Risk implications in site characterisation and analysis for offshore engineering and design

Prepared by **WS Atkins Consultants Ltd**
for the Health and Safety Executive 2004

RESEARCH REPORT 286

Risk implications in site characterisation and analysis for offshore engineering and design

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The aim of this project is to provide an overview of the advances and risks faced within the offshore geotechnical industry in the UK, through the views of key figures within the industry. The principal elements required to manage and mitigate these risks within offshore geotechnical engineering are generally considered by industry to be as follows:

- An integrated approach to site investigations
- The development of terrain models combining engineering geology, geophysics and geotechnics
- Quality assurance systems
- Risk assessment and mitigations assessments to be carried out at project commencement and re-assessed at each key stage throughout the life of the project
- Open and clear communication between all stakeholders
- The requirement for suitably qualified and experienced personnel (SQEP) – engineers, geologists, geophysicists, drillers, for example, to be fully engaged in project development

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

HSE BOOKS

First published 2004

ISBN 0 7176 2924 4

ACKNOWLEDGEMENTS

This study was carried out by WS Atkins Consultants Limited, Epsom UK under contract to the Health and Safety Executive, at the request of Mr. Roland Martland, Specialist Inspector with the Offshore Safety Division. Mr. John Arthur of Top-Hole Site Studies Limited contributed the sections on geophysical investigation methods.

The contributions made by various experts in the offshore engineering field, through interviews and their responses to questionnaires, form a very important part of this study. We would like to express our thanks to them for these valuable contributions.

CONTENTS

List of Tables

List of Figures

LIST OF ABBREVIATIONS

ALARP	'as low as reasonably practicable'
AISC	American Institute of Steel Construction
API	American Petroleum Institute
FEA	Finite Element Analysis
FPSO	Floating Production, Storage & Offloading facility
GBS	(concrete) Gravity Base Structure
HSE	Health and Safety Executive
ISO	International Standards Organisation
LBL	Long BaseLine (geophysical array)
LRFD	Load and Resistance Factor Design
NUI	Normally Unattended Installation
OSIF	Offshore Site Investigation Forum
PLEMS	PipeLine End Manifold System
POB	Persons on Board
SPAR	A moored buoy production facility
TLP	Tension Leg Platform
UKCS	United Kingdom Continental Shelf
UKOOA	United Kingdom Offshore Operators Association
VLA	Vertically Loaded Anchor
WSD	Working Stress Design

EXECUTIVE SUMMARY

There are many new risks and safety issues which need to be accounted for by the offshore industry, with the advances throughout the offshore industry driven by the need to exploit economically marginal shallow water fields, deep water fields and those driven by the developing offshore wind farm projects.

The aim of this project is to provide an overview of the advances and risks faced within the offshore geotechnical industry in the UK, through the views of key figures within the industry. The principal elements required to manage and mitigate these risks within offshore geotechnical engineering are generally considered by industry to be as follows:

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The report provides an overview of the technologies and techniques used in offshore ground characterisation. During the course of this study the industry has been successfully addressing the risks with steady advancement in techniques and technology.

The report describes industry's view on where advances are taking place. It aims to raise awareness of the key features of these advances to every level of the offshore industry so to inform geotechnical risk and mitigation strategy.

1. INTRODUCTION

The subject of risk implications in site characterisation and analysis within offshore engineering is a substantial topic area. This report aims to provide the reader with a 'snapshot' of selected issues as identified by the industry. The report is intended to provide guidance for generalists and to be of interest to industry specialists.

Traditionally, offshore engineering has been focussed on the exploration and production of oil and gas offshore from relatively 'shallow waters'. Originally the production of oil and gas in these cases was from fixed steel jacket platforms and concrete gravity based structures. More recently there have been a number of areas within the offshore industry in which advances are being made, for example:

- development of a variety of seabed structures often tied back to a main production platform
- marginal shallow water fields developed using smaller fixed steel jackets, for example, Normally Unoccupied Installations (NUIs) type platforms
- increased diversity of types of foundation, such as monopiles
- move towards exploration and production of oil and gas in progressively deeper waters using, for example, Floating Production Storage and Offloading facilities (FPSOs)
- renewable energy developments, for example, offshore wind farms and current turbines
- decommissioning – re-use, recycling and disposal of facilities

Geotechnical and structural offshore engineers are developing new methods of investigation and analysis to meet these changing demands.

This report presents the results of a study carried out for the UK Health & Safety Executive (HSE) to review risk implications in site characterisation and analysis for offshore engineering. The report covers, in a broad way, recent advances in geological, geophysical and geotechnical site characterisation and methods of geotechnical analysis and foundation design. The report focuses primarily on the UK offshore industry.

1.1 BACKGROUND

1.1.1 United Kingdom Continental Shelf (UKCS) oil and gas fields

An excellent background to the UK Oil and Gas Industry is provided on the United Kingdom Offshore Operators Association website (http://www.ukooa.co.uk).

North Sea Gas was first discovered in the southern North Sea in 1965. The giant Forties Field was discovered in 1970 and the first oil (from the Argyll Field) came ashore in 1975. The largest and most easily developed oil fields in the North Sea are now past their production peak but, recent and future fields in United Kingdom Continental Shelf (UKCS) waters are expected to remain productive at least until 2020.

The West Shetland basin, which lies within the Atlantic Margin, is the most recent area of development in the UKCS. It has one of the harshest open ocean environments in the world with storms gusting to over 160 km/h and waves which can reach heights of 25 metres and occasionally over 30 metres. The water depth in the Atlantic Margin ranges from 150 to 1500 metres. This represents some of the deepest waters in the UKCS, being considerably deeper than the North Sea where water depths range from 30 to 250 metres. These physical conditions present a much greater challenge to all aspects of exploration and production operations than those in the North Sea.

1.1.2 'Marginal' shallow water field developments

There have been advances in the engineering analysis and design approaches for structures in traditional water depths of the order of 150 metres in areas such as the North Sea and where generally ground conditions are more familiar.
In such cases there is an increasing wish to find cost-effective ways of developing fields with marginal productivity (Aldridge, 1997). This in general is being achieved by using more advanced geotechnical methods of investigation and analyses and also by developing alternative types of production facility such as NUIs and FPSOs, rather than the typical steel jackets founded on pile groups.

1.1.3 'Deep water' exploration and production

As fields are developed in ever deeper water, there has been a progressive change in the type of structures being deployed. Fixed structures with piled foundations are limited to about 500 metres of water depth, and tension leg platforms (TLP) to approximately 1500 metres. There is a trend towards sub-sea well-heads and templates, with pipelines running between them and risers to floating production units (Aldridge, 1997). These structures, along with the anchors for floating systems cover a much larger area than the foundations for a piled or tension leg structure (Walker, 1998). Good and accurate areal coverage is thus needed from site investigation whatever combination of techniques is used.

Driven by the wish to reduce costs and by the need to investigate much deeper and larger areas, offshore operators and their geotechnical contractors and designers are actively developing new ways of investigating and designing their facilities. With a single geotechnical borehole in these harsh deep water environments costing upwards of $1,000,000, there is increasing pressure to characterise the geotechnical conditions in deeper water environments by minimising the use of traditional drilling methods. There are risks in adopting such an approach which have to be carefully evaluated. The concept of a 'one-pass' geotechnical investigation is gaining favour and 'the integration of geophysics and geotechnics is seen as offering the only way forward' (Walker, 1998).

1.1.4 Renewable energy developments

The first offshore wind farm in the UK was constructed at Blyth, Northumberland in 2000. Offshore wind energy is expected to be a major contributor towards the UK Government's 2010 target for renewable generation (http://www.offshorewindfarms.co.uk). The development of offshore wind farms poses new challenges to offshore engineers. Foundations costs for these developments are 25-40 % of the total installation cost. This is significantly higher than the typical foundation costs for steel jacket foundations which are 1-2% of total costs (Finch, 2003). More recent renewable energy developments include marine current turbine and wave energy developments.

1.1.5 Decommissioning

In considering the 'whole life cycle' of offshore developments, increasing attention is currently being focussed on decommissioning of offshore facilities during the design and construction stages. Engineers are often having to assess the re-usability or decommissioning of the whole structure to make the development economically viable. The need to consider the whole life cycle of assets was reinforced by the Brent SPAR incident. (www.og.dti.gov.uk/upstream/decommissioning/programmes/approved.htm , Parliamentary Office of Science and Technology, 1995).

1.1.6 Risk

From a health and safety point of view, the Piper Alpha disaster in 1988 and the resulting Safety Case legislation have also given rise to a change in the 'traditional' concept of the steel jacket design by highlighting the need for a considerable reduction in the Personnel on Board (POB). This forms part of the requirement that safety risks are assessed and reduced to 'as low as reasonably practicable' (ALARP). These events have played a part in leading to the development and use of (NUIs).

A keynote paper by Suzanne Lacasse at the 2002 SUT Conference, addressed the issue of geotechnical risk in offshore engineering and highlighted the importance of the identification and analysis of the possible failure scenarios and the quantification of geo-risk based on site investigation.

1.2 SCOPE OF WORK

The scope of this report includes consideration of the following issues:

1.2.1 Offshore geotechnical site investigation techniques

- the implications of the increasing trend of integrating geophysics with geotechnical investigations
- the increasing cost of site investigations in deep water and the development of more economical, alternative approaches to site investigations
- the implications of the general advances in investigation and testing

1.2.2 Offshore geophysical site investigation techniques

- extraction of geotechnical seafloor properties from side scan sonar and swathe bathymetry
- new survey methods being developed, both with sub-surface and seabed-towed equipment to extract sub-seafloor properties
- possible effects of reduced intrusive investigation to verify geophysical data i.e. "ground truthing"
- trend of increased use of Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) in offshore site investigation

1.2.3 Seafloor geomorphology and engineering geology

- geological hazards in deeper water offshore environments and their impact on geotechnical design of offshore structures; continental slope geohazards

1.2.4 Methods of geotechnical analysis and foundation design

- new developments in offshore foundation concepts and associated analysis and design approaches
- increased use of probabilistic methods (e.g. probabilistic parameter determination)
- use of continuum and 3D methods

1.2.5 Risk assessment

- risk aspects of exploration in deeper, more inaccessible ocean areas
- inherent uncertainty due to soil spatial variability, uncertainty associated with geotechnical parameter selection, foundation design/analysis model uncertainty
- implications for risks arising from such uncertainties

1.2.6 Industry consultation

- solicitations of industries views and opinions on the current state and future advances within the offshore industry, are highlighted throughout the report

1.3 STUDY METHODOLOGY

Principal activities undertaken during the study were:

- A review of relevant published literature, including technical papers, company technical literature and information available via the internet
- Interviews with senior members of the UK's offshore geotechnical engineering community
- Preparation of questionnaires which were sent to people and organisations working in offshore geotechnical engineering
- Synthesis of the data and presentation of this report

The questionnaires prepared solicited views on the following 5 topics. A blank copy of each questionnaire section is provided in Appendix A.

a) General Overview of the Situation

b) Site Investigation Techniques

c) Foundation Analysis

d) Seafloor and Shallow Hazards

e) Engineering Geophysics

1.4 REPORT STRUCTURE

This report is structured as follows:

Section 2 TRENDS IN OFFSHORE ENGINEERING provides an overview of developments in offshore facilities and recent trends in site investigation, geotechnical analysis and design.

Section 3 SITE CHARACTERISATION ISSUES describes current industry practice and methodologies in geotechnical and geophysical investigations.

Section 4 GEOTECHNICAL ANALYSIS AND DESIGN describes current practice and methodologies based on views obtained from industry feedback.

Section 5 RISK MANAGEMENT ISSUES describes the general risk management approaches and how they relate to managing and mitigating risk in the context of offshore geotechnical engineering.

Section 6 SUMMARY AND THOUGHTS FOR THE FUTURE this section provides an overview, drawing in the key features of the study.

It should be noted that this report does not aim to be a single source of information, but rather to be viewed together with documents from the HSE and other sources. It does not aim to provide:

- a risk assessment of offshore ground engineering
- procedures or guidelines for the assessment of risk in offshore ground engineering
- a rigorous list of all offshore ground engineering investigation, analysis and design techniques and methods currently available
- a rigorous review of foundation types, the consequences of geotechnical failure or of risk mitigation methodologies

Instead, an overview of these subjects is given.

Initial research into trends in site characterisation and analysis for offshore engineering took place in 2000 and 2001. It is likely that some further developments have taken place between that time and the publication of this document. Additionally it should be noted that during this time several of the companies referenced in the report have either merged or been taken over.

2. TRENDS IN OFFSHORE ENGINEERING

Advances in offshore ground investigation, geotechnical and geophysical characterisation, engineering analysis, design and construction both drive and are driven by the developments in the offshore oil and gas industry. Developments are taking place in existing large fields in relatively shallow waters and in new deeper water fields.

To meet the oil and gas industries changing requirements, the offshore geotechnical industry generally views that:

a) an integrated approach to ground investigation is developed, where both geotechnical and geophysical methods are employed to complement one another

b) development of deeper water and marginal shallow water fields will require further novel design of production facilities from the 'traditional' large steel jacket platform founded on pile groups to FPSO's with drag anchors or suction anchors, for example

Industry Feedback – Some key points

The view of the offshore geotechnical industry is that these will have the following implications for the industry:

- *a reduction in borehole investigations and an increase in geophysical investigations due to the physical limitations of drilling vessels*
- *a lower confidence in the geotechnical parameters obtained from deeper water investigations*
- *a possible reduction in the safety consequences of foundation failure by greater redundancy, system robustness and reduced POB (nevertheless from a commercial and possibly environmental point of view the consequences of failure of such foundations can be considerable)*
- *greater uncertainty in using new techniques, or old techniques in untried environments, resulting in traditional empirical approaches which are not necessarily valid or lack calibrating data*
- *lower level of industry experience of these new techniques and environments when compared with 'traditional' techniques and environments*
- *different foundation types spread over greater areas (e.g. anchored foundations) resulting in much greater uncertainty in the soil profile*
- *engineering in new areas and deeper waters where the level of geological knowledge is lower and the potential for geohazards may be greater*
- *evolving regulatory environment imposing new safety, environmental and business risk standards and expectations*
- *increasing requirement for effective decommissioning or refurbishment of redundant structures*
- *uncertain future oil price leading to difficulty in ascertaining positive cost-benefit of developing new ideas and technologies*

2.1 OFFSHORE FACILITIES AND STRUCTURES

2.1.1 Types of offshore structures

The main types of offshore structures that require geotechnical input for their design, installation and operation include the following:

- exploration drilling rigs
- subsea pipelines, cables, manifolds and other small seabed structures (Power and Colliat, 2000)
- foundations for steel jacket production platforms (Smith, Turner and Mackenzie, 1998)
- concrete gravity base structure (GBS) / production platforms (Humpheson, 1998; Huslid, 2001)
- sub-sea anchors and riser bases for deep water mooring systems, e.g. FPSOs, TLPs, SPARs (Evans *et al*, 1998; Ruinen and Degenkamp, 2001)
- jack-up platform foundations (Vlahos *et al*, 2001)

In the conclusion to his review of the evolution of bottom-supported fixed North Sea structures, Laver (1997) provides a synopsis of structures associated with early, current and future offshore oil field developments. The highlighted points for future development in the North Sea include an increased emphasis on satellite platform developments tied into existing 'mother' platforms, fewer fixed platforms and an increased use of floating production platforms/facilities.

Two deep water oil fields now in production are Foinaven (Figure 1) and Schiehallion/Loyal (Figure 2) the first oilfields West of Shetland. These were developed using FPSO technology in water depths of between 350 and 550 metres, in arguably the harshest environmental conditions yet experienced offshore. These are examples of how developments in offshore facility technology required a change in the approach taken for offshore geotechnical engineering in the investigation and foundation design. The cost of the development is about £700 million. Evans *et al* (1998) provide a well-documented review of the geotechnical challenges faced in developing the new floating production systems. Traditional project time scales were halved by shortening and overlapping investigations for the two reservoirs and their respective facilities.

The Foinaven and Schiehallion/Loyal developments are similar. Each comprises discrete clusters of wells (called drill centres), connected through manifolds to flowlines which run over the seabed to flexible pipes (risers) ascending to a permanently stationed FPSO vessel. Crude oil is periodically offloaded from the FPSO by shuttle tanker and transported to a suitable terminal.

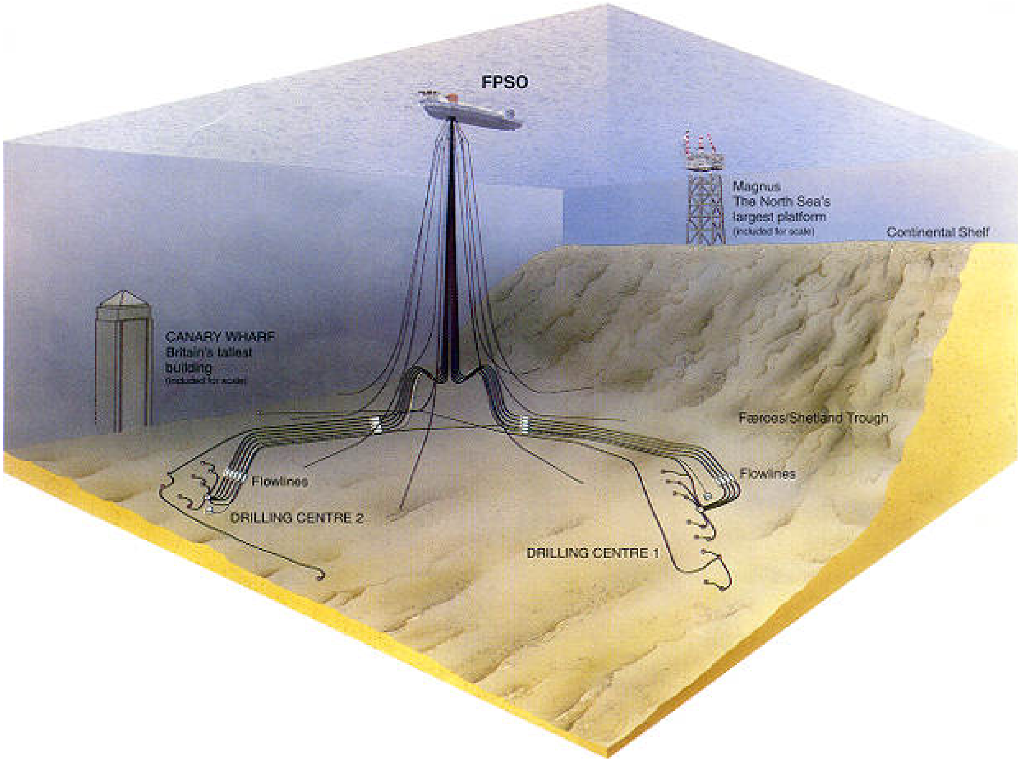


Figure 1 Foinaven field development (Offshore Technology website)

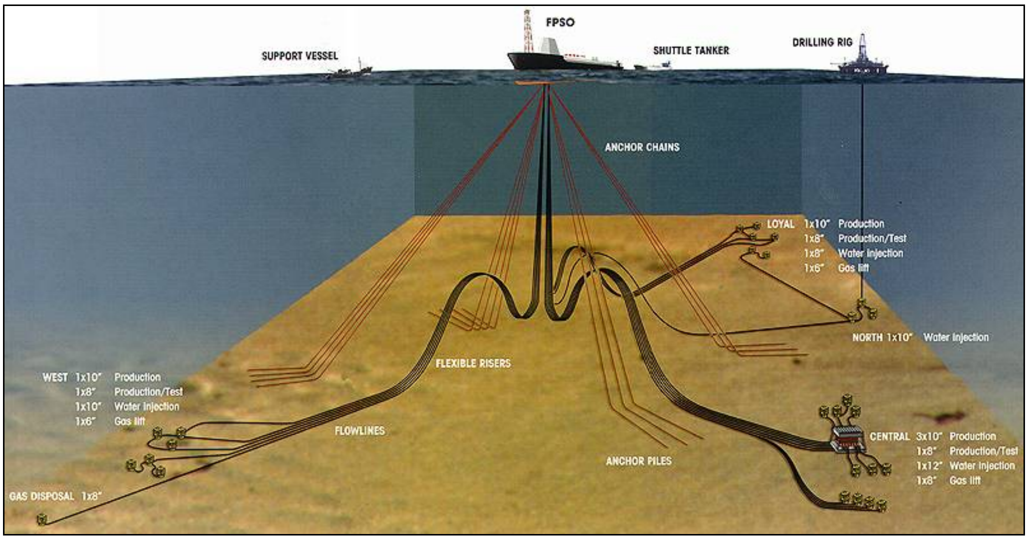


Figure 2 Schiehallion field development (Offshore Technology website)

Tension-leg platforms (see Figure 3 & Figure 4) are generally similar to large semi submersible vessels, but held in position using vertical tethers, which are more effective than catenary anchors at limiting lateral movement.

Whilst TLPs have been used around the world, there is only one in the UK North Sea – the Conoco Hutton TLP. Unlike piled platform foundations, the foundation piles are permanently loaded in tension and the design of these foundations requires very careful consideration. The foundation is not 'fail-safe'. Detailed understanding of the effects of cyclic loading is needed, the requirements of which include a detailed soil sampling programme, a standard and an advanced cyclic laboratory test programme and analysis (Aldridge, 1997).

