SOLCYP: A FOUR-YEAR JOINT INDUSTRY PROJECT ON THE BEHAVIOUR OF PILES UNDER CYCLIC LOADING

Alain Puech
Fugro-France, Nanterre, France

Jean Canou
ENPC-Navier, Marne-la-Vallée, France

Christian Bernardini
IREX, Paris, France

Alain Pecker
Geodynamique et Structure, Bagneux, France

Richard Jardine
Imperial College, London, United Kingdom

Alain Holeyman
Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Abstract
SOLCYP is a research and development project conducted in France to: *(i)* understand the physical phenomena conditioning the response of piles to vertical and horizontal cyclic loads; *(ii)* develop advanced design methods; and *(iii)* initiate pre-normative development of methodologies that may later be included in national and international codes or professional standards. The potential applications include conventional structures, such as electricity pylons or chimneys, high rise towers and high speed train bridges. However, a central emphasis is also given to more novel foundations for offshore and onshore renewable energy engineering. The paper describes the objectives and overall technical content of the project. Several companion papers focus on more specific aspects and the results obtained so far.

1. Introduction

The oil and gas industry has developed various procedures for considering the effects of large wave cyclic loads on foundations for offshore structures. Design guidelines include the American Petroleum Institute (API) RP 2GEO (2011); Det Norske Veritas (DNV) Foundations (1992) and the International Organization for Standardization (ISO) 19901-4 (2003). In addition, the offshore turbines industry is progressively adapting such methodologies given in DNV-OS-J101 (2011) and Federal Maritime and Hydrographic Agency (BSH) publication entitled, *Design of Offshore Wind Turbines* (2007).

Surprisingly, the effects of cyclic loading on foundations are largely ignored in most civil engineering and building activities. French codes and Eurocode7 (2007) reflect this poor level of consideration. A committee working under the umbrella of the French national agency, IREX, called for national engagement in an ambitious research and development project to address the present lack of guidance regarding piles under cyclic loading.

The SOLCYP project (French acronym for piles under cyclic solicitations) was launched in 2008 with the objectives of:

- understanding the physical phenomena conditioning the response of piles subject to vertical and horizontal cyclic loads;
- defining a methodology to assess the behaviour of cyclically loaded piles;
- developing design methods;
- initiating pre-normative actions with a view to introducing new methodologies in national (and international) codes or professional guidelines.

The project has a total budget approaching €5 million, financed by Agence Nationale de la Recherche (ANR) and Ministry for Ecology, Sustainable Development, Transports and Housing (MEDDTL) and private companies from the civil engineering and energy sectors. Details can be found on the project website at www.pnsolcyp.org.

This paper describes the objectives and overall technical content of the project. Several companion papers focus on specific aspects and initial outcomes. The term ‘cyclic’ loading is used in this paper generically to characterise variable loads that have clearly repeated patterns and a degree of regularity in amplitude and return period. Cyclic loads may be essentially environmental (e.g. wave, wind) or operational in origin.

2. Characterisation of Cyclic Loads

It is common in building works and civil engineering to consider applied loads as essentially static or quasi-static. Critical loads are defined by the maximum values expected under various load cases (operational, extreme, accidental, etc.). It is currently possible to consider the response of soil elements under cyclic loading in terms of:

- **mean load and cyclic load amplitude**: these components affect the evolution of permanent and reversible deformations differently;
- **loading frequency**: this parameter determines whether the response is drained or undrained in relation to the soil’s compressibility and permeability characteristics;
- **rate of loading**: this also has a direct impact on the undrained shear strength of clays. Periods of rest between cycles, or series of cycles, can allow total or partial drainage and pore pressure dissipation; and
- **number of cycles**: these, which characterise a cyclic event, can vary from a few critical cycles (as in small earthquakes to thousands or millions of cycles, for example under railway bridges).

These aspects are familiar in offshore oil and gas applications, which have wave loading periods of typically 10s, or restoring forces on anchored vessels with periods of typically 100s. (The maximum number of significant load cycles considered in such studies is typically less than 1000.) However, a greater awareness of these issues is required urgently in general civil engineering. The cyclic loading applied to the foundations of a wider variety of onshore and coastal structures need to be characterised properly. Collecting typical load case histories is part of SOLCYP’s work. Measuring pile head loads in structures such as wind turbines, bridges and cranes can provide critical new information.

