Oil & Gas, Europe - Timeline

1971

DESIGN AND INSTALLATION OF EKOFISK TANK IN NORTH SEA

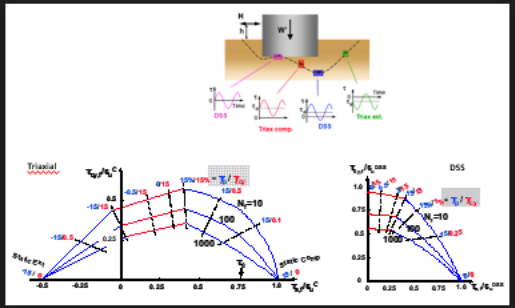
In 1971, NGI won its first contract associated with offshore work: the verification of the Ekofisk tank foundation for Det Norske Veritas. NGI gradually became involved in the design of offshore structures in the North Sea and abroad. NGI played a key role in the developement and acceptance of the gravity platforms made of concrete and with embedded foundation skirts, as a reliable alternative to piled structures in harsh environments. NGI was starting in a facsinating new field that would influence its entire future development.

1973 – 1978

INSTALLATION OF X CONDEEP PLATFORMS

Installation of X Condeep platforms with skirts ranging from ?m to 36?m in soils ranging from soft normally consolidated clays to very dense sand in ?m to 330m water.

A novel concrete GBS foundation concept with development started soon after the installation of the Ekofisk Tank.



1974

JIP ON CYCLIC LOADING OF SOILS

Large JIP with laboratory testing on clays in both triaxial and DSS tests.

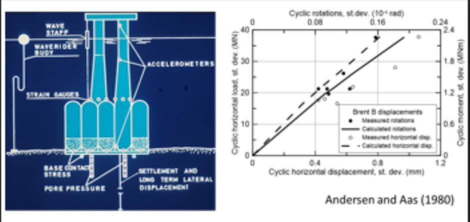
First establishment of cyclic contour diagrams that could be used for evaluation of cyclic behaviour of offshore structure. Pattern presented by Knut H. Andersen, NGI, that has later been further developed.

1978

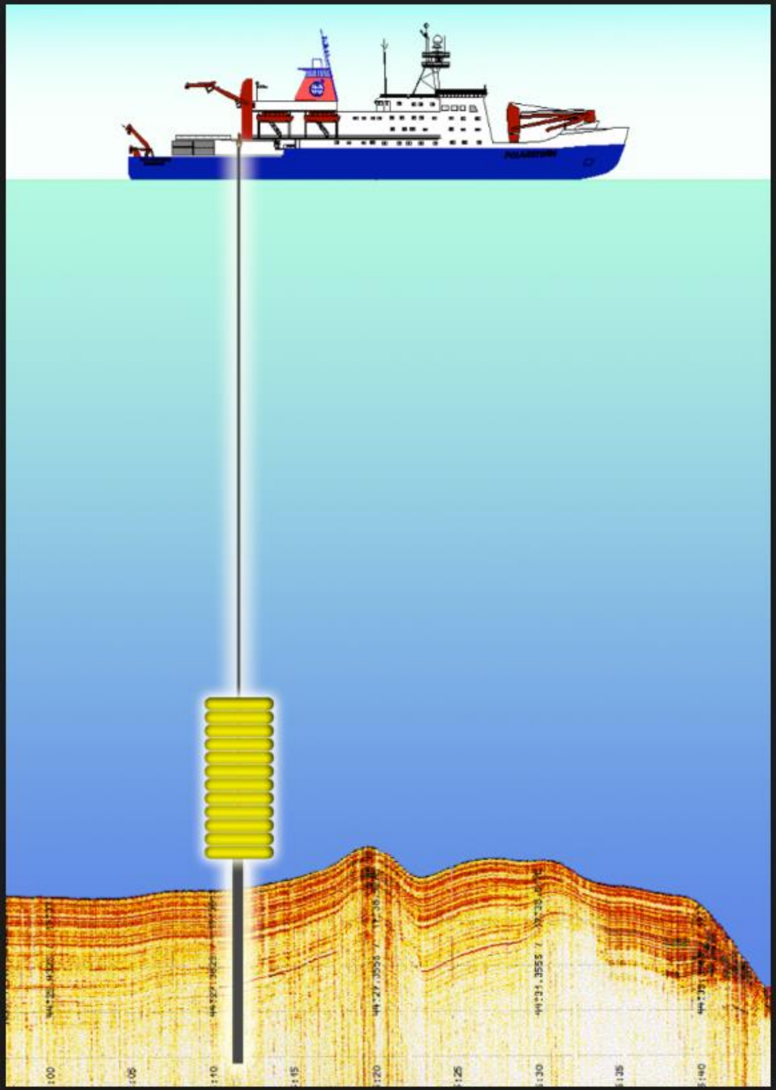
BRENT B INSTRUMENTATION PROJECT

Instrumentation, observations and interpretation of the Brent B Condeep GBS.

