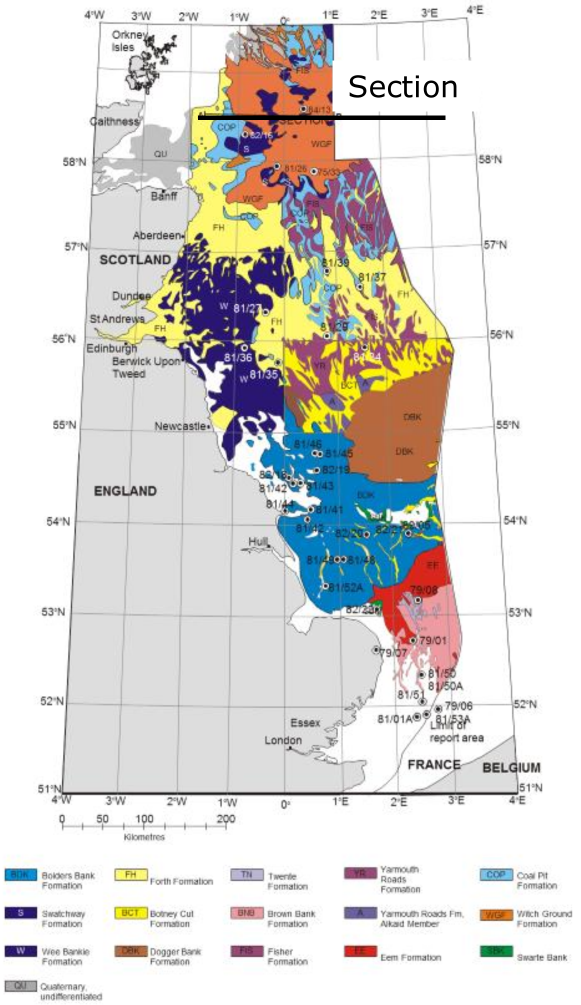


Figure 1 Summary of Quaternary geology of UK North Sea Sector, after Davies et al (2011).

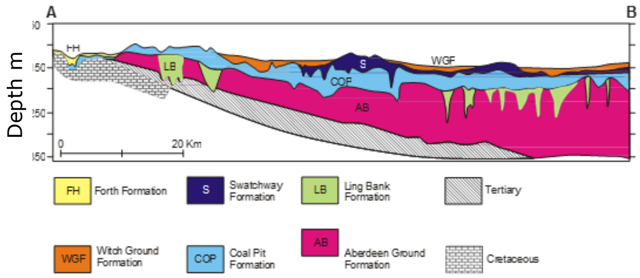


Figure 2 Example cross section across the Northern North Sea, considering depth to 350m below sea level on section identified in Figure 1, after Davies et al (2011).

The approaches available in the 1980s, which remain encapsulated in API (2014), treat single piles by a Winkler beam-column approach; axial and horizontal loading are considered one dimensionally without any interactive coupling. Non-linear axial shaft (*t-z*), lateral (*p-y*) and axial pile tip (*Q-z*) 'springs' are specified that depend principally on the local axial or lateral capacities found from simple empirical, generic, approaches. Little use is made of site-specific soil stiffness information. Pile group action is addressed by assuming the interactions are elastic and selecting 'operational' profiles of linear shear stiffness with depth. Checks against pile load tests conducted at onshore sites around the world indicated that axial capacity predictions made with the API approaches could be subject to wide statistical scatter and possible bias when assessed against load tests, particularly in sands. The methods' relatively poor predictive performances might indicate potentially inadequate reliability in service when applied in combination with the factors recommended in API's Working Stress Design (WSD) or related Load and Resistance Factor Design (LRFD) approaches; see Tang et al (1990). The behaviour of fixed and floating offshore platforms is less sensitive to their piles' lateral and rotational stiffness responses. However, it is essential to consider these aspects of pile stiffness in design. Straining and deformations provoked by lateral and moment loading can be critical when considering the fatigue lives of deep-water wells, Jeanjean et al (2015) and the serviceability of monopile wind-turbine structures; see Byrne et al (2017).

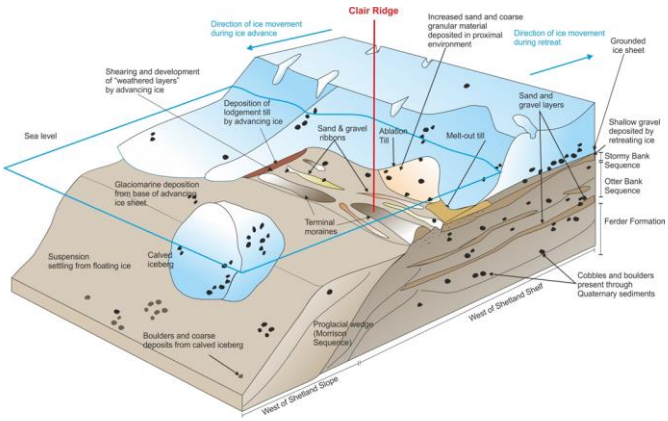


Figure 3 Schematic of the geomorphological features identified for the Clair Ridge development West of Shetland by Hampson et al (2017).

The degree of uncertainty surrounding the API design methods' reliability and a lack of pile load tests that represented North Sea geotechnical conditions adequately led to the industry launching the Magnus Foundation Monitoring Project (FMP) and Hutton TLP monitoring projects described in this paper, as well as other large scale pile testing programmes in the UK and The Netherlands. Professor Burland's links with the industry and UK research councils led to the Imperial College team being invited to make pivotal contributions to the Magnus (FMP) and Hutton TLP case histories that we summarise briefly below.