Measured load histories are often composed of a succession of load variations of irregular amplitude and relatively random distribution with time. However, laboratory cyclic soil element tests most usually apply load series of fixed frequency and regular amplitude. Cycle-counting methods (derived from rain-flow analyses) are routinely used in (metal) fatigue analyses to transform actual load histories into idealised series of cycles (e.g. American Society for Testing and Materials (ASTM), 2005). Similar approaches are proposed for soils (see Figure 1). For metallic materials, Miner’s damage concept (Downing and Socie, 1982) is applied to derive equivalent cyclic load patterns from *S-N* curves (obtained by plotting the number of cycles to failure of samples submitted to the series of constant cyclic stress amplitudes).

Analytical procedures have been developed to assess equivalent number of cycles to failure for geotechnical cases. Multistage cyclic loading methods have been applied to pore pressure generation and deformation analyses by Andersen (1988), Kaggwa et al. (1991) and Lin and Liao (1999). A major limitation is that Miner’s hypothesis has not been verified comprehensively for soils. Little is known regarding the effects of frequency and load history on stability and deformation analyses.

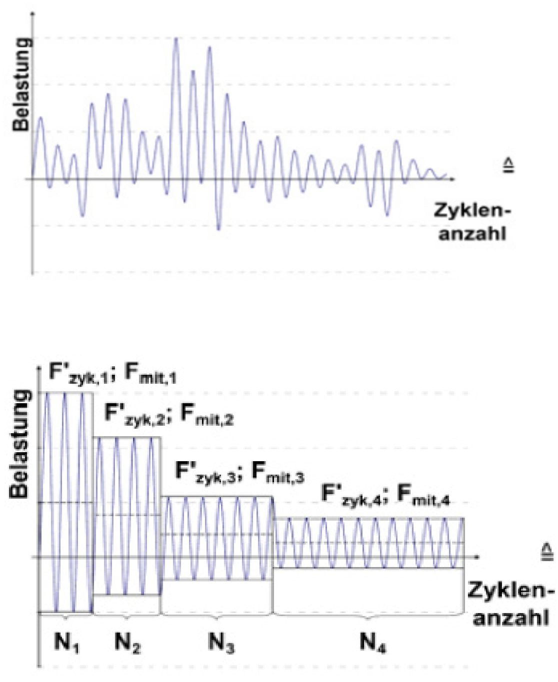

Figure 1: Transforming an actual load history into a series of regular amplitude cycles (BSH, 2007)

3. Cyclic Response of Soils

The response of soils to cyclic loading is often investigated in the laboratory using cyclic triaxial (CTX) and cyclic direct simple shear (DSS) tests. Samples are often consolidated anisotropically (typically under K_0 conditions) and sheared cyclically under undrained conditions. Such tests may consider different stress paths (e.g. DSS, CAUC, CAUE) to account for soil anisotropy. The variable shear stresses applied in cyclic testing stages are characterised by a mean component and a cyclic component oscillating around the mean. The latter generates excess pore pressures in the sample and irreversible deformations, which can be decomposed into mean and cyclic components. The response depends on:

- soil type;
- soil state (density of sands, degree of consolidation of clays);
- effective stress level, consolidation style and applied stress paths; and
- cyclic stress characteristics – in particular cyclic stress amplitude, the possibility of shear stress reversal and frequency.

A convenient way to capture the complete response of a particular soil is to construct cyclic interaction diagrams. Strain contour diagrams (Andersen, 1988) give the number of cycles to failure of cyclically loaded samples as a function of the mean and cyclic shear stress component (non-dimensionalised by the static undrained shear strength). Results can also be expressed as ISO values of excess pore pressures, permanent deformations or cyclic deformations. Contour diagrams may be proposed for particular testing modes (e.g. DSS, triaxial CAUC, triaxial CAUE) and loading frequencies. The laboratory testing programmes can be tailored to obtain a set of relevant contour diagrams. A limited number of complete diagrams are available for particular, stereotypical soils, such as Norwegian Drammen clay (Andersen and Lauritzen, 1988) and Gulf of Mexico Marlin clay (Jeanjean et al., 1998).

