30 Mar 2001, 8:00 am - 8:45 am

Marine Geotechnics

Farrokh Nadim

Norwegian Geotechnical Institute, Norway

MARINE GEOTECHNICS

Farrokh Nadim
Norwegian Geotechnical Institute
P.O. Box 3960 Ullevaal Stadion, N-0806 Oslo, NORWAY

ABSTRACT

The paper makes a brief review of the state-of-the-art in marine geotechnics. The design problems for different offshore foundation types, from traditional piled and gravity base foundations to the new lightweight skirted foundation concepts, are described. Geotechnical breakthroughs have enabled new and daring constructions offshore and opened the way to cost-effective solutions. At the same time, the requirements and conditions imposed by the offshore industry also greatly contributed to an improved understanding of the behavior of soils under new loading conditions. The paper looks into the development of enhanced site investigations and soil characterization, model testing, improved design methods and new foundation solutions. The challenges facing the geotechnical engineering profession when moving into deeper waters and the steps needed to meet these challenges are outlined.

INTRODUCTION

This paper presents an overview of the major geotechnical issues in the offshore industry and the present day state-of-the-art. Geotechnical progress, in particular with respect to understanding and modeling of soil behavior under cyclic loading, has enabled the offshore industry to move towards increasingly optimum solutions. Perhaps these contributions do not receive today the recognition they deserve. On the other hand, the needs and requirements of the offshore industry have contributed significantly to the advancement of geotechnical knowledge and this should also be recognized.

Over the past three decades, geotechnical practice has greatly evolved and improved, at times with giant leaps, because of the needs of the offshore industry. The first section of the paper takes a brief look at the progress made in site investigations, testing for soil characterization and evaluation of soil models. This is followed by the description of the state-of-the-art in offshore foundation design method with emphasis on cyclic loading effects, development of new foundation solutions, and geotechnical challenges faced in dealing with geohazards in deep water.

SITE AND SOIL INVESTIGATIONS

For adequate design of foundations, soil parameters need to be determined through a combination of interpretation of the local geology, in situ testing and laboratory testing. The impetus of offshore work had led to rapid developments in both in situ and laboratory testing. Equipment, testing methods, methods of interpretation and parameter determination are some of the aspects that have greatly benefited from enhanced research and attention.

In Situ Testing

In particular, the developments around the piezocone penetration test and new sampling devices to be used at increasingly greater depths have been noteworthy (Kolk and Campbell, 1997; Lunne et al., 1997). Without these methods and the reliability they have gained, the design today would be much more conservative. The uncertainties surrounding soil profile and soil parameters would have been significantly larger. These improvements would probably not have been possible without the offshore industry supporting research and demanding improved results.

Laboratory Testing.

Laboratory testing techniques have greatly improved, and the way of setting up testing programs has become a rational, cost-benefit oriented process. The necessity of reproducing as closely as possible the in situ conditions and the stress path under extreme loading is common practice today. The effects of sampling disturbance, although not easy to quantify, are a factor routinely considered when assessing soil parameters. The problem has now renewed interest as samples are recovered from greater water depths.

It was paradoxical for geotechnical organizations to play a key role in the development of new and cheaper foundation solutions involving skirts and anchors. By making the small lightweight skirted foundations a dependable solution (Andersen and Jostad, 1999), the organizations automatically reduced the demand for in situ and laboratory testing. The volume of work has greatly decreased, but by doing so the geotechnical profession gained credibility for encouraging more optimum designs, and established a close, and necessary, link in the design of the foundation.

Needs. Development needs within in situ and laboratory site characterization include improved sampling and laboratory testing techniques, in particular if the sediments contain gas. Improved interpretation of in situ tests, including obtaining parameters directly from geophysical results needs also to be developed. One should be able to use correlations of geological and geophysical features to geotechnical properties and to improve mapping techniques of the subsurface.

The author finds an important need related to our degree of specialization. We need a more integrated approach to the solution of site characterization, with active interaction of geologists, geophysicists and geotechnical engineers. This interaction has been suggested before (Doyle, 1998; Nauroy et al., 1998; Lacasse and Lunne, 1998), but we are taking too much time in making this team work.

Exploration in deep water represents one of the "last frontiers" for the geotechnical engineer. In this harsh, often remote, environment, the interplay of geology, geophysics and geotechnics becomes even more necessary than before. This interplay cannot be overemphasized. Improved communication is required. The expertise is gained after long university studies and years of experience and is highly specialized, thus making dialogue with other expertise areas difficult. The offshore industry and the geotechnical profession would greatly benefit from an improved dialogue among geologists, geophysicists and geotechnical engineers. A good integration will lead to safer and more cost-effective designs.

Model Testing

Model tests are among the best geotechnical tools to document the mechanism of failure, the deformation pattern, the soundness of a design method and the reliability of a calculation model. For offshore design, where prototype testing is rare, model tests have proven to be an excellent tool to verify and calibrate calculation procedures. Model tests can be 1-g models in the laboratory or in situ, multi-g centrifuge tests or full scale model tests. Table 1 presents examples of the results of successful 1-g model tests run to in the laboratory and in the field to evaluate the calculation models for the analysis of gravity foundations and tension leg platforms (Andersen et al., 1988, Andersen et al, 1993). For the tests listed, the calculation of failure loads was done before the model tests were run, thus providing an unbiased calibration of the calculated values to the measured values in the model test.

Model tests should not be used to extrapolate the results from a small model to a prototype, but to verify the calculations made of the model with the same calculation model used for design of the prototype.

Table 1. Verification of calculated bearing capacities.

Structure	Type of loading	Ratio between calculated and measured failure loads
Gravity Foundation	Static failure, test 1	0.98-1.01
	Cyclic failure, test 2	0.99-1.15
	Cyclic failure, test 3	1.16-1.17
	Cyclic failure, test 4	1.06-1.23
Tension leg platform	Static failure, test 1	1.00
	Cyclic failure, test 2	1.05
	Cyclic failure, test 3	1.06
	Cyclic failure, test 4	1.01

Model tests are expensive, and need to be carefully planned and run. They enable however to reduce considerably the uncertainty in a calculation model. Model tests are generally run to evaluate specific mechanisms of failure, and it is essential to use geometries and loads relevant for the offshore conditions.

Centrifuge testing is a complementary tool to do model test. In his thorough overview of the method, Murff (1996) argues that the centrifuge is an under-exploited capability for the geotechnical profession. The tests need also to be run under relevant conditions and with the proper care. The centrifuge technology is founded on sound principles. The approach has both advantages and drawbacks compared to 1-g model tests. On the one hand, centrifuge tests are probably the best approach to model sands under partly or fully drained conditions. Drawbacks include high costs, simplified soil profile, miniature instrumentation, time scale and drainage in clays. Some of these problems also exist for 1-g model tests, at times to a lesser degree. For example, 1-g models are generally larger than centrifuge models, and the tests can be run in the field on actual soil profiles. In large projects, both approaches should be considered and the one with best return value should be used.

Needs. One of the important needs in offshore geotechnical engineering is relevant model tests of high quality on which to calibrate design procedures. Gravity structures and skirted foundations and anchors in clays are so far well documented with model tests. Tests also exist for such foundations in sand, although not to the same extent as for clays.

For jack-up and piled structures, the documentation has not come as far. Pile load tests with dimensions and loads relevant offshore should be given priority. The extrapolation done today from small pile load tests to loads and dimensions 10 to 100 times greater is far too uncertain (Lacasse and Nadim, 1996). The results of the EURIPIDES prototype-size pile load tests in dense sand, run in the mid-90s, should become available after year 2000.