Observations during installation and several years of operation, incuding winter seasons with heavy storms provided valuable feedback on GBS prototype behaviour under realistic full scale conditions and data to validate and calibrate design methods.



Andersen and Aas (1980)



1983

FIRST OSIF (OFFSHORE SOIL INVESTIGATION FORUM)

The first Offshore Soil Investigation Forum was comprised of oil & gas companies, SI contractors and consultants. They met in Oslo to discuss issues of common interest including; standardization of equipment and procedures for in situ and sampling, contracts etc.

This was the first meeting of its kind and has since become an informal yearly event. The organization of the meeting has rotated between participants with some initiatives transferred to OSIG/SUT including Guideline for Pipeline soil investigations. There were no meetings in 2021 and 2022 due to COVID 19.

1985

GULLFAKS C PENETRATION TEST

The largest offshore soil penetration test ever undertaken was successfully carried out in 1985 in the Gullfaks Field, North Sea. At water depths of more than 200m - a large scale test structure successfully penetrated 22m into the seabed to importantly inform the design of the Gullfaks C fixed concrete platform which was installed in 1989.

The test showed that it was fully feasible to install deep skirts through clay and into a sand layer at 20m.

NORSOK STANDARD

G-001
Rev. 2, October 2004

Marine soil investigations

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Telephone: + 47 67 83 86 00
Fax: + 47 67 83 86 01
Email: petroleum@standard.no

1986
NORSOK STANDARD

NORSOK Standard for Marine Soil Investigation.

First International Standard covering all aspects of offshore soil investigation: planning, deployment, drilling, sampling, lab testing, in situ testing and reporting.

1993

SNORRE TENSION LEG PLATFORM ONSHORE MODEL TESTS

Large onshore 1 g field suction anchor model tests in soft clay.

The measured behaviour was in excellent agreement with Class A predictions and verified foundation design methods for suction anchors and TLPs under static and cyclic loading in clay. It provided confidence that suction anchors for anchoring of TLPs and other floating structures was a feasible concept.

HYDRAULIC FRACTURE AS A CRITERION FOR CONDUCTOR SETTING DEPTH IN CLAY

Knut H. Andersen   Norwegian Geotechnical Institute, Oslo, Norway

Tom A. Lunne   Norwegian Geotechnical Institute, Oslo, Norway

Colin G. Rawlings   Norwegian Geotechnical Institute, Oslo, Norway

Trond H. By   Norwegian Geotechnical Institute, Oslo, Norway

ABSTRACT

For offshore drilling, and in particular when drilling from fixed platforms in deep waters, the mud pressure will be high compared to the hydraulic fracture pressure (i.e. the formation strength) close to the seafloor. The first casing or the conductor will therefore have to be installed to a depth where the formation strength is sufficient to withstand the pressure from the drilling mud. Otherwise a hydraulic fracture will take place and the mud will flow into the formations.

The concequenses of a hydraulic fracture could be loss of circulation which will slow down the drilling. In cases where large quantities of mud are lost into the formations beneath the platform, this may even threaten the integrity of the foundation soils and create a safety problem. A conservative approach with too deep conductor setting depths will, on the other hand, lead to high unnecessary costs. Both for safety and economy it is therefore important to have sound criteria for the allowable mud pressure when drilling out below the first conductor.

This paper presents a rational approach to establish the maximum allowable drilling mud pressure in clay formations, and recommends use of partial safety coefficients which are dependent upon the consequences of hydraulic fracture occurring and the quality of the soil data. The highest quality data in this context is considered to be special in situ hydraulic fracture tests carried out as part of the soil investigation and special true triaxial laboratory tests which simulate the stress conditions in the soil adjacent to the borehole wall.

The soil properties from the laboratory tests are used as input to a new approach for calculating hydraulic fracture pressures. The new calculation approach considers two important factors which are generally not covered by theories found in the literature: non-linearity of the stress-strain properties of the soil and pore pressure changes in the soil due to changes in total normal stress and to shearing of the soil.