A complete characterisation of the cyclic response of four materials is planned within SOLCYP: (1) Speswhite clay, a kaolinite widely used for centrifuge testing; (2) Merville clay, an Eocene overconsolidated Flanders clay geologically equivalent to the UK London clay; (3) Fontainebleau sand, a fine poorly graded reference sand; and (4) Dunkirk sand. These materials are used for model testing (Speswhite and Fontainebleau) or field experiments (Merville and Dunkirk).

4. Behaviour of Soil-Pile Interfaces

The failure mechanisms of piles under monotonic axial loading are largely localised at, or very close, to the soil-pile interface. The processes followed depend on the characteristics of the soil, the pile material and the mode of installation.

In recent years significant advances have been made in understanding the friction mobilisation along driven piles. In sands, driving – which can be considered as a series of repeated extreme loading events – causes:

- severe crushing of the grains, so that the range of interface friction angles is relatively narrow, irrespective of the initial grain size distribution and relative pile roughness (e.g. Kolk et al., 2005; Yang et al., 2010);
- a progressive decrease of the mobilised soil-pile friction developed at a given level as the pile tip advances. This friction fatigue (*h/R*) phenomenon influences the radial effective stress distribution at end of installation (e.g. Lehane et al., 1993; Jardine et al., 2005).

Whether or not friction can increase under subsequent monotonic loading depends on sand density and pile dimensions. Dilation effects can be significant for small-diameter short piles, but may be minor for very large-diameter steel driven piles.

In clays, failure generally develops at or near the clay-pile interface, and installation may create a system of reduced strength residual shear surfaces (Jardine et al., 2005). However, it has been argued that full continuum failure may take place in other circumstances. Cyclic DSS tests can provide a model for the conditions close to the shaft that can help characterise the undrained shear strength properties. This is useful in cases where failure involves neither a residual surface nor soil-interface slip (Karlsrud and Nadim, 1990). Effective stress analyses have been proposed when residual surfaces or interface slips govern, as is common in many clays.

Cyclic DSS tests may also be applied in these cases to predict the rates of radial effective stress, and hence local shaft capacity, degradation under cycling (Jardine et al., 2005). Pile capacity in clays may be governed by peak or residual interface friction. The failure pattern, ductile versus brittle, depends on the clay fabric, which is affected by the past stress history of the soil and the mode of installation (driven versus cast in place). Progressive failure – where the ultimate (residual) shaft resistance is reached in the upper layers before the deeper strata near the pile toe have reached their peak resistance – is a major concern for long flexible piles. Ring shear interface tests provide critical information regarding the degree of brittleness and its rate of mobilisation with post-peak displacement (Jardine et al., 2005).

One specific SOLCYP task is to investigate the behaviour of soil-pile interfaces via laboratory testing. Steel-soil interfaces, which represent the type of driven piles used in offshore and port foundations, and concrete-soil interfaces, representing bored piles, are considered. The objective is to establish testing procedures for characterising soil-pile interfaces under cyclic loading. Several devices or test types have been implemented, as follows:

- shear-box testing at constant normal stiffness (CNS) in Fontainebleau and Dunkirk sands (Pra-ai and Boulon, 2011);
- cyclic DSS tests in clays with a high number of cycles;
- model pile tests with high numbers of cycles (>10 000) in sands and clay within small calibration chambers (Tali, 2011); and
- ring shear interface tests (Yang et al., 2010).

5. Cyclic Pile Design Parameters

The response of soils to cyclic loading is complex. While laboratory testing has been applied in practice, there is a need for recognised methodologies to guide cyclic parameters selection for design. Suitable documents will be developed for this purpose in collaboration with TC209 of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE). Design guidance will also be offered on cyclic interface parameters.

In France geotechnical parameter selection is mainly based on *in situ* testing. Pressuremeters are the most commonly used tools for onshore projects, although the cone penetration test (CPT) is becoming more widely used. Preliminary static and cyclic tests using the PAF 76 self-boring pressuremeter (SBP) were conducted in the beginning of the 1980s. Results were promising and the cyclic shear moduli *Gc* that was obtained compared favourably with observations made on a highly instrumented pile submitted to axial tension loads (Puech et al., 1982). This research avenue is being reactivated by SOLCYP, and attempts are being made to investigate the potential of cyclic CPT tests. A prototype tool is envisaged with a friction mantle that can cycle vertically about a mean position.