FOUNDATION DESIGN

The foundation of a typical offshore structure is exposed to a combination of permanent static loads due to gravity and buoyancy, pseudo-static loads due to currents and wind, and dynamic (cyclic) loads due to wave action. Dynamic loads may also be induced by earthquake, wind, or iceberg impact. The foundation design aspects include evaluation of bearing capacity, cyclic displacements, equivalent soil spring stiffnesses for use in dynamic structural analyses, soil stresses against the structure, and settlements due to cyclic loads.

The following section describes the modeling of cyclic soil response as practiced today in the design of shallow offshore foundations. Piled foundations and jack-up structures are addressed later in the paper.

Modeling of cyclic soil response – Shallow foundations

Concepts from the theory of elasticity may often prove satisfactory for practical design of foundations exposed to monotonic loading and/or very low amplitude vibration. This is found adequate although soils undergo irrecoverable deformations even at very low strain levels, and the directions of strain increments do not in general coincide with the directions of stress increments as assumed in the isotropic elasticity theory.

For situations with repetitive loading-unloading-reloading, cyclic strains as well as accumulation of permanent (irrecoverable, plastic) strains occur, and it is sometimes more important to be able to predict the latter than the former. By definition, the theory of elasticity alone, even if applied in non-linear incremental form, cannot provide estimates of these permanent deformations. One may resort to either plasticity theory or a numerical analysis utilizing experimental results from laboratory tests on soil samples exposed to approximately the same static and cyclic combinations as corresponding representative elements experience in the field. Practical design of offshore foundations is almost exclusively based on the latter approach.

The stress conditions in the soil beneath a structure subjected to cyclic loading could be quite complex. A simplified picture of the shear stresses in a few typical elements along a potential failure surface underneath a gravity structure is shown on Fig. 1.

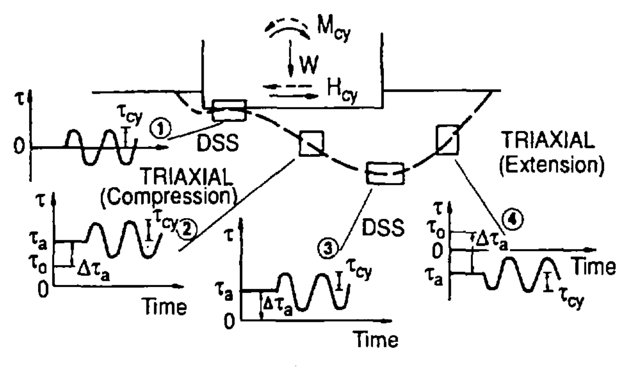


Fig. 1. Simplified stress conditions for some elements along a potential failure surface (Andersen, 1991).

The elements follow various stress paths and they are subjected to various combinations of average shear stresses τ_a, and cyclic shear stresses τ_{cy}. Herein, τ denotes the shear stress on the horizontal plane in the direct simple shear (DSS) test and on the 45° plane in the triaxial test. The average stress is cause by the initial shear stress in the soil prior to platform installation τ_0, and the additional static shear stress due to the weight of the structure. The cyclic shear stress is caused by the cyclic loads. In a storm, the wave height and period vary continuously from one wave to another and the cyclic shear stress will also vary from cycle to cycle.

To determine the soil properties needed in the foundation design analyses, it is necessary to perform laboratory tests where the stress conditions for the various soil elements are followed as closely as possible.

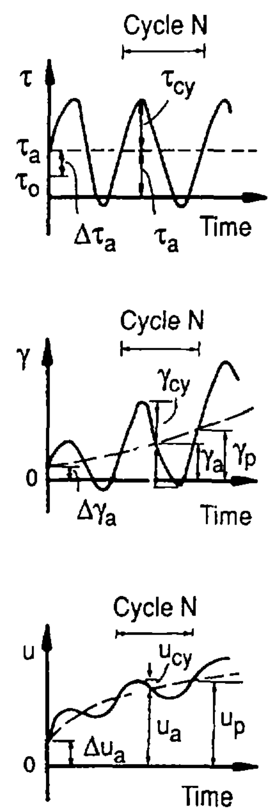


Fig. 2. Shear stress, shear strain, and pore pressure during undrained cyclic loading (Andersen, 1991).

The behavior of a soil element subjected to a combination of static and cyclic loads under undrained conditions (relevant for foundations on clay) is shown schematically on Fig. 2. When the static shear stress is increased by $\Delta\tau_a$ from τ_0 to τ_a, the soil will experience a pore pressure change Δu_a. The repeated cyclic shear stresses will cause a pore pressure development with cyclic and average components u_{cy} and u_a, which both increase with number of cycles. The pore pressure at the end of the cycle is called the "permanent pore pressure" u_p.

The shear strain varies in much the same manner as the pore pressure. When the shear stress is increased by $\Delta\tau_a$, the shear strain increases by $\Delta\gamma_a$. The cyclic shear stress causes a shear strain development with cyclic and average components which both increase with number of cycles.

The following soil parameters are needed to calculate the cyclic and permanent displacements under combined static and cyclic loading:

- Relationship between cyclic shear stresses and cyclic shear strains.
- Relationship between average shear stresses and average shear strains.
- Permanent pore pressure generated by cyclic loading.
- Post-cyclic recompression modulus.

Andersen and his co-workers have developed and refined a procedure for design of shallow offshore foundations on clay where these parameters are established from cyclic triaxial and DSS laboratory tests consolidated to the in situ effective stresses (Andersen, 1991). The procedure is based on the assumption that the foundation soil is undrained during the design storm. It aims at predicting the cyclic and average foundation displacements under the largest wave and at discrete instances during the storm, rather than following the foundation response throughout the design storm. Since the cyclic behavior depends on both cyclic and average shear stresses and type of loading, in this procedure the cyclic shear strain, average shear strain, and permanent or average pore pressures are plotted as functions of average and cyclic shear stresses. Examples for Drammen clay are presented on Figs 3, 4, 5 and 6. The shear stresses are normalized with respect to the reference static undrained shear strength for the relevant mode of shearing and with respect to the effective vertical consolidation stress.

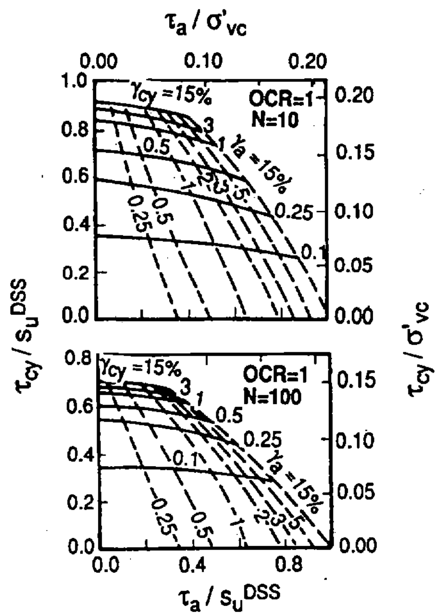


Fig. 3. Average and cyclic shear strains after 10 and 100 cycles in DSS tests on Drammen clay with OCR = 1 (Andersen et. al, 1988).

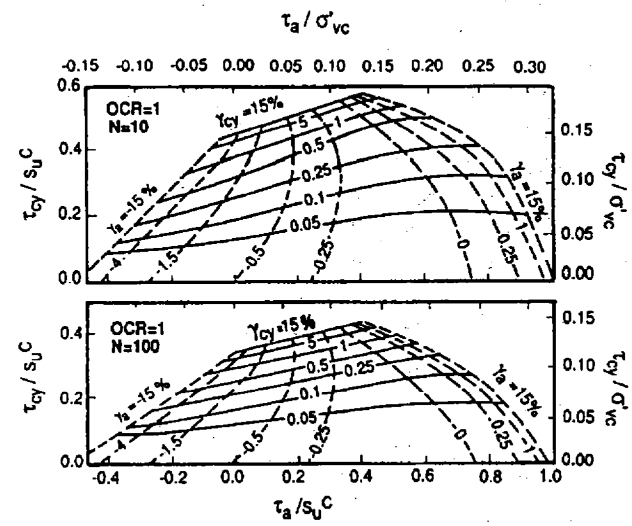


Fig. 4. Average and cyclic shear strains after 10 and 100 cycles in triaxial tests on Drammen clay with OCR = 1 (Andersen et. al, 1988).