2.1.2 New types of offshore foundations

In deep water, the use of traditional drag anchors, piled anchors or suction anchors are common foundation solutions for anchoring floating systems to the seabed. Where such systems are truly floating, the anchors tend to be arranged in a circular pattern at some considerable distance from the floating unit. In shallower waters, the loads into such anchors are predominantly horizontal, since the catenary profile of the anchor cables follows the seabed near to the anchor. For deeper water, and for tensioned systems, where the floating unit is pulled down into the water to reduce movements, the foundation anchors have to take a large component of vertical load, also with some lateral and moment loading (Aldridge, 1997).

The foundations used for the Heidrun and Snorre TLPs (see Figure 3 and Figure 4) are generally referred to as 'suction' foundations. However, it is important to note that it is not possible to use 'suction' to resist loads which are permanently in tension because tensile loading of soil over a long period reduces the strength of the soil and eventually allow the soil to fail under the loading. The Snorre TLP foundations resist the long-term uplift using the weight of the foundations, which therefore act as gravity blocks. (Aldridge, 1997).

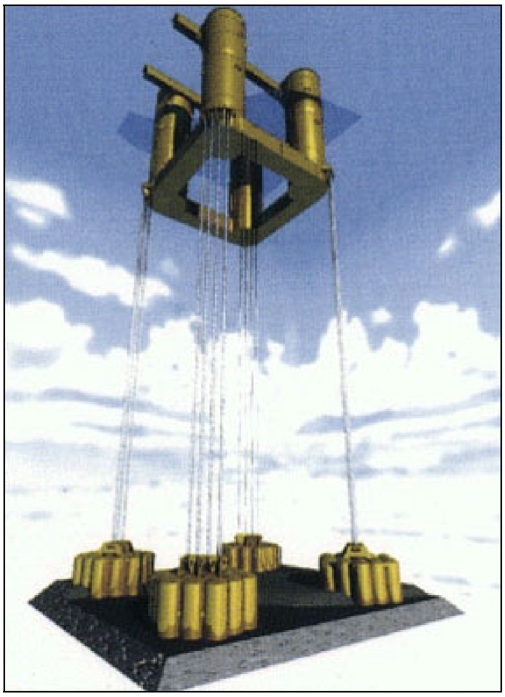


Figure 3 Heidrun TLP

Deepwater field developments generally comprise a TLP or floater of some kind connected by flowlines with a riser. The foundations generally comprise shallow anchors and given that the seabed soils are generally low strength, it is often difficult to ensure that these foundations have sufficient vertical and lateral stability. Suction techniques are being developed to improve the stability for anchor foundations for these structures.

Figure 4 Snorre TLP in production

In ‘standard’ water depths, the use of skirted mudmat foundations are commonly used as a temporary support for steel jackets during installation. The concept of skirted mudmats are being developed as a permanent foundation solution to replace piled foundations. The requirement for skirts of sufficient length is to resist the lateral and moment loads from the platform and to ensure that enough suction can be generated to resist the tensile loads. The skirts also reduce the risk of scour occurring around the foundation. Detailed analyses are required for skirted mudmat foundations to assess the effects of installation and subsequent foundation performance (Aldridge, 1997).

Skirted foundations and anchors have now become competitive solutions to other foundation types. One of the reasons is that they offer important cost savings related to fabrication, offshore installation (equipment and time), ease of accurate positioning, simple geotechnical and structural designs, and reusability of structure. Skirted foundations can be used in most soils types and for both fixed and floating platforms, including floaters, TLP’s, steel jackets, jack-up rigs, sub-sea systems and other protection structures (Lacasse, 1999).

Suction piles (Figure 5) or suction anchors, first introduced some 20 years ago, have applications for a great variety of fixed and floating offshore structures (Tjelta, 2001). Today their position and application are significant in the offshore oil industry world-wide. They are the preferred foundation type in major offshore development areas such as Brazil, West Africa, North Sea, Norwegian Sea, West of Shetland and the Gulf of Mexico, where reliable high-capacity foundations for catenary and taut legged moorings are required.

Figure 5 Suction installed anchor pile (Suction Anchor)

Suction pile technology has proven to be extremely adaptable to soil conditions, structural requirements and type and magnitude of loading. The suction pile used in mooring applications is a flexible foundation solution: geometry and aspect ratio can vary significantly. Installation methods can vary similarly and the anchors may be fabricated at a great variety of construction yards (Tjelta, 2001).

Key factors which have influenced the selection of suction anchors include (Tjelta, 2001):

- Reliable design methods both for installation and in service behaviour
- Predictable installation behaviour
- Installation may be reversed and repeated
- Cost efficiency
- Removal is easy if pre-planned

2.2 SITE INVESTIGATION

2.2.1 Current practice

'Site investigations for fixed offshore facilities are usually phased and a detailed investigation is not normally performed until the platform location is known. The maximum exploration depth for a fixed platform is typically about 150m and the area investigated is generally less than about 0.05 km^2' (Evans *et al*, 1998) Such surveys are generally only undertaken in water depths of up to 200 meters. They are very expensive, as they require specialist geotechnical vessels with on-board drilling facilities (Meunier, 2000), and therefore, the site investigation is usually limited to the proposed site of the offshore facility and its foundations.

Techniques for site investigation and design are evolving as exploration and production of offshore oil and gas moves into deeper waters where foundation conditions and geohazards can be significantly different from those experienced in shallower water (Hawkins and Markus, 1998; Meunier, 2000). Key to the success of these deep water site investigations is a staged approach in which work is done at three scales as the target areas are progressively identified and refined - the regional scale, the local scale and the site scale.

The *regional scale* survey corresponds to a 100 km^2 area and consists mainly in bathymetry and multi-beam echo sounder (Figure 6). The *local scale* represents a 10 km^2 area and the survey consists mainly in sonar imaging and high resolution seismics. The *site scale*, corresponding to a 1 km^2 area, consists of very high resolution seismics, sampling and in-situ measurements. As structures in deeper waters are founded on shallow foundations or on suction caissons, the optimized target depth of investigation in soils is generally of the order of 20 to 30 meters below seabed level (Meunier, 2000), which is significantly less than the depth of investigations needed for the deep piled foundations, traditionally employed for shallower water facilities.

2.2.2 Advances in geophysical investigations

Recent developments provide the geologist and geotechnical engineer with a range of techniques for constructing reliable sub-sea terrain models. The extraction of geotechnical parameters from geophysical data requires calibration against an information database that is gradually being accumulated. In a given case this will be derived from direct comparison with site-specific borehole information.

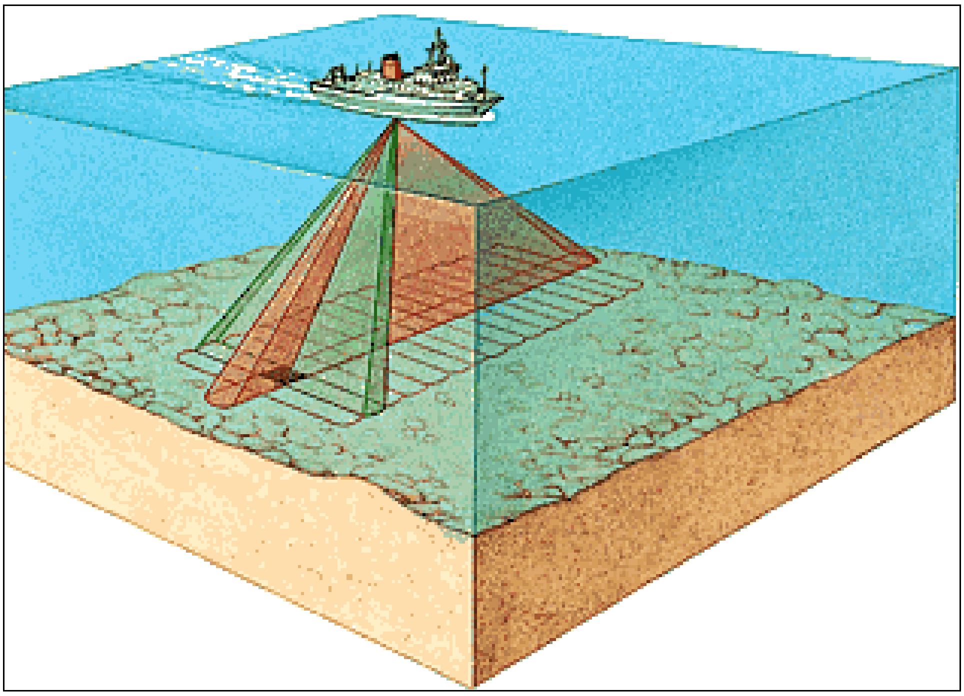


Figure 6 Multi-beam echosounder

Remote data acquisition systems

The technology that has made the greatest impact in the last few years, certainly in terms of imminent operation, has been the commercial availability of Autonomous Underwater Vehicles (AUVs), (Figure 7) also known as Unmanned Underwater Vehicles (UUVs). These have been under development for defence and scientific applications for over 50 years. Now that hydrocarbon exploration and production has moved into deeper waters, that is, deeper than 1,000m, existing techniques using towed survey systems or ROV-installed multibeam sonars, have not been appropriate to meet oil company requirements in relation to positional accuracy, speed and cost. In parallel, the AUV has started to demonstrate its capability and, most importantly, its reliability. Consequently, the survey industry, encouraged by the oil industry, has started to invest in AUV survey systems. Fugro Geosciences, Racal Survey, De Beers Marine and C&C Technologies have all announced contracts with AUV manufacturers since the middle of 1999. Manufacturers of AUVs include International Submarine Engineering, Canada; Bluefin Robotics, USA; Maridan AS, Denmark; and Kongsberg Simrad, Norway.

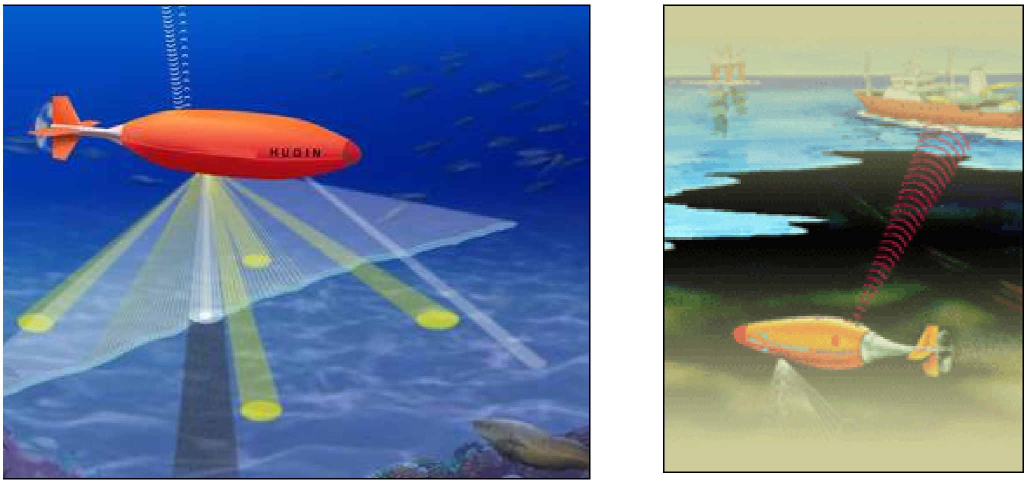


Figure 7 - Hugin AUV (C & C Technologies website)

The perceived advantages to using AUVs in deep water as against traditional methods include:

- Increase in survey speed from 1 to 4 knots
- Increased positional accuracy, when either the support vessel operates above the AUV or when the vehicle is commanded to maintain a constant position above the sea floor
- Significant reduction in `turns' and `run-ins' in grid or box surveys

This increased utilisation of AUVs is important for a number of reasons. The vehicle itself is purely a platform for carrying sensors in the most cost-efficient manner in order to collect either survey data or to undertake in-situ inspection. These sensors include multibeam or swathe sonar, side scan sonar, sub-bottom profiler and oceanographic sensors, in addition to collision avoidance sonars and other vehicle control systems, including communications and navigation. In order for AUVs to be more effective there will need to be parallel developments in power sources, handling systems, real-time high-speed acoustic telemetry of sonar data and/or video images, improved positioning systems and miniaturised sensors.

Another further development is the `hybrid' vehicle, whereby the AUV and ROV are integrated into one system. The `AutRov' concept consists of an AUV acting as both an autonomous survey system and a shuttle for an electric ROV. The latter is taken to a remote work place, at which the AUV connects to power and communication umbilicals and the ROV can fly, under control, via a tether, to undertake intervention tasks. This will ultimately provide the greatest opportunity for AUV technology as it will allow sub-sea inspection, maintenance and repair, without the need for expensive support vessels.

Although AUVs have distinct advantages for geophysical data acquisition, their use is limited in the short to medium term for soil sample collection.

Bottom- towed resistivity and refraction systems

Bottom-towed geo-electrical resistivity systems are now in use at depths of up to 1500 metres, for pipeline and cable route surveys to provide Burial Assessment Survey (BAS) data. With sophisticated processing techniques and ground truth calibration at specific locations, either by means of physical sampling or in-situ testing, such systems can provide a continuous profile along a route alignment.

Bottom- towed Resistivity and Refraction Systems like C-BASS (resistivity combined with Mini-CPT ground truthing), and REDAS (standalone resistivity) were pioneered around 1996 by Global Marine Systems Limited and Thales Geosolutions, respectively (both in joint development with Williamson and Associates), strongly encouraged by the submarine cable market's need to achieve continuous burial assessment. More recently, Fugro have developed the standalone RHOBAS marine resistivity system.

Thales Geosolutions also worked on a bottom-towed seismic refraction unit, the SHRIMP (Figure 8) with initially a 100 metre water depth capability and a penetration up to between 7 and 15 metres below the seabed. Fugro's GAMBAS seismic refraction unit can work in 300 metres of water. These systems provide an indication of continuous seabed and sub-seabed strength information, in smooth bottom areas, to complement the shallow seismic.

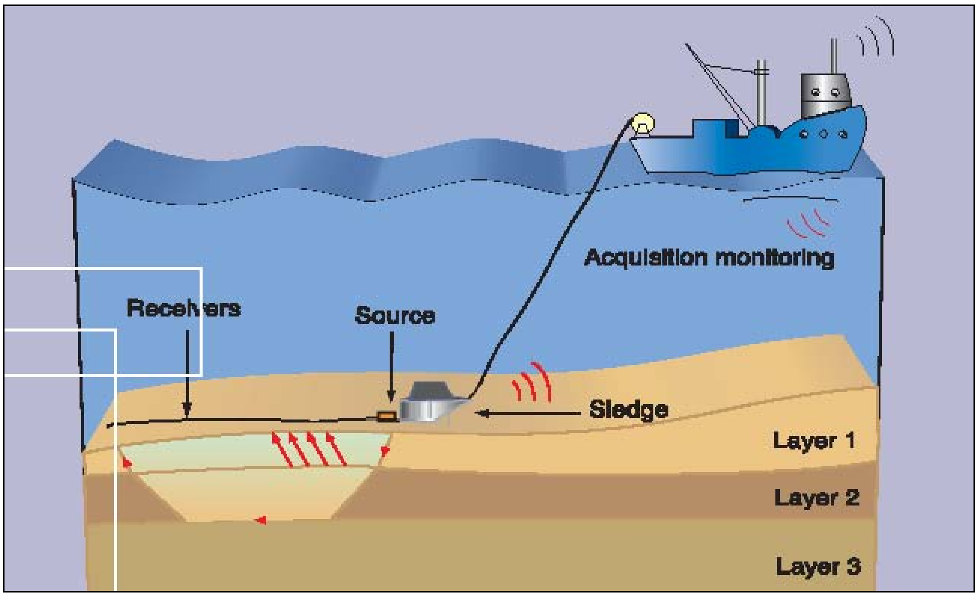


Figure 8 SHRIMP bottom-towed seismic refraction (Thales Group website)

Ocean bottom cables (OBC) and other developments

In-situ Ocean Bottom Cables are now being used for most deepwater field investigations to observe the reservoir depletion over time. These systems are strings of geophones laid on the seabed. It is considered that there may be opportunities for developments in offshore systems to obtain dynamic moduli in formations of interest to geotechnical engineers. Schlumberger, PGS, CGG and Western have all moved into this technology but have concentrated their activities on reservoir evaluation.

Bottom-dragged streamers have also been utilised in special circumstances and individual phones have been placed by ROV for special experimentation. It is believed that Southampton Oceanographic Centre has developed an in-situ P-wave and S-wave probe.

Fugro-Geoteam have performed detailed site studies for the installation of OBCs for hydrocarbon exploration but have not yet considered how this technology could itself be used for improving the quality and geotechnical value of shallow high resolution seismic.

General guidance on geophysics techniques and application is provided in Ciria Guide C562.

2.2.3 Advances in geotechnical investigations

Geotechnical drilling vessels

Power *et al*, (1997) provide a good discussion of those aspects of drilling in deeper waters (>700 metres) that require new technology to be developed to acquire suitable geotechnical soils data. New equipment developments that are beginning or advancing to meet the demands of deeper water offshore drilling are discussed in Power and Geise (1994).

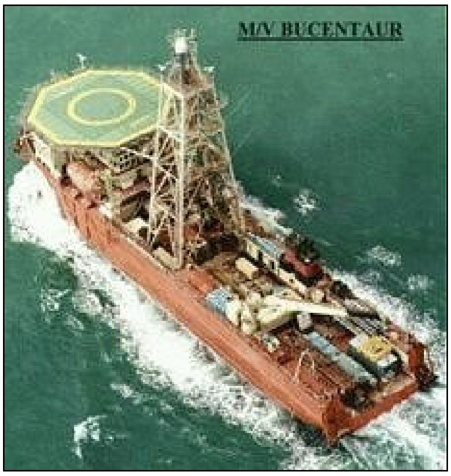


Figure 9 M/V Bucentaur

Early geotechnical drill ships were converted coasters or supply vessels which were held on location by means of a four-point anchor spread. The latest are purpose-built vessels such as the M/V Bucentaur *(*Figure 9*)* and Explorer which use dynamic positioning, in which satellite-guided computers control movable ship's thrusters, to main exact position over the borehole or test location (Power and Geise, 1994).

Drilling has traditionally been performed with standard 5″ API steel drill pipe, but its weight and the lifting capacity of the drill ship's draw works limits operations on this basis to a maximum water depth of about 800m. Specially manufactured aluminium drill pipe has to be used beyond this depth (Power and Geise, 1994). On the Bucentaur rig, use of aluminium drill string serves to reduce the weight of the drill string. Deploying downhole sampling and testing tools such as hydraulic push samplers and PCPT devices on conventional electro-hydraulic umbilical cables also becomes impracticable, due to size and weight constraints, beyond about 800m water depth (Hawkins and Markus, 1998).

Although dynamically positioned drill ships are predicted to be the mainstay of major soils investigations in water depths up to 2000 metres (Power and Geise, 1994), alternatives to large, expensive dedicated geotechnical drilling vessels are gaining in popularity for deeper water investigations (Humphrey and Adams, 1995). To aid in the design of particular structures, the industry is developing purpose-specialized insitu testing tools and samplers remotely deployable from cheaper multi-functional offshore support vessels, see discussion below of seabed frames (Meunier, 2000; Peuchen, 2000). The market leader in this area, Fugro, has overcome this difficulty by developing a suite of downhole tools that derive their power from mud pressure in the drill string and use miniaturised electronics and solid state memories to store test data (Hawkins and Markus, 1998).

The following comments regarding drilling vessels and the difficulty of downhole sampling and in-situ testing in deep water have been offered by industry:

- To address the difficulties associated with power delivery to the seabed using umbilicals, GEC Alstholm is reportedly conducting research and trials of a new subsea electrical power transformation and distribution system.

- Research is reported to be underway into Riserless Drilling Technology, a cheaper and lighter alternative to use of the traditional or composite risers. According to one questionnaire respondent, the development of a seabed-deployed deep drilling system known as DIODI (Drilling Independent of Depth) is a recent Aberdeen-based initiative by ITF (oil-company-sponsored Industry Technology Facilitator).

- When retrieval of a 30 m piston core is desired there was an expressed view from some people that a vessel of opportunity should not be considered as an alternative to a dedicated drilling vessel. They believed the use of a dedicated site investigation vessel in waters up to 2000 m deep was to be recommended. This would not preclude the opportunity to drill if penetration achieved with a cone penetrometer was insufficient. Other members of the oil industry were keen to promote the corer/vessel of opportunity combination. Research is ongoing to compare the results of geotechnical testing done using traditional methods and those using drop corers/cone combinations. The overall industry prediction is an increased use of probes and a reduced effort in traditional boreholes; the calibration is crucial.

- CTSRVs, or Coiled Tubing Surface Re-entry Vessels, are considered by one respondent to be expensive but has significant potential for future use in conducting deep water site investigations.

Coring, sampling in general

The long corer, push corer, pressurized corer, hammer sampler, push sampler, piston sampler and rotary corer provide means of collecting downhole samples from dedicated geotechnical drilling vessels (Zuidberg *et al*, 1986; Young and Honganen, 2000; Silva *et al*, 1999). A modified form of downhole 'push' sampling has also allowed the successful retrieval of a 1 metre long sample using the Sea Robin seabed unit (Hawkins and Markus, 1998). The NORSOK Marine Soil Investigation standard (NORSOK, 1996) provides guidance on choosing an appropriate sampling method and outlines some seabed and downhole sampling tools with recommended procedures specifically for marine soil investigations. Zuidberg *et al* (1986) provide a good explanation of the hammer sampling, push sampling and piston downhole sampling methods. Table 1 represents a selection of recently developed seabed coring and sampling tools.

