WHOLE-LIFE ASSESSMENT OF SUBSEA SHALLOW FOUNDATION CAPACITY

S Gourvenec, SA Stanier and DJ White
Industrial Transformation Research Hub for Offshore Floating Facilities,
Centre for Offshore Foundation Systems, University of Western Australia, Perth, Australia

N Morgan,
Lloyds Register, Aberdeen, Scotland, UK

M Banimahd
Woodside Energy Ltd, Perth, Western Australia, Australia

J Chen
Shell Global Solutions Inc (US)

Abstract
Geotechnical design of subsea shallow foundations is typically based on *in situ* seabed strength reduced to take account of cyclic load degradation, in conjunction with the peak design load. This design philosophy emerged for fixed structures, designed to survive storms. However, subsea shallow foundation loading sequences and the associated seabed response differ significantly from that for fixed structures. They have periods that are orders of magnitude longer than storm loading, allowing for excess pore pressure dissipation during or between loading cycles that can lead to cyclic hardening rather than cyclic degradation of the supporting seabed. In addition, an alternative philosophy of tolerable mobility allows design loads that result from expansions or misalignments to be relieved if the foundation can displace and the soil-structure interaction be quantified. Greater scrutiny of the whole-life loading, soil-structure interaction and the associated seabed response can lead to efficiencies in foundation footprint, easing installability and reducing cost. This paper describes this 'staircase' of improvements in subsea shallow foundation design philosophy that are being explored in the ARC Research Hub for Offshore Floating Facilities, and provides examples to support the ideas presented.

1 Introduction

1.1 *Context*

Offshore developments are increasingly adopting subsea architecture, comprising a network of flowlines and associated pipeline infrastructure serving multiple fields spread across the seabed and tied back to a processing facility, either floating in deeper water, fixed in shallow waters or directly to onshore. Subsea structures, such as manifolds, pipeline end termination structures (PLET) and in line structures (ILS) (Figure *1*) among others, are often supported on shallow mat foundations. Development in regions with soft seabeds, of deeper hotter reservoirs and the drive to move more processes subsea has led to the size of subsea foundations becoming too large and heavy to be installed with standard pipelaying vessels when designed with conventional geotechnical design approaches. This provides an imperative to optimize geotechnical design of shallow foundation for subsea applications. Optimization can be achieved through challenging the traditional paradigms of design methodology, design basis, parameter input and also the physical shape of the foundation underside, including the soil-structure interface materials (Gourvenec & Feng 2014). These opportunities are being pursued in the ARC Research Hub for Offshore Floating Facilities, and can be summarised by the staircase shown in Figure 2, via steps A-F.

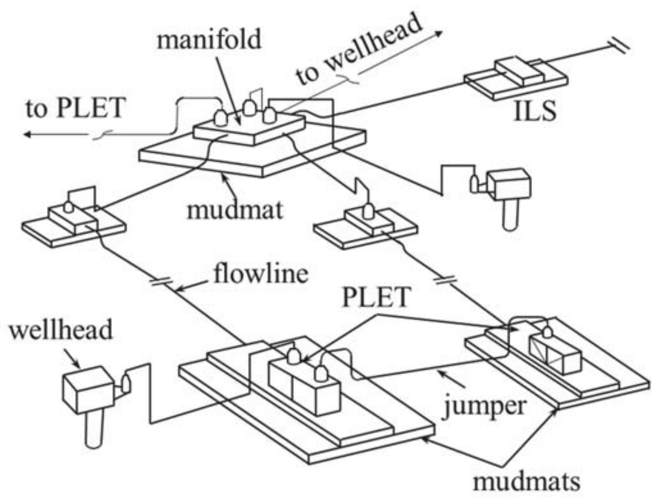

Figure 1. Schematic showing range of subsea structures supported on shallow foundations