6. Axial Pile Response and Friction Degradation

The most visible detrimental effects of cyclic loading on the axial response of a pile are: *(a)* a reduction of ultimate capacity, related to reductions in local skin friction; and *(b)* reductions in pile head stiffness (or increased displacements). The degradation of skin friction is not homogeneous along the pile wall, but propagates from head to toe under increasing severity of the cyclic loading and number of cycles. The flexibility of the pile determines the distribution of friction along the pile. Series of centrifuge tests on model piles have been performed in Fontainebleau sand and Speswhite clay, with a view of deriving stability diagrams such as those proposed by Poulos (1988). Tests are being conducted using the large centrifuge of IFSTTAR (formerly LCPC) in Nantes. Stability diagrams have been generated, an example of which is shown in Figure 2. This diagram illustrates the number of cycles for bored piles leading to failure as a function of the mean and cyclic load components, normalised by the pile capacity under monotonic loading (Guefresh, 2012).

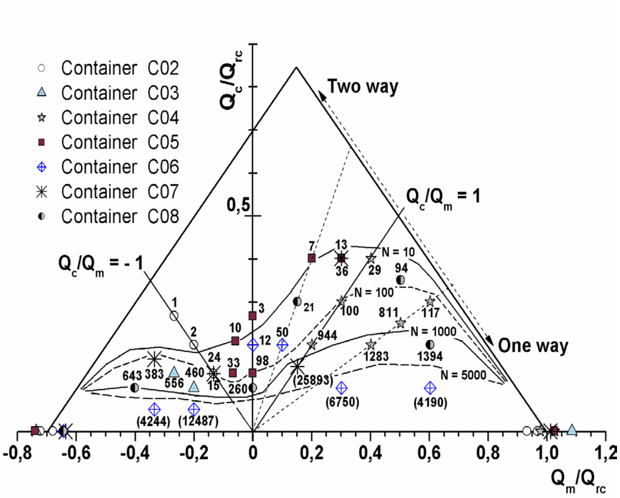

Figure 2: Stability diagram for axial cyclic tests on model piles in the centrifuge – dense Fontainebleau sand – cast in place piles (from Guefresh, 2012)

Highly instrumented displacement pile tests are also being performed in the large calibration chamber of the 3S-R Laboratory in Grenoble. These tests (carried out in collaboration with Imperial College London) provide valuable data (see Figure 3) on the mobilisation of interface pile-sand friction and its evolution with number of cycles (Tsuha et al., 2012; Rimoy et al., 2012).

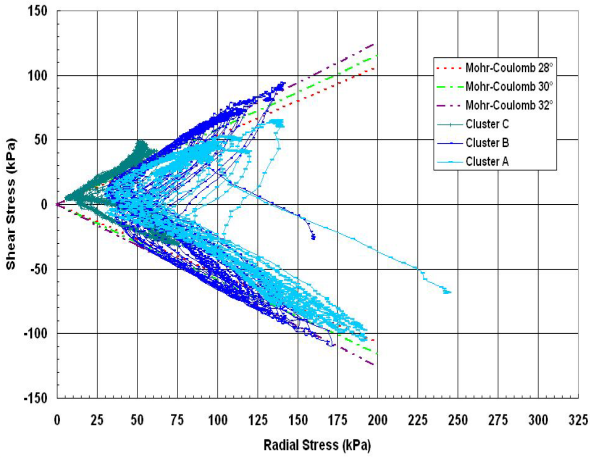

Figure 3: Stress paths measured in calibration chamber along a model displacement pile in Fontainebleau sand. Two-way large amplitude cycles generate successive phases of dilative/contractive behaviour at soil-pile interface (Tsuha et al., 2012)

In situ pile tests are being conducted at two experimental sites. The first is at Merville in the north of France, where overconsolidated plastic Eocene Flanders clay is encountered below 3m depth. Ten test piles were installed in March 2011, including 4 driven closed-ended tubular steel piles, 4 four bored piles and 2 screwed piles. The piles are 13.5 long with diameters of 406–420mm. Series of load tests were conducted over May to June 2001, including conventional incremental static tests, rapid load and cyclic load tests. The latter covered both tests that failed after relatively small numbers of large cycles, and those that extended to very large numbers (>10 000) of relatively low amplitude cycles. Details and preliminary results are presented in a companion paper (Benzaria et al., 2012).