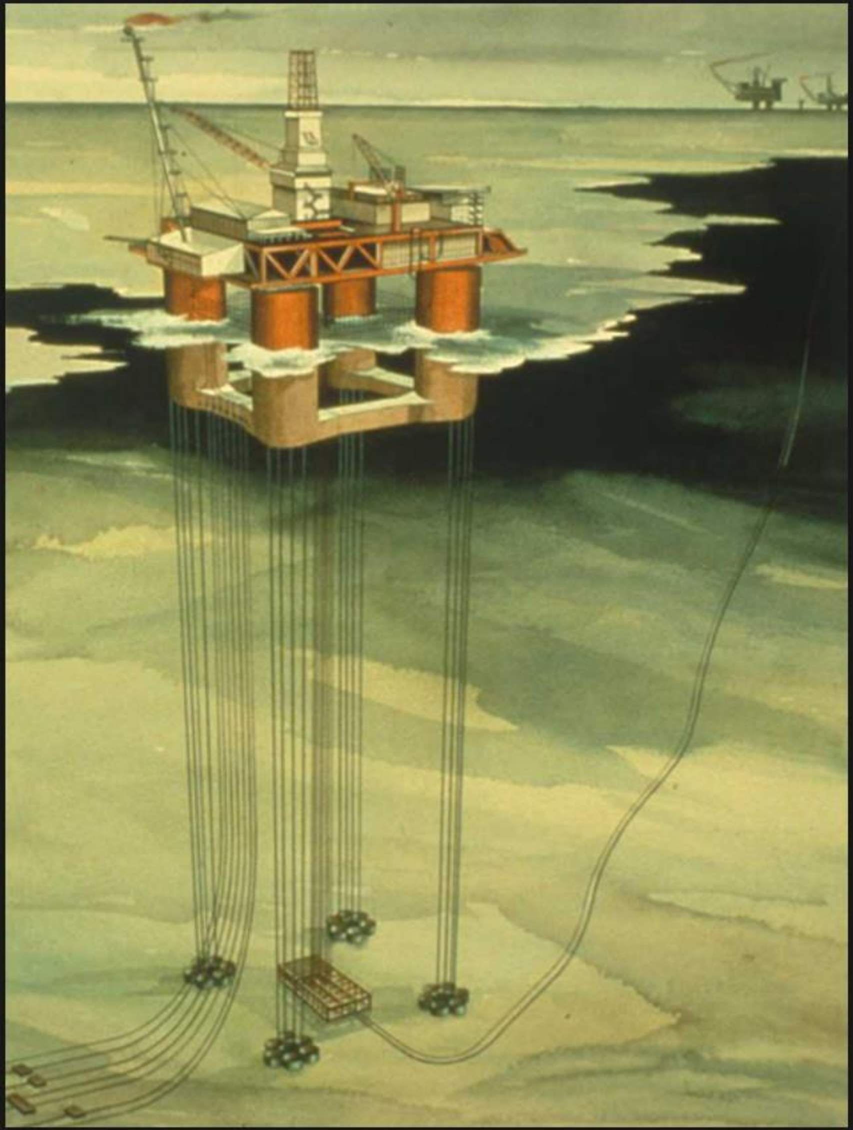
The proposed calculation approach has been verified against a series of laboratory model hydraulic fracture tests and in situ hydraulic fracture tests carried out at numerous offshore sites.

1993

JIP ON CONDUCTOR SETTING DEPTH IN CLAYS

A study to evaluate the existing method for conductor setting depth in clay. It was based on field and laboratory tests and analyses of all data from which a new method using SuDSS was developed.

Practical criteria for hydraulic fracture in sand was developed including a recommendation on partial factors.



1993

INSTALLATION OF SNORRE TLP PLATFORM

First TLP platform with suction anchor foundation.

OTC 7795

Geotechnical Experience from the Installation of the Europipe Jacket with Bucket Foundations

T. I. Tjelta, Statoil

This paper was presented at the 27th Annual OTC in Houston, Texas, U.S.A., 1–4 May 1995.

ABSTRACT

The Europipe jacket with bucket foundations replacing piles was installed in July 1995 in 70 metres water depth in the central part of the North Sea. The bucket foundations offer a new and economically attractive alternative to piled foundations and consist of circular mudmats with 6 metre deep skirts around the circumference, one under each jacket leg, Fig. 1. They have the ability to resist both tensile and compressive loads. Installation is provided by means of a suction system that enables the skirts to be fully penetrated into the sea bed.

The use of suction to install the Europipe bucket foundations is absolutely essential. The geotechnical aspects of this installation method are discussed in the paper and results from installation are provided.

INTRODUCTION

It is possible to use suction as an installation technique for suction piles, concrete skirt piles and model caissons (see Ref. 1) It is also possible to install steel structures without using piles as the foundation, e.g. the Maureen platform,
but never before the Europipe jacket had bucket foundations been used as the only permanent foundation with suction providing the primary foundation installation system. The need to penetrate steel skirts 6 m into very dense sand also goes beyond any experience previously obtained.

Due to the novel foundation method, the installation contractor was unwilling to accept responsibility for the skirt penetration operation. Consequently this operation was planned and carried out by Statoil personnel. This detailed planning process together with the actual recorded and observed installation results are briefly presented and discussed in this paper.

INSTALLATION ASPECTS

The installation of bucket foundations, (penetration of steel skirts into the seabottom) can be conveniently divided into three phases:

1. **Touch down and self weight penetration phase**: Jacket lowering from the point where the skirt tip is approximately 10 m above seabottom to where the skirts have penetrated under the jacket weight, i.e.touch down followed by the self weight penetration of the jacket. This penetration is uncontrolled compared to the following penetration phases.

2. **Ballast weight penetration**: The penetration of skirts into the seabottom

References and figures at end of paper

1994

EUROPIPE STEEL JACKET FOUNDATIONS

Successful installation of suction backet foundations in dense sand.

First example of bucket foundations being used as permanent foundations for a steel jacket structure, where suction was used as the primary installation system.

Documented example of caisson foundations in dense sand.