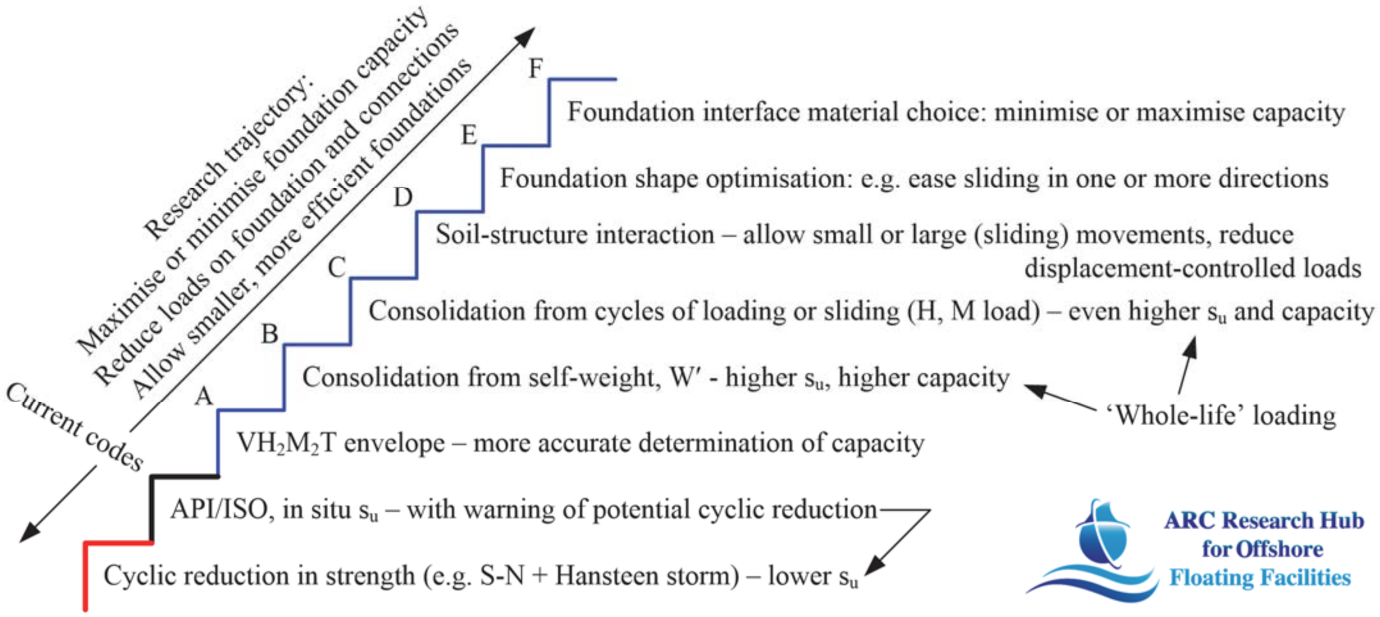

Figure 2. Staircase showing research trajectory to optimize shallow foundation design and performance

The failure envelope approach (step A) is an improved design methodology compared to classical bearing capacity theory to harness efficiencies for shallow foundation design for various structures (Bransby & Randolph 1998; Gourvenec & Randolph 2003; Feng et al. 2014; Shen et al. 2015). A design basis that allows tolerable foundation mobility (step D) has been explored to enable reduction in footprint of subsea mudmats (Cathie et al. 2008; Cocjin et al. 2014; Deeks et al. 2014; Stuyts et al. 2015). This paper illustrates the failure envelope method, but is primarily focused on optimization of parameter input by accounting for whole-life loading and the associated seabed response (steps B and C). While the emphasis of the work presented in this paper is subsea shallow foundations, the principles of whole-life seabed response are equally applicable to other foundation and anchor types. Steps E and F of the staircase follow from a design basis of tolerable mobility (step D). Mobile foundations that are designed for on-seabed sliding can be optimised to maximise their capacity in the non-sliding direction while minimising their capacity (and also the resulting settlement and tilt) in the direction of intended sliding, e.g. using uni-directional skirts.

1.2 *Whole-life loading and seabed response*

Whole-life loading of a shallow foundation supporting a fixed platform involves the self-weight of the foundation, ideally and typically acting centrically, and horizontal loads and moments derived from environmental forces acting on the structure. Peak loading corresponds to extreme weather events that involve high amplitude and frequency cyclic loading. The duration of an extreme weather event, typically a few hours or days, prevents significant dissipation of excess pore pressure in fine grained seabeds. Excess pore pressures therefore accumulate, leading to a reduction in effective stress and undrained shear strength of the seabed, i.e. cyclic softening (e.g. Andersen 2015; Zografou et al. 2016) and a subsequent reduction in foundation capacity (e.g. Andersen et al. 1988; Xiao et al. 2016).

The whole-life loading sequence of a shallow foundation supporting a subsea structure will depend on the function of the structure and the environmental conditions, but in many cases will be dominated by operational activities, i.e. the thermal expansion and contraction of the attached pipelines and spools during start up and shut down operations. The duration of these operational activities are orders of magnitude longer than storm loading (months rather than days), such that excess pore pressures generated during the loading event may dissipate, even in fine grained seabeds, prior to the subsequent cycle.

Intervening reconsolidation between cycles of loading can lead to an increase in the shear strength of the seabed, i.e. cyclic hardening. Cyclic hardening has been demonstrated with *in situ* characterization tools (Hodder et al. 2010, Cocjin et al. 2016) and for pipelines and foundations (Randolph et al. 2012, Cocjin et al. 2014). Cyclic hardening of soft soil beneath a pipeline undergoing episodic axial movements is routinely used in design (White et al. 2015). Figure 3 compares loading scenarios for a shallow foundation supporting a fixed platform and a deepwater subsea structure.

In addition, pipeline expansion loads transferred to a subsea foundation will be relieved if the system is compliant (whether through spool deflection, sliders or on-bottom foundation sliding). This contrasts with the environmental loading that dominates foundations for fixed platform structures, for which the compliance of the structure does not lead to a significant reduction of the applied loading.

Figure *4* illustrates the contrasting design strengths that apply for the two scenarios in Figure 3. The cyclic load history (shown in green) represents a subsea structure with slow cyclic loading associated with operating periods, which is shown to build up progressively, for example due to pipeline walking.

The blue lines represent the traditional approach to geotechnical design of a shallow foundation, derived for fixed structures. A large foundation is envisaged, to compensate for the loss of soil strength created by the undrained cyclic loading process. The degraded strength gives a capacity that exceeds the peak design load by the required material factor.

The red lines instead represent a case that is more relevant to this loading history, and are based on a smaller foundation. This reduction in foundation size is possible by considering the whole-life loading and consequent seabed response. The initial *in situ* strength is firstly enhanced due to consolidation under the self-weight dead load of the structure and subsequently due to reconsolidation between cycles of operational loading. The schematic profiles in Figure *4* show that the 'whole-life' approach allows a smaller foundation size while maintaining an adequate material factor, γ_m, throughout the life.