A similar testing programme is planned on piles installed near Dunkirk in the post-glacial Flanders sands. The number of driven piles has been reduced, due to the availability of previous cyclic pile testing by Imperial College in the same sands at a neighbouring site (Jardine and Standing, 2000). The Dunkirk tests were completed in spring 2012. Interpretation is ongoing at time of paper publication.

It is expected that the concept of pile stability diagrams, developed for field tests on clays by Karlsrud and Haugen (1985) and applied to sands by Jardine and Standing (2000), can be extended to encompass the new enlarged experimental database. It is also intended that interpretation of the instrumented pile tests will allow an improved understanding of the following: degradation phenomena taking place along cyclically loaded piles; local degradation as a function of stress history; distribution of cyclic effects along the pile walls; and the progressive transfer of load from the pile head towards the toe.

7. Cyclic Design of Axially Loaded Piles

The final objective of the SOLCYP project is to propose methods for designing piles under cyclic axial and lateral loading. The full design may involve complex processes that may not necessarily be justifiable for everyday practice. The objective is to propose different approaches corresponding to increasing levels of complexity and elaborate criteria to determine the appropriate level of analysis. Design approach criteria should be based on:

- sensitivity of structure to displacements and rigidity;
- relative importance of cyclic component with regard to permanent and mean component;
- nature of the soil and potential sensitivity to cyclic loading; and
- potential economic, human and environmental consequences of poor cyclic performance.

The relative success of current civil engineering practice (which often ignores the effect of load cycles) demonstrates that, in many cases, cyclic loading effects can be accommodated through reasonable engineering judgment and conventional safety considerations. But this is not always the case. Well documented stability diagrams may be very useful in identifying those critical loading conditions that justify special consideration in design.

Cyclic axial pile analysis can already be tackled through the load transfer curve analyses. Recommendations for constructing (*t-z*) curves (i.e. relationships between mobilised soil-pile shear transfer and local pile displacement) for monotonic loading are available (see API, 2011; ISO, 2003). These curves are conveniently used in simple structural finite element (FE) models where the pile is generally considered as a linear elastic rod. Developing cyclic *t-z* curves that could model given shear stress amplitudes and particular numbers of cycles would be a decisive step forward in the design of piles under cyclic loading. Specialised software has been developed to model the cyclic response of piles, such as SCARP (Poulos, 1989), RATZ (Randolph, 2003) or PAXCY (Karlsrud and Nadim, 1990). In these models, the interface shear strength degradation during cycling controls the resulting plastic deformation.

It is anticipated that the experimental data gathered within SOLCYP (including soil and interface behaviour, *in situ* SBP and cyclic CPT tests, model pile tests and *in situ* pile tests) will provide sufficiently representative and reliable elements to derive degradation laws in sands and clays. They should also allow for the evaluation and possible calibration of existing software, and finally the proposal of preliminary sets of cyclic *t-z* curves. This is one of the more challenging SOLCYP tasks (Benzaria et al., 2011). Simpler 'global' approaches may also prove useful in practice (Jardine et al, 2005).

8. Lateral Pile Response

Current design methodologies for assessing the response of piles under lateral loads most frequently refer to the concept of load transfer, or *p-y* curves. Recommendations for constructing static *p-y* curves that reproduce local horizontal soil-pile interactions under monotonic loading can be found in offshore codes and standards, considering soils from silica or carbonate sands to soft or stiff clays. They are based on either laboratory data (e.g. use of the ε_{50} parameter), or *in situ* data (e.g. use of shear modulus *G* obtained from pressuremeter tests).