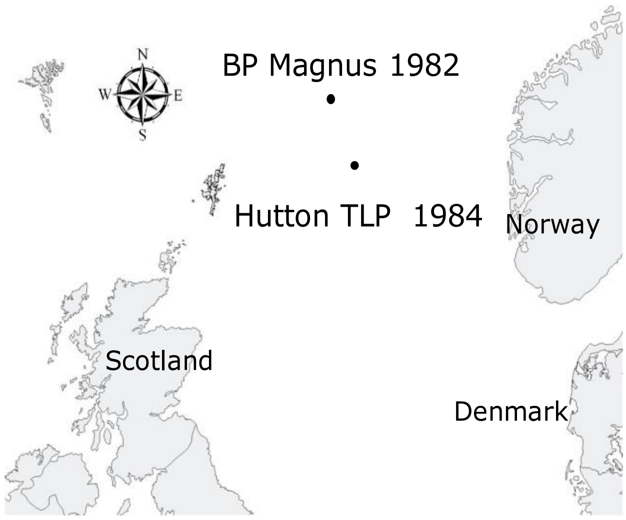


Figure 4 Location map for Magus and Hutton TLP platforms.

3.2 Magnus Foundation Monitoring Project

The Magnus platform was installed at the Northern North Sea location shown in Figure 4 where the mean water depth is 186m. It is founded on four circular groups of nine, 2.13m diameter, piles driven to 82m penetration through mainly hard to very stiff lean glacial tills. The piles carry large compressive loads and sustained wave and wind moment loading through a principally 'push-pull' pile arrangement. The platform was duly floated into place and installed in April 1982 through a complex ballasting operation that did not proceed as planned. Some piles had to be replaced and some instrument systems were lost; Sharp (1993).

The Imperial College team working on the associated Foundation Monitoring Project comprised Professor John Burland, Dr David Hight and Dr (later Professor) David Potts, Richard Jardine (then a post-graduate Research Assistant) and skilled technical staff. Their work involved first designing a system of instruments to monitor the axial movements of the pile groups, at the seabed level. John Burland proposed a differential pressure operating system in which a dual fluid (oil and mercury) pressure-sensitive datum reservoir unit was installed at a location set tens of metres from the pile group, mounted on a small-scale driven pile foundation. Twin lines hydraulically connected the datum unit to an instrument pod bolted to the pile group structure, where sensitive differential pressure transducers with local signal conditioning circuits could sense changes in elevation between the pile group and distant datum unit, independently of tidal or other sea level changes. Cables delivered electrical power to the pod and return signals to a gauge station mounted on the platform. Jardine (1985) reports on the instrument design and sets out how theory and calibrations were developed for factors such as how waves of varying wave lengths and periods might affect the data gathered during storm loading. The Imperial College settlement gauges were deployed after the jacket had been placed. Saturation divers worked with instrument deployment packs that had been integrated into the base of the jacket's structure before it was towed out to site from the Nigg Bay construction yard in NE Scotland.

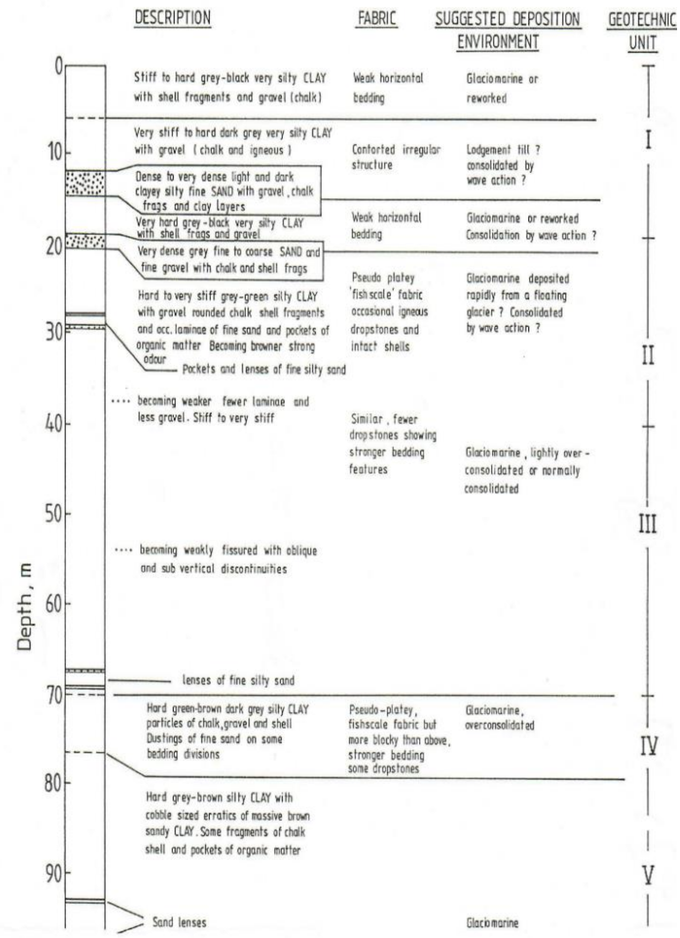


Figure 5 Magnus geotechnical profile, after Jardine (1985)

The Imperial College group also participated in the site characterisation undertaken for Magnus and made analytical predictions for the pile-group's load-displacement behaviour. Their site characterisation work included intensive stress path testing on high quality specimens of the clay tills present, which were retrieved by hydraulically pushed sampling in deep boreholes. Figure 5 summarises the geotechnical profile interpreted for Magnus by Jardine (1985). The Imperial College triaxial tests involved novel 'electrolevel' based local axial strain sensors, which were first proposed by Professor Burland and whose detailed design and capabilities were reported by Jardine et al (1984). The triaxial testing indicated the undrained shear strength trends plotted on Figure 6, showing variations with depth indicative of grounded ice being present towards the later stages of the glacial deposition process.