Table 1 Seabed coring and sampling tools

Corer / sampler	***Seabed or downhole***	***Reference***
Vibrocorer	S	OSIF,1999; NORSOK, 1996
Grab sampler	S	OSIF, 1999; NORSOK, 1996
Box corer	S	Fugro website: *www.fugro.net* Ocean Scientific*, NORSOK, 1996
Gravity corer	S	OSIF, 1999; NORSOK, 1996
Push corer	S / D	Zuidberg *et al*, 1986; Hawkins and Markus, 1998
Rotary corer	S / D	Power *et a,l* 1997; OSIF, 1999; NORSOK, 1996
Long corer	D	Silva *et al*, 1999; Young and Honganen, 2000
Pressurized corer	D	Zuidberg *et al*, 1986; HYACE
Push sampler	D	
Piston sampler	D	Zuidberg *et al*, 1986; NORSOK, 1996
Hammer sampler	D	Zuidberg *et al*, 1986

* *http://www.oceanscientific.com*

The vibrocorer, gravity corer, box corer (shown left to right, Figure 10) are methods of acquiring shallow seabed soil sample (OSIF, 2000), primarily for soil classification and approximate indication of strength.

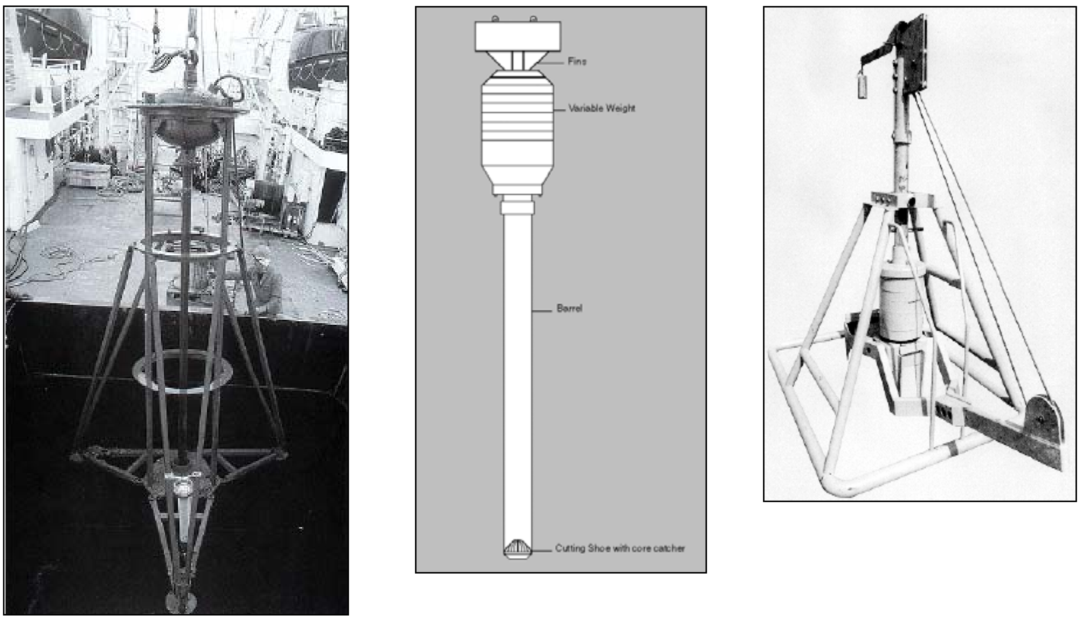


Figure 10 Vibrocorer, gravity corer, and boxcorer (*:* **www.fugro.net**)

Due to the significant pressure change experienced after recovery to surface, sample retrieval from high pressure environments is reported to make sample handling and transport both difficult and dangerous. The presence of dissolved gas in the insitu pore water reportedly introduces further sample disturbance potential. To minimise this disturbance, use of overshot samplers with vacuum/wax encapsulation has been suggested. Nonetheless, it is recommended to increase emphasis on insitu tests, i.e. CPT, SPT, shear vane etc., to avoid dependence on structurally disturbed or even destroyed samples for prediction of operational geotechnical soil design parameters.

To achieve good sample quality in very soft to soft clays, the use of a piston sampler and thin-walled sample tubes is recommended by a number of survey respondents. One respondent even suggests attempting piston sampling in firm to stiff clays, and another has had success collecting also cohesionless soils samples with the piston sampler. Except for rotary coring and hammer sampling, all the corers and samplers listed have limited penetration in cohesionless soils and hard clays. The remaining samplers (vibrocorer, long corer, push corer, box corer, pressurized corer, and grab sampler) can be used to retrieve surficial samples or samples acceptable for environmental but limited to soil type classification and index testing for geotechnical uses. Three survey respondents forecast an increasing use of long corers in deepwater in the future as a means of economically extracting soft clay samples from 20-30 m depth. When deployed in combination with in-situ strength (i.e. cone or vane) tests the dubious sample quality is not as great a concern. Push samplers are used in soft to very stiff clays, hammer samplers in hard clays and dense sand and rotary coring in hard to very hard clays and weak rock. Often combined with Standard Penetration Testing, hammer sampling is carried out where retrieval of undisturbed samples is difficult.

Considered useful in deep water, the vibrocorer is viewed by two survey respondents to be useful for pipeline studies. Although limited to coring through sandy soils, it is also reportedly used for seabed frame surveys. The long corer, push corer, box corer, pressurized corer and grab sampler are also recommended for use in deepwater sea bottom baseline and/or pipeline and seabed frame surveys.

The trends with respect to downhole and seabed coring and sampling, are discussed in the following two sections.

Downhole coring and sampling

Over the past 50 years, offshore soil investigation techniques have evolved from extremely basic modified land drilling and sampling systems to purpose developed systems for high quality sampling and in-situ testing in deep water. For water depths greater than 30 m, offshore investigations require specialized equipment and procedures (Zuidberg *et al*, 1986). In 1986 the two common types of downhole sampling techniques were the push and hammer (percussion) samplers, both deployed from a wireline within the drill pipe. For soft clay or silt sampling the push sampler was modified to include a fixed piston, i.e. piston sampling (Zuidberg *et al*, 1986).

Downhole sampling and in-situ testing methods which do not require an umbilical have been available since 1985 (Peterson and Johnson, 1985). This system, referred to as the ‘Dolphin’ by Fugro, allows a PCPT, shear vane or piston sampler to be dropped down a drill string and pushed into soil through the bottom of the borehole using mud pressure. The data is stored in the downhole tool’s memory module, and the tool is retrieved with a wireline overshoot (Power and Geise, 1994; Lunne and Powell, 1993).

Without an international standard or unified code on sampler types and sampling methods, various types of samplers are being used in various countries based on the characteristics of the soil, availability of regional expertise and technology and subjective preferences of geotechnical engineers (Tanaka et al, 2001).

The Fugro *WISON and WIP XP* Systems are downhole PCPT and Push Sampling systems, respectively, designed initially for use from deepwater oil exploration rigs and which are now in operation both from exploration rigs and geotechnical drill vessels (Fugro, 1995; Hawkins and Markus, 1998).

Further upgrading of the WISON and WIP XP systems has recently taken place and new features include (Hawkins and Markus, 1998):

- extended penetration PCPT test (3m, increased from original 1.5m)
- piston sampler version of push sampler to provide higher quality and greater recovery in very soft soils
- pore water sampler for performing geochemical tests and assessing types and volumes of dissolved gases.

A *Deepwater Gas Hydrate Sampler* is currently under development (Hawkins and Markus, 1998). As hydrocarbon development moves into very deepwater one of the concerns is the possible occurrence of naturally occurring gas hydrates. As part of an EU sponsored project, Fugro is developing a downhole hydraulic hammer sampler for obtaining gas hydrates in their natural solid ice-like state (Hawkins and Markus, 1998).

Downhole sampling and in-situ testing methods adapted to meet the demands of deeper water investigations are listed in Table 2.

Table 2 Deep-water downhole sampling and in-situ test tools

Tool	***Reference***	***Comments***
WISON Mk III	*Fugro, 1995*	• downhole jacking CPT unit with a 3 metre stroke and 90 kN thrust capacity • deployed together with rotary drilling system • tests possible to 650m below drillfloor
WIP Sampler	*Fugro, 1995*	• 1 m long thin-walled sample tubes • can sample in soft to very hard clay to medium dense/dense sand and soft rocks
Deepwater Gas Hydrate Sampler	*Hawkins and Markus, 1998*	• modified downhole hydraulic sampler • under development (1998)

Seabed coring and sampling

The move into deeper waters has sparked research efforts into new technology that will allow for shallow (30m or less) seabed sampling and in-situ testing without the high costs and time investment which characterises investigations using dedicated geotechnical drilling vessels (Meunier, 2000). Hawkins and Markus (1998) introduce two new seabed sampling tools, the Abrams Coring System and the High Performance Corer. Bienvenue and Bessonart (2001) provides an overview of a number of existing sampling and coring tools and introduces a new STARFISH system, which enable sampling and testing directly from a seabed frame, recently developed by MARINE GEOSYSTEM.

Further coring and sampling tools, some of which have been mentioned above, modified for seabed sampling in deep water environments are listed in Table 3.

Table 3 Further recently developed seabed coring and sampling tools

SAMPLER/CORER	***REFERENCE***	***COMMENTS***
Drop (gravity) core sampler	*Industry comments*	• used for pipeline and seabed frame surveys but yield samples that are disturbed • tendency to choose this sampler over the thin-walled tube (piston sampling) variation should be avoided
Abrams Coring System	*Hawkins and Markus, 1998*	• designed by Fugro to optimise sample recovery using standard gravity coring techniques and to increase sampling efficiency • provides a rapid method of obtaining shallow core samples in water depths up to several thousand metres
High Performance Corer (HPC)	*Hawkins and Markus, 1998*	• developed by Fugro to cope with the demand for longer sample recovery in dense granular and stiff cohesive materials • utilises improved vibrocorer technology
CALYPSO Giant Corer and STACOR	*Bienvenu and Bessonart, 2001; Lunne, 1996*	• both corers developed by the IFRTP (French Institute of Research and Technology for Austral Territories) • CALYPSO can be fitted up to 10 tons and 60 metres long • STACOR is a large-diameter corer with rigid immobility of piston during penetration
Bowers and Connelly Megacorer	*DEEPSEAS equipment web site**	• quantitative seabed sampling tool, used to take high quality sediment cores from any depth of water • Sampling of near-seabed seawater, shallow gas and surficial seabed soil in greater than 2000m depth is possible, but limited success so far with gas sampling

SAMPLER/CORER	*REFERENCE*	*COMMENTS*
JUMBO piston corer (JPC)	*Silva et al, 1999*	• Uses steel barrel with 4-inch I.D. PVC pipe for a liner. • A lighter version of the Giant Piston Corer (JPC) • Tapered steel nose cone and foil catcher at the lower end • This corer is reputed to extract samples that are significantly disturbed
Large-diameter Gravity Corer (LGC)	*Silva et al.,1999*	• 4-inch I.D. PVC core barrel • tapered steel nose cone and foil core catcher at the lower end
Multi-corer (MC)	*Silva et al, 1999* *Ocean Scientific Web Site***	• can take up to eight cores per deployment • useful for collecting replicate samples of surficial sediments
SELCORE sampler	*Bienvenu and Bessonart, 2001*	• developed by SELANTIC
STARFISH system	*Bienvenu and Bessonart, 2001*	• Geotechnical static sampler recently patented by the French Geotechnical Consulting and Services Company (IFRTP). • Reportedly capable of operating in water depths to 6000 metres with a depth of investigation of up to 30metres below seabed

*http://www.soc.soton.ac.uk/GDD/DEEPSEAS/equipment.html
** http://www.oceanscientific.com

In-situ testing equipment

The cone penetration test (CPT) has become the most widely used in-situ testing technique for offshore geotechnical investigations (Peuchen, 2000). While a deepwater environment offers a favourable environment for cone penetration tests in terms of temperature (relatively constant or slow to change) and soil consistency (generally soft and saturated as opposed to desiccated as is found at ground surface), the very high water pressures pose a potentially adverse situation for measurement accuracy (Peuchen, 2000). Although the requirement for an increased measuring range in pore pressure leads to some reduction in sensor accuracy, the high pressures in deep water force gas bubbles into solution, thus maximising the chances of a fully saturated pore pressure measuring system (Peuchen, 2000).

Since the T-bar's load cell only has to measure a differential pressure, it can be made more sensitive and thus more accurate for measuring undrained shear strength in very soft to soft clays near the mudline (Randolph *et al* , 1998). A comparison of data from a site investigation, where both the cone and T-bar penetrometer were used in parallel (Randolph *et al* , 1998), indicates that the cone and T-bar penetrometers give extremely consistent results.

Figure 11 T-bar penetrometer

There are a number of 'standard' in-situ test tools, which have been developed from or incorporate the cone penetrometer. Most such tools are discussed in Lunne and Powell (1993) and are summarized in
Table 4. Annex B of the NORSOK standards (NORSOK, 1996) also provides an overview of the system configuration, testing/data acquisition procedure, calibration/required accuracy and recommended results presentation for the following in-situ tests: Cone Penetration Test, Seismic Cone, Electrical Conductivity Cone, Field Vane, Dilatometer, Bar Probe Test and Hydraulic Fracture Test.

Table 4 CPT and CPT-related equipment

Cone tool	***Reference***	***Comments***
Cone Penetrometer (CPT)	Robertson and Campanella, 1983; Fugro, 1995; Lunne and Powell, 1993	• Cone resistance, qc and sleeve friction, fs are the basic recorded parameters • Near-continuous vertical soil profiling
Piezocone (PCPT)	Robertson and Campanella, 1983; Lunne and Powell, 1993; Fugro, 1995	• Cone resistance, qc , sleeve friction, fs and pore pressure, u are the basic recorded parameters • Near-continuous vertical soil profiling
Seismic cone (SCPT)	Fugro, 1995; Lunne and Powell, 1993	• Shear wave measurements using a dual array seismic piezo-cone penetrometer • Hammer impact on block at surface is shear wave energy source • Can calculate dynamic shear modulus, Gmax from measurement of shear wave velocity, Vs
Electrical Resistivity cone (ECPT)	Fugro, 1995	• A measure of soil conductivity
Lateral Stress cone	Lunne and Powell, 1993	• Measures in-situ lateral stress to improve strength parameter interpretation from CPT data
Pressuremeter Cone (CPMT)	Lunne and Powell, 1993; Fugro, 1995	• For determination of in-situ horizontal stress • Pressuremeter module mounted behind cone spacer on standard cone penetrometer/piezocone • Only used onshore (1993)
Small-diameter Seabed Mini-Cone	Fugro, 1995	• 100 mm2 cone base area cone deployed from Seascout

Cone tool	*Reference*	*Comments*
'T-bar' in-situ test	Randolph *et al*, 1998; Hawkins and Markus, 1998	• version of cone penetration testing recently developed by Fugro for very soft soils • originally developed for laboratory use • a short cylindrical bar that is attached perpendicularly to the penetrometer rods • Operating in high porewater pressure environments does not pose a problem for the T-bar, an advantage over the PCPT which has resolution difficulties in such an environment

The PCPT, more useful than the CPT due likely to the dynamic pore pressure measurement capability, is considered an essential tool in subsea soils and a practical, cost-effective yet accurate tool in deep water. Industry respondents state that cone factors, while already well-established for continental shelf sediments, need to be determined for deepwater sediments on a field-specific basis from calibrations against otherwise measured referenced strengths (i.e. in-situ shear vane).

Figure 12 2cm^2 Subtraction Type Mini-Cone

The mini-cone (or small diameter seabed cone, see http://www.datem.com) has been offered as an improved cone data resolution tool. Datem's latest development is a digital non-subtraction type mini-cone. Small diameter seabed cones are considered useful for pipeline, cable, seabed frame and drag anchor surveys in deep water. However, as their dimensions are non-standard they reportedly need calibration against undrained shear strength measured using a standard field method. While mini-cones are useful in testing very dense sands and in limiting the required seabed frame weight, the large diameter cones are recommended for use in soft clays. Smaller cones and rods are less robust so there is a trade-off between weight of frame, thrust requirement and vulnerability of equipment.

The seismic cone is currently used as a tool for determining low-strain shear modulus G_{max} from the measured shear wave velocity. One respondent predicts that the seismic cone will play an increasing role in offshore investigations and that its costs will go down. Another reports extensive use of seismic cone measurement-determined soil stiffness properties from shear wave measurements for ocean bottom cable, gravity structure and jack-up design. Upper and lower bounds are established for the validity of extrapolating soil types using geophysical data which identify a particular depositional environment. However, in vertical section geophysical data does not currently match the resolution of Cone data. Nevertheless correlation tools for digitised high-resolution 2D seismic profiling tools in deep water are being developed for the first 30 metres of sediment.

The lateral stress cone and cone pressuremeters are not commonly used outside of academic research. One respondent claims that interpretation is difficult with the lateral stress cone.

The T-bar shows promise, for use particularly in very soft clays near the seabed (i.e. low effective stress). There appears to be generally a positive industry impression for use of the T-bar to obtain shear strength of the upper sediments in cohesive, soft soils. In cohesionless or calcareous soils, however, the T-bar is perceived not to be as effective as the cone. This may be due to the dependability and long-standing record that the CPT and PCPT share coupled with the relative novelty of the T-bar test. One interviewee views the T-bar and CPT the most useful tools for determining stratigraphy. Another interviewee does not believe the T-bar, despite its distinct advantage in shallow subsea soils, is likely to displace the cone for popularity.

Other in-situ soil characterisation tools

Despite the popularity of the cone, there are probes and sensors of use for offshore in-situ soil characterisation that are not (or were originally not) designed to be a cone attachment but are considered tools in their own right (Lunne and Powell, 1993). These tools, which include the shear vane, the hydraulic fracture probe, the thermal conductivity sensor, the electrical conductivity sensor, the pressuremeter, the instrumented plough and the offshore dilatometer, are well described in Lunne and Powell (1993). The temperature probe, a CPT variation, is documented in Fugro (1995).

Table 5 lists other tools of use in the offshore industry.

Table 5 Other tools

Other Tools	***Reference***	***Comments***
Shear vane	NORSOK, 1996 Zuidberg, 1986 Lunne and Powell, 1993	• Accepted method of measuring in-situ undrained strength of soft to medium (less than 200 kPa) clay
Hydraulic Fracture probe	Fugro, 1995 NORSOK, 1996 Lunne and Powell, 1993	• For assessing maximum allowable mud pressures for evaluating conducting setting depth • Not yet a standardized or well documented *in-situ* technique
Temperature probe	Fugro, 1995	• CPT tool modified with added temperature sensor
Nuclear Density probe		
Thermal Conductivity sensor (Heat Flow Probe)	Lunne and Powell,1993	• Temperature rise measured of thin wire in a steel tube at tip of probe • Useful for hydrocarbon potential assessment, pipeline investigations and nuclear waste burial sites
Electrical Conductivity sensor (Electrical Resistivity Probe)	Lunne and Powell,1993	• Bulk soil resistivity, pore water resistivity and porosity needed to interpret results • For determining *in-situ* density and porosity • Can assess corrosivity in upper soil layers
Pressuremeter	Lunne and Powell, 1993	• Self-boring pressuremeter deployed downhole • For determination of in-situ horizontal stress • Limited offshore experience
Instrumented Plough	Lunne and Powell, 1993	• pull speed and pull force measured during pull • trenching capacity of 0.9 m • can deploy CPT when stopped
Offshore Dilatometer	Lunne and Powell,1993 NORSOK, 1996	• modified, smaller form of onshore dilatometer • lowered through inner diameter of drill pipe • for assessment of K_o
In-situ Permeameter		• downhole in-situ measurements of permeability

Seabed deployment systems

Given the recent advances and high confidence in PCPT technology coupled with the high costs of boreholes in deep water, there exists a myriad of seabed frames which enable in-situ testing at shallow depths below the sea floor (Meunier, 2000; Bienvenu and Bessonart, 2000; Peuchen, 2000; Power and Geise, 1994; Lunne and Powell, 1993).

Fugro developed the Wheeldrive Seacalf PCPT system, the Modified Seacalf system, the Deepwater Seascout Mini-CPT system, the Modified Deepwater Seascout, the 'Sea Robin' seabed PCPT system and the Seasprite (Fugro, 2001). Thereafter, they developed two new deepwater CPT systems for a variety of cone sizes (1 cm^2, 2 cm^2, 10 cm^2, 15 cm^2, 33.3 cm^2) and in-situ vane tests were developed (Hawkins and Markus, 1998). The first system is similar to the deepwater Seascout. The second system is a modified Seacalf system.

The Tethered Sea Floor Platform has been in development since 1981 (Power and Geise 1993). It is seabed unit for mounting in-situ testing tools, but differs from its predecessors in a number of significant details:

- designed to eventually operate in water depths of 3000-3500m
- up to 70m of the 38mm diameter test rod is coiled on the seabed frame
- reaction force is provided by an integral suction anchor

GEOCEAN-SOLMARINE, in cooperation with IFREMER, is developing two new CPT seabed cone deployment systems. One, referred to as 'Penfeld', is for shallow (20-30 m) penetration in up to 6000 m water depth. This system makes use of coiled tubing technology, whereby a flexible stainless steel tube is wound around a drum, and is straightened as the test proceeds and the tube unwinds. A second system, the DS7000, is operated with the same principle as the Penfeld but has a greater penetration force and is limited to operation to 2000 m water depth.