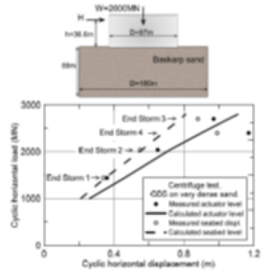


Figure 19.2 Comparison between calculated and measured displacements in centrifuge tests of a gravity platform on very dense sand (based on Andersen et al. 1994).

1994

GBS MODEL TESTS IN SAND

Execution of centrifuge model testing to support understanding of GBS performance in sand.

Example of high quality model tests, with Class A prediction.

Geotechnical and Geophysical Site Characterization – Huang & Mayne (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-46936-4

Effects of sample disturbance on consolidation behaviour of soft marine Norwegian clays

T. Lunne, T. Berre, K.H. Andersen, M. Sjursen & N. Mortensen
Norwegian Geotechnical Institute, Oslo, Norway

ABSTRACT: After many years of research the issue of sample disturbance is still very important as regards to determining reliable and representative soil parameters for soft clays. Parallel laboratory tests, including constant rate of strain oedometer tests (CRSC), have been carried out on high quality block samples and on standard piston tube samples from 4 deposits of Norwegian marine clays. The test results show significant effects of sample disturbance on a number of parameters interpreted from the CRSC tests: change in void ratio when the sample is consolidated back to the best estimate of *in situ* vertical effective stress, apparent preconsolidation stress, p'_c, constrained modulus, M, coefficient of consolidation, c_v and coefficient of permeability, k_v. Based on the test results a recommended test procedure for oedometer tests has been worked out, that includes some periods with constant vertical stress and re-load unload loops.

1 INTRODUCTION

A comprehensive study has been carried out at NGI on the effects of sample disturbance on measured parameters in oedometer, triaxial and direct simple shear tests (DSS) on samples obtained of soft Norwegian marine clays.

Comparison of parallel laboratory tests on high quality block samples and standard tube samples form the main basis for the evaluations in NGI's study.

The results of the study on strength and deformation behaviour as measured in triaxial and DSS tests were reported in detail by Lunne *et al.* (2006) and Berre *et al.* (2007).

This paper concentrates on the effects of sample disturbance on consolidation parameters as measured in constant rate of strain consolidation (CRSC) tests and incremental loading oedometer tests.

2 CLAYS TESTED

The four clays included in this paper were all deposited after the last glaciation about 10.000 years ago, and they are all in the Oslo and Trondheim areas. The Lierstranda and Onsøy sites have been investigated in much detail as described by Lunne *et al.* (2006).

The two other sites (Kvenild and Nykirke) have been investigated in connection with projects NGI have been involved in (Jensen, 2001 and Sandven *et al.*, 2004). Table 1 summarises the properties of the four clays. It should be noted that Nykirke and Kvenild are quick clays.

3 SAMPLE EQUIPMENT AND PROCEDURES

Table 2 gives a summary of key features of the samplers used and also shows at which sites the various samplers have been used.

3.1 *Sherbrooke block sampler*

The Sherbrooke block sampler was developed and tested at the University of Sherbrooke, Quebec, in the period 1975–1978 (Lefebvre and Poulin 1979). This special sampler allows the carving of a cylindrical block of diameter 250 mm and height 350 mm at desired depths from the surface.

NGI believes this sampler still gives the highest quality samples available for onshore practice.

3.2 *NGI 54 mm composite sampler*

This sampler was developed and designed by NGI at the end of the 1970's, and it is the most common sampler used in Norway (Andresen and Kolstad, 1979). The sampler is a composite piston sampler using plastic inner cylinders. The displacement method is used; wherein the sampler (with the piston in front of the sample tube) is pushed down to the desired sampling depth without pre-augering.

1995 – 1998

JIP ON EFFECT OF SAMPLE DISTURBANCE ON SOFT CLAY

Criteria developed for quantification of sample quality in terms of change in void ratio when a sample is consolidated back to same stresses it had in the field.

The criteria was adopted in ISO19901:8:14 on Marine soil investigation.

2002

VALHALL WATER INJECTION PLATFORM

Failure of jacket piles during installation - associated with pile tip collapse.

The failure provided improved industry understanding of this critical issue, with implications for installation and design.

2013 – 2016

PISA JIP

Pile Soil Analysis (PISA) Project - Improved design methods for laterally loaded piles.

Development of design methods for offshore wind monopile foundations in clay and sand seabed conditions, supported by field and numerical studies.