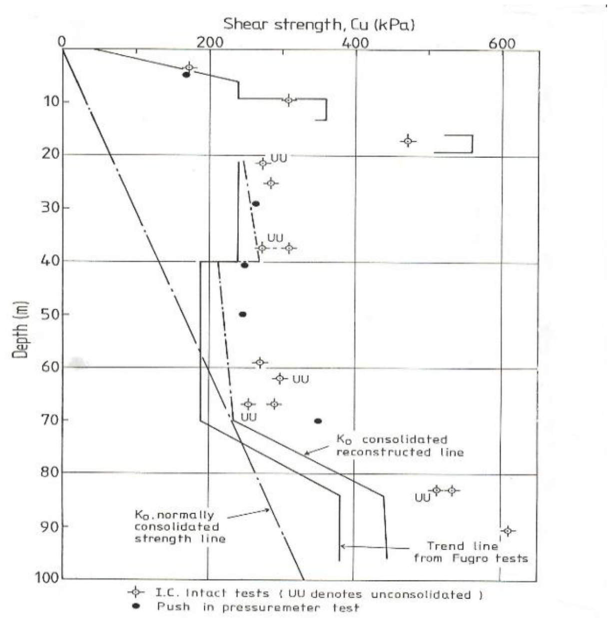
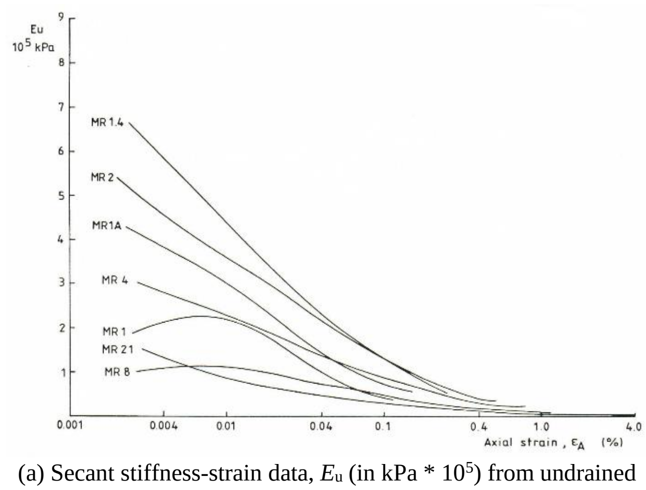
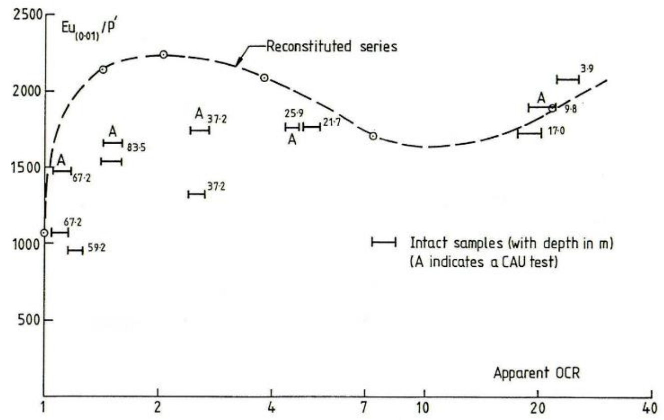


Figure 6 Undrained shear strength profile for Magnus, after Jardine (1985)

The new electrolevel local axial strain sensors revealed new information regarding the intact tills' highly non-linear stiffness behaviour which was supplemented by parallel programmes of tests on reconstituted samples. Figures 7 and 8 summarise the till's highly non-linear undrained secant Youngs modulus stiffness (E_u) characteristics and show how the values determined at 0.01% strain, $E_{u(0.01)}$, grew with increasing mean effective stress (p') and therefore depth, and decayed with strain level (as expressed by the parameter $L(\varepsilon) = E_{u(\varepsilon)} / E_{u(0.01)}$) when loading was applied in either triaxial compression or extension. A wide range of other index and mechanical tests were also conducted, including interface ring-shear tests which were undertaken to establish the relationships that governed local pile shaft failure.



(a) Secant stiffness-strain data, E_u (in kPa * 10^5) from undrained compression tests on Magnus Reconstituted (MR) samples K_0 consolidated to vertical effective stress of 400 kPa before unloading to OCRs indicated by number given after code MR.



(b) Secant stiffnesses at 0.01% strain normalised by pre-shear *p'* and plotted against OCR from undrained compression tests on intact and reconstituted samples K_0 consolidated to vertical effective stress of 400 kPa before unloading to plotted OCR

Figure 7. Variations of undrained secant stiffness ratio $E_{u(0.01)}$ with strain from locally instrumented triaxial stress path tests at various OCRs for Magnus clay till samples, after Jardine (1985).

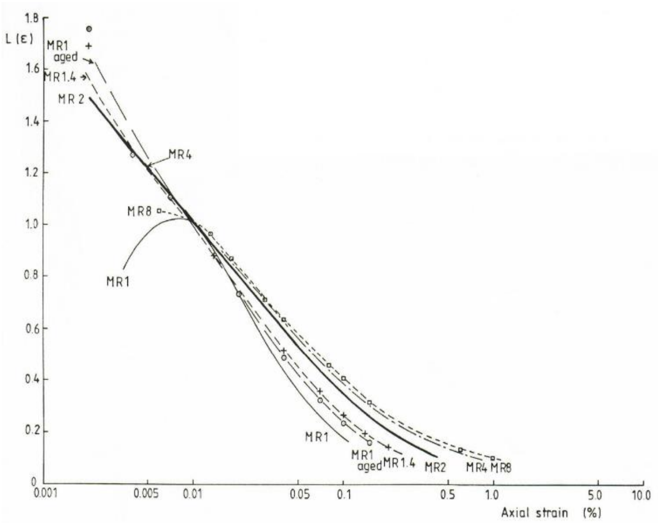


Figure 8 Normalised stiffness linearity parameter $L(\varepsilon) = E_{u(\varepsilon)} / E_{u(0.01)}$ for tests shown in Figure 7, where $E_{u(\varepsilon)}$ and $E_{u(0.01)}$ are secant stiffnesses at strain ε and 0.01%, after Jardine (1985).