Evans *et al* (1998) discuss some of the challenges faced by geotechnical engineers working on the first oilfields West of Shetland, Foinaven and Schiehallion/Loyal, both developed using FPSO's. Technical difficulties associated with deploying seabed PCPT's were caused by weak soils at the mudline and included excessive settlement of the seabed frame in addition to buckling of seabed PCPT rods due to low lateral support.

Current in-situ seabed tool deployment systems are listed in Table 6.

Table 6 Seabed deployment systems

Seabed tool	*Reference*	*Comments*
Wheeldrive Seacalf PCPT System.	*Meunier et al, 2000* *FUGRO, 2001*	• penetration thrust capacity of up to 20 tonnes • in use for offshore SIs since1972 • capable of pushing cone penetrometers 20 m into dense sand and 30-60 m in softer clays • uses a hydraulic umbilical, limited to 800 m water depth
Modified Seacalf system	*Hawkins and Markus, 1998*	• 2000 m operating water depth • can perform 10 cm^2, 15 cm^2 and 33 cm^2 CPTs and shear vanes to 40 m penetration • deployed with twin line lifting cable and logging cable
Tethered Sea Floor Platform	*Humphrey and Adams, 1995* *Meunier et al, 2000* *Power and Geise, 1994*	• Developed for collecting geotechnical data in up to 3000 m water • Thrust capacity of 180 kN (pushing) • Designed for up to 70 m penetration (soft clays) • Deployed on a single lift line umbilical • Can deploy CPT, PCPT, seismic cone, core pressuremeter, and shear vane
Deepwater Seascout mini CPTsystem	*Power et al, 1994* *FUGRO, 2001*	• deploys a mini-cone (1cm^2 cross-sectional area) • assembled on tripod weighing less than 10 kN [i.e. light frame] • miniaturised version of heavy seafloor CPT units such as 'Sea Sprite' and 'Sea Calf'. Penetration depths of up to 6 to 10 m possible • 4^{th} version can operate in 2000 m water depth • thrust driven by underwater hydraulic power pack • separate hoisting and power cables
Modified Deepwater Seascout	*Hawkins and Markus, 1998*	• can perform 1 cm^2 or 33 cm^2 CPTs and in-situ vanes to 5 m penetration depth • thrust machine • operates in up to 3000 m water depth • Light frame
'Sea Robin' Seabed PCPT System	*Hawkins and Markus, 1998* *Fugro, 2001*	• designed to perform large numbers of consecutive PCPT's in deep water • designed for long distance submarine cable route investigations • lowered to the seabed on combined lifting/signal/power umbilical • 2 m PCPTs, 1m long push samples and grab samples possible • penetration force provided by Fugro 'Wheeldrive' system, hydraulically driven wheels
Seasprite	*FUGRO, 2001*	• designed primarily for pipeline route soil investigations • can penetrate with PCPT up to 5 m • water depths up to 1500 m • combined power and signal umbilical
Penfeld	*Meunier,2000*	• limited to 40 kN penetration • up to 20 m penetration in soft soil

Light seabed frames are reportedly capable of generating limited penetration for in-situ test devices (approx. 5 m) and limited sampling thrust but they are extremely light and portable, characteristics essential for deep water purposes. They are considered suitable for mounting testing equipment which provides pipeline routing and drag anchor survey data. To facilitate deeper penetration, smaller diameter probes are recommended to be tried. It is hoped that seabed frames of similar geometry and weight but capable of penetrating to 50 metres below seabed will be developed.

Heavier frames deployed from multi-functional vessels capable of pushing to greater depths are already reported to exist. Downhole tools are considered replaceable with heavy seabed frames, which are currently capable of up to 40 metres penetration in soft soils. According to our industry response, heavy seabed frames are generally used for pipeline, jack up mudmat and drag anchor surveys. However, settlement of heavy seabed frames is considered a potential concern in soft soil.

Although the trend is to increasingly use sea bed frames deployed from non-specialist vessels to operate in-situ testing tools or samplers, premature refusal is an issue. In-situ tests and sampling deployed from sea bed frames may not reach the target penetration due to thrust limitations and/or deviation of test device. Hence sole reliance on this type of device carries increased risks of incomplete investigation.

2.2.4 Integrated ground investigations

In the opening address of the 1998 SUT conference, (Walker, 1998) discussed the high cost of soil borings in deep water and the greater uncertainty faced by design engineers when information from only a few boreholes is available, albeit combined with shallow geophysical data that may enable feature mapping between boreholes. The accelerated pace of development may mean the traditional 2-stage survey programme – preliminary followed by detailed ground investigation – will be reduced to a single stage integrated investigation (or one ‘bite at the cherry’, Walker, 1998).

There are few case studies of ground investigations implementing geophysical surveys for the purpose of optimizing geotechnical data collection. Three examples are described below.

Marlin deepwater field – Gulf of Mexico

Jeanjean et al (1998) conducted an integrated geophysics-ground investigation to characterise the Marlin Deepwater Field on the Gulf of Mexico continental slope for input to suction caisson holding capacity calculations. After completion of all geophysical surveys (surveys in 1986, 1993 and 1995) including surface and deep-towed sub-bottom profiler, multi-channel processed seismic and side scan sonar data, a ground investigation was conducted comprising four boreholes positioned to investigate known conditions in the vicinity of the proposed structures and at locations where shallow gas/mass movements were known to exist. The geotechnical properties between boreholes were able to be interpolated with increased confidence along lines of deep-tow geophysical data (Jeanjean *et al*, 1998).

Foinaven and Schielhallion / loyal fields – west of the Shetland Islands

Evans *et al* (1998) reviewed the geotechnical challenges faced in planning and conducting site investigations and design work for FPSO production systems at the Foinaven and Schiehallion/Loyal fields west of the Shetland Islands (both are now in production). The time taken for reservoir appraisal, engineering design and construction were shortened and overlapped for the two prospects (so-called Parallel Engineering), resulting in a completion time of about half the time required for a traditional approach to oil field development. Bathymetric and high-resolution seismic surveys covering an area of 900 km^2 were performed before geotechnical investigations were conducted. The geotechnical investigation's objective was to conduct enough exploratory boreholes and in-situ tests in a single investigation to characterise the main units and to calibrate the geophysical surveys. The geotechnical work comprised box core, piston sampling and thin-walled piston sampling in addition to seabed and downhole PCPT's and in-situ vanes tests. The results showed that for relatively uniform soils (such as at Foinaven) it is possible to combine shallow 3D geophysics with a one-off programme of selective drilling and soil testing to develop a geotechnical model suitable for designing anchors and sub-sea structures for a planned FPSO development. However, when the shallow soils are variable (as at Schiehallion and Loyal) it is likely that further boreholes or in-situ tests will be needed to avoid over-conservative designs and/or unacceptable installation risks (Evans *et al* 1998).

GEOSIS project

Nauroy and Dubois (1998) outlined the work of the 'GEOSIS' project, the objective of which was to improve the integration of shallow seismic and geotechnical data for offshore site investigations. The research group conducted a very high resolution (VHR) shallow seismic survey, combined with vertical seismic profiling (VSP) and cone penetration tests in geotechnical boreholes. VSP and seismic cone data was used to determine the P-wave velocity (Vp) and S-wave velocity (Vs) respectively in the soil sediments for calibration of the surface VHR seismic data. A correlation between P and S-wave velocities and CPT tip resistance, qc, enabled the VHR seismic time section to be transformed to be a CPT cone resistance versus depth plot across the VHR lines profiled. While the results proved promising, there is still no universal (non site-specific) P and S-wave velocity-tip resistance correlation and the costs of such a study may be currently too high to be justified for industry application.

Some further case studies of integrated investigation

Further cases where geophysics and geotechnical investigation have been integrated are presented by Raaij *et al*, 2002. These have been presented for investigations for the Mikkel development and Kvitebjorn pipelines. The benefits were shown to be:

- Reduced program of laboratory testing
- Higher confidence with regard to strata thickness and variability
- Increased spatial awareness with regard to position of boulders for optimising location of conductors and skirted foundations

Similarly a deepwater site investigation in the Gulf of Mexico, presented by Liedte (2002), where the geophysics and geotechnics investigations were integrated was performed primarily to identify geohazards and provide good quality soils information for foundation design in a cost effective manner. This was achieved by using a combination of Hugin 3000 AUV, PCPT and boreholes.

With the high costs associated with deepwater boreholes it will be increasingly difficult to justify the benefits of a large ground investigation comprising a sufficient number of boreholes to characterise the areal coverage required for installations in deeper water. As a result more economic methods of obtaining ground information, such as geophysics, to complement boreholes are likely to be undertaken more frequently. The concept of developing a terrain model using limited borehole information to provide an initial evaluation of soil conditions, linked to a programme of geophysics to aid the assessment of stratigraphy variation, deserves serious consideration. This is often more important in deepwater projects where anchor locations for FPSO's can cover a very large area and key locations during planning can often be subjected to change after the ground investigation period.

There is the possibility that having regional coverage may tend to reduce the likelihod of undertaking subsequent detailed surveys. This would not be a desirable trend though, used properly, well constructed regional surveys supplemented by terrain models of site specific areas would be advantageous and almost certainly cost and safety effective.

2.3 GEOTECHNICAL ANALYSIS AND DESIGN

2.3.1 Current situation

The great majority (95%) of substructures of facilities in the UK sector of the North Sea are steel. The American Petroleum Institute (API) and American Institute of Steel Construction (AISC) codes have dominated substructure design (Laver, 1997), but in the last few years there has been a considerable amount of effort in the development of new codes for the offshore industry in Europe and the USA. This effort has been coordinated by the International Organisation for Standardisation (ISO) and the American Petroleum Institute (API). Up until recently, the API recommendations took the form of a working stress design (WSD) approach, which has proved historically to result in 'safe' and installable foundations in the North Sea. New developments in the analytical approaches to design, including an ever increasing requirement to assess the reliability of each component of a jacket design (including the foundations) has led to the production of a load and resistance factor design (LRFD) version of API RP2A. This LRFD version is to be used as the basis for the new international standard for offshore structures, ISO 13819 (Aldridge, 1997). In the future, there is likely to be an industry shift towards this new harmonised ISO standard for the design of offshore structures (Laver, 1997).

In the LRFD approach, loads and component strengths are modified by partial safety factors representing their individual statistical uncertainties. Such an approach results in a more uniform reliability (safety) for a wide range of load and load combinations and component types, when compared with the existing working stress approach (Laver, 1997).

Re-certification of existing platforms for continued use is now a requirement in the API's RP2A Code, and this may therefore be expected to become part of the new International Standard for offshore structures. Such re-certification requirements depend on whether the platform is manned or not, and on the consequences of platform failure. For the ultimate strength analysis the code permits the use of full analyses of the foundation, implying detailed numerical analysis be used (Aldridge, 1997).

The questionnaires and interviews solicited general responses on a wide range of analysis and design issues.

The principal findings were:

- *there are uncertainties with using the current methods for more geotechnically complex problems as a result of inexperience with newer foundation types, geohazards and cyclic loading issues*
- *design will continue to be largely empirical, but this is expected to change in the future*
- *it is wrong to reject empirically based design methods that have worked in the past*
- *model or scale testing is important for our understanding of foundations*
- *it is important to realise that in some areas of offshore engineering (e.g. computing dynamic response) the concept of safety factors (either lumped or partial) is itself not a sensible way of addressing reliability*

2.3.2 Pile foundation design

Lacasse (1999) believes that there is confidence, especially for clays, in the API RP 2A for offshore driven pile design. However, API design formulations for piles in sand can often lead to uncertainties in pile capacity prediction (Smith *et al,* 1998).

New methods have emerged for clays and sands and it would be worthwhile to evaluate these on the same basis as the earlier analysis methods, although many feel that pile resistance is a mature issue and that there is no reason to support further research. However, some important design aspects still contain important uncertainties or are not well understood. These aspects include: 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, strain-softening, loading rate and cyclic loading effects. (Lacasse, 1999).

The partial factors recommended for foundation design under the LRFD approach are based on calibrations carried out using data and practice applicable to the Gulf of Mexico and US waters. Smith *et al* (1998) describe a Joint Industry Project to investigate the applicability of the LRFD method for pile design for foundations in the North Sea.

They report that:

- the WSD and LRDF lead to very similar design pile length requirements for piles in clay soils
- the LRFD method can give considerably longer piles in sand (particularly when tension governs)
- a comparison of pile capacity calculations from the API formulations with results from pile load tests has shown that the API models give poor predictions for sands
- furthermore, the current API design methods do not account for many of the factors known to affect pile capacity, such as loading rate - recent methods are able to provide more accurate assessments of capacity

Jardine and Chow (1996) summarise a new procedure for assessing axial capacity of offshore piles, Imperial College Method, which was the product of an extended programme of research by a group from Imperial College, London. The new procedures offer theoretical and possible practical advantages over existing approaches (which include the new API method). When tested against a newly assembled database of high-quality field tests, this method can reputedly produce more accurate predictions for the medium-term shaft and base load capacities of single piles in both sands and clays. The research work also identified important effects of time and group action for piles in sand.

2.3.3 Skirted/suction foundation design

Skirted foundations and anchors are competitive alternatives to more traditional foundation solutions for offshore platforms (Anderson and Jostad, 1999). Design methods to predict capacities for suction piles are not standardised to the same extent as for conventional piles (Tjelta, 2001). No general rules and regulations exist that specifically reflect this new foundation technique. However, some codes (e.g. NORSOK codes) have made certification or authority approval easier and, as such, have contributed to the rapid growth of this foundation solution (Tjelta 2001).

Work has been progressing within API to establish the state of practice in design of deep water anchors. The objective is to develop a widely applicable recommended practice for the design and installation of deep water anchors (Tjelta, 2001).

Suction pile design is not yet standardised and consequently project-specific design procedures are developed (Tjelta, 2001). With the knowledge now available in suction anchor design, it should be possible to design a standard suction pile that can be used in a variety of soil conditions by varying length and which is sufficiently robust for different installation techniques (Tjelta, 2001; Anderson and Jostad, 1999).

Two comments from industry are relevant here:

- full-scale tests under permanent tension are required to reduce the uncertainty in design of suction caissons for TLPs and of taut leg moorings for SPARs. Recommended design methods included FEA (Finite Element Analysis) and centrifuge test results.
- the importance of considering the suction installation, because the installation process modifies soil properties (i.e. weakens the soil). It is a factor that is not adequately accounted for in some design approaches. The adoption of higher than normal factors of safety may be required.

2.3.4 Model testing

The testing of physical geotechnical models can be a very valuable way of investigating the mechanism of foundation failure, the deformation pattern, the soundness of a design method, and the reliability of a calculation model. Physical models enable a considerable reduction of the uncertainty in a calculation model. Model tests can be 1-g models in the laboratory or in-situ, multi-g centrifuge tests, or full scale model tests. However, model tests are expensive and need to be carefully planned and run (Lacasse, 1999). Nonetheless the benefits of physical modelling are well accepted by the offshore industry and has greatly attributed to the development of new physical models (Lacasse, 2002).

2.3.5 The observational method

The Observational Method must always be applied in a disciplined and structured manner with appropriate caution. The technique is best applied after thorough ground characterisation and analysis and where there still remains some degree of residual risk.

It is important to make as thorough subsurface investigations as practicable, to set a course of action on the basis of all possible set of circumstances and to formulate in advance the actions to be taken when each circumstance is encountered. It is essential to have fully worked out designs and contingency plans with all necessary material and manpower on hand. The technique requires real time observation, measurement and analysis. In the right circumstances the OM is a powerful tool. A significant issue for OM with offshore foundations is appropriate contingency measures if performance does not match that anticipated.

The merits of the observational method have also been noted by Lacasse, (2002), in her keynote address at the SUT Conference.

2.3.6 Training and technical competence

Feedback from the industry interviews indicated concerns in the training of engineers. It was recognised as being most important that skilled staff were being continuously developed through formal training and gaining experience under the supervision of older members of the peer group. Some interviewees felt that experienced geotechnical practitioners are leaving the industry and that there are currently insufficient experienced, qualified people within the industry.

One interviewee stated that there has been a loss of expertise within the oil and gas companies as they have let staff go and/or abandoned the concept of a central soils/geotechnical group advising internationally.

There does appear a case for greater integration of offshore training covering a range of fields such as geophysics, geomorphology and geotechnical engineering. However such an educational approach would undoubtedly lead to dilution of the level of expertise in what are regarded as separate disciplines. The size of the market and its probable longevity must be borne in mind if steps are taken to train scientists and engineers in the offshore sector.

The issue of succession planning in many sectors of the economy is of considerable concern to the UK's scientific and engineering community.

3. SITE CHARACTERISATION ISSUES

In ground engineering, where there will always be imperfect knowledge of the ground and its behaviour, any assessment of hazards must also consider uncertainties. Some types of uncertainties in ground engineering are listed in Table 7 and illustrated graphically in Section 5, figure 22.

Table 7 Some uncertainties in ground engineering

1.	*Spatial*: proportion of ground sampled and tested tiny in comparison to area (volume) of site; uncertainties in the geological understanding (the geological model)
2.	*Parameter*s: inherent natural variability of soils and soil parameters, and difficulties in measuring them.
3.	*Geohazards*: e.g. instability, erosion, methane hydrate, submarine slide
4.	*Bias*: from investigation methods, sample extraction (disturbance) and testing
5.	*Modelling*: uncertainty in both the accuracy and applicability of numerical models and simplifications required
6.	*Error*: in site investigation, interpretation, design, construction, communication
7.	*Construction and operation*: e.g. structural dimensions and loadings

3.1 GEOPHYSICAL INVESTIGATION TECHNIQUES

3.1.1 2D multi-channel seismic and high resolution profiling

Conventional site survey data is still being gathered for geohazard surveys utilising the highly successful ‘Sleeve’ AirGun developed in the late eighties utilising clusters of guns to provide a minimum phase (i.e. very short) pulse. Although 2D seismic is now considered a mature technology, a double chambered Airgun (the GI source) has recently been developed by Michel Gross of Sodera to improve suppression of the unwanted bubble pulse behind the initial signal. This has been as successful as the clustered Airgun approach using only a single unit slung under a buoy. Source is expected to provide 8/10 bar metres 20-200Hz signal with a Primary to Bubble ratio of 15 to 1 (i.e. an initial pulse which is 15 times the amplitude of the following unwanted bubble ‘train’). None of these guns can be operated at depth and retain the high frequency energy. This seems a stumbling block to acquiring 2D data of high quality in deep water (i.e. getting source and streamer close to seabed. Some experimentation is being undertaken by Ifremer with the old Sparker method for the COSTA project. The French are also developing a hybrid system with a shallow source but a deep towed streamer to minimise weather interference (the PAISAR system). Development of a swept medium-frequency P-wave source (equivalent to land Vibroseis) was reported by Schlumberger in 1999 at an IAGC/UKOOA workshop; an S-wave vibrator source, the Vibropile, for better evaluation of soil/rock parameters was reported at EAGE 2004.

BP Amoco adopted a ‘fast track’ site survey approach at the Foinaven deep water prospect to enable the field to be developed in a very short space of time. With the benefit of an experienced in-house seabed survey specialist, Andy Hill, the developers were persuaded that 2D coverage of Mini-Airgun with six channel recording (to provide data down to the first water bottom multiple) plus high frequency Boomer (to give data for engineering considerations) should be acquired over the whole of the area of potential field right at the beginning of the programme rather than the traditional well by well survey. From a 2/3 month survey up-front, coupled with the conventional 3D data for intermediate depths, all geohazard/engineering integration was efficiently achieved and interpreted as needed. The comprehensive data coverage achieved at Foinaven project has been revisited for detailed interpretation several times now.

In a similar manner ‘Ultra High Resolution’ 2D digital data has been gathered with a Sodera S15 sleevegun for Shell in conjunction with Swathe Bathymetry and Sonar (Fledermaus).

Whilst the basic technology on the multi-channel data collection has been in place for many years there are on-going developments in source development and use which tend to favour much lower power units than had been used previously with less emphasis on penetration than increase in resolution. Thus 3.5 seconds of Very High Resolution data with an 80 cu.in. air gun has been obtained in deep water. The benefits of multi-tool use in respect of utilisation of good weather periods still apply but do bring particular constraints with respect to differing tow depth and speed requirements.

3.1.2 3D Seismic

Use of exploration data

Together with 2D Seismic, near trace data from oil exploration data is used by geotechnical engineers to provide a semi-regional setting for the ground investigation. As these are additional data extracted from an ‘oil exploration’ coverage, it is very low cost in respect of the information recovered. But, whilst it provides a view of geohazards, it gives little information in respect of geotechnics. However 3D data has been used to obtain first seismic arrivals from seabed (seabed picks) to produce extremely effective seabed maps and can also, through horizontal ‘time slices’, provide higher resolution data at shallow depth than can be studied in purely vertical time/depth sections with respect to ambient frequency spectrum (70 / 80Hz) of sources employed. 3D data point separation (bin sizes) of 12.5, 17.75 and 25 metres which are currently employed limits the horizontal resolution available.