Subsea structures are typically placed on the seabed some months (or in some cases more than one year) ahead of operation of a field, so the consolidation under the self-weight of the foundation and structure in the absence of other in-service loading can be significant. Once the subsea infrastructure is operational, the foundation will be subjected to episodic cycles of loading from thermal expansion and contraction of the attached pipelines and potentially axial walking (Carr et al. 2006).

During operations, for a PLET/PLEM with a sliding mechanism to absorb the line expansion and contraction, the most critical design scenario will not occur until the accumulated line walking distance (global and/or localized) exceeds the tolerance in the sliding mechanism (typically between one and five years after initial operation based on design prediction).

The loads applied to the foundation may therefore ramp up over a period, and with loading cycles of a duration that allow for significant intervening reconsolidation – leading to cyclic hardening of the supporting seabed. The peak design load may therefore be married with an enhanced, cyclically hardened, seabed shear strength, enabling a smaller foundation footprint.

In this paper, methods for predicting seabed response to whole-life subsea foundation loading are presented. A hypothetical, idealized but realistic example is used to illustrate the potential efficiencies from greater scrutiny of the whole-life operational loading and the associated seabed response.

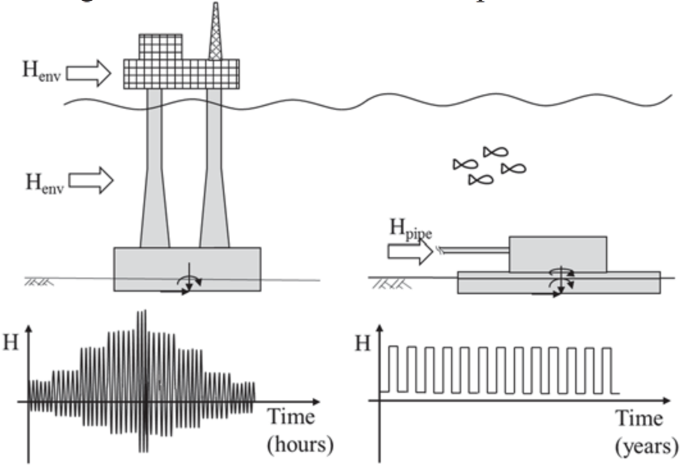

Figure 3. Comparison of loading scenarios on a shallow foundation supporting a fixed platform and subsea structure

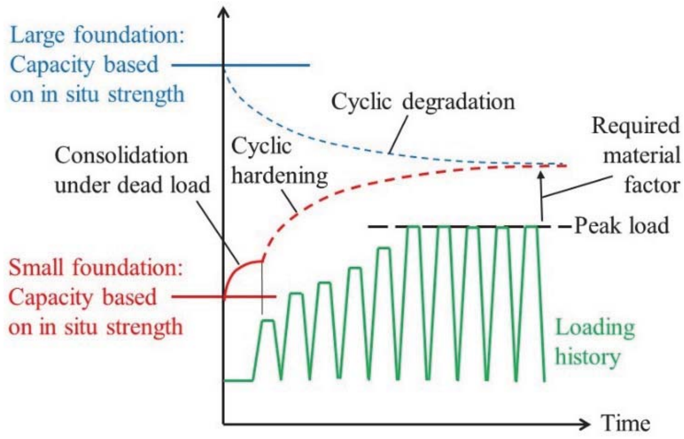

Figure 4. Alternative approaches to prediction of shallow foundation capacity: blue: conventional, red: 'whole-life'

2. Whole-Life Consolidated Strength

2.1 Self-weight preloading

The act of setting a structure on a fine grained soft seabed will lead to generations of excess pore water pressures beneath the foundation. In time these will dissipate, leading to a reduction in the void ratio of the supporting soil and corresponding increase in shear strength, at a rate dependent on the permeability, stiffness and drainage path length. The increase in shear strength is non-uniform over the soil domain, greatest at the foundation-soil interface and decreasing with distance from the foundation and varies with foundation geometry, level of self-weight or 'preload', degree of consolidation and foundation flexibility (Feng & Gourvenec 2017a). Figure *5* shows an example of seabed strength changes after full consolidation beneath a rigid circular surface foundation under a self-weight operative vertical load of 40% of the undrained vertical bearing capacity based on the initial in situ shear strength, derived from finite element analysis.

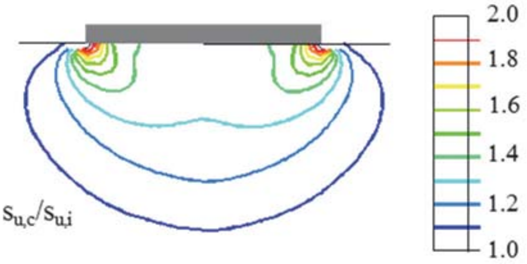

Figure 5. Increase in undrained shear strength beneath a rigid shallow foundation from self-weight consolidation

Identification of strength changes beneath a shallow foundation is one part of the puzzle, the key engineering question is "what is the effect of the strength change on foundation capacity?".

An answer to this question has been proposed through a theoretical framework based on critical state concepts. The affected area of soil is treated as a 'lumped element' and traditional critical state relationships between changes in effective stress, void ratio and shear strength are adopted. The applied preload, v_p, is scaled by a stress factor f_σ, to account for the non-uniform distribution of stress beneath the foundation (and to account for the vertical rather than mean stress being considered) and defines an 'operative' preload. The operative shear strength, $s_{u,op}$, is defined from the change in void ratio, Δe, under the operative preload, adjusted by a constant shear strength factor, f_{su}, to account for the non-uniform distribution of the shear strength increase in the soil zone controlling the consolidated capacity.