The Magnus field investigations incorporated the first use of the offshore Push-in-Pressuremeter (PIP), which was installed in deep boreholes to obtain in-situ shear strength and shear stiffness data. John Burland had been involved in developing the PIP instruments while working previously at the UK Building Research Establishment (BRE). The Magnus PIP data were analysed by a non-linear approach that recognised the features discovered in the laboratory testing programme, as described by Jardine (1985), (1992).

The above data were invaluable to the advanced, fully non-linear, effective stress based numerical analyses undertaken by David Potts with his code ICFEP (Imperial College Finite Element Program, see Potts and Zdravkovic 1999, 2001) to predict the axial behaviour of the Magnus foundations; see Jardine and Potts (1993) and Potts and Zdravkovic (2001). The latter analyses represented the clay tills with an extension to the Modified Cam Clay model, proposed by Roscoe and Burland (1968), that incorporated a new formulation for the till's highly non-linear stiffness response (see Jardine et al 1986) as well as a Coulomb effective stress interface failure criterion. Consideration was also given to the effects of pile installation on the effective stress regime established around the driven piles, although this was recognised as an area of considerable uncertainty; see Jardine and Potts (1988). The analyses added an approximate non-linear superposition procedure to model axial pile group interaction from ICFEP analyses of single piles and so make 'Class A' (Lambe 1973) predictions for the axial displacements developed in the field under a range of loads. Ganendra (1994) later extended the axial ICFEP modelling to cover lateral and moment loading cases without changing the non-linear soil models' input parameters, or the assessed soil effective stress conditions.

Kenley and Sharp (1993) describe the dynamic measurements made of the Magnus foundations' response to major storm loading events in January 1984 and January 1986. Potts and Zdravkovic (2001) report on the close agreement between the Class A ICFEP Finite Element predictions that made use of data from the new laboratory testing techniques. In comparison, the standard API *t-z*, *Q-z*, *p-y* and elastic group action calculation approaches employed by the Magnus platform designers over-estimated the pile groups' movements by factors of between four (for axial load) and two for the lateral response. While this better-than-expected field performance was highly encouraging to the platform owners, it also indicated considerable scope for improving design procedures.

3.3 Hutton Tension Leg Platform

The 'Hutton' Tension Leg Platform, whose northern North Sea location is identified in Figure 4 relied on four groups of driven steel tubular piles that were broadly similar to those driven for Magnus. Each group comprises eight, 1.83 m diameter, piles that were driven in 148 m of water to 58 m penetration through hard tills and dense to very dense sands. The differences between the Hutton and Magnus profiles are summarised in Figure 9.

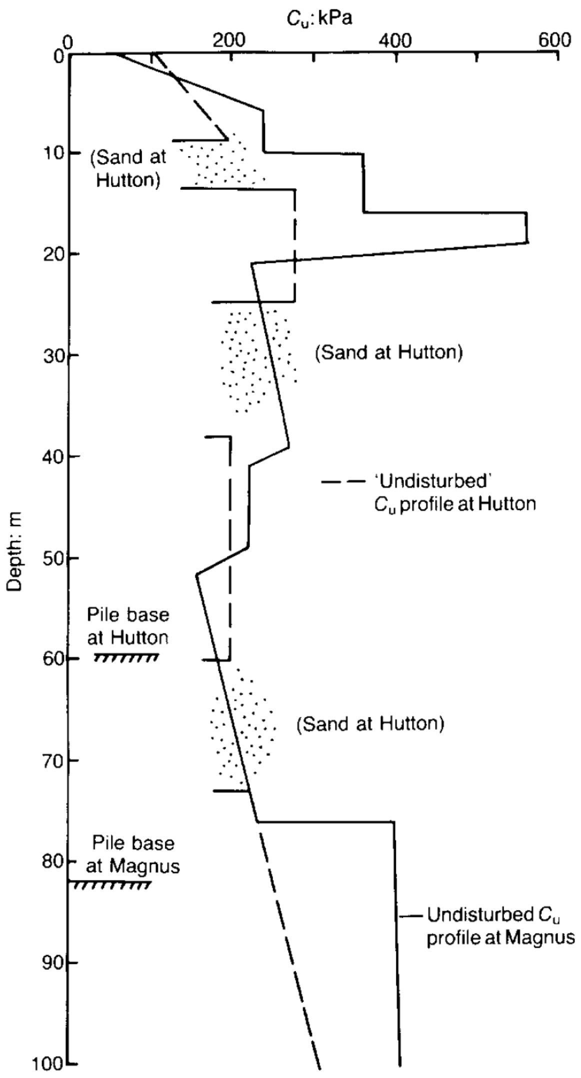


Figure 9 Undrained shear strength (C_u) profile for Hutton TLP compared with that for the Magnus platform location, after Jardine (1985).

Figure 10 Schematic of Hutton TLP, showing foundation arrangements, after Jardine (1985).