Houlsby, G. T. (2016). *Géotechnique* **66**, No. 10, 791–825 [http://dx.doi.org/10.1680/jgeot.15.RL.001]

Interactions in offshore foundation design

G. T. HOULSBY*

This paper presents some examples of design problems for offshore foundations, drawn from the jack-up industry and the wind turbine industry. The examples are chosen to illustrate some general points about foundation design, geotechnical engineering and its interaction with other disciplines. The first example is drawn from the assessment of the safety of installation of jack-up units (large mobile offshore drilling rigs). It illustrates how more rational approaches can be achieved through a deeper use of probabilistic methods in both the prediction of performance and the assessment of field observations. The second example also comes from jack-up practice, but has wider application too: it addresses the classical problem of the performance of foundations under combined loading, and how this can be understood in a simple theoretical and practical framework based on plasticity theory. The final example comes from the renewables sector, where the rapidly expanding offshore wind industry poses new foundation challenges for geotechnical engineers. Practical and economic foundation solutions are required if the UK is to meet its ambitious plans to exploit larger turbines in deeper waters. Both conventional (monopile) and novel solutions (suction caissons, screw piles) to the foundation problem are discussed. The paper also demonstrates how interactions with other disciplines can enrich geotechnical engineering, illustrated by specific practical examples from the author's experience.

KEYWORDS: clays; footings/foundations; model tests; offshore engineering; piles & piling; plasticity; sands; soil/structure interaction; statistical analysis

INTRODUCTION

The subject of this paper is the design of foundations for offshore structures. The structures of interest have in the past been mainly for the offshore oil and gas industry, but increasingly during the last decade the focus has shifted to the offshore renewables sector, especially offshore wind. No attempt is made here to present a detailed or comprehensive review of foundations for offshore structures; instead this paper presents a selection of topics that illustrate certain important themes, some with application throughout geotechnical engineering, not just offshore foundations.

The paper is divided into three main sections. The first two use examples from the design and analysis of jack-up units, which are mobile drilling rigs of enormous importance in the oil and gas industry. Part 1 addresses the prediction of the behaviour of a jack-up unit during installation at a particular site – an important consideration because each unit may be moved to different sites several times in a year. In this section a framework is presented in which the predictions, and the comparisons of performance with predictions, are made within a probabilistic framework. This leads to a clear conclusion that there are opportunities to improve geotechnical practice by a more sophisticated application of probability theory than is current.

Part 2 addresses the performance of jack-up units in service, and especially how their safety can be assured during extreme storm conditions. Emphasis is placed on the development of models of soil behaviour based on plasticity theory, effectively generalising the concept of bearing capacity to multi-axial loading. This approach provides a conceptual basis for jack-up behaviour, and is also used to develop detailed numerical models. The models developed also have application to onshore foundations subjected to combined loads.

Part 3 is devoted to the offshore renewables sector, examining the options available for offshore wind turbine foundations as they move to larger installations in deeper water. Both conventional (monopile) and less conventional (suction caisson and screw pile) approaches are discussed.

Although geotechnical engineering forms the core of this paper, the opportunity is taken to emphasise links with other disciplines. The 'interactions' in the title deliberately has a double meaning. First it represents geotechnical problems where the interactions between different forces are important, and each component of the problem cannot be treated in isolation. Second, there are problems where interactions with other disciplines are important for geotechnical engineers, as it is at these interfaces that the most challenging and interesting problems arise.

PART 1: INSTALLATION OF JACK-UP UNITS

A jack-up unit, Fig. 1, is a mobile rig mainly used for drilling either exploration or production wells, although it is also sometimes used for other purposes such as accommodation. The principal concern here is with the very large units used in the oil and gas industry. The large rigs almost always have three lattice-work legs, and very occasionally four. Typically the legs are up to 180 m long, the spacing between them is about 60 m, and large rigs can operate in up to about 120 m of water. A large jack-up has a mass of around 30 000 t. Much smaller units, of a rather different design, and with four or more legs, are used for inshore work in shallower waters.

The legs can each be moved up and down independently, usually by a rack-and-pinion system, Fig. 2, with multiple driving pinions on each leg. On the bottom of the legs are large, roughly circular footings which are called 'spudcans'. They usually have a shallow conical base, often with a

Manuscript received 22 December 2015; revised manuscript accepted 26 April 2016. Published online ahead of print 17 August 2016.
Discussion on this paper closes on 1 March 2017, for further details see p. ii.
* Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK.