The framework was intially developed and verified for gain in vertical bearing capacity from vertical self-weight preload and consolidation of surface foundations on deposits of varying over consolidation ratio (Gourvenec et al. 2014). For normally consolidated conditions, in which all of the applied stress causes plastic compression of the foundation soil, the gain in undrained vertical bearing capacity due to self-weight loading and full consolidation can be given simply by

$$\frac{V_{cu\_max}}{V_{uu}} = 1 + f_\sigma f_{su} R \left(\frac{V_p}{V_{uu}}\right) N_{cv} \quad (1)$$

where $V_{cu,\_max}$ is the maximum undrained vertical bearing capacity, i.e. after full consolidation; V_{uu} is the unconsolidated undrained vertical bearing capacity factor; f_σ and f_{su} are as described above; R is the normally consolidated undrained strength ratio, $(s_u/\sigma'_v)_{nc}$; V_p is the applied self-weight preload and N_{cv} is the vertical bearing capacity factor for undrained unconsolidated conditions. N_{cv} can be determined from either classical bearing capacity theory or from numerical and analytical solutions for various boundary conditions (e.g. Gourvenec & Mana 2011, Feng et al. 2014). Foundation gains for durations of preload that allow only partial consolidation can be scaled as a function of the degree of consolidation, U = w_c/w_{cf}.

This 'lumped' approach to model the overall effect of the changes in soil strength beneath the foundation is very reliable when benchmarked against numerical analyses. The success of the 'lumped' approach is partly because changes in the shape of the failure mechanism have minimal influence on the operative bearing capacity factor (Stanier & White 2017).

The framework has been extended to capture gain in multi-directional foundation capacity following vertical (self-weight) preload and consolidation in normally consolidated deposits (Feng & Gourvenec 2015). Figure *6* shows gains in uniaxial multi-directional capacities following vertical preload and full consolidation. It can be seen that horizontal and torsional capacity, often the governing load cases for subsea shallow foundations, can double under realistic levels of vertical preload.

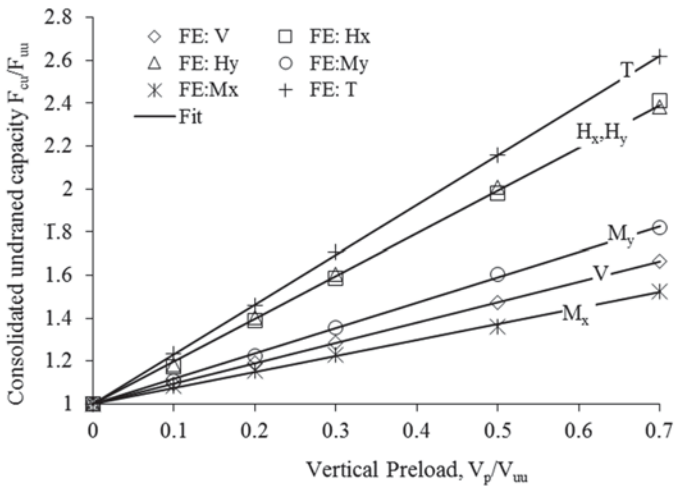

Figure 6. Self-weight-induced consolidation gain in undrained multi-directional capacity of a 2:1 rectangular mudmat on a normally consolidated deposit (after Feng & Gourvenec 2015)

The study showed that the unconsolidated undrained failure envelopes in any plane of fully 3-dimensional loading (V-H_x-H_y-M_x-M_y-T) can be scaled by the consolidated undrained capacities, which can each be scaled by the degree of consolidation. Each multi-directional capacity can be predicted with Equation 1 by substituting direction-dependent capacities and stress and strength factors to account for the interaction of the susequent failure mechanism with the zone of enhanced soil strength (e.g. Table 1).

Table 1: $f_\sigma f_{su}$ direction-dependent factors for Equation (1) to predict multi-directional consolidated undrained capacities of a rectangular 2:1 mudmat

V	H_x	H_y	M_x	M_y	T
0.439	0.919	0.919	0.345	0.538	1.071

2.2 Horizontal preloading

A gain in seabed strength and corresponding increase in foundation capacity can also be derived from dissipation of excess pore pressures induced by a level of horizontal load ('preload') that is maintained, leading to consolidation. Sustained horizontal loads may derive from misalignment of connections, hydrotesting of an attached pipeline or sustained currents acting on the structure. This effect is also the building block for cyclic sustained horizontal loading (Section 2.3), for example from episodes of pipeline startup and shutdown.

For the case of a sustained horizontal load prior to operation, gains in seabed strength from dissipation of the pore pressures induced by the horizontal load can be superposed on those from self-weight consolidation (Feng & Gourvenec 2017b). Figure *7* illustrates the potential gain in undrained horizontal capacity of a rectangular mudmat under vertical and horizontal preloading and full consolidation. The lower limit to the set of curves, i.e. under self-weight consolidation, is identical to the 'H_x, H_y' data series in Figure *6*, and can be predicted by Equation 1.