Vertical resolution is limited by source signal, its frequency content and the (common) digital sampling interval of 2 milliseconds. The latter sampling can theoretically provide 350Hz signal if the source has energy at this high level. Spectral and amplitude response of the seabed and sub-seabed are not yet being routinely extracted for correlation with borehole information. Whilst there is likely to be little flexibility in modifying geometry to assist with near surface data recovery, more care is now being taken to produce a good shallow sub-seabed record due to overall swifter processing capabilities with the new generation of computers.

In the late 1990s conventional exploration vessels were occasionally used to simultaneously gather high resolution data (Horizon/Geco) vessels. However this practice has not been known recently, possibly due to incompatible tow depths of streamers/guns and/or extra complications of deploying additional equipment. Mobil are known to have used a conventional exploration vessel to gather high resolution data, post a blow-out, when need for immediate data and cost, rather than technical requirements applied. The use of near trace bottom arrivals and the early part of the exploration record in deep water in 3D studies has been used to produce bathymetry and provide an overview of shallow potential hazards. Total are also known to use conventional 3D data to evaluate site and then do a site specific study depending on the likelihood of gas and the history of the area.

Site specific conventional 3D

3D shooting configurations for high-resolution data acquisition were initially developed several years ago for Total in the North Sea. This is typically used in medium depth waters where the risk of Shallow Gas Blowouts is potentially of more significance and where higher seismic frequencies are of prime importance. However Britsurvey/Svitzer (merged into FugroSurvey Ltd in June 2003), who were commissioned by TotalFinaElf to do the first of these some time ago, found that oil companies were reluctant to spend the money (on extended weather down-time waiting on good shooting conditions for shallow tow streamer) to gain this superior type of data. Thales Geosolutions (formerly Sage Survey and now taken over by Fugro) also question whether oil companies are likely to be willing to pay for site specific 3D studies. Nevertheless, such surveys have been carried out with 4/6 streamers of 12.5 or 6.25m channel spacing with 0.5 sampling and 500Hz source (4x10cu.inch or 2x10+2x20cu.inch sleeve guns). One such study was to investigate deep piling conditions in difficult ground.

Fugro-Geoteam have used a 140 cu.in. airgun source with 3 Streamers for shallow water/target for Site Specific HR 3D seismic data collection and have had interest in this approach from Enterprise and Marathon.

Short offset 3D data

This is a development first mooted by Paul Newman, then of Horizon, in 1988 for use in shallower waters. He proposed that for shallow sub-seabed investigations high resolution data was available from single reflection point data at short offsets without going into multiple trace ‘binning’ from multi-channel longer offsets as is conventionally undertaken. Some such recording has been done during conventional 3D exploration surveys with offsets as short as 100/200m. In order to recover high frequency data the recording hydrophones, although sometimes placed at the front end of a conventional ‘exploration’ streamer, actually require to be towed at shallower depths to recover the required spectrum. This apparently has been done (Svitzer have interpreted such data) and assisted in identifying Quaternary channels which were subsequently identified in time slices, not seen in the original exploration time section. If shallow tow is used this becomes much more weather dependent (as with conventional site surveys) and loses its cost benefit.

Whilst UK contractors had not utilised this approach, several very successful surveys have been undertaken in the Gulf of Mexico (GoM) deep water with outstanding results both in presentation of sea floor conditions and fine resolution of subsurface features. The methodology uses six short (100 metre) streamers and a small volume airgun or airgun array. The first Short Offset 3D survey was collected in 1996 for Shell in the GoM in an area with known shallow flow problems. Initial take up by the oil industry was slow but much data has now been acquired data for Shell, BP Amoco, and ExxonMobil. Many of the smaller operators have not yet arrived at the development stages of their deepwater prospects and over the next few years it is expected that there will be an increasing demand for this service. The significantly increased spatial resolution and frequency content offered by this technology helps reduce drilling and development costs by allowing operators to:

- explore and develop shallow reserves on the continental shelf
- conduct research studies for subsurface modelling
- collect 3D seismic in congested field due to the operational efficiency of short-offset
- evaluate the shallow stratigraphy for potential hazards and engineering constraints such as streamers

High resolution 3D seismic data bridges the resolution gap by providing detailed, near-outcrop scale imaging of the shallow sediments that is missing from 3D conventional data.

3.1.3 Geotechnical data extraction

Seismic wavelet processing

Whilst high resolution contractors are aware that phase, frequency and amplitude can be extracted from the return wavelet there was no use of this technology at the time of the interviews. Svitzer had used attributes to assist in mapping buried debris flow. The increasing requirement for faster turnarounds could reduce time spent on analytical work. The Fugro Geoscience Division now operates exploration seismic vessels as well as site survey craft. Seismic processing is performed using fully maintained versions of DISCO / FOCUS from Paradigm Geophysical. This well-established software is used throughout the industry by both oil companies as well as service companies. This is complemented with proprietary, internally developed algorithms and Hampson and Russell’s AVO software and the widely recognised SEGY compressional software, Seispact from Aware Incorporated. It is therefore likely that this technology will become available for ground investigation in the near future.

Seafloor characterisation

High frequency piezo-electric and hydro-mechanical sources on long tow cables have been in use for deep water cable route surveys for many years. Early versions of these, such as the Huntec (not strictly deep tow), had signal analysis capabilities enabling some quantitative assessment of bottom conditions to be made (RoxAnn System).

For several years a seafloor characterisation project has been running under the co-ordination of the University of Trondheim with EU financial support (EU MAST III programme MASa-CT95-0046). Five exploitable results have been identified by the Technology Implementation Plan of the ISACS (Integrated System for Analysis and Characterisation of the Seafloor) programme are shown in Table 8 .

Table 8 Seabed geophysics software packages

Software name	***Comments***
XFEM-S	a computer tool for model studies of acoustic scattering
SirOb	inversion software for seabed parameter estimation from acoustic back scattered data
FARIM	software for estimation of roughness and acoustic impedance of the sea bottom
SURF3D	software package for processing and visualisation of volumetric sonar data
TRISMAP	software for processing of bathymetric data

Of the software packages shown above, SirOb and FARIM would seem to hold particular interest. The former is a Matlab-based package for analysis and inversion of normal incidence backscattered data from parametric sonar instruments. It has the potential to become an additional analysis tool in the data process of seabed acoustic surveys. The key innovative feature of SirOb is the use of a generalised time-frequency domain transform in order to extract relevant features from the raw data. The current software requires precise source calibration and expert tuning of inversion parameters and has already been used to obtain estimates of geo-acoustic parameters on a test site. FARIM is a computer tool for acoustic seabed characterisation, estimating the roughness and impedance of the seafloor. The processing speed is high allowing real time processing. The method is applicable to normal incidence backscattered low frequency (few kHz) broad band time series signals from acoustic echosounders.

The incorporation of these tools within the developing AUV/ROV swathe bathymetry, sub-bottom profiling and side scan systems, correlated with adequate ground truth, may provide the means to extrapolate measured soil properties over large areas in a controlled manner. At least one such system is already on the market. The ECHOplus ground discrimination system was launched in February 2001 using second echo techniques to determine ground roughness and hardness. This may extend to determination of grain size and possibly density.

It is considered that there is considerable technical merit in wide beam interferometry which can act as pseudo side scans sonar. Both Submetrics and GeoArcadis have promising tools. The earlier development of RoxAnn is not regarded as a technical tool although it has some value for 2D seabed lithology profiling.

It is expected that developments will ultimately extend the technology into the sub-bottom sediments.

3.1.4 Swathe bathymetry

Swathe bathymetry has been in widespread use since 1994 (Figure 13). Systems are usually hull-mounted, generally reliable and able to recover data at up to 7/8 knots in 5/6 sea state (30 kHz) and even 7/8 (14 kHz). Systems are available for both shallow and deep water but it is important to select correct frequency-for-task with the usual constraint that deeper water requires lower frequency (due to signal attenuation being frequency dependent) with consequential lower resolution. The higher resolution higher frequency systems have been mounted on AUVs and ROVs to get closer to the target zone. Footprint may be up to twice the water depth/tow height.

Up to now, the ability of systems to record a backscattered signal response (to provide reflectivity index and hence relate this to sediment type) has been less successful, and it is claimed that the processing development described above will raise the credibility of the technique. There has been an instance in the Gulf of Mexico where a low frequency system failed to record the 'true' seabed as it was a thick soupy mud and recorded the top of underlying material as the seafloor. Developers will need to give more attention on the QC side, improve visualisation methods and pursue the use of high frequency systems on AUVs for maximum usefulness in deep water. Statoil have sponsored a Simrad AUV project for pipeline survey route work.

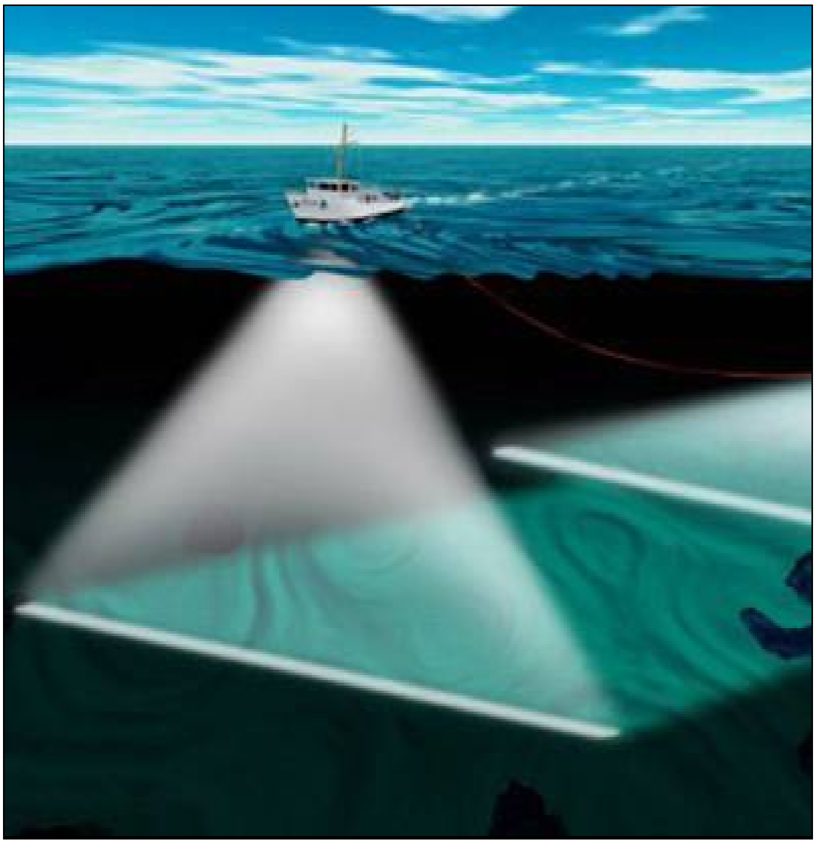
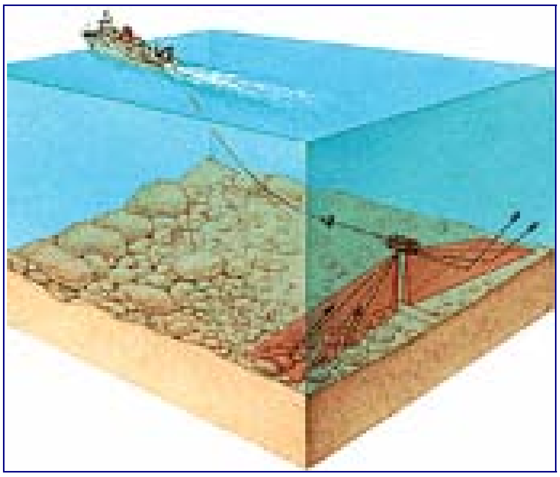


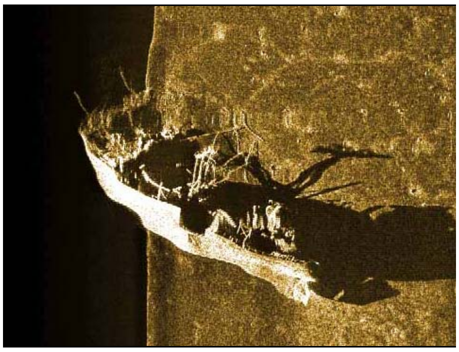
Figure 13 Multi-beam swathe bathymetry

3.1.5 Side scan sonars

This old but extremely useful technology has not advanced much recently. The new digital system of Klein (http://www.l-3klein.com) provides better data at long range and this enables the higher frequency units (500 kHz) with their finer resolution to obtain good data out to 60 or 70 metres across track. With a digital signal the requirement to build an on-screen mosaic of adjacent traverses becomes more readily possible.

On-screen interpretations however are not deemed as yet to be effective. Data balancing to achieve uniform output can compromise the meaning of the data without ground truth. There is therefore, a need to achieve better data manipulation and to be wary of current interpretative practices.





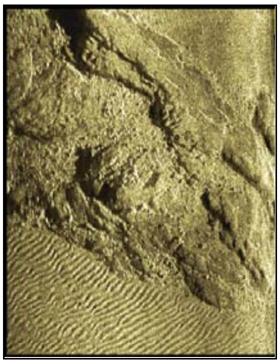


Figure 14 Side scan sonar and images

3.1.6 Sub-bottom profilers

Wide band digital sub-bottom profilers (Sub-Bottom Profilers - Figure 15) are now available which transmit an FM pulse that is linearly swept over the frequency range between 0.5 and 24 kHz. These 'chirp' systems transmit a signal burst of between 20 and 40 milliseconds. Received data is stored in an industry standard digital format enabling subsequent processing. Correlation with bottom sediment type in deep water environments (where they are being used for submarine cable route surveys) is being developed. However, whilst there have been advances, it is considered that the capabilities of the chirp systems have been oversold as penetration is frequently lower than expected.

There is a body of opinion that the technology of the early deep tow sources such as Huntec Boomer and Nova Scotia Research Foundation sparker was prematurely regarded as obsolete. However the move towards digitisation of high frequency profiler data has produced benefits enabling cleaner signals, higher resolution and processing to ultimately achieve quantification of the soil type.

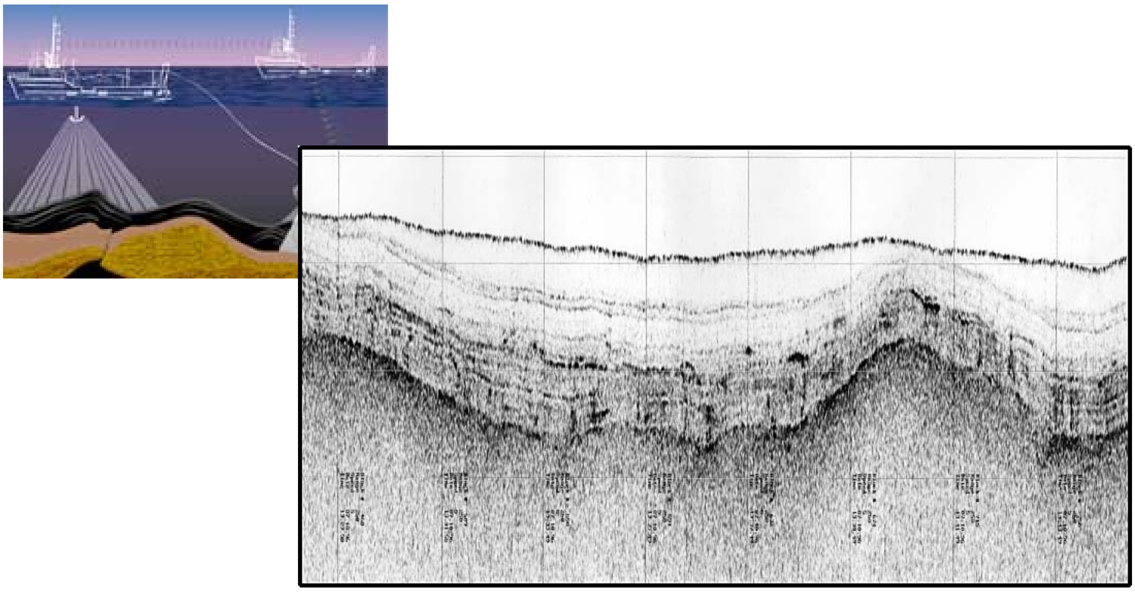


Figure 15 Sub-bottom profiling

Geophysics

Industry feedback - Some key points

- *Relatively little feedback comments on geophysics which may reflect that this field is less well understood by the offshore geotechnical industry*
- *Integration is considered to be the only way forward to investigate larger areas*
- *One pass investigation with geotechnical and geophysical investigations may be attractive on economical grounds, but is not considered practical and multiple passes may often prove necessary*
- *One pass investigation may also prove impractical due to the nature of a stationary vessel requirement, for the geotechnical investigations and trawling vessel for the geophysical investigations , such that real-time integration of the two is difficult to achieve*
- *Oil industry accepts and understands the importance of an integrated approach*
- *There are concerns with the detail that can be offered by current geophysical methods in general*
- *The sequence for carrying out an investigation is more important when undertaking an integrated investigation. Ideally a layered approach should be adopted for the site investigation with increasing level of detail added at each stage*

3.2 GEOTECHNICAL INVESTIGATION TECHNIQUES

The Offshore Site Investigation Forum (OSIF) has produced excellent technical guidance notes on acceptable good practice in the collection of geotechnical data for use in design, installation and operation of small sub-sea structures (OSIF, 2000).

Below is a selection of issues, presented to provide the reader with some further details related to geotechnical investigation techniques.

The degree of sample disturbance and hence parameter uncertainty is one of the most important considerations in geotechnical engineering design. Disturbance during the sampling process and the handling and testing of the sample involves some form of breakdown of the soil or rock fabric due to the mechanical action of the sampler and changes in the stresses imposed on the sample following its removal from the sea bed (Buckley *et al*, 1994). Collecting representative samples of weak soils at the mud line can be difficult (Lunne *et al,* 1998; Evans *et al,* 1998).

These concerns may be made more acute with the trend towards deep water site investigation. Lunne *et al* (1998) summarise the main reasons that deep water soil samples are more disturbed than those obtained in shallow water or onshore as follows:

- less control of sampling process
- use of simple sampling equipment from general survey vessels
- soil is more sensitive due to geological factors (e.g. brittle ooze material)
- stress relief during recovery causing expansion and disturbance
- melting of gas hydrates and subsequent expansion and disturbance to soil structure

These problems have a potentially major impact on the determination of the strength and compressibility of the sampled materials. But they are less important where the samples are required only for the identification of sediment type, the determination of geotechnical index properties or the lithological calibration of geophysical data.

The degree of uncertainty associated with a sampling method changes with sediment type. Acquisition of high quality undisturbed samples from cohesionless material (such as sands) is extremely difficult; foundation design parameters for such materials are therefore usually determined from in-situ tests such as the CPT (Tanaka *et al*, 1996).

In cohesive soils, thin-walled piston sampling is likely to produce the least uncertainty, although attention must be paid to the deployment techniques to ensure minimal sample disturbance. Techniques for reducing associated uncertainties by correcting for the effects of disturbance are the subject of continuing research.

Lunne *et al,* (1998) report that in deep water areas, gravity coring often prevails over the use of thin-walled piston sampling due to 'operational aspects'. Their study investigated the uncertainties in sample quality arising from both the use of (thick-walled) gravity corers instead of piston samplers and the effect of decompression during sample retrieval. They also attempted to quantify the degree of disturbance and to devise empirical procedures for overcoming the associated uncertainty by correcting laboratory consolidation and strength test results. However, further observations will be required before their empirical correction technique can be widely accepted or refined.

Recent trends in development and use of sampling techniques have occurred primarily in response to the move to deeper water sampling sites. Many of the established systems have been modified for use in deep water. State-of-the-art developments noted by one of the questionnaire respondents include a 'Mega Corer'. This follows the previous development of the Giant Piston Corer (Hollister *et al*, 1973) , the Advanced Piston Corer (Driscoll and Silva, 1977) and the Jumbo Piston Corer (Silva *et al*, 1999) whereby sample quality is improved by increasing the volume of the sample. The Mega Corer can be modified to sample seawater near the seafloor and to concurrently sample shallow gas and the sediment column; it is described as being able to operate in water depths of more than 2000 m.