The Hutton TLP applied entirely tensile loads, as shown in Figure 10, and it represented the prototype of a completely new class of production platforms for offshore oil, gas and now wind-energy. Successful deployment at Hutton led to multiple TLPs being installed for subsequent projects, many of which were in the Gulf-of-Mexico, in water depths extending down to around 1500m; see Jardine (2020). Concerns were expressed regarding the safety of the novel TLP foundation scheme in service and a monitoring system was required for certification. Noting that the tension forces could be monitored by load cells installed in the floating structure's mooring compartments, John Burland proposed deploying multiple sets of the axial foundation displacement sensors developed originally for Magnus to monitor the pile groups' long-term response to service loading.

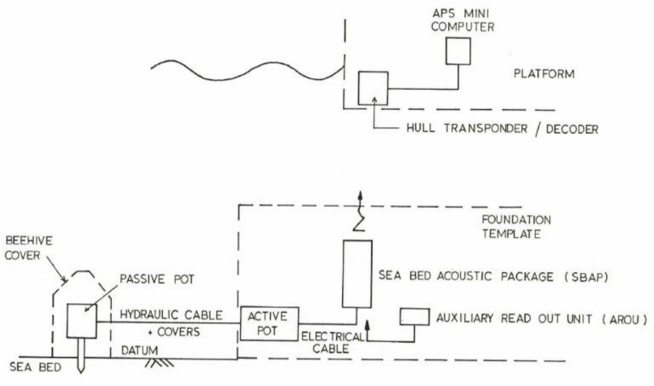


Figure 11 Schematic of Imperial College vertical movement gauges deployed for Hutton TLP, after Jardine (1985).

The Hutton foundations represented a major new challenge: no cables could be provided between the floating structure and the seabed. Instead, as indicated in Figure 11, the gauges had to be equipped with an autonomous long-term (battery) power supply pack, microprocessor based local management system and an advanced coded acoustic telemetry communication capability, with the latter being integrated into sealed 'SBAP' units. The gauges could be woken by coded acoustic signals from the surface, undertake a round of axial movement measurements, relay back a statistical summary of the data recorded and then power down until the next measurement cycle. Jardine et al (1988) describe how the systems deployed at Hutton were upgraded from the Magnus design to deliver a fine (0.03mm) pile group movement resolution while implementing a far greater degree of overload protection. Robust systems with remote and local datum units were developed successfully. Other protective measures included deploying reinforced concrete protection covers for the armoured hydraulic cables and ventilated reinforced 'beehives' that provided protection to the datum units against any falling debris. Aiming to avoid any potential misuse of the gauges, Jardine was seconded to the diving team that installed and maintained the gauges offshore and helped to supervise the saturation diving operations in the field.

The Hutton pile groups were driven through their seabed templates more than one year in advance of the TLPs arrival on site and connection to its foundations. The sea-bed instruments were also placed in advance, allowing one of the gauge systems that had been destroyed by a ship's anchor to be replaced before the TLP arrived at site. Jardine et al (1988) describe how the TLP's installation process allowed very high-resolution measurements to be made concurrently of the varying pile group loads, loading eccentricities and pile group movements. The tensions were applied as essentially known line forces located at precisely known anchor points, so allowing precise measurements to be made of the groups' axial and moment-rotation stiffness characteristics.

Parallel work was undertaken at Imperial College to predict the foundation response. As described by Jardine and Potts (1988) ICFEP predictions were made that again modelled the clay till and sand layers' highly non-linear stiffness behaviour based on locally instrumented laboratory stress path tests. The calculations adopted variants of the Modified Cam Clay and Mohr Coulomb models for the clay tills and sands respectively whose small-strain stiffness formulation was similar to that set out by Jardine et al (1986). Shaft-soil slip was also captured with interface failure criteria from ring-shear interface tests and allowance made for the effects of pile installation on the initial stresses, based on a review of all available evidence. Pile group interaction was addressed through a similar non-linear procedure to that developed for Magnus, based on single pile FE analyses.

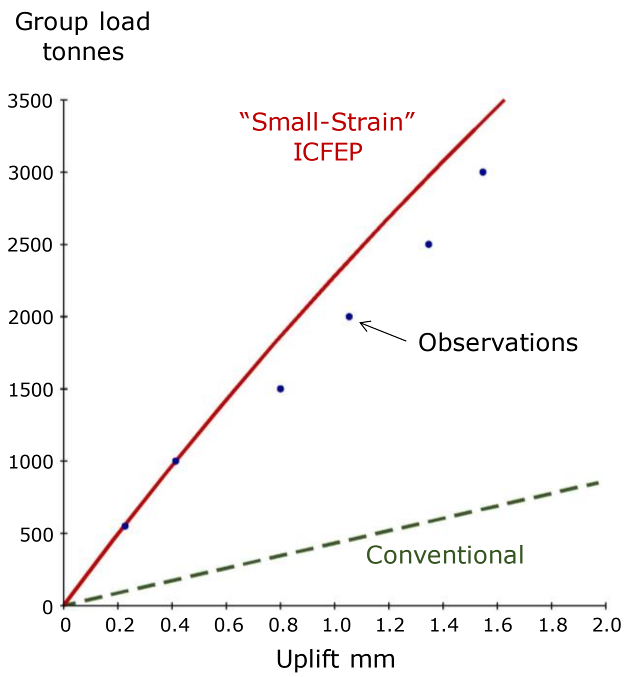


Figure 12 Predictions and measurements for Hutton TLP pile groups' vertical load-displacement behaviour, considering centrally applied loading, after Jardine (1985).

An example of the predictions and measurements made for the Hutton TLP pile groups' axial stiffness response is presented in Figure 12, indicating (as at Magnus) very good agreement with the axial load-deflection measurements gathered during the Hutton TLP's installation phase. The field measurements also confirmed the predictions made for the pile groups' moment rotation stiffness behaviour. Also shown are the predictions form the conventional API procedures by the platform designers. As at Magnus, the latter were around four times softer than proven by the field measurements.