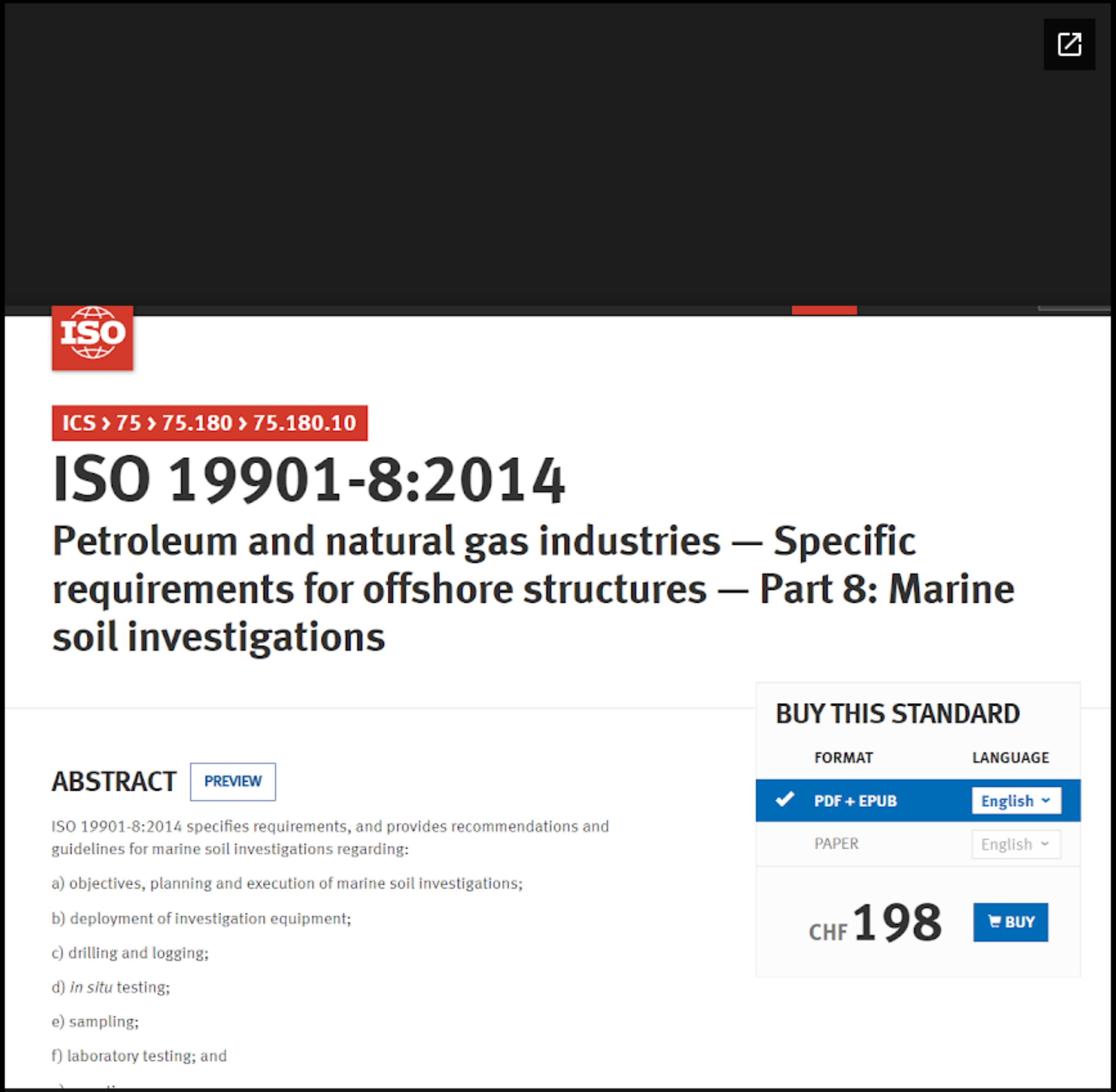
Σελίδα 1 / 35

2014

RANKINE LECTURE - GUY HOULSBY

Interactions in offshore foundations design.

The lecture covered several examples of design problems for offshore foundations from the jack up and the wind turbine industry.


ICS › 75 › 75.180 › 75.180.10

ISO 19901-8:2014

Petroleum and natural gas industries — Specific requirements for offshore structures — Part 8: Marine soil investigations

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PAPER	English

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ABSTRACT PREVIEW

ISO 19901-8:2014 specifies requirements, and provides recommendations and guidelines for marine soil investigations regarding:

a) objectives, planning and execution of marine soil investigations;

b) deployment of investigation equipment;

c) drilling and logging;

d) *in situ* testing;

e) sampling;

f) laboratory testing; and

2014

ISO STANDARD

ISO Standard for Marine Soil Investigation.

First edition of standard covering all aspects of offshore soil investigation: planning, deployment, drilling, sampling, lab testing, in situ testing and reporting.


Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 45 No.4 December 2014 ISSN 0046-5828

A FE Procedure for Foundation Design of Offshore Structures – Applied to Study a Potential OWT Monopile Foundation in the Korean Western Sea

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[1]Norwegian Geotechnical Institute, NGI, Oslo, Norway
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ABSTRACT: A finite element based calculation procedure that accounts for the effect of cyclic loading of soils under undrained conditions is presented. A material model called UDCAM that uses 3D strain contour diagrams from undrained cyclic and monotonic triaxial and DSS tests is used in the procedure. The model accounts for cyclic degradation by using the cyclic strain accumulation procedure developed at NGI in the seventies. The load history is idealized by a load composition containing load parcels with constant average and cyclic loads in each parcel. The applicability of the procedure is verified by back calculating a model test of a gravity base structure (GBS) in soft clay subjected to monotonic and cyclic loading. The procedure is then used to predict the behaviour of a monopile for a potential offshore wind turbine (OWT) in the Korean Western Sea. These results are compared with results obtained with traditional beam-spring analyses.