Geotechnical Investigation

Industry feedback - Some key points

- *'Suitability-for-purpose' seems to be the guiding principle. For example, whilst the vibrocorer is extensively used, it is recognised as providing samples of poor quality as far as geotechnical laboratory testing is concerned, but is useful for providing lithological information in cohesionless soils which are otherwise difficult to sample. On the other hand, the box corer is often assumed to provide relatively high quality samples (when the acquired sediment volume is sub-sampled) but is limited by the possible depth of penetration (US Army Corps of Engineers document EM1110-1-1906, 1996)*
- *When asked specifically about the importance of minimising sample disturbance, particularly in very soft soils, most questionnaire respondents and interviewees said that thin walled piston coring (stationary or hard tie compensation) was the most suitable instrument to use, although the Mega Corer and box corer could also be used in shallower soils*
- *One respondent pointed out that sample disturbance was not a severe problem if empirical design routines that are followed are based upon relationships derived using samples of similar quality. However, sample disturbance was critical for designs which relied on newer, novel design techniques*
- *Larger investigation areas are required, for example assessment of soils at anchor location. Also often proposed site locations change after completion of site investigation*
- *Top few metres of soil is now often more critical, for example the design of small sub-sea structures compared to previously, for example the design of deep piled foundations*
- *Studies of correlations between long piston / drop corers and cones and other more conventional sampling techniques are being undertaken and more studies are required*
- *Concerns with sample disturbance especially associated with deep water sampling need to be investigated further*
- *Non-specialist site investigation vessels are considered by contractors not to be sufficient, since if the samples taken from such vessels are poor, (often considered to be the case in deepwater <2000 metres), then there is no opportunity for a borehole investigation. The oil industry's view is that there can be difficulties with the availability of specialist vessels and their associated costs compared to a non specialist vessel can be significantly higher*

3.3 GEOLOGICAL HAZARDS – GEOHAZARDS

Geohazards can be described as site and soil conditions having a potential (a certain probability) of developing into a failure event, causing loss of life or investments (Kvalstad *et al*, 2001). Some of the more common geohazards identified in reference sources, that may cause engineering difficulties for offshore foundation systems, are listed in Table 9.

Table 9 Geohazards

Geohazards		***Recent references providing description and /or discussion of geohazards in UK offshore areas***
Sea floor instability (episodic sediment flows)	Landslides and mass gravity flows (turbidity currents , debris flows and mudflows)	Borowski & Paull, 1997
Sea floor variability	Rough seabed, channels and ridge-canyon systems	Holmes *et al*, 1997
	Iceberg plough marks / scouring	Holmes *et al*, 1997
Gas / fluid pressure related features	Gas seepages and blow-outs	Holmes *et al*, 1997
	Over-pressured sediments	Holmes *et al*, 1997
	Pockmarks	Hugget & Masson, 2001
	Gas Hydrates	Kvalstad *et al*, 2001
		Long, 1993
Seismicity		Long, 1996
Faults		Long and Gillespie, 1997
Variable engineering properties	Very soft soils and oozes, disturbed ground, brittle sediments etc.	Long *et al*, 1998
		Long & Holmes, 2001
		Masson *et al*, 1998
		Musson *et al*, 1997
		Newman, 1990
		Read, 1998
		Simpson *et al*, 1998

Long (2001) reports on the work of the Western Frontiers Association group which was set up to investigate the extent of knowledge regarding the shallow geology of the area defined in this report as the West Shetland Basin (WSB). As part of the study, attention was drawn to potential and real geohazards in the area, with comparisons being made directly with the 'more familiar' North Sea area. It was already known that the ground conditions were more varied and the distribution of potential geohazards more extensive in the West Shetland Basin as compared to the North Sea (Long, 1993). Indeed, certain geohazards seen in the WSB are either not seen widely in the North Sea, for example, iceberg plough marks (both surficial and buried), or not seen at all as with debris flow slope failure (Long, 2001). Whereas in the North Sea shallow gas is of major concern, in the WSB the shallow gas can potentially also exist in hydrate form, further complicating the nature of the hazard. Sediment transport tends also to be more active in the WSB, with sediment waves being formed and moving at up to 500 metres per annum, sometimes driven by the locally strong slope-parallel contouric currents (Long, 2001). The WSB area tends also to experience seismic activity of greater intensity than the North Sea, and these have been known to induce slope failures in the past (Bugge, 1993). Brief descriptions of these geohazards and methods for their investigation are given below.

3.3.1 Sea floor instability

Slope instability and soil wasting have the potential to damage the installations located in the instability zone and downslope in the track of the slide blocks, debris flow materials and turbidity currents (Kvalstad *et al*, 2001). Because of the nature and state of the seafloor sediment and the associated failure mechanisms, slope failure can occur at very shallow slope angles. They can develop to affect upslope (and alongslope) areas by retrogradation and their run-out distances can be several hundred kilometres. For example, the slope failure associated with the 1992 Grand Banks earthquake caused major disruption of the seafloor over an area of at least 160,000km^2 (about the size of England). As such, they pose a potential hazard to interested third parties over a very wide area (Kvalstad *et al*, 2001).

Potential triggers for submarine slides include the following:

- rapid sedimentation
- gas and fluid vents
- zones with excess pore water pressure and gas pressure
- gas hydrates
- mud diapers and volcanoes
- earthquakes
- fault planes and active faulting
- weak unstable soils, e.g. ooze sediments
- man made activities, e.g. drilling

Evans *et al* (1998), state that the whole northern slope of the North Sea area has a 'long, but as yet chronologically poorly defined history' of slope instability. Significant ancient landslides include the AFEN, Storegga and Traenadjupet slides which occurred in the cold waters of the glacially modified continental slopes in UK and Norwegian waters (http://www.ig.uit.no/costa/project-des.htm).

The AFEN landslide (named after the Atlantic Frontier Environmental Network organisation) is a 'small' landslide, 3km wide and 13 km long discovered NW of Shetland, but it is considered to be of major significance. The landslide was identified from detailed TOBI (Towed Ocean Bottom Instrument) long range side scan sonar data collected for environmental purposes. It was an event that is postulated to have occurred at the end of the last Ice Age when large amounts of sediment were being washed into the area as the ice sheets and glaciers melted. Several episodes of slope failure have occurred over the last 10,000 years, in a geological environment similar to the present (Holmes *et al*, 1997). Although the AFEN website (http://www.ukooa.co.uk/issues/Afen/index.htm)states that studies of seabed stability by the British Geological Survey and others indicate that the seabed is now stable, it is nevertheless described as a 'modern' rather than a 'relict' process in the geological sense (Long, 2001).

The Storegga Slide is located on the Norwegian Margin in the NE Atlantic area of the UK and is one of the world's largest submarine slides. The scars of the slide, which is thought to have developed by three separate events, show evidence of gas hydrates and free gas. The slide is believed to be related to sediment weakness stimulated by dissociation of gas hydrates after a thermal warming affected the area since last deglaciation. The failure is of such a large scale that its activation is known to have created a tsunami event (c. 7400 years ago) which affected coastlines from the north coast of Scotland to the lowlands of northern Europe which skirt the North Sea Basin (Dawson *et al*, 1988; Dawson and Smith, 2000; http://www.ig.uit.no/costa/main.htm).

Recent datings of the Traenadjupet slide to the north of Storegga indicated that this slide is younger, possibly only 4000 years old, well after the cessation of marked sea-level rise associated with the end of the last Ice Age.

A considerable amount of work is currently underway to understanding submarine slides, given their potentially catastrophic consequences. Despite the low probability of their occurrence, the associated risks are still high. It is considered important to understand where relict slide surfaces are (given the potential for delayed failure), and where new slide events could potentially occur.

Regional studies by high resolution profiling and sidescan sonar with careful evaluation of the data by an experienced seabed terrain specialist will help to identify such areas. However only those features which exhibit dimensions at a scale resolvable by the equipment employed will be identified. To avoid uncertainty in the setting of a given location it is essential to re-identify features from lower frequency tools at the site investigation stage.

3.3.2 Sea floor variability (canyons and channels)

Canyons represent large channel-like morphological features which act as a significant conduit for sediment transport between shelf and deep water areas. They are usually very large morphological features such as those found on the slope of the UK South Western Approaches. Arminshaw *et al*, (1998), in a study of the Hebrides Slope define three types of canyon at that location which are comparatively small features: shelfbreak canyons (1 – 4km long, 'narrow' and of 15m to 50m bathymetric relief); slope canyons (10 – 20km long, 0.5 to 2km wide and up to 100m relief); and slide-margin canyons (up to 15km long, 100 – 600m wide and with a relief of up to 100m).

Seafloor channels can pose a potential geohazard in as much as they are often infilled and associated with abrupt changes in lithology from the surrounding sediments, often leading to rapid changes in the engineering properties of the seafloor. Masson (2001) reports on the geological context, areal extent and distribution of channels in the WSB area. Many are not infilled and pose a hazard as a morphological feature. Their appearance is generally restricted to between the 650m and 1000m contour – shallower occurrences are thought to have been subsequently infilled. They are between 50m and 250m in width and can reach depths of up to 40m. It is postulated that they were feeder channels for debris flows. An additional area of infilled channels occurs between about the 500m and 550m isobaths but is not described further (Masson, 2001).

Much valuable use has been made of near trace offset data from conventional 3D exploration data to map such features. Where proposed facilities are situated on or adjacent to such features it will not be adequate to rely on such data to identify changes in engineering properties.

3.3.3 Iceberg plough marks/scouring

The grounding of icebergs causes local loading and some overconsolidation of underlying sediments and scouring may cause remoulding of the surface sediment. Iceberg activity is climatically controlled and buried scours are likely to be coincident with regional unconformities. Such relict ice-scoured surfaces have been identified to the north and west of Scotland where the break between shelf and slope is fringed by iceberg scour marks, forming a cross-cutting network of furrows, typically 20m wide, 2m deep and up to 5.5km long (Masson, 2001). Such relict ice-scoured surfaces are also evident in the central North Sea, around the margin of the Witch Ground Basin (Stoker & Long, 1984).

Scours are likely to be infilled with recent, low shear strength muds. Uncertainty concerning the nature of immediate seabed conditions will only be resolvable with multiple frequency, narrow beam echosounder to complement swathe/multi-beam data.

3.3.4 Gas/fluid pressure related features

Gas seepages and blow outs

Gas seepages can result from sources such as biogenic methane production or may be derived from petrogenic gases seeping from depth. Gas under pressure can cause a reduction in effective stress in the soil and hence a decrease in shear strength, and pile foundations sited above shallow gas horizons are likely to be affected by unpredictable bearing properties, as well as providing potential gas migration routes. Large gas pockets, if ruptured, pose significant dangers from blow out, ignition or in extreme cases, loss of buoyancy for floating vessels where large quantities of gas escape into the water body (Fannin, 1980). Gas bubbles filling voids in sediments are common in many parts of the North Sea and several shallow gas ‘blowouts’ have occurred during North Sea drilling (Fannin, 1980).

Overpressured sediments

A number of geological, geophysical and geochemical processes can lead to excess (higher than hydrostatic) pore pressure generation:

- rapid sedimentation
- smectite-illite conversion
- pressure and temperature changes in gassy soils
- gas hydrate melting
- underground blow-out
- earthquake and shear strain induced pore pressures

(after Kvalstad *et al*, 2001)

Overpressured sediments generated at significant depths (800m to 3000m) below sea bed may result in fluid flow through overburden and along faults and fluid escape features, such as mud volcanoes. Underground blow-outs may generate connection between a deeper, high pressure zone and shallow strata leading to increased pore pressure at shallow levels. In the shelf area this may lead to extensive cratering and loss of foundation support of installations within the affected area. On continental slopes this can be even more critical. The rapid change in total stress caused by loss of overburden in submarine slide areas might lead to ex-solution and expansion of free gas in the backwall area and in deeper strata, effective stress reduction, and could thus contribute to retrogressive and staged development of the sliding process (Kvalstad *et al* , 2001).

Pockmarks

Pockmarks are shallow depressions formed in soft clay sediments. It is generally accepted that pockmarks are an escape phenomena and model experiments in soft clay have shown that gas bubbles will produce a shallow depression (Fannin, 1980). The danger they represent may be due to either or both their morphology or mode of formation (Fannin, 1980). These features are common in the northern North Sea (Fannin, 1980) and have been recorded over much of the lower slopes and basin floor of the northern Rockall Trough (Hugget and Masson, 2001). Typically in the northern North Sea pockmarks are oval in form with a long axis of around 57m with a mean depth of 2m, though they may be up to 8m deep, see (Fannin, 1980).

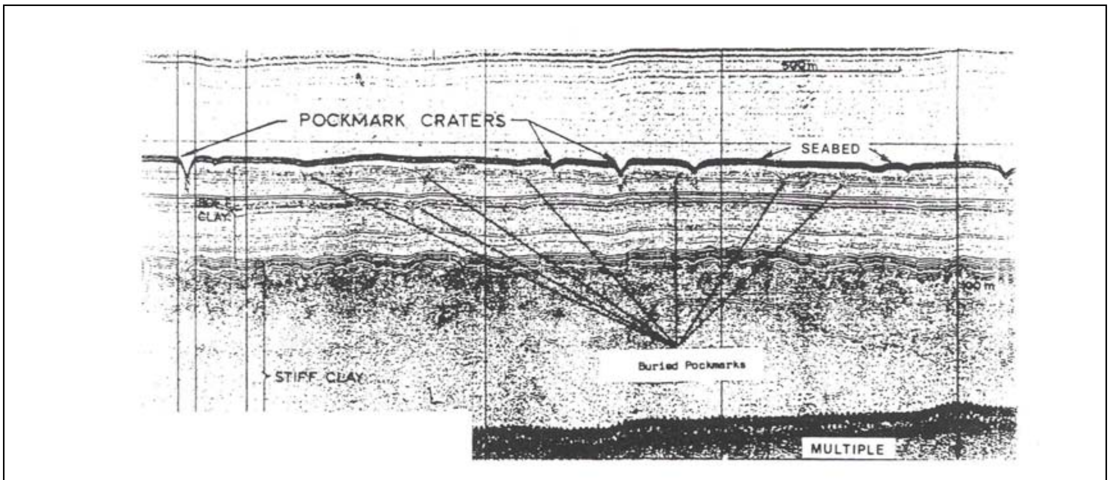


Figure 16 Acoustic record of pockmarks – North Sea

Gas hydrates

Gas hydrates are a solid phase composed of water and low molecular weight gases (predominantly methane) which forms under conditions of low temperature, high pressure and adequate gas concentrations – conditions common to deep-water environments on continental margins (typically below 1250 metres). Below the gas hydrate stability zone hydrates are not stable, and methane will exist as free gas or be dissolved in the sediment pore fluid.

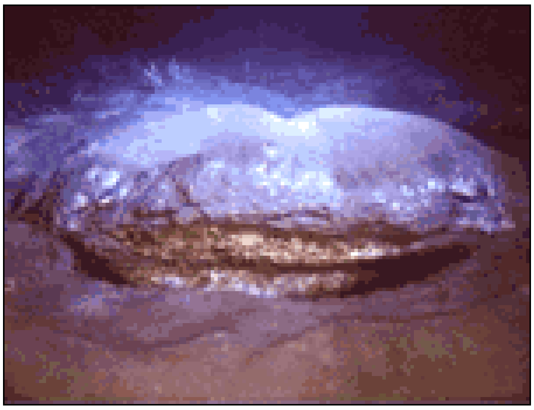


Figure 17 Methane gas hydrate mound on sea floor

Methane gas hydrates form as solid, ice-like mixtures of methane gas and water. Problems associated with gas hydrates are:

- reduced shear strength and consequent sediment instability
- corrosion and dissolution of materials
- sea bed erosion
- environmental concerns associated with methane gas release
- formation of seafloor biological communities that subsist on methane
- thaw settlement when heated
- dangers from blow out, ignition or in extreme cases loss of buoyancy for floating vessels.

Gas hydrates are also an important factor in seabed instability as changes in hydrate stability may be a trigger for major landslides (Long *et al*, 1998). Features associated with hydrates have been identified west of Shetland (Holmes *et al*, 1997).

High resolution seismic studies continue to be used to anticipate such features. Until such time as data is routinely gathered in 3D the extent and thickness of gas bearing zones will be uncertain. Further analytical work is required on recognising overpressure zones from seismic velocity and other seismic attributes to reduce uncertainty in these circumstances.

3.3.5 Seismicity & faults

The North Sea area has been subject to significant passive monitoring for seismic activity for the last 15 years and it is apparent that seismic activity can differ greatly from adjacent onshore areas. The monitoring programme has been successful in generating sufficient data to permit meaningful risk analyses to be performed (Marrow, 1992; Musson *et al*, 1997). Long and Holmes (2001) state that the northern end of the North Sea is quite seismically active, with 90 events of magnitude 3.0 ML or greater being detected over the last 30 years. Long (2001) reports on the installation of a series of new seismograph stations along the NW coast of Scotland in order to monitor the seismic activity in the WSB area. Preliminary results would indicate that 'only limited areas are at risk of slope instability' (Long, 2001).

Where faults are active numerous problems can arise, as the ground is prone to moving, thereby potentially rendering large areas unstable. Also active faults can be associated with the release of gases.

For example, on the continental slope west of Shetland three prominent shallow faults zones have been identified:

'A 7km long E-W aligned system with 100ms (85m) total depth range lies close to the northern margin, while a 6km long NE-SW overlapping pair of fractures follows the eastern half of the southeastern margin, with similar vertical range. A 3km long NE-SE system in the northwestern corner also displays multiple sets, with a vertical range of 30-60ms (25-53m).' (Read, 1998)

Following the acquisition of high resolution survey data another study should be made to identify evidence for late stage movement of the sediments above each fault line. Such evaluations should reduce the uncertainty in the assessed probability of sediment movement caused by local subsurface fault reactivation.

Geohazards

Industry feedback - Some key points

- *Lack of experts in this field who are able, for example, to understand the causes of the Storegga Slide*
- *Risk issues in deepwater in relation to geohazards are not perceived as critical compared to shallow waters, with the exception of steep slope areas*
- *It is considered that deep water geological features and hazards such as slides and canyons tend to be more regional than local*

3.4 GEOLOGICAL MODELS – INDUSTRY FEEDBACK

Responses were solicited from two areas: the first related to geological modelling (some including geohazard identification and mapping) and how that would be affected by recent technological advances; the second related to the availability of geological information to interested parties.

Respondents were initially asked to comment on the adequacy of conceptual geological models based on data obtained from new technologies (e.g. geophysical methods). It was pointed out, by the respondents, that most geological models were constructed from a combination of both direct sampling and remote sensing (geophysical) tools. Inadequacy in the models often resulted from the limitations of vertical and lateral resolution in the geophysical data and to soil types, which could be very variable over short distances. This problem of rapid lateral changes in sediment type was not perceived by some respondents to be such a concern for deep water sediments, where sediment erosion, transport and depositional processes were considered to be 'benign', but it was especially a concern for glacial sequences. Another source of uncertainty in the integration of sample information and geophysical data was the unpredictable nature of the relationship between lithofacies and seismic 'facies' or seismic response (Talbot *et al*, 1994).

Looking at future trends in the characterisation of seafloor morphology by the use of geophysics, most of the respondents agreed that this would increase in prominence in response to the introduction of imaging tools capable of providing increased resolution. The questionnaire also specifically asked what the respondents considered to be the future trends in the identification and quantification of geohazards in terms of technological and conceptual models. One company noted that the predicted increased geophysical image quality would lead to a better understanding of hazards and engineering behaviour.

The particular technological advances identified were increased use of 3-D seismic surveying and of swathe bathymetry. More specifically however, it was envisaged that increased imaging capability would increase our knowledge on two fronts: first, a greater appreciation and understanding of the geological setting of geohazards could be attained; and secondly the actual imaging of the hazards as such may increase our knowledge about the physical processes involved with the particular geohazard under investigation. Similar sentiments are also manifest in statements observed in previous publications: 'The concerns of geotechnical engineers involved in geohazard risk assessment are related to our ability to define the relevant failure modes, their consequences and their probability of occurrence' (Kvalstad, 2001).

The questionnaire also asked respondents to state if they thought that geohazard surveys should be regulated in a similar manner to environmental issues (i.e. with a strong emphasis on auditing). It would appear that opinions were fairly evenly divided, with a small majority agreeing with the proposition.

As well as commenting on the potential for increased knowledge and understanding of geohazards, respondents were also asked to comment on issues relating to dissemination of regional and site specific data for desk studies of UK offshore areas. In particular, they were asked to comment on present circumstances and future trends. It was apparent that many of the respondents were strongly in favour of increased dissemination of knowledge, although one thought that data availability was 'perfectly adequate'. Two respondents indicated that the British Geological Survey (Continental Shelf Unit) was an excellent source of information on a regional scale, with one stating that the BGS should make more of the data available in the public domain. Many stated that site specific data was difficult to obtain and it is not clear from the responses whether or not the desire for increased dissemination needed to, or could include, site specific data.

When asked to comment on whether or not they thought that archive data would become increasingly more difficult to access, the majority disagreed. This would only be the case if funding of the UKCS became a limiter or if those involved in the dissemination were influenced by 'short sighted confidentiality' issues. However, one respondent suggested that less data would become available because of the technical issues related to the possibility of the formatting and the storage of archive data being incompatible with the modern equivalent. Long *et al* (1998) point out that the dissemination of geological data is of mutual benefit to all concerned. They state that the advantages for industry, when they work as joint groups, is that it ensures common standards of interpretation, uniform nomenclature and economies of scale. Individual company data for a specific site can be interpreted better in the light of the greater understanding that comes from regional studies, but at the same time the findings can contribute towards that regional understanding.

In terms of future trends in sourcing site investigation desk study data, most agreed that data would have to be collected from a wide range of sources (not just oil and gas exploration and production companies). Indeed, it was pointed out that this is currently the case, with one respondent indicating that with increased environmental issues associated with exploitation on the seafloor, the breadth of information sources utilised will expand further.

The industry responses indicate that, in general, less localised variation exists in water deep enough to be outside the glacially modified areas. The perceived homogeneity may be due to lower seabed currents which results in less erosion and material displacement than is found in shallower waters. Deep water features such as diapers, canyons and slides tend to be more regional than local.