In the strain contour networks shown on Figs 3 and 4, the solid curves represent the cyclic shear strain and the dashed curves represent the average shear strain. The strain contours for γ_{cy} = 15% and γ_a = 15% give the outer bounds in the diagrams. These strain levels are very large and may be defined as failure conditions. The term "cyclic shear strength" is defined as the sum of the ordinate τ_{cy} and the abscissa τ_a for points on the bounding strain contours. It is this cyclic shear strength which is used in the bearing capacity calculations for suction anchors and foundations of offshore gravity structures on clay (Andersen and Lauritzsen, 1988).

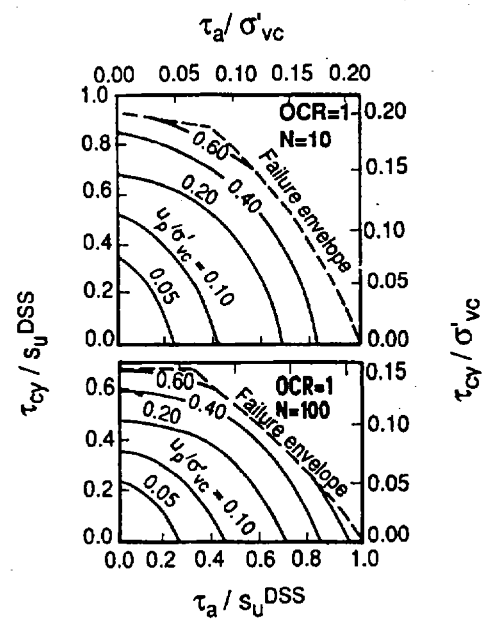


Fig. 5. Average pore pressure after 10 and 100 cycles in DSS tests on Drammen clay with OCR = 1 (Andersen et. al, 1988).

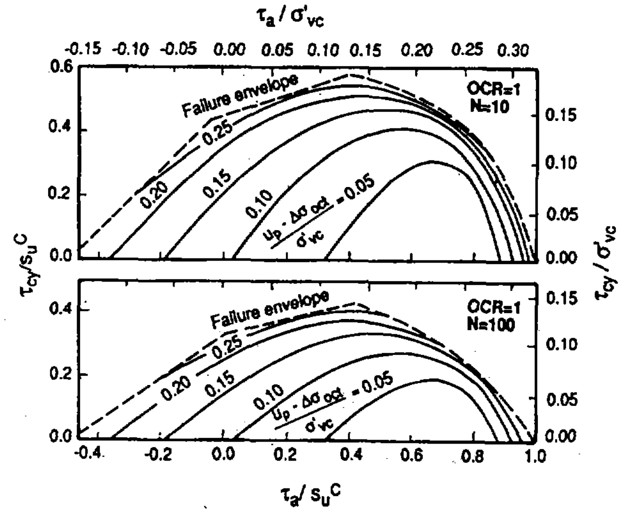


Fig. 6. Average pore pressure after 10 and 100 cycles in triaxial tests on Drammen clay with OCR = 1 (Andersen et. al, 1988).

Diagrams for Drammen clay with an overconsolidation ratio (OCR) of 4 and some other soils are presented in Andersen et al. (1988).

Analysis of response of sand foundations under cyclic loading is more complicated because the soil can no longer be assumed to remain undrained throughout the design storm. To predict the cyclic and average foundation displacements, it is essential to evaluate the pore pressure generation and dissipation during the storm. Andersen et al. (1994) describe an extension of the procedure developed for foundation design on clay to sand. The basic assumption is that pore pressure generation and dissipation occur simultaneously during the storm, but the soil is essentially undrained during a single load cycle. The pore pressure change in the sand is caused by the pore pressure build-up generated by cyclic loading, the cyclic pore pressure due to dilatancy, and cyclic changes in the octahedral effective stress. The reader is referred to Andersen et al. (1994) for details.

Modeling of waves in the design storm. The diagrams on Figs 3 and 4 give the cyclic shear strengths for elements where the shear stresses are constant during the cyclic load history. In a storm, however, τ_{cy} will vary from cycle to cycle. The equivalent number of cycles of the maximum shear stress, N_{eqv} that gives the same effect as the actual cyclic load history must therefore be determined. Procedures to determine N_{eqv} are presented by Andersen (1991). For clays (i.e. undrained conditions) N_{eqv} may be computed by keeping track of the cyclic shear strain during the cyclic load history. This 'strain accumulation' procedure is described by Andersen (1991). For sands, N_{eqv} may be computed by accumulating the permanent pore pressure generated during the cyclic load history (Andersen, 1991). The reason for using the accumulated pore pressure for sands is that drainage is likely to occur during the design storm in sands. To account for the drainage, it is necessary to keep track of the pore pressure in the computations. Drainage will have a positive effect in the sense that some of the permanent excess pore pressures generated by cyclic loading may dissipate during the storm. Cyclic loading accompanied by dissipation of permanent pore pressures ('precycling') may also change the structure of the sand and increase the resistance to excess pore pressure generation during subsequent cyclic loading. On the other hand, one needs to be cautious about relying upon the beneficial effect from reduced pore pressures which may develop in dense dilating sand deposits during individual cycles, since these cyclic pore pressures may also dissipate.

The irregular loading in a storm is taken into account by keeping track of the development of the permanent pore pressure during the cyclic load history. The pore pressure accumulation calculation is performed using a pore pressure contour diagram established from cyclic stress-controlled laboratory tests. The dissipation of the permanent pore pressure, due to both drainage towards free drainage boundaries and redistribution, may be determined by finite element analysis or, for idealized situations, by closed-form solutions.

In addition to the drainage and redistribution of the permanent pore pressure during the storm, the pore pressure variations within individual cycles may also be influenced by drainage and redistribution. For dense sands which tend to dilate during shear, this may mean that a part of the pore pressure reduction that prevents the sand from developing large shear strains may be lost. The cyclic shear strength may then be less than with fully undrained conditions. The redistribution of the pore pressure within individual cycles may be determined by finite element analyses or from closed-form solutions.

In principle, the cyclic shear strength could also be computed for clays by accumulating the permanent pore pressure. In practice, however, laboratory pore pressure measurements are more difficult to perform with good accuracy in clays than in sands. Since drainage will not take place in clays, it is, therefore, preferable to use the shear strain to determine the cyclic shear strength for clays. For situations where the cyclic shear strength and the cyclic shear moduli under undrained conditions are of primary interest, the shear strain will also be a more direct parameter than the pore pressure.

Design of shallow foundations for calcareous sediments requires special considerations. Two key features of this type of sediment are:

- spatial variability in effective particle size and degree of cementation, even at similar depths in adjacent boreholes;
- high angularity of individual particles, leading to relatively high void ratios and high compressibility by comparison with terrigenous soils; this characteristic also leads to increased susceptibility to volume collapse under the action of cyclic loading, but can lead to dilation under monotonic loading, over an extensive strain range.

The spatial variability has important consequences for shallow foundation design, particularly for skirted rafts or caissons, since cemented inclusions may impede penetration of the skirts.

Stratigraphies where low strength material underlies stronger layers may lead to punch-through type of failures, or to large settlements. Randolph and Erbrich (1999) discuss the geotechnical design issues for shallow foundations on calcareous sediments.