KEYWORDS: Offshore Engineering, Numerical modelling, Soil/structure interaction, Cyclic Loading, Clays, Monopiles, Wind Turbines

1. INTRODUCTION

Offshore wind turbine (OWT) structures are subjected to a combination of cyclic wind and wave loading. These loads together with the weight of the OWT and its equipment need to be carried by the soil without causing a foundation failure in the ultimate limit state (ULS) or unacceptable displacements and rotation in the serviceability limit state (SLS). In addition, the soil stiffness and damping will generally influence the dynamic behaviour of the OWT structure, including the natural frequencies and the dynamic amplification factor, and thus the fatigue limit state (FLS) of the structure.

Undrained cyclic loading of water saturated soil will generally reduce the shear stiffness and the undrained shear strength of the soil. NGI has during the last 30 years developed a framework to characterize and define the soil behaviour under cyclic loading (e.g. Andersen et al., 1988; Andersen, 2009), as well as calculation procedures (e.g. Andersen and Lauritzsen, 1988, Andersen and Hoeg, 1991, Andersen, 1991) based on this framework. These procedures have been verified by several model tests, e.g. Andersen et al. (1989 and 1993), Keaveny et al. (1994), and used in the design of a large number of offshore structures such as gravity base structures, e.g. Brent B, Troll A and Gullfaks C, tension leg platforms, e.g. Heidrun and Snorre, and suction anchors for mooring of floating structures all around the world (Andersen et al., 2005).

In finite element (FE) analyses, cyclic soil models that seem to work fine in time domain for some few regular cycles tend to accumulate errors with increasing number of cycles and more irregular load histories. When hundreds or thousands of cycles are applied, the accuracy of such models is questionable. In addition, such models still require significant computational time and cost.

In this paper a description of a FE based procedure for undrained cyclic accumulation is presented. The model, which is called UDCAM (Undrained Cyclic Accumulation Model), accounts for degradation under undrained cyclic loading using the strain accumulation principle developed at NGI (Andersen et al., 1976). Instead of analyzing the cyclic load history in the time domain (implicit method), it considers the behaviour during application of the loads in so-called load parcels of constant average and cyclic load amplitudes (explicit method). The model then finds the reduced cyclic stiffnesses and accumulated permanent strains as described in this paper. At large strains, the calculated stresses are limited by anisotropic undrained cyclic shear strength. This model is implemented into the commercial finite element code Plaxis 3D Foundation (Brinkgreve et al., 2007). It should be recognized that some other models also account for cyclic loading by an explicit method, e.g. as the high cyclic accumulation model for sand (Niemunis et al., 2005) and the degradation stiffness model also for sand (Achmus et al., 2009).

The applicability of the presented procedure is verified by back calculating a model test of a gravity base structure (GBS) in soft clay subjected to monotonic and cyclic loading (Dyvik et al., 1989). Then, the procedure is used to predict the behaviour of a monopile for a potential OWT in the Korean Western Sea. These results are compared with results obtained with traditional beam-spring analyses using p-y and t-z curves based on American Petroleum Institute (API, 2011). The model is applicable also for other foundation types such as gravity base structures and skirted foundations or caissons subjected to undrained cyclic loading.

2. CURRENT INDUSTRY PRACTICE

Current industry practice for monopile is to calculate capacity and displacements by semi empirical methods based on beam column models with the soil support represented by so called p-y and/or t-z springs. However, some special studies have been performed using the finite element method.

2.1 Beam column method with p-y and t-z springs

In semi empirical methods based on beam column models the soil is represented by uncoupled, non-linear soil springs along the pile (e.g. McClelland and Focht, 1958; API, 2011). In some formulations, the p-y curves include post-peak softening in order to account for effects of cyclic loading (Matlock, 1970; API, 2011). The semi empirical method has been used for analyses of piles for many years and is a familiar tool for many geotechnical engineers. However, the method has a number of limitations. It is based on empiricism from a limited amount of model tests on small piles. Therefore, it does not consider the severity of cyclic loading (e.g. variation in the cyclic load history) or that the cyclic behaviour depends on the soil type, other than grouping the soil into a few different soil types (soft clay, hard clay and sand). It does not account for the initial stiffness of the soil (dynamic stiffness) at small displacements or unloading/reloading cycles. It ignores coupling between the soil springs along the pile, which may be especially important for layered soils and short piles. It also ignores the coupling between horizontal and vertical soil springs. Further, it does not include independent ... resistance components at the pile interface

2014 – 2015
DEVELOPMENT OF ADVANCED FE CODES

Development of advanced FE codes with soil models that can handle cyclic shear strain and pore pressure accumulation and dissipation in the integration points as well as redistribution of average and cyclic stresses under variable external cyclic loads.

These advanced FE codes enabled more accurate prediction of strains and displacements during cyclic loading and accounted for stress redistribution and potential progressive failure during cyclic loading.

NGI

3rd ISSMGE McClelland Lecture

Cyclic soil parameters for offshore foundation design

Knut H. Andersen
Norwegian Geotechnical Institute

Cyclic soil parameters for offshore foundation design

Main goals

- Cyclic contour diagram framework
- Data base with contour diagrams and correlations of required parameters

NGI

Presentation

- When do we need cyclic soil parameters?
- What param

2015

MCCLELLAND LECTURE - KNUT H. ANDERSEN

Key lecture at the 3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG) 2015 hosted by NGI in Oslo, Norway.