Glacial environments, however, are complex and heterogeneous. A considerable amount of work is currently underway to understanding submarine slides, given their potentially catastrophic consequences. Despite the low probability of their occurrence, the associated risks are still high. It is considered important to understand where pre-existing slide surfaces are (given the potential for delayed failure), where new slide events could potentially occur and potential impacts on drilling operations. Possible causes of submarine slides are diapirism and rapid sediment deposition leading to overpressures in brittle soils.

4. GEOTECHNICAL ANALYSIS AND DESIGN

This section describes the industries views with respect to uncertainties and concerns on geotechnical analyses and design.

The principal uncertainties in geotechnical analysis and design are the geotechnical parameters and the determination of the applied loads to a foundation structure. Another, perhaps secondary uncertainty or variable, is the reliability of the available analytical techniques.

As described in section 2.3, there have been a number of developments in the fundamental approaches taken in foundation analysis. The first of these is that API recommendations and ISO procedures have been developed using a load and resistance factor design basis (LRFD). Secondly, the use of probabilistic (as opposed to deterministic) approaches to analysis is starting to become more widespread. This type of analysis can encompass load, resistance, modelling uncertainty, sampling errors and statistical uncertainty and derive a notional value of failure probability; essentially most of the uncertainties in geotechnical design as noted by Becker (1996).

Increased understanding of soil mechanics and behaviour of individual foundation types have been brought about by a number of developments, most recently by the increased use of numerical models for testing design concepts, physical modelling in the centrifuge and some field trials.

The attitude towards the increased use of theoretical or ‘advanced’ analysis in foundation design is generally very positive, especially if empirical alternatives are perceived or known to be too conservative. The interview responses with respect to geotechnical analysis and foundation design are discussed in the following sections.

4.1 PERCEIVED UNCERTAINTIES OF ASSESSING FOUNDATION CAPACITY

When asked to rank the uncertainty associated with particular foundation types (over a 5 point scale from ‘low’ to ‘high’), the interviewees listed many as being of ‘medium’ uncertainty. There were, however, some foundation types that clearly invoked a more definite response: a relatively low level of uncertainty was associated with pile foundation assessment (driven piles as well as drilled and grouted piles) and a relatively high degree of uncertainty was recognised for drag anchors, plate embedment anchors, and to a lesser extent, suction installed piles and caissons. At the same time, the predicted future frequency of use would indicate that greater use is expected of suction installed piles and caissons, and plate embedment anchors – mirroring the predicted increased use of FPSO, spar and TLP structures.

Comments specifically made regarding drag anchor design centred around the fact that design methods were perceived as difficult to formulate and that behaviour and capacity depended largely on ‘performance during installation’ or ‘embedment depth’. However, one respondent pointed out that drag anchor capacity was now the subject of a DNV Recommended Design Practice, but as yet, recommended factors of safety are not based on reliability analyses. Reliability analyses are used to assess the reliability of a method quantitatively using a statistical approach. This can be used to define a factor of safety to ‘safely’ deal with the inherent variations of a particular method. On studying the published literature, it would appear that some theoretical approaches have been formulated (e.g. Neubecker and Randolph, 1996; Thorne, 1998), but there is no evidence in the questionnaire response that these approaches have received widespread application in drag anchor design.

Capacity prediction for driven piles would appear to be a mature area of analysis, hence it is considered generally less uncertain than many other foundation types. However, some uncertainties were alluded to by the interviewees. Whilst the general consensus was that the design methodology was accurate, it depended very much on the availability of appropriate input data. Also, greater uncertainties existed for tension capacities as opposed to compression. Similar comments were noted for the drilled and grouted piles, although it was stated by one that more overall uncertainty may arise due to the effect of drilling. In practice though, drilling and grouting was thought by one interviewee to preclude many of the design problems associated with piling applications.

The section of the questionnaire dealing with suction installed piles did not provoke the same type of comments as those associated with piling. Design procedures are 'available' but they are never described as highly developed or accurate. Concerns are raised about the lack of model testing and about the possible change in foundation soil properties upon installation which are not accounted for during analysis. Indeed, one respondent feels that higher factors of safety need to be used.

Whilst some interviewees point out that there are a wide variety of established design methods to choose from concerning suction caissons, some uncertainties are noted. Full-scale testing under permanent tension is required, particularly for TLP and Spar applications according to one respondent. Also, it is pointed out that suction caisson behaviour becomes less certain when a passive suction is relied upon to resist a sustained load.

Many of the uncertainties relating to plate embedment anchors were similar to those for suction piles and for drag anchors.

For spudcan footings, greatest risk concerns the prediction of punch-through, emphasising the criticality of establishing the soil property profile at the site. The greatest number of structural failures, offshore, have been jackup failures. Of these failures a substantial proportion are due partly or wholly to foundation failure. Punch through is a common failure but there are others e.g. blowout.

Uncertainties associated with the analysis of shallow foundations appeared to centre round the need to obtain good quality soil property data, especially near the mudline. Difficulties in doing this in weak soils increase the associated risk. Amongst the properties recognised as important in analysing risk for shallow foundations is liquefaction potential.

4.2 THE ROLE AND MERITS OF EMPIRICAL APPROACHES TO DESIGN

As well as uncertainties arising for specific foundation types, there are more general issues to discuss. The first concerns the current and future role of empirical approaches to foundation design. Views were solicited from industry specifically regarding this issue.

Respondents' comments fall into two types: The first emphasises the practical reality that most offshore design is empirical and as such it has a critically important role to play both now and in the future i.e. at both shallow and deep water sites. Indeed, one comment indicated that offshore engineers will always want to be able to fall back on empirical design formulae at some stage. The second type of comment stresses the inherent lack of insight into the response of soil to loading that empirical methods provide and as such, they should be applied with caution and understanding.

Most respondents consider that the application of empirical methods can be made for ‘routine’ engineering design cases, for example total stress design of traditional foundation types. In such cases these empirical methods are considered by respondents to be more cost-effective than more theoretically-based design procedures. It is also generally considered by respondents that it is important where possible to use empirical and theoretical methods to complement one another. Many of the interviewees were supportive of the further development of fundamental or theoretical models whilst at the same time retaining the empirical approach. Indeed, some of the recent ‘theoretical’ models incorporate empiricism at some level (e.g. Taiebat and Carter, 2000). It was also emphasised that for newer foundation designs, there is a paucity of observations of field performance, making reliance on empirical procedures uncertain or impossible.

It is expected then, that empirical approaches will be extended to new foundation designs but that practical performance observations is currently limiting their applications for new foundation types (as well as limiting the testing of theoretical predictions).

When asked for their comments regarding what they thought the appropriate factors of safety (or resistance factors) both now and in the future would be, some respondents stated that they would (or hopefully would) decrease with increased understanding of soil-foundation interaction. Others made the point that it was difficult to make general comments, since safety factors depended on many parameters, and that design factors of safety needed to be derived from calibrated reliability analyses. However, when asked whether or not safety factors would need to be increased if less field data became available as SI moved to deeper water sites, there was a mixed reaction from questionnaire subjects.

One respondent disagreed with the statement, indicating that more use may be made of local experience and regional databases under such circumstances. Indeed, there is much academic research in site characterisation using uncertain or small data sets; these are based around probabilistic approaches (VanMarcke, 1983), geostatistics (e.g. De Groot, 1996), information theory (Mazzocola *et al*, 1997), or neural networks (Juang *et al*, 2001). However, there is no evidence in the questionnaire responses to suggest that such approaches have gained wide acceptance in offshore site investigation studies. All other respondents expressed qualified agreement with the need to increase factor of safety (FoS) when field data were sparse. It was pointed out by one respondent that the necessary increased conservatism could be passed to the design parameters. Also, the degree to which factor of safety had to be altered would depend on the quality as well as the quantity of field data available.

4.3 FINITE ELEMENT MODELLING (FEM)

The use of finite element analysis (2-D and 3 D) in analysing soil response (e.g. Zdravkovic *et al.*, 2001; Martin and Houlsby, 2001; Taibet and Carter, 2000; Hu *et al*, 1999) is not widespread, although finite element models (FEMs) have been applied to offshore foundation behaviour for some time (Meimon, 1992). In studies FEM has been used in research to produce potential design charts for routine design use. However, whilst the FEM approach is perceived by respondents to be mainly concerned with assisting in gaining a fundamental understanding of soil behaviour, it is also recognised that a trend exists in that the methods are starting to be applied to the actual design process and in analysing offshore slope stability. However, little use appears to be made of FEM-based methods at the present time. Some uncertainty was felt about the requirement for high quality sediment property data of the investigated site – to the effect that current quality standards were not sufficient to act as reliable input to the models.

Aldridge (1997) suggests that data from in-situ geotechnical tools may be combined with shallow 3-D seismic data to provide the large volumes of information which may be needed to allow FEM methods to be successfully used. However, this would imply that, even if it were possible to bridge the gap between seismic and geotechnical data, the reliability of FEM methods would be constrained by the reliability of parameters interpreted from the instruments. On inspection of the literature, it would appear that many of the models require parameters which are quite specific and easily obtained from the in-situ test data currently available.

4.4 PHYSICAL MODELLING FOR REDUCED UNCERTAINTY

Another source of uncertainty linked to the development of more sophisticated analysis techniques relates to the need to test theoretical procedures with physical laboratory models. Where such physical model tests are not available or feasible (e.g. for slope failure problems), some form of 'calibration' of any numerical model is required. Many interviewees appreciate the need for physical modelling to test and develop theoretical techniques, drawing particular attention to centrifuge modelling as a means of doing so.

4.5 ATTITUDE TO NOVEL AND THEORETICAL APPROACHES

As a means of enquiring into the current practice in relation to methods utilised in pile foundation design, respondents were asked specifically about the MTD/Imperial College pile design method (see section 2.3.2 - Jardine and Chow, 1996). Questions addressed the degree of familiarity with this 'advanced' method as well as the implications for SI data acquisition strategy. Of the seven respondents, three had no experience of the method. The response to the 'familiarity with method' question would suggest that all respondents have experience in driven pile design, implying that other methods must be used by these interviewees. It would appear that some have used the method exclusively in sands, some exclusively in clay, as a complimentary or secondary method. When asked specifically to state the safety factors which should be used with the MTD method, it was apparent that none of the respondents were sufficiently familiar with the method to have such information easily to hand.

However, when asked whether current practice in SI provided them with the data necessary to perform this advanced analysis, most stated that it did not. One respondent elaborated on the point, stating that piezocone data sufficed for sandy material, but many agreed that the soil/steel interface shear ring test required for clay soils was not 'standard' at this moment in time. These test data form input parameters into the model and without them, the calibrated design procedure is compromised. Ramsey *et al* (1998) show that in-situ data is preferred to empirical prediction of ring-shear data from plasticity index. Whilst most questionnaire respondents stated that they would have less confidence if input data was compromised, the interviewees were apparently not familiar enough with the method to know how sensitive the model output is to the reliability of input data.

In general, however, respondents were very open to the application of new and more advanced methods in design such as the MTD approach provided that they are tested in some way so as to provide acceptable levels of reliability. One respondent pointed out that the strength of developing techniques from a fundamental geotechnical approach could lead to the potential for increased applicability e.g. across a wider range of soil types. Another interviewee stated that the acceptance of new methods is essentially governed as much by the client as the contractor and this can make acceptance a drawn out process.

4.6 QUALITY OF DATA INPUT COMPARED TO REQUIRED QUALITY FOR NOVEL APPROACHES

With the increased use of novel, theoretically based methods, there is a concern that the data required for input into the models are not of sufficient quality. Respondents were asked to comment on whether or not consideration was given to the degree of confidence in the input data in comparison with the accuracy of the analytical model. Responses were quite varied. Many simply agreed that it was critically important that consideration should be made of the uncertainty associated with input data. One agreed with the underlying sentiment, that the analytical methods were presuming the availability of data that was of higher quality than was the case in reality. Another pointed out that it was important that the degree of confidence in field or laboratory test data was always assessed with some qualitative, experience based element (rather than adopting a purely statistical approach). Another respondent expressed the similar opinion that the quality of the input data could sometimes only be assessed qualitatively and by experienced engineers. One interviewee stated that, with the introduction of reliability based design (see 4.11), assessment of the reliability of each uncertainty was equally analysed and treated as a stochastic variable. In summary, all respondents appeared to appreciate the need to maximise data input quality, but the methods of achieving this so as to give meaningful model output were varied.

4.7 CYCLIC LOADING

Responses to the question of cyclic loading were remarkably mixed. The most positive stated that, in general, the industry is very careful to design for cyclic loading, whilst another stated that it was satisfactorily dealt with by most clients and contractors in their area (response solicited from NGI). At the other extreme, respondents claimed that the present approach was 'poor', possibly too conservative, or 'taken into account, but with significant uncertainties'. Little guidance is present in the codes according to one subject. Two contributors stated that the effect is generally incorporated in an empirical way, applying additional factors of safety (hence possibly too conservative). It was reported that some larger operators may be using more scientific techniques for pile design, but that in general, any rigorous incorporation of the effects of cyclic loading were restricted to gravity based structures.

4.8 INCORPORATION OF AGEING INTO FOUNDATION DESIGN

Responses to the question relating to the extent to which ageing was incorporated into design methods showed far more agreement than the cyclic loading issue. Most stated that the effect was rarely incorporated in any way and that it was not yet an issue. One respondent did however point out that research is underway in this subject, specifically relating to a study of the change in pile bearing capacity with time. We understand empirical evidence on the effects of ageing on driven pile capacity have been used on various occasions to justify revised loadings on platforms with driven pile foundations (e.g. Forties platforms).

4.9 OTHER ISSUES SPECIFIC TO DEEP WATER SITE INVESTIGATION

Respondents were asked for their views on any other issues related to the design of offshore structures and foundation systems in the context of the trend towards deeper water site investigation. The concerns raised fell into two distinct categories.

It would appear that there is some concern presently that more research and specifically more field trials of VLA's and suction piles needs to be performed. So, whilst a trend towards the increased use of these foundation types is foreseen, there is some uncertainty at present concerning their field performance predictability, particularly with reference to production units (FPSOs, TLPs).

The second issue raised by many of the respondents was the concern regarding the effects of geohazards (see section 3.4) that are associated with deep water and continental slope environments. In particular, the potential external loads of a geologic nature on foundation material have received little attention in the more geologically passive shelf sites previously investigated.

4.10 PROBABILISTIC VS. DETERMINISTIC ANALYSIS

In current practice, risks associated with structure and foundation failure are not usually explicitly quantified in design. Instead, they are more commonly addressed using deterministic design models and safety factors. Design models are developed using a combination of analytical modelling and calibration against experiment. The current trend in design codes is to use a partial safety format, or a 'Load and Resistance Factor Design' (LRFD) format, e.g. ISO 19902 or API RP2A 20th Edition LRFD codes for jacket structures.

Probabilistic analysis provides a rational means of quantitative assessment of the risks associated with structural or foundation failures. Probabilistic analysis can incorporate uncertainties associated with load, resistance, modelling uncertainty, sampling errors, statistical uncertainty etc. and derive a measure of failure probability which accounts for all these parameters. This type of analysis is becoming more widespread, and is used in code calibration studies (e.g. Morandi and Virk, 2000).

A number of reliability studies have been performed on piled foundations, e.g. Lacasse and Nadim (1996). An important aspect of such analyses is the fact that, since tensile and compressive capacity are dependent on the accumulated soil properties over the depth of the foundation, the effects of soil variability and sampling variability is effectively 'smeared out' over the length of the pile, and the overall variability in total axial capacity is not as high as might be expected.

Clukey, Banon and Kulhawy, (2000) used structural reliability analysis to explore design rules for deepwater suction caissons with the objective of achieving comparable levels of safety with shallow water piled foundations. One aspect of this study was that suction caissons depend for their strength on a far smaller volume of soil than do piles. They will therefore have greater variability in their strength since uncertainty and variability in soil strength is not 'smeared out'. This implies that, in order to achieve similar levels of reliability, the caisson would need a comparatively greater factor of safety (assuming the certainty of input parameters is constant) above its mean strength than a piled foundation.

The above finding will be an aspect common to foundations which depend on a small volume of soil for their strength, and must be fully appreciated when developing new foundation types. For the caissons to achieve an equivalent level of reliability as piles, they must either be designed to be intrinsically more robust, have better and more accurate characterisation of the soil properties, or be part of a more redundant system.

A recent trend in reliability analysis, which is particularly associated with soil characterisation involves using Bayesian updating of a 'prior' random field model of a site using information from a borehole set at some distance from the site (Gilbert and Gambino, 1999). This method depends on the amount of correlation expected between the soil properties at the two locations.

The important assumption is made that the same random distribution of properties applies at the new site. In order to derive information about this correlation, the soil spatial variability needs to be extremely well characterised (e.g. using Kriging). This effectively implies that there needs to be an extensive knowledge of the geological conditions even if the conditions at the specific site are not known. This type of assessment would not be of great value unless the homogeneity and random field properties of the site were already known to a sufficient level of statistical accuracy.

It should be noted that the structural failure probabilities thus derived rarely correspond to so called 'actuarial' or 'frequentist probabilities'. Rather they are better considered to be notional measures (see Melchers, 1999). The main reason for this is that it is generally not possible to model accurately all the contributory factors. In particular the effects of gross human error and human intervention are not readily quantified but have been identified as the prime cause for the largest proportion of observed structural failures. The selection of distributions for basic variables and approximations in analysis also contribute to the notional nature of the calculated failure probability.

The numerical and analytical techniques used in reliability assessment can be more complex than many engineers are used to, and many engineers find probabilistic analysis very daunting. However it should be noted that it is very common in geotechnical engineering to perform parameter studies where there is known to be uncertainty in the actual value of a parameter, and it should be a relatively small step to performing probabilistic assessment.

It is important that suitable training be provided both in the use of these methods, the development of the statistical models to be used in the analysis and the interpretation of the results. As has been noted above, it is very tempting to consider the failure probability derived in a reliability analysis to be an absolute value and directly comparable with calculated or observed probabilities derived for completely different scenarios. However, it is important to appreciate the notional nature of reliability calculations, and to consider carefully exactly which uncertainties have been modelled, how they have been modelled and how accurately. There is a role for parametric analyses and Monte Carlo simulations.

Despite being notional values, calculated values of reliability are very useful as comparative measures of probability. Notional failure probabilities derived using essentially identical models can be meaningfully compared. However, a meaningful comparison between notional failure probabilities derived using different models or different approximations cannot always be made unless it can be shown that they are both modelled to equivalent levels of complexity. An implication of this is that target levels of acceptable failure probability depend on the models that are used in their development. Thus target levels of acceptable reliability need be derived from analysis of a structural component that is known from operational experience to have 'adequate' reliability and to be sufficiently similar in physical properties and analysed to a similar level of detail.

4.11 RELIABILITY BASED DESIGN (RBD)

Interviewees were asked to comment on their attitude to RBD procedures in the context of the potential deep water limitation of sparse data sets (as noted above, probability approaches have been used in such circumstances). Many of the respondents did not feel they were familiar enough with the subject to pass comment. Of those who did respond, many thought that probabilistic techniques would be a welcome addition to their methods of analysis, but that the approach was yet to be widely applied.

One pointed out that the move to RBD was inevitable as the need to quantify risks for subsequent decision making increased. However, the applicability of methods which have, in the past, been applied to structural reliability should be adapted in the light of our relatively poor understanding of, and the natural variability in, the behaviour of soils. Another respondent went further and expressed the opinion that probabilistic methods applied to soils and foundations were unlikely to warrant a high degree of certainty. Many of the interviewees, when given the option of choosing a probabilistic approach to working around the confines of a sparse data set or adopting a higher factor of safety, chose the latter.

However, one respondent reasoned then that the problem with this approach would be to know by how much this factor should be raised. This particular response concluded by stating that what was important was that an acceptable level of reliability was achieved through the application of consistent design practice.

With some of the deep water systems the loading demands on the foundation and its cost may be relatively rather modest. However, the consequences of failure may be high (e.g. loss of installation. In such cases the cost of "overdesign" may be entirely justified. Small cost savings could cause a disproportionate increase in risk.

Geotechnical Design

Industry feedback - Some key points

- *Traditional and empirical design methods are considered appropriate for routine work and should be used in conjunction with newer methods*
- *A better understanding of the factor of safety is required. With the new developments of sampling, laboratory testing and design methods the factor of safety currently being applied may not be entirely appropriate and should be continually re-assessed*
- *Concerns with the relatively small numbers of qualified and experienced companies and individuals who can carry out designs and more importantly audit and verify these designs*
- *Concerns expressed regarding some of the newer foundation technologies such as suction caissons and the use of existing technologies such as jack up rigs*
- *All design methods should be based on a database for comparison or to project specific data such as field tests*
- *Centrifuge and model testing considered important in understanding the behaviour of new technologies*
- *Concerns regarding the understanding of installation and decommissioning methods*
- *Offshore cyclic design approaches often determine design requirements, however there are concerns that this behaviour is not adequately understood*

5. RISK MANAGEMENT ISSUES

5.1 DEVELOPMENT OF OFFSHORE HEALTH AND RISK MANAGEMENT

Health and risk management has developed in offshore engineering following legislation such as the Health and Safety at Work Act (HSWA, 1974) and in response to incidents such as the Piper Alpha disaster (1988) which lead to the Offshore Installations Safety Case Regulations (SCR) and other safety regulations listed in Table 10. The HSE's approach to the management of health and risks has been developed progressively and is described in more detail in section 5.3.2.