The offshore oil and gas industry uses cyclic *p-y* curves for designing jacket piles under extreme environmental loading. Potential problems exist in extrapolating this approach to other applications. Cyclic *p-y* curves were derived in the 1970s on the basis of tests performed on relatively small-diameter piles ($12^3/_4$–24in) for soft clays (Matlock, 1970), stiff clays (Reese and Cox, 1975), and sands (Cox et al., 1974). The piles were submitted to series of cyclic loads, representative of load histories imposed by Gulf of Mexico storms on jacket piles. The final results were 'envelope curves', which aimed to reproduce the soil-pile response of piles monotonically loaded at the end of the extreme event (the centennial storm). The limitations are as follows:

- Cyclic *p-y* curves (as in API/ISO documents) are applicable for modelling the head displacements and maximum bending moments of long flexible piles of *moderate* diameter after a storm loading history.
- They are used, perhaps inappropriately, to model the response of *large*-diameter offshore jacket piles that remain flexible because of their large aspect ratios.
- Present *p-y* curve formulations are not valid for the caisson piles employed in wind turbine monopiles, where the assumption of a flexible system with independent soil 'slices' acting at different depths is no longer applicable (Lam, 2009).
- Cyclic *p-y* curves are also inappropriate for modelling cases where horizontal displacements remain small, as they assume mechanisms that require relatively large displacements (e.g. Cao et al., 2005).
- Cyclic *p-y* envelopes are not applicable when considering in-storm stiffness response under dynamic or slow cyclic loading.

The SOLCYP project may not be able to resolve all the foregoing questions, however, it is committed to making advances in two directions. The first involves developing a methodology to assess the horizontal cyclic response of flexible piles subject to loading histories other than typical offshore storms. This might be based on developing 'true' cyclic *p-y* relationships that relate to given numbers of cycles (N = 10, 100, 1000, ...) and a stepping procedure that follows specified loading histories. Such true cyclic curves are being derived from the SOLCYP centrifuge tests (Khemakhem, 2012; Khemakhem et al., 2012) with Fontainebleau sand and Speswhite clay (see Figure 4).

The second avenue concerns the behaviour of short rigid piles or caissons under lateral loading. The 3D FE analyses (FEA) will be used to derive vertical, horizontal and moment (VHM) envelopes for rigid circular foundations with a slenderness ratio (*L/B*) in the range 5 to 15. The FEA will also be used to study the associated failure patterns. It is expected that the methodology currently employed for assessing the cyclic response of offshore suction emplaced caissons can be adapted to these embedment ratios. The lateral rigidity of these foundations will be investigated by introducing appropriate constitutive laws into the FEA.

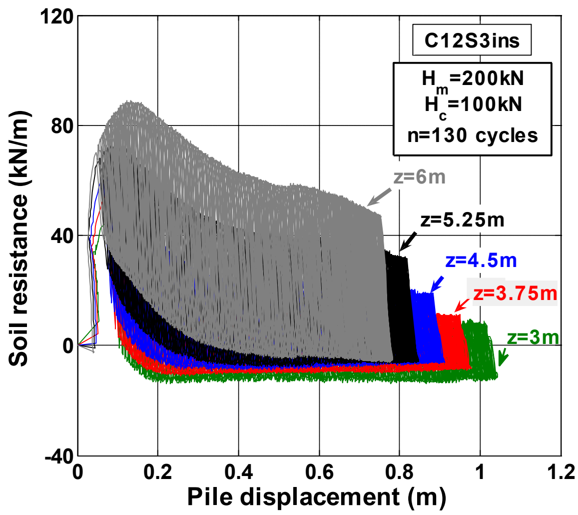

Figure 4: Cyclic p-y curves obtained on model piles in the centrifuge – NC clay (Khemakhem, 2012)

9. Numerical Modelling

Simulating the cyclic response of piles by continuum models is an extremely challenging task. Several issues are critical. For example, describing the cyclic behaviour of soils requires sophisticated constitutive laws that often involve many parameters. These parameters are difficult to measure. Extensive (and expensive) series of complex laboratory tests are needed. Modelling the behaviour of interfaces under cyclic loading is an additional area that has received only limited consideration to date. Finally, implementing these laws into FE models presents difficulties when large numbers of cycles are considered. Calculation times rapidly become excessive and uncontrolled divergence in the calculation process may arise.

SOLCYP team members are making progress in the following directions:

- improving constitutive laws for describing the behaviour of soils (Bagigli, 2011); and
- developing alternative methods to the cycle-by-cycle simulation technique, such as the time homogenisation method (Papon, 2010), or skipped cycles method (Cao et al., 2012).