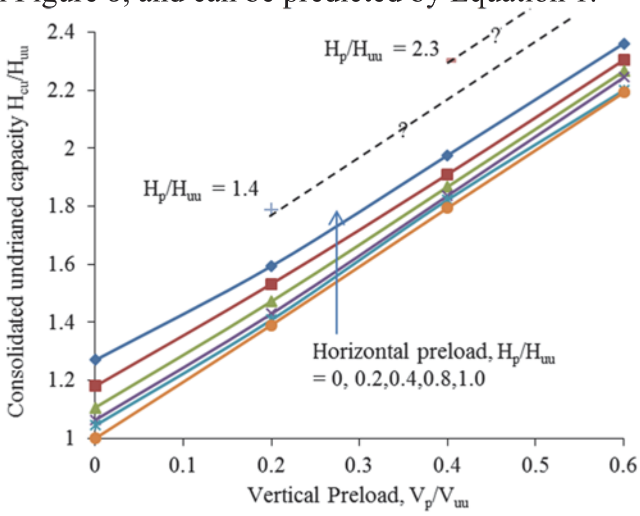

Figure 7. Foundation capacity gains from vertical and horizontal preload and consolidation; 2:1 rectangular mudmat on a normally consolidated deposit (Feng & Gourvenec 2017)

Figure *7* shows that the horizontal capacity can be increased by up to 20% compared to that under self-weight consolidation alone, for the same vertical preload. Alternatively, this illustrates that a given increase in capacity compared to that based on the initial in situ strength, can be achieved by different combinations of vertical and horizontal preloading. For example, a doubling in undrained horizontal capacity can be achieved under a vertical preload of $0.5V_u$ in the absence of a horizontal preload; or $0.4V_u$ in conjunction with a horizontal preload equal to the (initial) ultimate unconsolidated undrained capacity. Horizontal preloads in excess of the initial ultimate unconsolidated undrained horizontal capacity can be applied if the seabed strength has been enhanced due to the vertical preload prior to application of the horizontal preload. Examples are shown in Figure *7*, for H_p/H_{uu} = 1.4 and 2.3, (for vertical preloads > $0.2V_{uu}$ and $0.4V_{uu}$ respectively), realising even greater gains in horizontal capacity. H_p/H_{uu} > 1 are defined based on initial strength but take advantage of the strength gain from self-weight consolidation so the horizontal preload doesn't cause sliding failure.

In practice, it may be difficult to predict the level of horizontal preload that may occur, and the example above is towards the upper limit of what could be sustained without failure. However, if the foundation is designed to slide (by targeting a low capacity) or is temporary (thus must be removable by crane), these potential gains in capacity should be considered, as they are unconservative to ignore.

2.3 Episodic horizontal loading – without 'failure'

Episodes of horizontal loading over the life of the structure may be caused by pipeline expansion, walking or tidal or soliton currents. These can cause a further increase in seabed strength, and hence operative foundation capacity. This behaviour is illustrated by centrifuge test results of a shallow skirted foundation in normally consolidated kaolin clay (Gourvenec & White 2017).

The foundation was subjected to 10 cycles of sustained horizontal load of ±$0.67H_{cu}$ (where H_{cu} is the capacity after consolidation under self-weight; a separate test determined that $H_{cu} = 2H_{uu}$, where H_{uu} is the *in situ* horizontal capacity). The horizontal load did not fail the foundation, and the cyclic movements were <50 mm at prototype scale. The cycles included intervening periods of consolidation. After 10 cycles the foundation was pushed sufficiently far to mobilise the post-cyclic undrained horizontal capacity.

Different periods of consolidation were permitted between cycles with the greatest gains from the longer periods of consolidation. Post-cyclic capacities of up to $H_{cu\text{-}cyc} = 3H_{uu}$ were observed. The measured capacities are well matched by the theoretical framework described in Section 2.1 (Gourvenec et al. 2014, Feng & Gourvenec 2015).

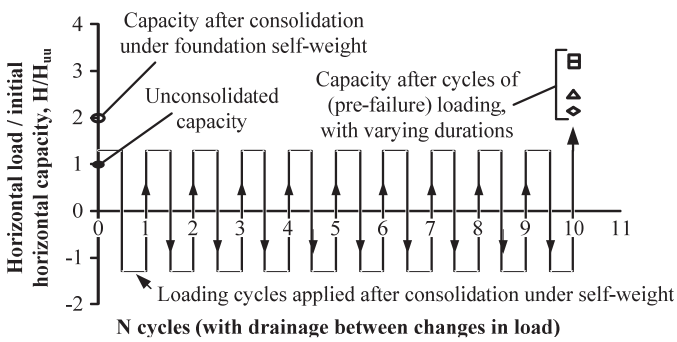

Figure 8. Gain in horizontal capacity of a shallow foundation following episodic horizontal loading and consolidation

2.4 Episodic horizontal loading – with 'failure'

Subsea shallow foundations may alternatively be designed to 'fail' and displace a greater distance across the seabed in response to imposed pipeline expansion and contraction loading (Cathie et al. 2008, Cocjin et al. 2014, Deeks et al. 2014, Stuyts et al. 2015, Feng & Gourvenec 2016). The concept of a tolerably mobile foundation is illustrated in Figure 9. For this design approach, the foundation capacity may require to be minimised, not maximised, in order to relieve the load in the attached pipeline. Also, settlement and tilt of the foundation are important design criteria, as they impose bending in the attached pipes and spools.

The effect of large amplitude horizontal sliding with intervening consolidation on the sliding resistance of a subsea mudmat has been investigated through centrifuge testing (Cocjin et al. 2014). The foundation consolidated under self-weight (modelled as $0.3V_{uu}$ and $0.5V_{uu}$) prior to 40 cycles of large amplitude horizontal sliding. A prototype period of three months was permitted between slides to reflect a typical field condition. Similar to the case of the static mudmat, horizontal resistance stabilises at a maximum of approximately three times the capacity based on initial *in situ* strength (Figure *10*).