The Hutton TLP monitoring systems remained in operation for several years after installation, with occasional maintenance being required by divers when operating errors or other difficulties called for systems to be replaced. Stock et al (1992) summarised how the systems verified the foundations' service performance, with little or no permanent displacements occurring after major storm events. Environmental considerations led to mercury being barred from use in further applications of similar systems. Krytox oil (which has a specific gravity around 1.9) was employed in its place in a new system designed by Jardine in conjunction with Fugro Structural Monitoring for the Draupner East 'Europipe' gas supply pipeline structure, which was installed in 1994 offshore Norway as the world's first jacket structure founded on 'suction-bucket' foundations.

3.4 Impact of Magnus and Hutton TLP monitoring projects on research and design method developments for offshore piles

The finding that the Magnus and Hutton TLP pile groups' axial responses were far stiffer than expected did not resolve fully the original uncertainty expressed concerning axial pile capacities under North Sea geotechnical conditions. Recognising the need for new field tests to failure, two joint industry groups undertook research with instrumented 762 mm Outside Diameter (OD) piles driven at stiff clay and dense sand sites in the UK and Holland; Clarke (1993), Kolk et al (2005). The Imperial College team progressed with parallel research involving smaller and far more highly instrumented piles installed at four clay, two sand and one chalk site in the UK and France. Their experimental programme led to the ICP effective-stress axial design methods: see Jardine and Chow (1996), Jardine et al (2005a) and Jardine (2020), which give far better predictions for axial capacity than the Main Text API approaches, particularly for sand sites: see Yang et al (2017) and Lehane et al (2017). The new methods are now employed widely; see for example Overy (2007).

The standard API load-displacement design methods' marked over-estimation of field pile-group movements in stiff-to-hard North Sea clay tills (and also dense sands, as noted later) has significant implications for the fatigue lives of structural members and for foundation performance monitoring. While the offshore industry has until recently retained the standard API approaches for routine design, assuming perhaps that the outcomes would be conservative, it is now appreciated that this is not always true; Jeanjean et al (2015). The standard API *p-y* treatment can have unacceptably costly consequences when assessing fatigue lives for well-conductors. Improvement has become an urgent priority for the oil and gas industry, especially for very high value deep-water wells. Jeanjean et al (2017) propose new rules for defining *p-y* curves for clays that employ site-specific simple shear laboratory testing and offer better performance than the previous API guidelines.

The alternative 'small-strain' FE approach developed for Magnus and Hutton TLP is generic and has been applied to many other types of boundary value problems since the 1980s, including slope stability and urban projects where ground movements and soil-structure interaction can govern design for foundations, retaining walls, tunnels and deep excavations. Generally good matches have been demonstrated between predictions and field measurements in multiple case histories reported with colleagues at Imperial College and Geotechnical Consulting Group (GCG, London); see for example Jardine et al (1991), Higgins and Jardine (1998) and Jardine et al (2005b). The approach taken for offshore piles has been extended to consider their response to 3-D loading; see Potts and Zdravkovic (2001). Recent advances in the 'small-strain' triaxial stress path laboratory measurement systems (see for example Jardine 2013) and modelling approaches (Taborda et al 2019 and Zdravkovic et al 2019) have been applied in recent analyses of the large monopiles employed to take lateral and moment loads applied by offshore wind-turbines. The latter contributions to the PISA research JIP (Byrne et al 2017) have allowed considerable cost savings to be made in renewable energy production (see Manceau et al 2018, Schroeder et al 2020 or Carbon Trust 2020).

4. GULLFAKS-C GRAVITY BASE STRUCTURE

4.1 Background

As noted in the introduction, concrete Gravity Base Structures have also been employed in the North Sea, particularly within the Norwegian Sector over the 1970 to 1990 period when local industrial and geographical conditions favoured GBS solutions. Shallow foundation design approaches have been adopted for most GBS platforms. However, a gradual progression into deeper water and consideration of softer foundation conditions led to a suite of hybrid 'deep skirted' platforms, of which Gullfaks C was the first.

4.2 Gullfaks-C design investigations

The Gullfaks C platform illustrated in Figure 13 was installed off the Norwegian Coast in May 1989 and is one of the largest and heaviest offshore concrete structures ever built. Designed for 220 m water depth it has a displacement of more than 1.4 million tonnes. However, the upper 45 meters of soils present at the site consist predominantly of normally consolidated soft clay and loose clayey and silty sands with interbedded dense sand layers. Tjelta et al (1990) describe the new foundation concept proposed for Gullfaks C which consists of sixteen 28 m diameter circular concrete cells, the 0.4 m thick concrete walls or skirts of which penetrate 22 meters into the seabed to ensure adequate bearing capacity under the anticipated axial, lateral and moment loading, including cyclic effects.

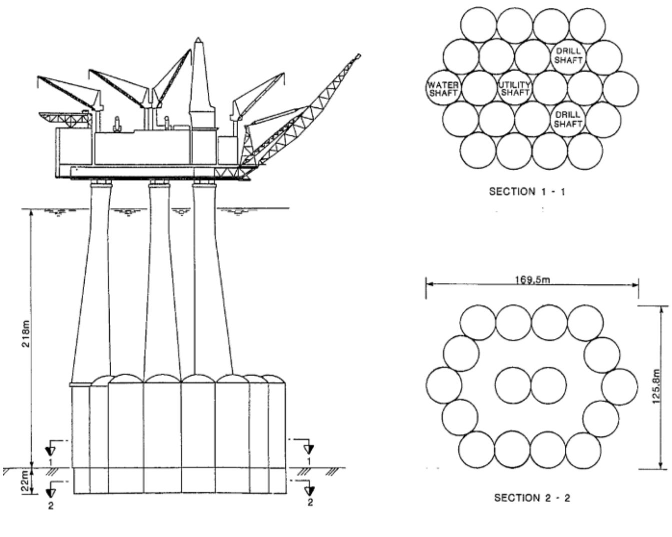


Figure 13 Gullfaks-C deep skirted gravity base structure, after Tjelta et al (1990).