Jack-up structures

Mobile jack-up rigs, although extensively used, face far greater risks than other engineering structures. A characteristic of all mobile offshore structures is that they face far greater risks than do most other engineering structures (Poulos, 1988). Accident rate for jack-up rigs averaged 2.6% of the fleet annually between 1955 and 1980. In a risk analysis of jack-up rigs, Sharples et al. (1989) summarized the causes for jack-up rig mishaps for the structures surveyed over a 10-year period. As many as 50 of the 226 accidents were associated with "soils". Punch-through, failure due to wave loading and scour were the dominant causes.

Jack-up rigs are typically supported by three or four legs with a conical footing called spud can beneath each leg. The bearing capacity of a jack-up spud can foundation is strongly dependent on the installation procedure for the unit. The typical installation procedure for spud cans is described by Schotman and Efthymiou (1989). The main feature of installation is vertical preloading of the jack-up. The foundation reaction during preloading on any one leg must be greater than the vertical reactions rising from gravity loads and 100% of the design environmental loads.

As shown on Figs. 7 and 8, evaluation of the bearing capacity of a spud can foundation with shallow penetration is similar to other shallow embedded footings. However, the failure mechanism for a spud can foundation with deep penetration is more complicated.

Much of the recent work on behavior jack-up foundations is focused on the evaluation of effects of partial rotational fixity of the spud cans and the resulting local overturning moment on the footing. In many marginal offshore fields, jack-ups are being

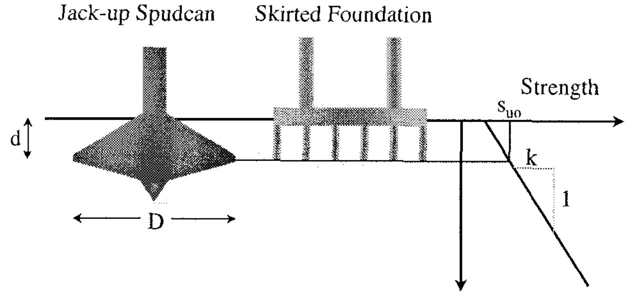


Fig. 7 Typical embedded offshore foundations (Randolph, 1998a).

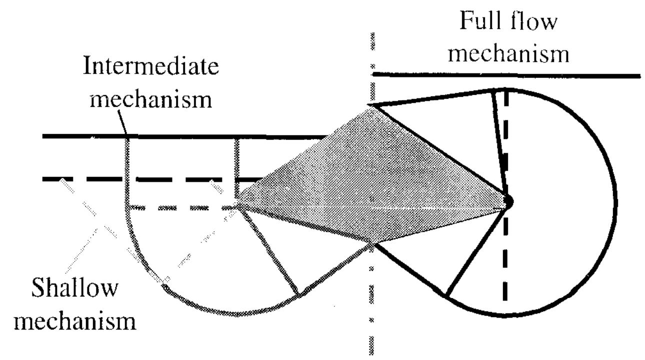


Fig. 8 Failure mechanisms around spudcan (Randolph, 1998a).

used as permanent installations for several years and exposed to severe winter storms. The evaluations of the cyclic loading history on each of the spud can footings required a sophisticated dynamic response analysis of the structure. The foundation boundary conditions have a major influence on the dynamic characteristics and dynamic response of the jack-up, which in turn govern the loads on the spud cans. An illustrative example of the evaluation of dynamic response of a jack-up in deep water (about 100 m) and storm-induced loads on the different footings of the jack-up is provided in DNV and NGI (1996). In some situations, the spud cans are equipped with skirts and are designed as bucket foundations or suction anchors. These foundation types are discussed later in the paper.

Because of the frequent foundation problems, a number of studies were initiated in the early 90's to improve the design procedures. The reader is referred to the following references: Schotman (1989), Jostad et al, (1994), Joint Industry Jack-up Forum (1997), Randolph (1998a), Nadim and Lacasse (1992), Murff et al. (1991).

Needs. The most pressing needs in the foundation design for jack-up structures are improved methods for evaluation of foundation-structure interaction and stream-lined procedures for evaluation of dynamic response of the jack-up during the design storm. The strongly non-linear foundation response makes the latter very difficult. Better models for load-displacement response of spud cans under cyclic loading on sands are also needed.

Pile Design

Pile design has come a long way since the early days of the Gulf of Mexico. A landmark OTC paper in 1993 summarized the evolution of offshore pile practice (Pelletier et al., 1993). For clays especially, there is confidence in the API RP2A recommended practice, even if the method is based on empiricism and model tests with dimensions and loads far away from the actual offshore conditions. New methods have emerged for clays and sands (Karlsrud and Nadim, 1990; Kolk and van der Velde, 1996; Jardine and Chow, 1996), and is would be worthwhile to evaluate these on the same basis as the earlier analysis methods.

The trend in the design of pile-supported offshore structures is to move away from large pile groups to a single pile under each leg. This removes much of the inherent redundancy in the foundation and requires a more accurate prediction of the pile response, particularly under the cyclic wave loading.

Models for predicting the cyclic performance of piles must take into account both load- and displacement-controlled loading, and must satisfy compatibility in terms of both cyclic and average stresses and displacements. For this purpose the strain contour network diagrams described earlier are well suited.

For a driven pile the static and cyclic pile-soil interface friction is modelled well by direct simple shear tests on remolded, reconsolidated soil when effective stresses at onset of loading are properly considered. The soil-pile interaction is numerically modelled by non-linear 't-z' springs (Fig. 9), and the cyclic and permanent soil strains are defined through a strain contour network like that in Fig. 10. The network of shear stresses and strains is transformed to a network of spring forces (t) and displacements (z) by numerical integration of shear strains over the radial thickness of the soil affected by the soil-pile interaction (Karlsrud and Nadim, 1990).

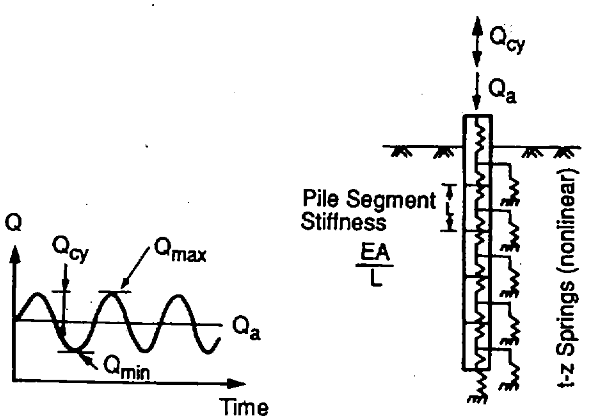


Fig. 9. The numerical soil-pile model with 't-z' springs.

The cyclic loading is described as a train of load parcels at the pile top. An average load, a cyclic load amplitude and number of cycles, define each load parcel. Since the soil elements along the pile experience different cyclic load histories, the response of each element is followed independently.

Figure 11 shows a comparison between the measured and computed response for one of the tension pile tests carried out by NGI in an overconsolidated clay deposit (Karlsrud and Haugen, 1984). It may be noted that even though the permanent pile top displacement (pull-out) increased rapidly after about 100 load cycles, the magnitude of the cyclic displacements (δ_{cy}) stayed fairly constant.