Whole-life episodic horizontal loading and consolidation has been modelled through a generalised critical state framework (Cocjin et al. 2017, Corti et al. 2017). The soil beneath the foundation is idealised as a one-dimensional column of elements, each subject to a vertical total stress and cycles of horizontal shear stress, and responding according to a simple form of critical state model. Sliding of the foundation leads to shear stress in the seabed, which in turn leads to the generation of excess pore pressure. Dissipation of the pore pressure leads to a gain in strength and an accumulation of foundation settlement.

The framework can be applied in a cycle-by-cycle manner, solving for the response at each soil element to determine the cumulative change in void ratio and the variation in shear stress and settlement at the soil surface. The framework, set out in detail in Cocjin et al (2017) can be programmed into a spreadsheet or calculation script to be used as a predictive tool.

This approach is akin to the oedometer method of foundation settlement analysis, but considering shearing as well as one-dimensional compression. The approach is highly flexible, and can incorporate additional levels of complexity if required. For example, the normal compression and critical state lines can be curved to match observed effects of soil structure; the critical state line can migrate to a lower voids ratio under cyclic loading, to reflect observed behaviour; the foundation can be split into multiple elements, each resting on an independent column of critical state soil horizons, allowing any eccentricity of vertical load or applied moment to be modelled, to reproduce the corresponding tilt.

The framework has been validated against centrifuge test results (such as shown in Figure *10*) and is shown to capture the essential elements of the soil-structure interaction, which include (i) the changing soil strength from cycles of sliding and pore pressure generation, (ii) the regain in strength due to dissipation of excess pore pressure (consolidation), and (iii) the soil contraction and consequent settlement of the foundation caused by the consolidation process.

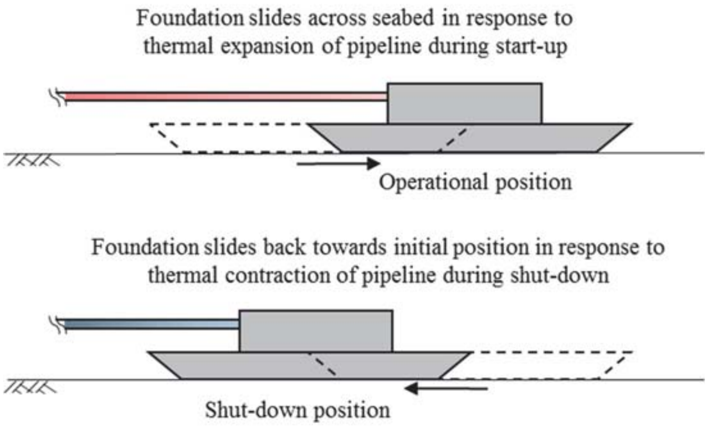

Figure 9. Schematic representation of mode of operation of a tolerably mobile subsea mudmat

2.5 Whole-life and end of life

Whole-life seabed response has implications for end of life removal of subsea shallow foundations as well as performance during the service life. Seabed strength gains from consolidation under self-weight, installation and operational loads may cause structures to be harder to remove from the seabed than potentially anticipated (Small et al. 2015, Gourvenec & White 2017). Ideally subsea shallow foundations could be vented to relieve suctions and reduce retrieval loads, but this may not always be possible particulary with aged structures.

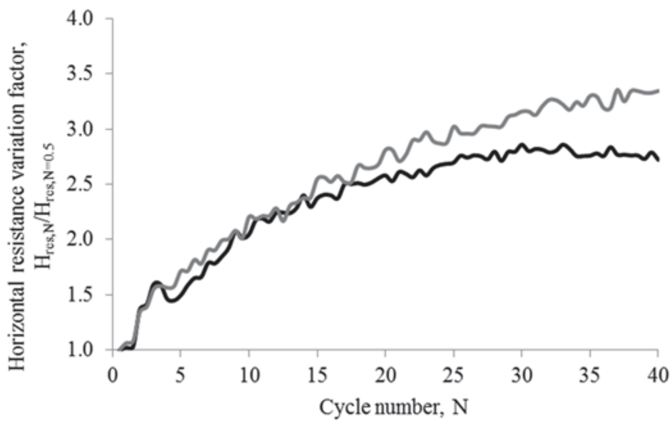

Figure 10. Increase in sliding resistance over whole-life sliding and reconsolidation (after Cocjin et al. 2014)

3. Application Example

3.1 Overview

The whole-life concepts introduced in this paper are illustrated in this section through a hypothetical example; a mudmat to support a pipeline end termination (PLET) on a silty clay with the properties and loading scenario as summarised in Table 2. For simplicity, uniaxial centric vertical and horizontal loading are selected for illustration.