10. Conclusion

The SOLCYP project is an ambitious research and development programme aimed at investigating the behaviour of piles under cyclic loading. Key aspects are being addressed either experimentally or numerically. The first results, some of which are presented at this conference, have been promising. The final objective is to develop guidelines for the design of pile foundations under cyclic loading, with special attention to novel structures such as wind turbines.

References

American Petroleum Institute (API) and International Organization for Standardization (ISO). (2011) ANSI/API Specification RP 2GEO. Geotechnical and Foundation Design Considerations for Offshore Structures. Washington, DC: API.

Andersen KH.(1988). Properties of soft clay under static and cyclic loading. *Proceedings of the International Conference on Engineering Problems of Regional Soils*. Beijing, China, 7–26.

American Society for Testing and Materials (ASTM). (2005). ASTM E 1049-85 Standard practices for cycle counting in fatigue analysis. West Conshohocken, PA: ASTM International.

Bagigli Y. (2011). Modélisation du comportement cyclique des sols et des interfaces sol-structure, Thèse, Ecole Centrale de Lyon.

Benzaria O, Le Kouby and Puech A. (2011). Experimental and numerical analysis of the cyclic axial response of a single pile. *Proc. 15th ECSMGE*, Athens.

Benzaria O, Le Kouby A and Puech A. (2012). Cyclic axial load-tests on driven and bored piles in overconsolidated clay. In: *Proc. 7th Offshore Site Investigation and Geotechnics: Integrated Geotechnologies – Present and Future.* London: Society for Underwater Technology (SUT).

BSH. (2007). Standard/Design of Offshore Wind Turbines. Hamburg: Federal Maritime and Hydrographic Agency.

BSH. (2011). Guidance for use of the BSH standard “Design of Offshore Wind Turbines”. Hamburg: Federal Maritime and Hydrographic Agency.

Cao J, Li Y, Tjok KM and Audibert JME. (2005). Validation of the use of the beam-column method for suction caisson design In: Gourvenec S and Cassidy M. (eds.). *Proc. Int. Symp. Frontiers in Offshore Geotechnics, ISFOG 2005.* London: Taylor and Francis.

Cao J, Mroueh H and Burlon S. (2012). Skipped cycles method for geotechnical structures under large number of cycle loads. In: *7th Int. Conf. on Offshore Site Investigations and Geotechnics: Integrated Geotechnologies – Present and Future.* London: SUT.

Cox WR, Reese LC and Gubbs BR. (1974). Field testing of laterally loaded piles in sand. OTC 2079. Proc. Offshore Technology Conference, Houston, USA.

Det Norske Veritas (DNV). (1992). Classification Note 30-4, Foundations. Olso: DNV.

DNV. (2011). DnV-OS-J101 Design of Offshore Wind Turbines Structures, DnV Offshore Standards. Olso: DNV.

Downing SD and Socie DF. (1982). Simple rainflow counting algorithms. *International Journal of Fatigue* **4**: 31-40.

European Committee For Standardization (CEN). (2005). *Eurocode7: Geotechnical design, Part 1: general rules*, NF EN 1997-1. Brussels: CEN.

Guefresh A. (2012) Pieux sous sollicitations cycliques axiales dans un massif de sable – Essais en centrifugeuse. Rapport interne SOLCYP.

ISO. (2003). ISO 19901-4 Petroleum and Natural Gas Industries, Specific requirements for offshore structures, Part 4: Geotechnical and Foundation Design Considerations. Geneva: ISO.

Jardine RJ and Standing JR. (2000). Pile load testing performed for HSE cyclic loading study at Dunkirk, France. 2 Vols. Offshore Technology Report OTO 2000 007. London: HSE.

Jardine RJ, Chow FC, Overy R and Standing JR. (2005). *ICP Design Methods for Driven Piles in Sands and Clays*. London: Thomas Telford.

Jeanjean P, Andersen KH and Kalsnes B. (1998). Soils Parameters for Design of Suction Caissons for Gulf of Mexico deepwater clays. OTC 8830. Proc. Offshore Technology Conference, Houston, USA.