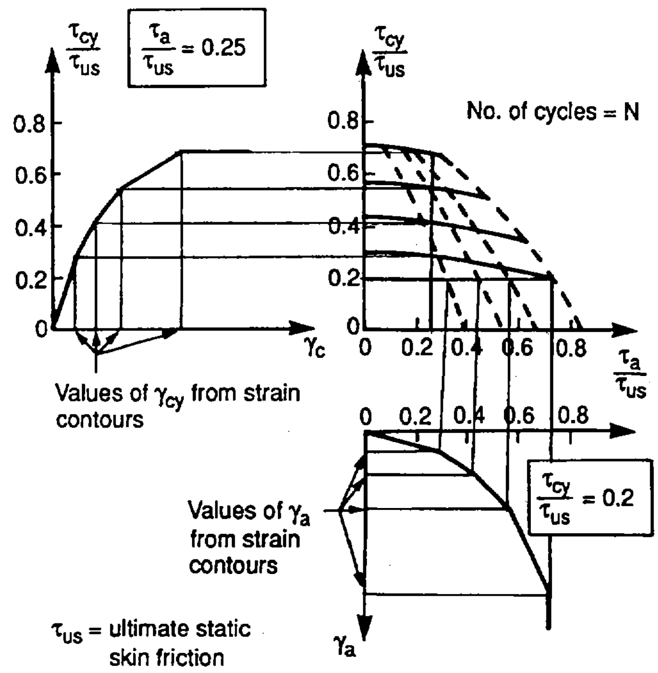


Fig. 10. Construction of stress-strain curves from strain contour network for a given number of cycles.

Although the computational model in this case overestimated the number of load cycles before significant pull-out displacements occurred, the model certainly captured the essential features of the response.

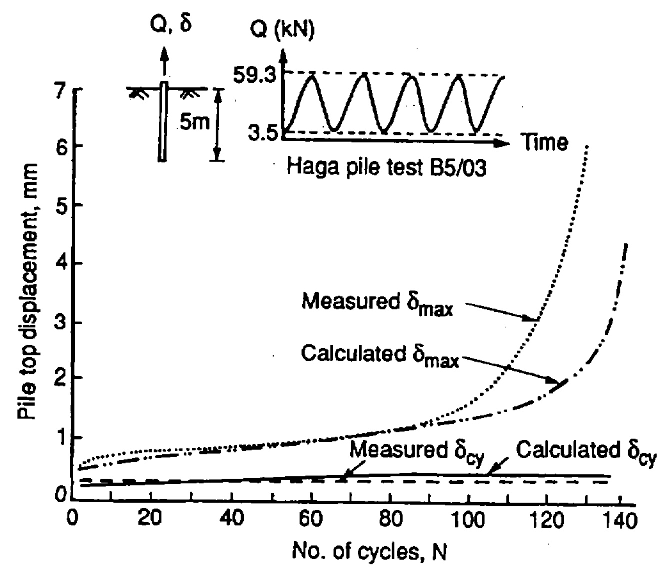


Fig. 11. Calculated and measured test pile response in clay (Karlsrud and Nadim, 1990).

The numerical model used for the predictions on Fig. 11 is a research tool. A simplified, commercial version of the model is now used extensively for the design of pile-supported structures on the Norwegian Continental Shelf. The program is called PAX2 and is described by Nadim and Dahlberg (1996).

The computer program RATZ developed by Randolph (1989) is another software that is used for predicting the axial response of a pile under cyclic loading. RATZ is also based on the 't-z' model for soil-pile interaction, but in contrast to PAX2, it tries to model the pile response through every cycle of a design storm.

Needs. Although many feel that pile resistance and pile design is a mature issue and that there is no reason to support further research, there remain important uncertainty areas. Coring and plugging of piles in sands, skin friction distribution and degradation along a pile in sand, relationship between dynamic and static resistance to driving in clays, and enhanced use of observations during pile driving are some of the main topics. Strain-softening, loading rate and cyclic loading are not well understood when trying to obtain the actual field capacity.

The design of gravity structures and skirted foundations use "more advanced" methods than piled foundations. Yet there are over 6000 offshore piled structures around the world, and they have existed much longer. Understanding better the components of basic pile behavior and adopting "rational" and more "refined" analytical methods for pile are necessary. The latest API RP2A guidelines encourage the designer to use all research advances available to them.

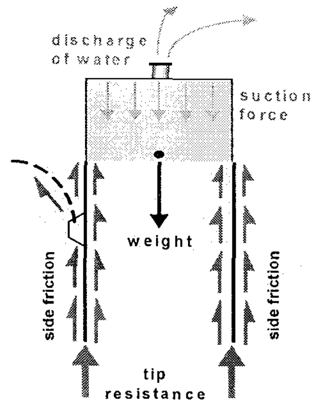
As mentioned earlier, pile load tests with dimensions and loads relevant offshore should be given priority. The industry and academia are still awaiting the publication of the results of EUROPIDIS field tests. In the meantime, the field tests carried out by Prof. Jardine of Imperial College at Dunkirk have clearly demonstrated the importance of cyclic loading on the pile capacity in silica sands (Martland, 2000).

SKIRTED FOUNDATIONS AND ANCHORS

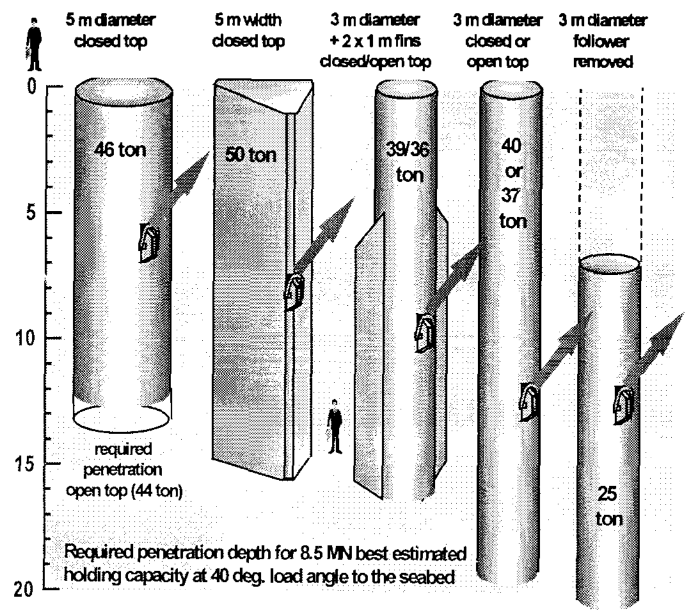
Skirted foundations and anchors have now become competitive alternatives to other foundation solutions. One of the reasons for the success of skirted foundations is that they offer important cost savings. The savings are related to fabrication, offshore installation (equipment and time), ease of accurate positioning, simple geotechnical and structural designs, and re-usability of the structure. Skirted foundations can be used in most soil types and for both fixed and floating platforms, including floaters, TLP's, steel jackets, jack-up rigs, subsea systems and other protection structures (Andersen and Jostad, 1999). Figure 12 explains the principles of the suction installation and holding capacity of skirted foundations and anchors. Figure 13 illustrates the failure modes for skirted foundations.

Some main reasons for the success of skirted foundations and anchors are that they give potential for:

- Significant cost savings compared to more traditional foundations and anchors. Skirted foundations and anchors may be cheaper to fabricate, need less expensive installation equipment, can be installed by controlled and simple marine operations, and require shorter offshore installation time.



(a) Penetration of skirted foundation



(b) Holding capacity for different designs

Fig. 12 Principles of skirted foundations and anchors (Guttormsen, 1998)

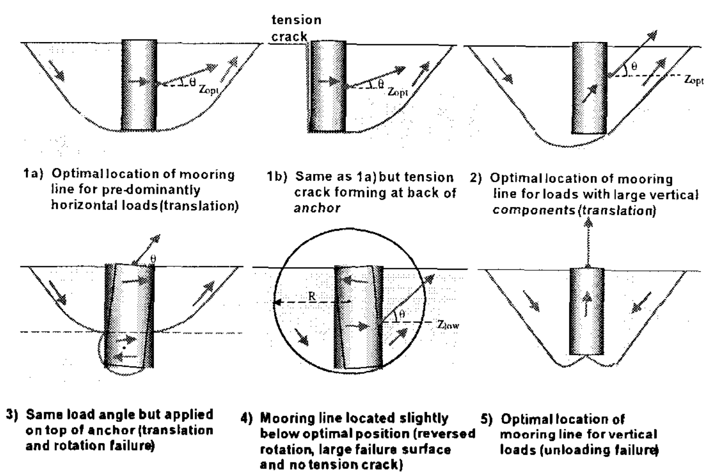


Fig. 13 Failure modes for a skirted foundation.