Table 2: Input for example PLET design problem

Design	
Load due to subsea equipment, V'_{eqmt} (kN)	100
Stress due to foundation self-weight σ'_{fnd} (kPa)	4
Vertical self-weight preload period, t_V (months)	1
Maximum horizontal load, H_{max} (kN)	320
Operating period between shutdowns, t_H (months)	1
Operational life (years)	25
Material factor on undrained shear strength, γ_M	1.25
Settlement limit, w_{max} (mm)	300
Soil conditions	
Initial mudline strength, s_{um} (kPa)	2
Strength gradient, k (kPa/m)	1.5
Sensitivity, S_t (-)	3
Effective unit weight, γ' (kN/m^3)	5
Coefficient of consolidation, c_v (m^2/yr)	100
Slope of Normal Compression Line (NCL), λ (-)	0.25
Slope of recompression line, κ (-)	0.05
Voids ratio on NCL at σ_v'=1 kPa, N (-)	3
Undrained strength ratio, $(s_{u0}/\sigma_{v'})_{nc}$ (-)	0.3

The required mudmat size was determined assuming:

1. a fixed foundation solution with:
   a. unconsolidated undrained capacity following Feng et al. (2014);
   b. consolidated undrained capacity due to vertical self-weight preloading following Feng and Gourvenec (2015);
   c. consolidated undrained capacity due to vertical self-weight and horizontal preloading following Feng and Gourvenec (2017); and
2. a sliding foundation solution using a simplified variant of the Cocjin et al. (2017) model (no CSL migration; linear NCL in e-ln(σ_V') space).

For the vertically and horizontally preloaded fixed foundation (case 1c) the horizontal preload was taken as 80% of the consolidated undrained horizontal capacity determined in the vertically preloaded example (case 1b). The sliding foundation (case 2) was sized so that the horizontal capacity was always less than the design load (so sliding and stress relief in the flowline can occur) and the settlement was limitied to less than 300 mm throughout the operational life of the facility taken as 300 cycles.

Figure *11* illustrates that the plan area and weight of the fixed foundation solutions are approximately halved if the effect of consolidation prior to operation are accounted for. If a sliding concept is adopted the foundation can be further reduced. The size is then limited not by capacity but by the settlement, which must be predicted and kept within limits to avoid overstressing the pipeline connections.

In Figure 11 the sliding capacity triples due to episodes of sliding and consolidation (and the vertical capacity will also increase). This effect must be considered to ensure that the maximum load exerted by the foundation on the attached pipeline does not exceed the design compression load in the pipeline (or cause an unwanted rogue buckle, for example).

Figure *12* shows the settlement and horizontal capacity predictions due to cycles of sliding and reconsolidation over the operational life of the sliding PLET. The horizontal capacity asymptotes to ~150 kN after ~30 cycles of operation, whereas the settlements continue to accumulate throughout the operating life due to cyclic densification of the soil column beneath the foundation.

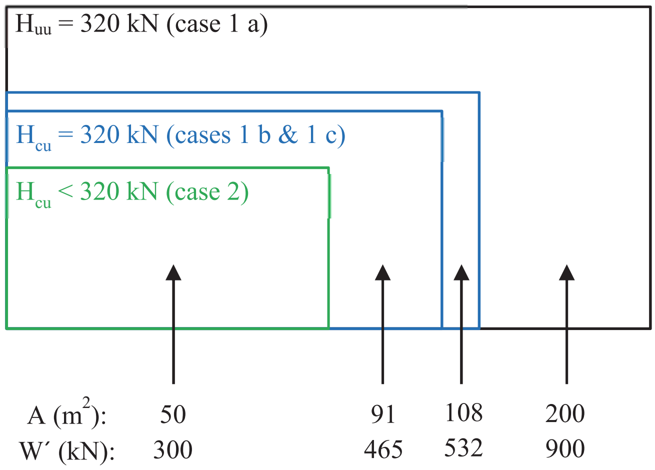

Figure 11. Size and weight of PLET and mudmat required for various fixed and sliding design philosophies

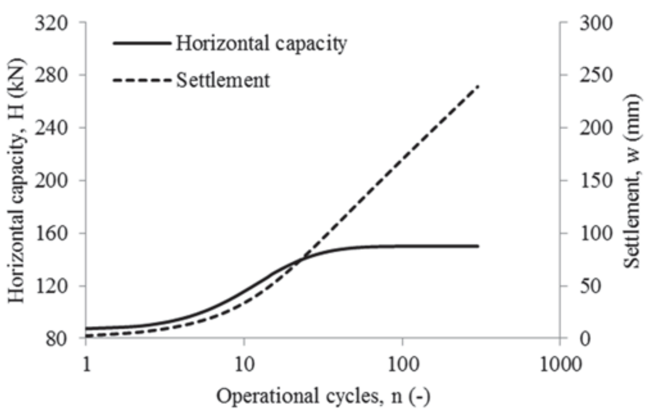

Figure 12. Horizontal capacity and settlement of the sliding PLET during 300 cycles (25 years) of operation

4. Outlook and Concluding Remarks

This paper has outlined a 'staircase' of improvements in shallow foundation design practice beyond conventional code approaches, which are currently being pursued. Two key themes of this work are (i) potential gains in soil strength and foundation capacity from considering 'whole-life' loading and the resulting improvements in soil strength and (ii) tolerable mobility, in which loads are relieved by allowing foundation movement (and even 'failure', by sliding), to allow more efficient design. Some steps in the staircase are well established, although further work is needed to broaden the experience to a wider range of soil conditions and to close the loop with field observations. A coordinated programme of physical modelling, numerical simulation and field testing is underway within the ARC Research Hub for Offshore Floating Facilities, to establish accepted guidelines for more efficient design and installation of subsea facilities. Some of the calculation tools used in this paper are freely available as webapps at www.webappsforengineers.com.

5. Acknowledgements

This work forms part of the activities of the Centre for Offshore Foundation Systems, supported as a node of the ARC Centre of Excellence for Geotechnical Science and Engineering (CE110001009), and the ARC Industrial Transformation Research Hub for Offshore Floating Facilities, supported by Shell, Woodside, Lloyds Register and Bureau Veritas (IH140100012). The industry authors acknowledge their companies for allowing them to prepare this paper. The paper reflects the opinions of the authors and does not imply endorsement by their companies.