John Burland was asked by Statoil (now Equinor) to provide an overview of the novel foundation concepts. Installation of the skirts was achieved by platform water ballasting and under-base suction. The platform weight was initially carried as base contact pressures. A soil strengthening scheme, involving accelerating soil consolidation by the installation of more than 800 single filters, enabled the operational platform submerged weight of 500.000 tonnes to be largely transferred to the soil as skirt tip resistance and skirt wall friction within 3 months. John invited Dr Edmund Hambly, then President of the UK Institution of Civil Engineers, and Dr David Hight of GGG (and formerly of Imperial College) to join him. John and Dr Hambly focussed on the buckling stability of the skirts during penetration into the seabed.

Resistance to penetration of the 22 m long platform skirts was uncertain, particularly through the clayey sands in which CPT penetrations were highly variable, as shown in Figure 14. A decision was taken by the Gullfaks C project team to perform a large-scale field test at the site by penetrating a segment of the skirt wall into the seabed in 1985. The test, its instrumentation and the results of the monitoring are described by Tjelta et al (1986). Data from the test was invaluable in the assessment of buckling stability. The Gullfaks C design studies were supported by novel FE analyses conducted with ICFEP by Professor David Potts to consider the behaviour of the foundation under static and storm loading (Hight et al, 1988). The latter included both axisymmetric and plane strain analyses of the base, with the soils being modelled by similar constitutive approaches to those employed for Magnus and Hutton. Special attention was given to the effect of the soil contained between the deep skirts and to the caisson shell stiffness in the plane strain simulations. The analyses provided insight into the load-transfer and failure mechanisms of the deep-skirted gravity base.

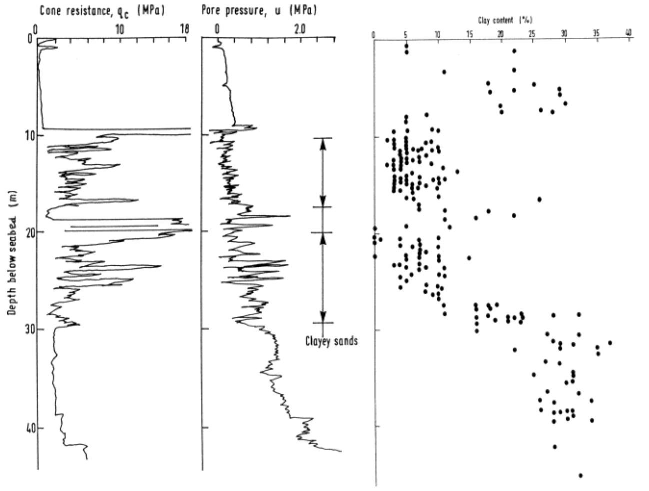


Figure 14 Geotechnical profile for upper 45 m at Gullfaks-C site, showing variations in CPT tip resistance (MPa), excess pore pressure (MPa) and clay content (%) with depth, after Hight et al (1994).

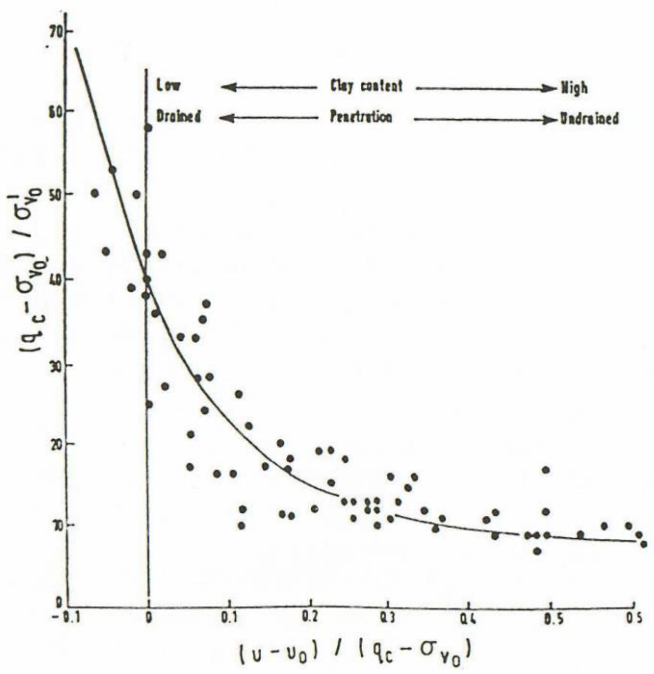
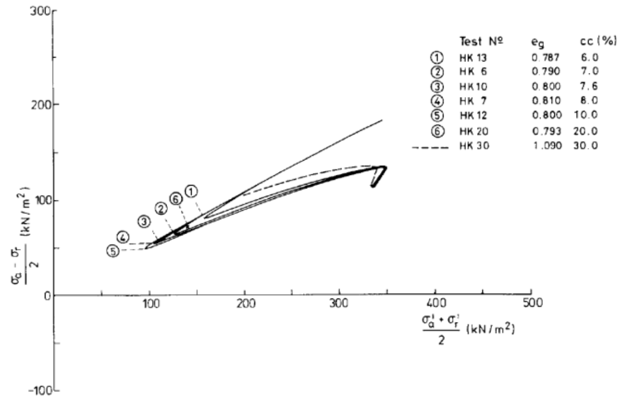
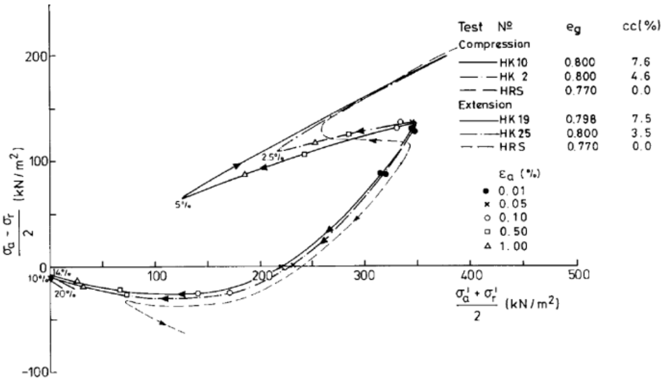