- Shorter anchor lines and accurate positioning of anchor. Skirted anchors have significant uplift load capacity, high positioning accuracy, and require no drag-in operation or proof loading. This reduces interference with mooring systems of other structures and with other platforms. It also makes them well suited for fiber rope applications.
- Removal and reuse. Relocatable structures can be used at more than one site and may make marginal fields profitable. Removal of the structure also provides a clean site after exploitation and accommodates environmental concerns.

The following geotechnical aspects have to be analyzed for skirted foundations and anchors:

- Penetration and removal
- Capacity
- Displacements (consolidation, cyclic displacements, permanent displacements due to cyclic loads)
- Soil spring stiffnesses
- Soil reactions or soil structure interaction analyses for structural design

Displacements are needed for jackets and TLP anchors, but may not be required for anchors for floaters, as these may not be sensitive to displacements. Soil spring stiffnesses are mainly needed for load distribution analyses for jackets. The structural design has to be done for the underpressure needed to penetrate the skirts and for the stresses during loading.

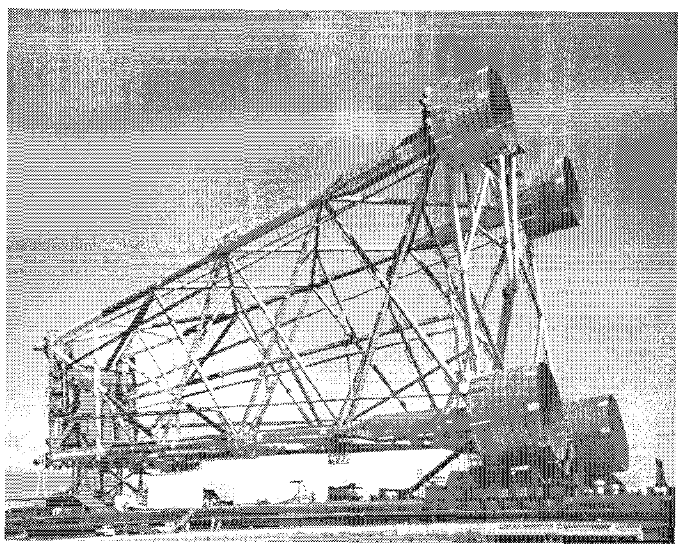


Fig. 14 The North Sea Draupner jacket with skirted foundations (Photo by Statoil).

The reader is referred to the papers by Andersen and Jostad (1999) and Randoph (1998b) for a detailed discussion of these topics.

Figures 14 and 15 show the skirted anchor foundations for two platforms in the North Sea. The skirted foundation concept has now been developed for applications other than supporting offshore platforms, e.g. for support of near-shore submarine pipelines (Sparrevik, 1998). The foundation works well in the presence of uneven seabed and unstable slopes.

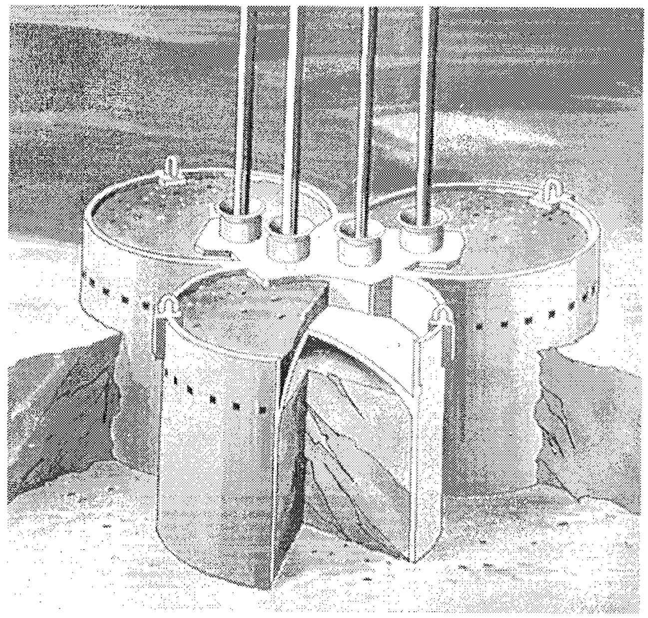


Fig. 15 Multi-cell skirted anchor for the Snorre TLP

Needs. The important geotechnical issues for skirted foundations that need further studies are the interaction between the structure and the soil, in particular the effects of plastic yielding of the structure on the holding capacity, and feasibility of relying on permanent suction for resisting capacity in the operation phase.

The holding capacity of a suction anchor in stiff clays is significantly reduced if a tension crack develops behind the anchor. No satisfactory procedures exist today for evaluating whether or not a tension crack would develop for a given situation. Improved methods for assessing this problem are urgently needed.

RISK ANALYSIS

The offshore industry has been at the forefront in applying reliability-based analysis to assist in decision-making, This has contributed to the documentation of case studies where reliability concepts have been used.

The usefulness of the approach is illustrated with the case study of an offshore structure where conventional and probabilistic analyses of its pile foundation were done at two times. First in 1975 before platform installation, when limited information and limited methods of interpretation of the soil data were available. Second in 1993, after a re-interpretation of the available data using the geotechnical improvements done in the interim, additional laboratory tests, a re-analysis of the loads, and an analysis of the installation records. The structure is a steel jacket installed in 110 m of water in the North Sea. The jacket rests on four pile groups, one at each corner. Each pile group consists of six piles. The piles in the groups are 60" diameter tubulars, with wall thickness of 3 and 2.5". The soil profile consists of mainly stiff to hard clay layers, with thinner layers of dense sand in between.

The profiles used in the analysis originally showed wide variability in the soil strength, with considerably higher shear strength below 20 m. No laboratory tests, other than strength index tests, were run to quantify the soil parameters, and sampling disturbance added to the scatter in the results. During pile installation, records were made of the blow count during driving. These records were used 20 years later to adjust the soil profile, especially the depth of the stronger bearing sand layers. New samples were also taken and triaxial tests were run. The new evaluation indicated less variability in the strength than before. The axial pile capacity was calculated with the API RP2A recommended practice. The requirement was a factor of safety of 1.50 under extreme loading and 2.0 under operation loading. The uncertainty analyses used the first-order reliability method, where each of the parameters in the calculation and the calculation model were taken as random variables, with mean and standard deviation. The results of the analyses are given in Table 2 and Fig. 16.

Table 2. Pile capacity analyses of most loaded pile under extreme loading (Lacasse and Nadim, 1994).

Analysis	**Factor of safety FS**	**Probability of failure P_f^***
1975, before pile driving	1.73	0.020
1993, new data	1.39	0.008

* P_f = area beneath curve where FS is less then 1 (Fig. 16)

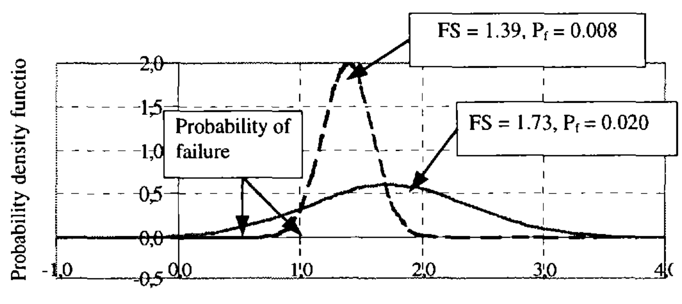


Fig. 16 Safety factor and probability of failure for most loaded pile.