Kaggwa WS, Booker JR and Carter JP. (1991). Residual Strains in Calcareous Sand due to Irregular Cyclic Loading. *Journal of Geotechnical Engineering* **117**: 201–218.

Karlsrud K and Haugen T. (1985). Behaviour of piles in clay under cyclic axial loading – results of field model tests. 4th International Conference on Behaviour of Offshore Structures, BOSS'85, Delft, pp. 589–600.

Karlsrud K and Nadim F. (1990). Axial pile capacity of offshore piles in clay, OTC 6245, Offshore Technology Conference, Houston, USA.

Khemakhem M. (2012) Etude expérimentale de la réponse aux charges laterales monotones et cycliques d'un pieu fore dans l'argile, *Thèse,* Ecole Centrale de Nantes, 314pp.

Khemakhem M, Chenaf N and Garnier J. (2012). Centrifuge modelling of piles in clay under cyclic lateral loads. In: *7th Int. Conf. on Offshore Site Investigations and Geotechnics: Integrated Geotechnologies – Present and Future*. London: SUT.

Kolk H, Baaijens AE and Vergobbi P. (2005) Results from axial load tests on pipe piles in very dense sands: the EURIPIDES JIP. In: Gourvenec S and Cassidy M. (eds.). *Proc. Int. Symp. Frontiers in Offshore Geotechnics, ISFOG 2005*. London: Taylor and Francis.

Lam IPO. (2009). Diameter Effects on p-y curves. Fountain Valley, CA: Earth Mechanics.

Lehane BM, Jardine RJ, Bond AJ and Frank R. (1993). Mechanisms of shaft friction in sand from instrumented pile tests. *Journal of Geotechnical and Geoenvironmental Engineering* **119**: 19–35.

Lin SS and Liao JC. (1999). Permanent strains of piles in sand due to cyclic lateral loads. *Journal of Geotechnical and Geoenvironmental Engineering* **125**: 798–802.

Matlock H. (1970). Correlations for design of laterally loaded piles in soft clay. OTC 1204. Proc. Offshore Technology Conference, Houston, Texas.

Papon A. (2010). Modélisation numérique du comportement des sols sous très grand nombre de cycles. Homogénéisation temporelle et identification des paramètres, Thèse, Ecole Centrale de Nantes, 152pp.

Poulos HG. (1988). Cyclic stability diagram for axially loaded piles. *Journal of Geotechnical Engineering Division* **114**: 877–895.

Poulos HG. (1989). SCARP Users' Manual. Centre for Geotechnical Research. Sydney: The University of Sydney, Australia.

Pra-ai S. and Boulon M., (2011). Direct shear on granular soil-structure interfaces involving a large number of cycles and preliminary interpretation, *Proceedings XVth ECSMGE*, Athens.

Puech A, Brucy F and Ma E. (1982). Tension pile design using self-boring pressuremeter test results. *The pressuremeter and its marine applications.* Paris: Editions Technip, 361–375.

Randolph M.F. (2003). RATZ Version 4-2: Load Transfer Analysis of Axially Loaded Piles.

Reese LC and Cox WR. (1975). Field testing and analysis of laterally loaded piles in stiff clay. OTC 2312. Proc. Offshore Technology Conference, Houston, USA.

Rimoy S, Jardine R, Silva M, Foray P, Tsuha C and Yang Z. (2012). Local and global behaviour of cyclically loaded instrumented model displacement piles in sand. In: *7th Int. Conf. on Offshore Site Investigations and Geotechnics: Integrated Geotechnologies – Present and Future*. London: SUT.

Tali B. (2011) Comportement de l'interface solstructure sous sollicitations cycliques. Application au calcul des fondations profondes, Thèse, Université Paris – Est, Navier-Cermes, 231pp.

Tsuha CHC, Foray PY, Jardine RJ, Yang ZX, Silva M and Rimoy SP. (2012). Behaviour of displacement piles in sand under cyclic axial loading. *Soils and Foundations* **52**. In press, available online 8 June 2012.

Yang ZX, Jardine RJ, Zhu BT, Foray P and Tsuha CHC. (2010). Sand grain crushing and interface shearing during displacement pile installation in sand. *Géotechnique* **60**: 469–482.