6. References

Andersen KH. (2015) Cyclic soil parameters for offshore foundation design, *Proc. Frontiers in Offshore Geotechnics III* (ISFOG 2015) Oslo, Norway, Taylor and Francis, 5-82.

Andersen KH and Lauritzsen R. (1998) Bearing capacity for foundations with cyclic loads. *Journal of Geotechnical Engineering ASCE*; 114(5):540–555.

Bransby MF and Randolph MF. (1998) Combined loading of skirted foundations. *Géotechnique* 48(5):637–655.

Cathie D, Morgan N and Jaeck C. (2008) Design of sliding foundations for subsea structures. *Proc. BGA Int. Conf. Foundations.* Dundee, Scotland, 24–27.

Cocjin M, Gourvenec S, White DJ and Randolph MF. (2017) Theoretical framework for predicting the response of tolerably mobile subsea installations *Géotechnique* ahead of print http://dx.doi.org/10.1680/jgeot.16.P.137

Cocjin M, Gourvenec S, White DJ and Randolph MF. (2014) Tolerably mobile subsea foundations – Observations of performance. *Géotechnique* 64(11):895-909.

Corti R, Gourvenec S, Randolph, MF and Diambra A. (2017) Application of a memory surface model to predict whole-life settlements of a sliding foundation. *Computers & Geotechnics* 88:152–163.

Deeks A, Zhou H, Krisdani H, Bransby F and Watson P. (2014) Design of direct on-seabed sliding foundation. *Proc. 33rd Int. Conf. Ocean, Offshore & Arctic Eng.* San Fran., USA.

Feng X and Gourvenec S. (2017a) Effect of foundation flexibility on consolidation gains in undrained capacity. *Proc. Soc. Underwater Tech. OSIG Conf.*, London, UK.

Feng X and Gourvenec S. (2017b) Improving subsea mudmat efficiency through self-weight and pre-operational horizontal loading and consolidation (under review).

Feng X and Gourvenec S. (2016) Modelling sliding resistance of tolerably mobile subsea mudmats. *Géotechnique*, 66(6):490-499.

Feng X and Gourvenec S. (2015) Consolidated undrained load-carrying capacity of mudmats under combined loading in six degrees-of-freedom. *Géotechnique,* 65(7): 563-575.

Feng X, Randolph MF, Gourvenec S and Wallerand R. (2014) Design approach for rectangular mudmats under fully three-dimensional loading, *Géotechnique* 64(1): 51-63.

Gourvenec S and White DJ. (2017) In situ decommissioning of subsea infrastructure, *Proc. Conf. Offshore & Maritime Engng; Decom. of Offshore Geotech. Structures, Hamburg.*

Gourvenec S and Feng X. (2014) Frontiers in deepwater geotechnics – Optimization of subsea foundation design. *Australian Geomechanics,* 50(4):77-96.

Gourvenec S and Mana DKS. (2011) Undrained vertical bearing capacity factors for shallow foundations. *Géotechnique Letters*, doi: 10.1680/geolett.11.00026.

Gourvenec S, Vulpe C and Murthy T. (2014) A method for predicting the consolidated undrained capacity of shallow foundations on clay. *Géotechnique,* 64(3):215–225.

Gourvenec S and Randolph MF. (2003) Effect of strength non-homogeneity on the shape of failure

envelopes of strip and circular foundations on clay. *Géotechnique*, 53(6):575-586.
Hodder MS, White D and Cassidy MJ. (2010) Analysis of soil strength degradation during episodes of cyclic loading. *Int. J. Geomechanics*, 10(3), 117-123.
Randolph MF, White DJ and Yan Y. (2012). Modelling the axial soil resistance on deepwater pipelines. *Géotechnique* 62(9): 837–846.
Stuyts B, Wallerand R and Brown N. (2015) A framework for the design of sliding mudmat foundations. *Proc. Int. Symp. on Frontiers in Offshore Geotechnics (ISFOG)*, Oslo.
Shen Z, Feng X and Gourvenec S. (2015) Effect of interface condition on the undrained capacity of subsea mudmats under six dof loading, *Géotechnique* 67(4):338-349
Small A, Cooke G, Egborge R and Ejidike A. (2015) Geotechnical aspects of North Sea Decommissioning, *Proc. Int. Ocean & Polar Eng. Conf.*, Kona, Hawaii, 1308–14.
Stanier SA and White DJ. (2017) Enhancement of bearing capacity from consolidation: due to changing strength or failure mechanism? (under review)
Vulpe C, Gourvenec S, Leman B and Fung KN. (2016) Failure envelopes for consolidated undrained capacity of surface foundations. *Geotech.& Geoenv. Engng*. 142(8).
White DJ, Westgate Z, Ballard JC, de Brier C and Bransby MF. (2015). Best practice geotechnical characterization and pipe-soil interaction analysis for HPHT flowline design. *Proc. Offshore Tech. Conf. Houston.* OTC26026-MS
Xiao Z, Tian Y and Gourvenec S. (2016) A practical method to evaluate failure envelopes of shallow foundations considering soil strain softening and rate effects, *Applied Ocean Research,* 59:395-407.
Zografou D, Gourvenec S, O'Loughlin C and Boukpeti N. (2016) Definition of failure in cyclic direct simple shear tests on normally consolidated kaolin. *Proc. 5th Int. Conf. on Geophys. & Geotech. Site Char.*, Brisbane. 583-588.