The newer deterministic analysis gave a safety factor (FS) of 1.39, which is below the requirement of 1.50. However, the newer information reduced the uncertainty in both soil and load parameters. The pile with a safety factor of 1.39 has significantly lower failure probability (P_f) that the pile which had a safety factor of 1.73 twenty years earlier.

Taking into account the uncertainties showed that the pile, although with lower safety factor, had higher safety margin than the pile with a much higher safety factor, as perceived at the time of pile driving. The lower uncertainty in the parameters led to a reduction in the probability of failure by a factor of 2.5. Factor of safety is therefore not a sufficient indicator of safety margin because the uncertainties in the analysis parameters affect probability of failure. The uncertainties do not intervene in the conventional calculation of safety factor. The essential component of the probability of failure estimate was geotechnical expertise. Experience and engineering judgement was also needed. The most important contribution of uncertainty-based concepts to geotechnical engineering is increasing awareness of the uncertainties and of their consequences. The methods used to evaluate uncertainty, probability of failure and risk level are tools, just like any other calculation model or computer program. Reliability and risk approaches are therefore a complement to the conventional analyses.

Needs. The risk approach has the following major needs:

- reducing model uncertainty by obtaining and analyzing performance data of high quality
- quantifying acceptable risk level
- sensitivity analyses to identify the most significant parameters in an analysis
- convincing the designer to view the value-added in uncertainty-based analyses

Establishing the basis for acceptable risk criteria is difficult and controversial. Society requires increasingly that analyses be done to determine the risk imposed on the public.

DEEP WATER

Oil and gas exploitation at greater and greater water depths has been the focus over the last years. Although the technology for drilling and production developed separately, the evolutions follow similar curves (Veldman and Lagers, 1997). Because of ever increasing activities in the deeper waters, the geotechnical techniques and methods needed to be adapted to ever-greater depths rapidly. In less than 20 years, Shell Oil's deepwater milestones in the Gulf of Mexico have gone from depths of 300 m to 1650 m (Warren, 1997). One of the newer foundation solutions with important applications in deepwater are skirted foundations and anchors (Andersen and Jostad, 1999).

Geohazards are a major issue in deep water, mainly because the nature, extent and effects of geohazards are not well known. Geohazards include for example, submarine slides, gas hydrates and free gas, over-pressured sand zones, and very soft, brittle soils such as oozes. These need to be carefully evaluated before field development can start. An important issue is the detrimental effect they can have on the capacity of a foundation or anchoring system. Here too, the integrated evaluation by geologists, geophysicists and geotechnicians is essential.

Deepwater issues are relevant worldwide. Slope instability is probably one of the most important issues. For example for the

Storegga slide area in the Møre and Vøring basin areas offshore Norway, the following features were identified for slope instability assessment (Bryn et al., 1998): slide scars and slide sediments, diapirism, gas hydrates and free gas, seabed grooves, gas leakage and slide areas, fracture zones and earthquakes.

Slide scars and slide sediments were observed in the area, as well as mounds with steep slopes. The Storegga slide scar may indicate progressive backsliding combined with creep, but it is not known if these processes are active today. Diapirs were also identified in several areas. The cause of the diapirs and the driving forces are not fully understood, but they may be susceptible to sliding. Gas hydrates and free gas were believed to be present because of reflections and bright spots on reflectors. Fluid or gas escape features were also observed. On the Storegga slide, several seabed grooves and zones of vertical disruption were identified on the seismic data and the bathymetry. The seabed revealed pockmarks probably indicative of gas leakage. The groove features may have gas-loaded sediments. It is not known if the grooves are a result of an active process or if they are a documentation of a previous event that has since stabilized. Several signs of gas leakage were observed in the Storegga slide area. Upward gas leakage is expected to have a destabilizing effect.

The present knowledge, as exemplified by the Møre and Vøring basins, is not sufficient to draw firm conclusions on the instability of the area. Extensive research on geohazards, in particular on slope instability and effects of gas on soil response, is currently being performed. The work involves geologists, geophysicists and geotechnical engineers. The aspects considered are local and regional geology, site investigation methods, slope instability, consequences of instability, exploration drilling problems, and monitoring. For slope instability, triggering agents, mechanisms of failure, soil parameters, laboratory and in situ testing methods, calculation procedures and back-calculation of documented submarine slides are being studied.

The problems related to geohazards have inspired development of new soil models to understand the response of deep water marine clays to external loads such as earthquakes (Pestana et al., 2000). However, streamlined procedures to evaluate the risks associated with slope instability have not yet been developed. Ideally a slope instability study would include the following components:

- Investigation of observed slide areas, dating of sliding event and mapping of active faults or other activities
- Correlation of seismic, geotechnical and geological data to explain observed features
- Mapping of possible triggering mechanism(s) (earthquake, current, scour/erosion, fluid gas escape, shallow gas, gas hydrates, wave pressures, ...)
- Influence of geohazards on slope stability/instability
- Slope stability calculations accounting for the observed geology and risk due to geohazards

CONCLUSIONS

The needs of the offshore industry have been a major driving force in the advancement of geotechnical profession, in particular with respect to understanding and modeling of soil response under cyclic loading.

Major advances in the state-of-the-art are expected in the coming years in the following areas: (1) effects of geohazards, including submarine slope instability, (2) integration of geological, geophysical and geotechnical data, (3) follow-up of field instrumentation and performance observations programs, and (4) novel foundation and anchoring concepts.

Geotechnical engineers need to communicate better with the related fields of geology, geophysics, structural engineering, and hydrodynamics. Much has changed since the early days where foundation design was an extrapolation of land-based methods and experience with piers and jetties. Today, the geotechnical design of piers and jetties and other structures on land can greatly improve because of the geotechnical developments made offshore.

The geotechnical offshore research and industry is highly professional, taking pride in building on new ideas and on advancing technology. This makes marine geotechnology a fascinating field to work in.

ACKNOWLEDGEMENTS

The author is indebted to his NGI colleagues, Dr. Suzanne Lacasse and Mr. Knut Andersen, and Prof. Mark Randolph of University of Western Australia for their input to this manuscript.

REFERENCES

Andersen, K.H. [1991]. "Foundation design of offshore gravity structures", Chapter 4 *in "Cyclic Loading of Soils. From Theory to Design"*, Edited by M.P. O'Reilly and S.F. Brown, Publ. by Blackie and Son Ltd., Glasgow and London.

Andersen, K.H., A. Kleven and D. Heien [1988]. "Cyclic soil data for design of gravity structures", J of Geotech. Engrg., ASCE, Vol. 114, No. 5, pp. 517-539.

Andersen, K.H. and R. Lauritzsen [1988]. "Bearing capacity for foundation with cyclic loads", J. of Geotech. Engrg., ASCE, Vol. 114, No. 5, pp. 540-555 (1988)

Andersen, K.H., Lauritzsen, R., Dyvik, R. and Aas, P.M. [1988]. "Cyclic Bearing Capacity Analysis for Gravity Platforms; Calculation Procedure, Verification by Model Tests, and Application for the Gullfaks C Platform", Proc. Intern. Conf. BOSS'88 Trondheim, Norway. Vol. 1, pp. 311-325.

Andersen, K.H., Dyvik, R., Schøeder, K., Hansteen, O.E. and Bysveen, S. [1993]. "Field Tests og Anchors in Clay. Predictions and Interpretation", Journ. Geotech. Engg ASCE, 1993, Vol. 113, No. 10, pp. 1532-1549.