Figure 15 Relationship between clay content and CPTu response for upper 45m of soils at Gullfaks-C, where q_c is tip resistance, σ_{v0} is free field total stress, σ'_{v0} is free-field vertical effective stress, u is recorded pore pressure and u_0 is hydrostatic pore pressure, after Hight et al (1994).

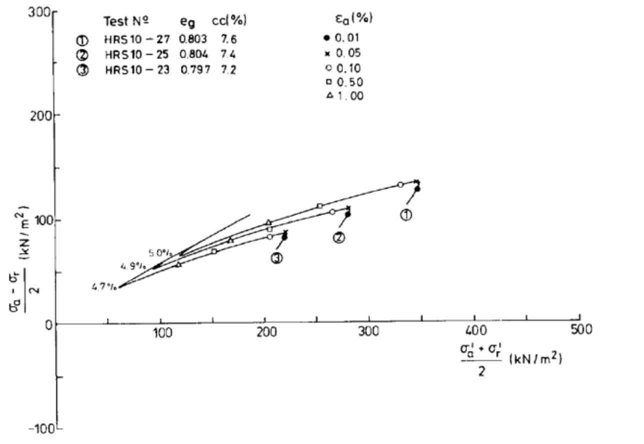
Other spin-offs from John Burland's involvement in the Gullfaks C project included: research into the undrained and drained behaviour of clayey sands through which the skirts would penetrate (Georgiannou et al. 1990, 1991a and 1991b)) and detailed interpretation of the CPTU data which was reported by Hight et al (1994). The CPTU data involved drained, partially drained and undrained penetration through the clayey sands that allowed correlations with clay content to be established, as shown in Figure 15. The research prompted into the behaviour of clayey sands demonstrated the importance of clay content on not only permeability but on undrained brittleness and memory of stress history; some of these effects are illustrated in Figure 16.



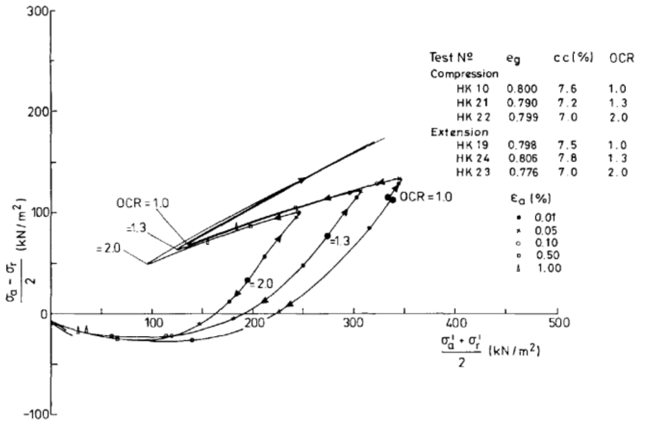
(a) Effective stress paths in *t-s'*, displaying sensitivity of undrained compression paths of OCR = 1 samples to clay content and intergranular void ratio.



(b) Effective stress paths in *t-s'*, displaying sensitivity of undrained compression and extension paths of OCR = 1 samples to clay content (cc) and intergranular void ratios e_g, also showing axial strains.



(c) Effective stress paths in *t-s'* space, displaying sensitivity of undrained compression paths for OCR = 1 samples with circa 7.5% clay content to applied consolidation stress level, also showing axial strains.



(d) Effective stress paths in *t-s'*, displaying sensitivity to OCR of undrained compression and extension paths for samples with circa 7.5% clay contents, also showing axial strains.

Figure 16 Evidence from CAU triaxial tests of behaviour of clayey sands depending on clay content (*cc*) and intergranular void ratio (e_g) manifesting undrained brittleness and showing 'memory' of its previous stress history, after Georgiannou et al (1991a, b).

5. SUMMARY

This paper has revisited research undertaken by the Authors with Professor J B Burland in which key contributions were made to pioneering oil production platform projects in the North Sea. John Burland's close liaison with industry and advocacy of an integrated approach that combined high quality laboratory and in-situ testing with cutting-edge numerical analysis and accurate observations of full-scale field behaviour were central to the improved predictive capabilities developed and proven through these highly significant projects.

After re-emphasising the central importance of understanding regional geology, the paper has reviewed how projects initiated by John Burland led to new laboratory and field monitoring instruments as well as experimental and numerical approaches that have had a lasting impact in many areas of geotechnical engineering.

Recent developments that sprang from these and associated projects have been highlighted above. Particular emphasis has been given to subsequent improvements to pile design methods whose development started with the Magnus FMP and Hutton TLP case histories and are now underpinning a major shift towards renewable, low-carbon, wind-energy production in the North Sea and, increasingly, worldwide.

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