First establishment of cyclic contour diagrams that could be used for evaluation of cyclic behaviour of offshore structure. Pattern presented by Knut H. Andersen, NGI, that has been further developed since.

Jardine, R. J. (2020). *Géotechnique* **70**, No. 1, 3–59 [https://doi.org/10.1680/jgeot.18.RL.001]

Geotechnics, energy and climate change: the 56th Rankine Lecture

RICHARD J. JARDINE*

Geotechnical engineering has matured sufficiently to contribute to resolving some of society's grand challenges. The 56th Rankine Lecture considered one of the most pressing global problems: maintaining vital energy supplies while also recognising, mitigating and reducing the climate consequences of fossil fuel consumption. This written version reports geotechnical research relating to these wide-ranging issues, considering paired topics within its three main parts and illustrating these with specific practical examples. Part 1 focuses on supporting offshore hydrocarbon production, considering advances in understanding and designing the driven piles that support most continental shelf platforms, before moving to the large underwater landslides that can affect deeper water developments. Part 2 describes investigations into the geotechnical impact of climate change in a permafrost region and a peatland study that contributes to alleviating flood risks exacerbated by climate change. Part 3 outlines research that is improving the economics of renewable offshore wind energy for multi-pile and monopile supported turbines. Integrating geology and rigorous analysis with advanced laboratory and field experiments is shown to be essential to resolving the complex geotechnical problems considered, as is careful full-scale checking and monitoring. Close cooperation with co-workers from industry and academia was central to the studies described and the contributions of many collaborators are emphasised. The concluding section identifies examples of significant questions from each of the six topic areas that remain to be resolved fully.

KEYWORDS: footings/foundations; landslides; piles & piling

GEOTECHNICS AND ENERGY

Geotechnics has developed over the last century into a discipline that engages thousands of professional specialists worldwide. The first two conferences of the International Society for Soil Mechanics and Foundation Engineering, held in 1936 and 1948, mark perhaps the two most significant events in the practical assimilation of the seminal contributions of Coulomb (1776), Rankine (1857), Prandtl (1920), Terzaghi (1925), Hvorslev (1937) and other early pioneers. Tremendous advances have followed since, many of which have been recorded in the 55 Rankine Lectures delivered before this contribution, ranging from critical laboratory experiments to rigorous theoretical investigations and from computer coding triumphs through to large-scale field studies. Research motives have ranged from pure curiosity through to a wish to address urgent industrial or societal questions; these researchers' combined efforts have created extensive bodies of new knowledge.

As geotechnics matures, ever greater resources appear necessary to achieve significant advances. Research teams are often encouraged to focus their efforts on the 'grand challenges' that are most critical to human societies and quality of life, as well as sustaining or improving the quality of our natural and built environments. Among the most pressing questions to resolve over the next decades are those related to energy production. Choosing this main theme reflects the seminal contributions in thermodynamics of Rankine (1850) that led, with his later publications, to lasting international recognition. For example, the process employed in steam-operated electricity generators is known widely as the 'Rankine cycle'.

Pasten & Santamarina (2012) present convincing evidence of the social benefits of increasing energy provision per capita, especially in the developing world. Collating data from the world's 22 most populous nations, they show that positive outcomes, including greater average life expectancy, longer schooling years and higher incomes correlate directly with the 5 to 10 kW/capita consumption range enjoyed by economically leading nations. Negative measures such as infant mortality rates fall greatly as energy consumption levels rise. Conservation measures and other factors are leading to energy use per capita reducing in some advanced nations (see e.g. World Bank, 2018). However, global demand is currently growing by 20% per decade as the world's less prosperous populations gradually achieve better living standards.

More than 85% of global energy production is derived currently from fossil fuels that produce large masses of carbon dioxide (CO_2) by-product according to Natural Resources Canada (NRCan, 2017). Maintaining or increasing production cannot be reconciled with the internationally acknowledged environmental need to cut greenhouse gas emissions drastically in the decades ahead. Each kWh of electricity generated from coal produces approximately 1 kg of carbon dioxide, depending on coal grade, while oil and natural gas fuel produce less, around 0·75 and 0·5 kg/kWh, respectively. Meeting the internationally agreed greenhouse gas targets calls for a rebalancing of energy production away from coal and towards gas and renewable sources. There remains intense international debate on how to achieve such changes without disrupting energy supplies, blocking economic growth or holding back developing nations.

Engineers from all disciplines are contributing to the world's 'grand challenge'. Geotechnical researchers are active in areas ranging from ground energy storage and production schemes

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2016

RANKIN LECTURE - RICHARD JARDINE

"Geotechnics and Energy"

Covered a range of topics relevant to offshore geotechnics (Part 1 considers design of driven piles supporting continental shelf platforms).