Andersen, K.H., Allard, M.A., and Hermstad, J. [1994]. "Centrifuge model tests of a gravity platform on very dense sand; II: Interpretation", 7th International Conference on Behavior of Offshore Structures, BOSS'94, Cambridge, USA, Proc., Vol. 1, pp 255-282.

Andersen, K.H. and Jostad H.P [1999]."Foundation Design of Skirted Foundations and Anchors in Clay", OTC Paper 10824, 31st Annual OTC, OTC'99, Houston.

Bryn, P., Østmo, S.R., Lien, R., Berg, K. and Tjelta, T.I. [1998]. "Slope Stability in the Deep Water Areas Off Mid Norway", OTC Paper 8640, *30th Annual OTC, OTC'98*, Houston.

Det Norske Veritas and Norwegian Geotechnical Institute [1996]. "Guidelines for offshore structural reliability analysis – Examples for jack-ups", DNV report No. 95-0072, February.

Doyle, E. [1998]. "The Integration of Deepwater Geohazard Evaluation and Geotechnical Studies", OTC Paper 8590, 30th Annual OTC, OTC'98, Houston, pp. 112-118.

Guttormsen, T.R. [1998]. "Anchors in Combination with Taut-Leg Mooring Systems. The Alternatives", Technical Developments in Moorings and Anchors for Deep and Ultra-Deep Water Fields, Aberdeen, 12-13 Oct..

Jardine, R.J. and Chow, F.C. [1996]. "New Design Methods for Offshore Piles", MTD Publication 96/103.

Joint Industry Jack-up Forum [1997]. "Recommended practice for site specific assessment of mobile jack-up units", Rev. 1, May.

Jostad, H.P., Nadim, F., and Andersen, K.H. [1994]. "A computational model for fixity of spud cans on stiff clay", Proc., 7th Int. Conf. on Behaviour of Offshore Structures, BOSS'94, MIT, Cambridge, USA, 12-15 July.

Karlsrud, K. and Haugen, T. [1984]. "Cyclic loading of piles and pile anchors – Field model tests, Phase II", Norwegian Geotechnical Institute report 40018-11, June.

Karlsrud, K. and Nadim, F. [1990]. "Axial capacity of offshore piles in clay", *22nd Annual OTC,* OTC'90, Houston, Texas.

Kolk, H. and van der Velde, E. [1996]. "A Reliable Method to Determine Friction Capacityof Piles Driven into Clays", OTC Paper 7993, *28th Annual OTC,* OTC'96 Houston, Proc. pp. 337–346.

Kolk, H.J. and Campbell K.J. [1997]. "Significant Developments in Offshore Geosciences", 8th Int. Conf. BOSS '97, Vol.1, pp. 3-40.

Lacasse, S, Goulois, A., Robberstad, L. Andersen, E. and Boisard, P. [1991]. "The Foundation of the Frigg CDP1 Gravity Platform: A Case Study", OTC Paper 6512, 23rd Annual OTC, OTC'91, Houston, pp. 125-131.

Lacasse, S. and Nadim, F. [1994]. "Reliability issues and future challenges in geotechnical engineering for offshore structures", Proc., 7th Int. Conf. on BOSS, BOSS'94, MIT, Cambridge, Mass., USA, 12-15 July.

Lacasse, S. and Nadim, F. [1996]. "Model Uncertainty in Pile Axial Capacity Calculations", OTC Paper 7996, 28th Annual OTC, OTC'96, Houston, Proc. pp. 369–380.

Lacasse, S. and Lunne, T. [1998]. "Geological and Geotechnical Challenges at Deepwater Sites", 8th IAEG Conf., Vancouver, 20-24 Sept.

Lunne, T., Robertson, P.K. and Powell, J.J.M. [1997]. "Cone Penetration Testing in Geotechnical Practice", Blackie, London.

Martland, R. [2000]. "Research shows importance of cyclic loads on piled offshore structures", Offshore Research, Issue No. 128, May, Web address: www.orf.co.uk.

Murff, J.D. [1996]. "The Geotechnical Centrifuge in Offshore Engineering", OTC Paper 8265, 28th Annual OTC, OTC'96, Houston, pp. 675-689.

Murff, J.D., Hamilton, J.M., Dean, E.T.R., James, R.G., Kusakabe, O., and Schofield, A.N. [1991]. "Centrifuge testing of foundation behaviour using full jack-up rig models", Exxon Production Research Company & A.N. Schofield and Associates.

Nadim, F. and Lacasse, S. [1992]. "Probabilistic Bearing Capacity Analysis of Jack-Up Structures", *Can. Geot. Journ.*, V. 29,, No. 4, pp. 580-588.

Nadim, F., and Dahlberg, R. [1996]. "Numerical modelling of cyclic pile capacity in clay", *28th Annual OTC,* OTC'96, Houston,Texas, USA, 6-9 May, Proc. Paper 7994.

Nauroy, J.F., Dubois, J.C., Colliat, J.L. Kervadec, J.P. and Meunier, J. [1998]. "The GEOSIS Method for Integrating VHR Seisimic and Geotechnical Data in Offshore Site Investigations", SUT Conf. Offshore Site Investigation and Foundation Behaviour – New Frontiers, Sept.

Pelletier, J.H., Murff, J.D. and Young, A.G. [1993]. "Historical Development and Assessment of the API Design Method for Axially Loaded Piles", OTC Paper 7157, *25th Annual OTC,* OTC'93, Houston, Proc. pp. 253–282

Pestana, J.M., Biscontin, G., Nadim, F., and Andersen, K.H. [2000]. "Modeling cyclic behavior of lightly overconsolidated clays in simple shear", Submitted for publication in Soil Dynamics and Earthquake Engineering.

Poulos, H.G. [1988]. "Marine Geotechnics", Unwin Hyman Ltd., London, U.K.

Randolph, M.F. [1989]. "RATZ – Load transfer analysis of axially loaded piles", User's manual for modified version for Woodside Offshore Petroleum, October.

Randolph, M.F. [1998a]. "Modelling of offshore foundations – Part I: Bearing capacity", E.H. Davis Memorial Lecture 1997, The University of Western Australia, Nedlands, Australia.

Randolph, M.F. [1998b]. "Modelling of offshore foundations – Part II: Anchoring systems", E.H. Davis Memorial Lecture 1997, The University of Western Australia, Nedlands, Australia.

Randolph, M.F., and Erbrich, C. [1999]. "Design of shallow foundations for calcareous sediments", 2nd Int. Conf. On Engineering for calcareous sediments, Bahrain, Ed. Al-Shafei. Balkema Rotterdam, ISBN 90 5809 037X.

Schotman, G.J.M. [1989]. "The effects of displacement on the stability of jack-up spud can foundations", OTC Paper 6026, *21st Annual OTC,* OTC'89, Houston, USA.

Schotman, G.J.M., and Efthymiou, M. [1989]. "Aspects of the stability of jack-up spud-can foundations", *2nd Intern. Conf. Jack-Up Drilling Platform, Design, Construction and Operation,* Elsevier, London, UK, pp.245-269.

Sharples, B.P.M., Trickey, J.C. and Bennet, W.T [1989]. "Risk Analysis of Jack-Up Rigs," *2nd Intern. Conf. Jack-Up Drilling Platform, Design, Construction and Operation,* Elsevier, London, UK, pp.101-123.

Sparrevik, P.M. [1998]. "Suction Anchors – A Versatile Foundation Concept Finding its Place in the Offshore Market", *OMAE'98 Conf.*, Lisbon, Portugal.

Veldman, H. and Lagers, G. [1997]. *"50 Years Offshore",* Foundation for Offshore Studies, Delft, 1997.

Warren, T.N.: [1997]. "Offshore – the future deepens", *8th Int. Conf. BOSS'97*, Delft, The Netherlands, separate preprint.