5.2 OFFSHORE ACCIDENTS AND INCIDENTS AND THEIR IMPLICATIONS

The first major accident in the United Kingdom Continental Shelf (UKCS) area was the collapse of the drilling rig Sea Gem in 1965 due to a brittle fracture of the structure. This resulted in the passing of the Mineral Workings (Offshore Installations) Act of 1971.

The Piper Alpha disaster in 1988 was the single event that has most influenced health and safety thinking in the offshore industry. Although it was a result of a hydro-carbon release, it has affected every aspect of offshore health and safety risk management. The disaster resulted in the Cullen Enquiry of 1990 which produced recommendations centred on Safety Cases, Safety Management Systems, Independent Assessment and Survey and a Regulatory Body.

Events surrounding the proposed decommissioning of the Brent SPAR in 1995 (see section 1.1.5) resulted in a rethink of how the offshore industry reacts to societal concerns over risk issues, and largely lead to the publication of the UK Offshore Operators Association (UKOOA)'s *Framework for Risk Related Decision Support* (see Table 11).

5.2.1 UK general safety regulations

The Health and Safety at Work Act (HSWA, 1974) provides the basis of offshore safety regulation on the UKCS. It imposes on the employer a duty *'to ensure, so far as reasonably practicable, the health, safety and welfare at work of all his employees'*.

The Management of Health and Safety at Work Regulations (MHSWR, 1992) supports the general duties under HSWA by requiring employers to undertake risk assessments for the purpose of identifying the measures that need to be put in place to prevent accidents and protect people against accidents.

5.2.2 Additional UK offshore safety regulations

The primary safety regulation document for the offshore industry is the Offshore Installations (Safety Case) Regulations (SCR, 1992). The regulation requires that the duty holder (i.e. the owner or operator) prepares a safety case for each fixed and mobile installation, which must be accepted by the HSE before the installation can be operated on the UKCS. The duty holder must *'include in the safety case sufficient particulars to demonstrate (amongst others) that:*

- *all hazards with a potential to cause a major accident have been identified*
- *risks have been evaluated and measures have been, or will be, taken to reduce the risks to persons affected by those hazards to the lowest level that is reasonably practicable'*

The Safety Case Regulations are complemented by other regulations dealing with specific features of offshore safety including the Offshore Installations and Wells (Design and Construction) Regulations (DCR, 1996). This includes requirements for safeguarding the integrity of the installation throughout its life. This applies specifically to offshore hazards affecting the structural integrity, strength, stability and buoyancy of an installation. DCR includes no specific requirement for risk assessment, but risk assessments required under SCR and MHSWR will help meet DCR's requirement to ensure integrity 'so far as is reasonably practicable'.

DCR and SCR require the duty holder to establish a 'verification scheme' using 'independent and competent persons' to ensure that 'safety-critical elements' on the installation are suitable and remain in good condition. The 'safety-critical elements' are parts of the installation that might contribute to or prevent or mitigate the effects of a major accident. Identification of these should be the outcome of a risk assessment.

Table 10 presents a list the relevant regulation documents that apply within the UK and Table 11 presents a list of some relevant guidance risk management documents available.

Table 10 UK offshore health and safety regulations

Regulation	***Abbreviation***	***Year***
The Offshore Installations and Wells (Design and Construction) Regulations 1996	DCR	1996
Statutory Instruments 1996 No. 913, ©Crown Copyright 1996	SI913	1996
Health and Safety at Work Act	HSWA	1994
Management of Health and Safety at Work Regulations	MHSWR	1992
Offshore Installations (Safety Case) Regulations	SCR	1992
Mineral Workings (Offshore Installations) Act		1971

Table 11 Some relevant guidance on offshore health & safety and risk management

Guideline	***Year***
Reducing Risks, Protecting People, (R2P2) Health and Safety Executive	2001
Marine Risk Assessment, Offshore Technology Report, 2001/063. Prepared by Det Norske Veritas for the Health and Safety Executive	2001
ISO/DIS 19901-4 *Petroleum and Natural Gas Industries – Offshore Structures – Part 4: Geotechnical and Foundation Design Considerations,* updated 05 March 2001, Document ISO TC67/SC7 N288	2001
ISO/CD 19902, Draft E, *Foundation Design* (Formerly ISO13819-2), Section 17, 19 June 2001, Document ISO TC67/SC7 WG3. Primarily Offshore Piled Foundation Guidance.	2001
ISO/DIS 19900 Draft for Review and Comment - *Petroleum and Natural Gas Industries – General Requirements for Offshore Structures,* 31 October 2000. (formerly ISO 13819-1)	2000
ISO 13628-1:1999 *Petroleum and Natural Gas Industries -- Design and Operation of Sub-sea Production Systems – Part 1: General Requirements and Recommendations*	1999
UKOOA *Industry Guidelines on A Framework for Risk Related Decision Support*, United Kingdom Offshore Operators Association (UKOOA), Issue 1	1999
Crawley, F.K, *The Change in Safety Management for Offshore Oil and Gas Production Systems* Trans IChemE, Vol 77, Part B	1999
A Guide to the Offshore Installations (Safety Case) Regulations 1992 L30. HSE Books ISBN 0 7176 1165 5	1998
Assessment Principles for Offshore Safety Cases HSG181. HSE Books ISBN 0 7176 1238 4	1998
The Association for Project Management's Project Risk Analysis and Management (PRAM) Guidelines	1998
Step Change in Safety	

Of the guidance documents on health and safety risk, the HSE's *Reducing Risks, Protecting People* (R2P2) and HSE's Offshore Technology Report (OTR), 2001/063 *Marine Risk Assessment*, are generally considered to be most commonly used by the offshore industry.

5.3 APPROACHES TO RISK MANAGEMENT

In general, the approach to risk management can be outlined as follows, (as presented in HSE's OTR 2001/063 *Marine Risk Assessment*):

'The purpose behind almost any risk assessment is to support some form of decision making on safety matters. Decisions may be needed on issues such as:

- *whether or not an activity should be permitted*
- *whether measures are necessary to reduce the risk*
- *which of various options, involving different combinations of safety and expenditure, should be selected*
- *how much should be invested in enhancing the safety of an installation'*

Several approaches have been developed to answer these issues and are generally seen as mutually compatible rather than competing philosophies. To provide a background some of these approaches to risk are presented as follows:

- Association for Project Managers (APM) Project Risk Analysis and Management (PRAM) covering the full scenario in which risk is assessed.
- HSE overall approach to Health and Safety
- UKOOA framework dealing with offshore oil and gas industry safety
- Geotechnical risk management as part of a project's overall risk management

5.3.1 Association for project management's PRAM guidelines

Health and safety risk management follows the same basic principles as other types of risk management with the important overlay of the ALARP principle (see Figure 20).

The Association for Project Management's *Project Risk Analysis and Management (PRAM) Guidelines* (1998) follow the accepted (or 'classical') approach to Risk Management. They set out the basic steps to be taken in any risk assessment and require a consideration of:

(i) Project Scope and Purpose

(ii) Hazard Identification

(iii) Risk Quantification (requiring consideration of the likelihood and consequences of the identified hazard)

(iv) Risk Evaluation (which for a safety risk requires consideration of Individual Risk and Societal Risk in accordance with the HSE's ALARP principle)

(v) Identification of possible control (mitigative) measures, their costs and the resultant residual risks

(vi) Identification and implementation of the most appropriate control measure

This approach is similar in scope to the HSE's six-stage process described in *Reducing Risks, Protecting People* (R2P2, 2001) in the following respect:

Stage 1 in the HSE R2P2 considers whether a project should come under the auspices of the HSE

Stage 2 in the HSE R2P2 is broadly encompassed by points 1 to 4 of the PRAM Guidelines, which covers project scope and purpose, hazard identification, quantification and evaluation

Stage 3 in the HSE R2P2 encompassed by point 5 of the PRAM Guidelines, which covers identification of mitigative measures, costs and residual risks

Stages 4 to 6 in the HSE R2P2 by point 6 of the PRAM Guidelines, which covers identifying and implementing the most appropriate control measure

5.3.2 The HSE approach to risk

The HSE approach to managing health and safety risks is set out in *Reducing Risks, Protecting People* 2001 (R2P2). In this regulation, a six stage risk management process is laid out, as presented in Table 12. The overarching principal governing health and safety risk is the ALARP (As Low As Reasonably Practicable) principle, set out in the HSE's Tolerability of Risk (TOR) framework. This intends that risks to people (affected parties) should be reduced to as low as reasonably practicable and requires that no-one should be subject to an intolerable level of risk. In assessing tolerability of risk, the method requires consideration of Individual Risk (IR), which is defined as the annual probability of death or injury to an individual from the activity.

Table 12 HSE Approach to managing risk as defined in reducing risks, protecting people 2001 (R2P2)

Stage 1:	Decide whether the issue is one for the Health and Safety Commission (HSC) or for the Health and Safety Executive (HSE)
Stage 2:	Define and characterise the issue (*which involves understanding of project purpose and scope, and hazard identification, quantification and evaluation*)
Stage 3:	Examine the options available for addressing the issue, and their merits (*which includes identifying options, their costs and residual risks and consideration of stakeholder opinion*)
Stage 4:	Adopting a particular course of action for addressing the issue efficiently and in good time, informed by the findings of the second and third points above and in the expectation that as far as possible it will be supported by stakeholders
Stage 5:	Implementing the decisions
Stage 6:	Evaluating the effectiveness of actions taken, and revisiting the decisions and their implementation if necessary

In relation to foundation issues, the risk associated with a particular hazard (e.g. extreme storm loading, corrosion, mudslides) is calculated in broad terms as the product of the likelihood of the hazard with the consequences should the hazard occur. The total risk is the sum of the risks associated with the identified hazards, and the total Individual Risk takes into account all hazards and their annual likelihood and consequences for the individual considered.

In the UK, the acceptable level of risk that can be imposed on an individual by a third party is not defined explicitly. The principle is expressed in the HSWA (1974) and its operation has been defined by case law through the years. The legislation requires a duty holder to do whatever is reasonably practicable to reduce risk. A level of risk is considered to be tolerable under the ALARP principle if the cost of risk reduction is disproportionate to the benefit from risk reduction gained (or grossly disproportionate where the level of risk approaches the intolerable threshold).

The ALARP principle is illustrated graphically in Figure 18. At the lower end of the scale, a level of risk is considered broadly acceptable if it lies below a certain threshold. The threshold levels are measured in terms of Individual Risk. The HSE consider a value of Individual Risk of 10^{-4} (i.e. 1 in 10,000 chance of a fatality per year) for workers and 10^{-6} for the public exposed to the risk as being broadly acceptable. For risk levels lower than this no action need be taken. At the top end of the scale, if the risk lies above a tolerable value, then it is considered to be unacceptable (or intolerable) and action needs to be taken to mitigate this risk, regardless of the cost, time or effort involved. The threshold for unacceptable risk is taken by HSE to be between 10^{-3} for workers and 10^{-6} for members of the general public exposed to such a risk. Between these two thresholds lies the 'ALARP Region' where risks must be reduced if reasonably practicable in terms of the cost, time and effort involved in reducing the risk.

A precautionary approach is used where there is limited data and knowledge of the frequency of hazardous occurrences and the consequences are significant. Examples of significant consequences include multiple fatalities and major environmental impacts.

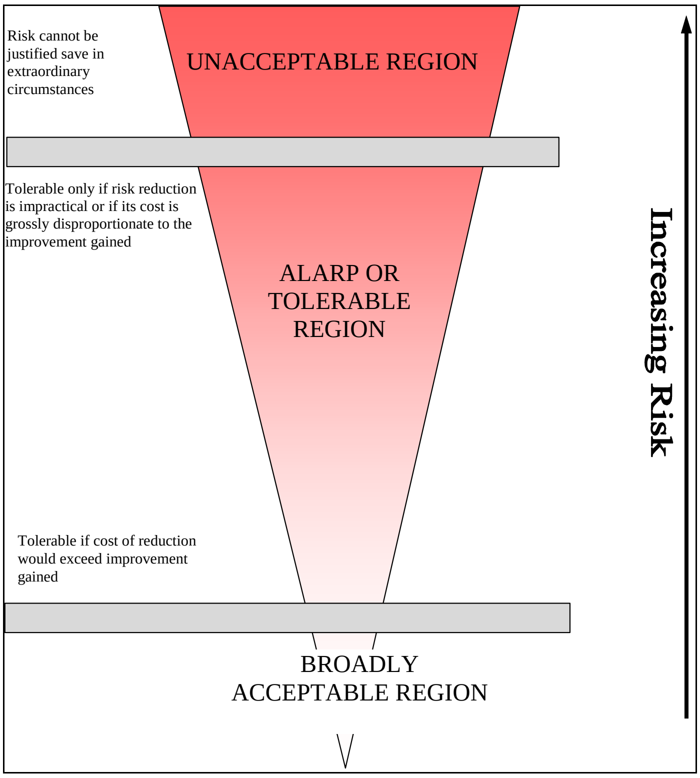


Figure 18 Illustration of the ALARP principle

A further perspective on risk considers societal concerns. R2P2 states:

'societal concerns or the risks or threats which impact on society and which, if realised, could have adverse repercussions for the institutions responsible for putting in place the provisions and arrangements for protecting people, e.g. Parliament or the Government of the day. This type of concern is often associated with hazards which give rise to risks which, were they to materialise, could provoke socio-political response, e.g. risk of events causing widespread or large scale detriment or the occurrence of multiple fatalities from a single event. Typical examples relate to nuclear power generation, railway travel, or genetic modification of organisms. Societal concerns due to the occurrence of multiple fatalities in a single event are described as societal risk.'

Societal risk may relate to society in general or to a specific group (e.g. workers or by-standers)

5.3.3 UKOOA framework for risk related decision support

The HSE's OTR 2001/063 *Marine Risk Assessment* summarises the UKOOA's framework as follows :

'The UK offshore oil and gas industry has developed a framework to assist risk-related decision-making (UKOOA 1999), which helps decision-makers choose an appropriate basis for their decisions.

Below (Figure 19 in OTR 2001/063) shows the Risk-Related Decision Support Framework (UKOOA, 1999). The framework takes the form of a spectrum of decision bases, ranging from those decisions dominated by purely engineering concerns to those where company and society values are the most relevant factors. Down the right hand edge of the framework are typical characteristics which indicate the decision context for a specific decision. Once this level has been identified, reading horizontally across the framework shows the suggested balance of decision bases to be taken into account in the decision. Some means of calibrating or checking the decision base are shown in the left hand side of the framework (UKOOA 1999). To relate the UKOOA framework to the current guide, 'risk assessment' may be considered to consist of structured engineering judgement and risk based-analysis. This approach shows that risk assessment has a major input into Type B decisions, involving some uncertainty, deviation from standard practice, risk trade-offs, etc. In Type A and C decisions, risk assessment is still relevant but is likely to be much less influential in reaching the final decision. International Maritime Organisation, IMO regulations and classification rules are representative of 'codes and standards', and are a major input into Type A decisions, with less influence on Type B and C.'

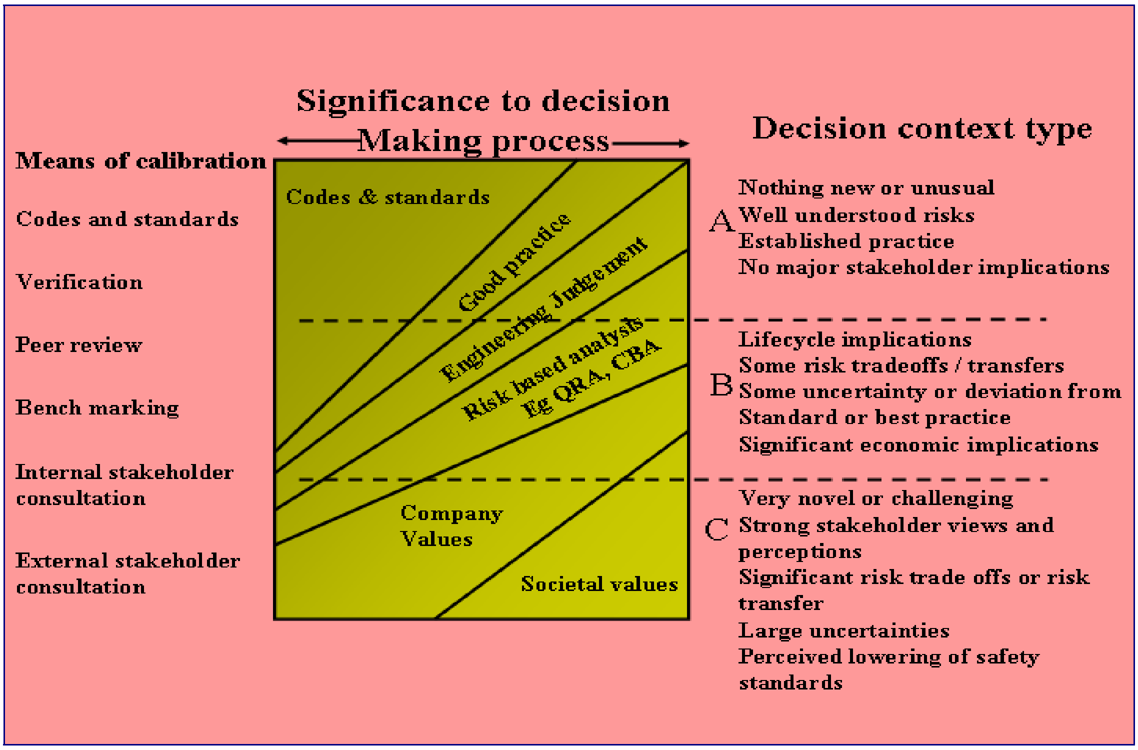


Figure 19 Risk-related decision support framework (UKOOA 1999)

5.3.4 Geotechnical risk management as part of a project's overall risk management

Various approaches to geotechnical risk management have been developed for differing challenges largely based on approaches to risk management in other fields. They are not mutually exclusive and several approaches can be applied in combination and are presented as follows:

- Risk studies as part of project management – APM's PRAM approach; use of Risk Register and Risk Profiling
- Qualitative v. quantitative approaches - use of Fault and Event Tree Analysis, Monte Carlo Simulation and Risk Matrices
- Cost Benefit Analysis , 'Optioneering' (consideration of options, optimisation of cost and risk)
- Risk studies to identify, assess and manage site engineering hazards (Clayton and Power, 2002)
- Risk study to optimise cost-benefit of site investigation
- Probabilistic Design approach – use of Failure Probability instead of Factor of Safety (Whitman, 1984; Chowdhury, 1992) combined with HSE's ALARP Principle for safety applications
- Societal values / risk perspective (factors outside probabilistic risk assessment) to assess peoples attitudes to imposed risks
- Natural Hazards Studies (landslide, seismic, etc.)
- Application of CDM regulations, to geotechnical site safety

5.4 RISK MANAGEMENT IN OFFSHORE GEOTECHNICAL ENGINEERING

5.4.1 Geotechnical risk management through a project's life-cycle

Risks in offshore site investigation, foundation engineering and design are present throughout the life-cycle of a project, from conception to decommissioning. Industry practice divides the main risks into two categories:

- Health and safety risks of drillers, operators and construction workers working offshore during the site investigation, foundation construction & installation and decommissioning of marine structures - health and safety risks resulting from these aspects are a sub-set of the many risks to which the personnel on board (POB) and third parties are exposed
- Risk of facility structure failure as a direct result of geotechnical foundation failure. Such geotechnical failures could be caused by inadequate geotechnical investigation, foundation design and construction, or from offshore geohazards (seismic, slope instability, sub-sea landslide, gas blow outs, etc.)

Table 13 provides an illustration of the health and safety risks to the POB and places geotechnical risk in context as they might appear in a Quantified Risk Assessment for a Safety Case for an operating offshore structure.

Table 13 An illustration of health and safety risks to offshore (platform) workers (with geotechnical risks shown in italics)

Main Categorisation	Secondary Level Categorisation	Tertiary Level Categorisation	Fourth Level Categorisation
Hydrocarbon Hazards	Explosions, fires, etc.		
Non-Hydrocarbon Hazards	Occupational	Occupation based	Rough-necks, driller, etc.
		Helicopter Travel	
	Other	Helicopter / Plane impact	
		Turbine failure	
		Structural	Extreme weather (wind, wave)
			Ship impact
			Other structural (fatigue, poor design, foundation failure, etc.)
			Geohazard (seismic, slope instability, undersea landslide, gas blow-outs, etc.)

5.4.2 The geotechnical risk process

The assessment and management of risk requires the following steps (in this case given in accordance with the APM's PRAM Guidelines but similar steps are used in the HSE approach or UKOOA approach):

- Understanding the Issues: Scope and Purpose (which would include consideration of the UKOOA Framework)
- Hazard Identification
- Risk Assessment and Quantification (requiring consideration of the likelihood and consequences of the identified hazard)
- Risk Evaluation (which for a safety risk requires consideration of Individual Risk and Societal Risk in accordance with the HSE's ALARP Principle)
- Identification of possible control (mitigative) measures, their costs and the resultant residual risks
- Identification and implementation of the most appropriate control measure taking into consideration other factors as indicated in the HSE R2P2 and UKOOA Guidance

The flow chart in Figure 20 presents a conceptual geotechnical risk model which shows this process diagrammatically.

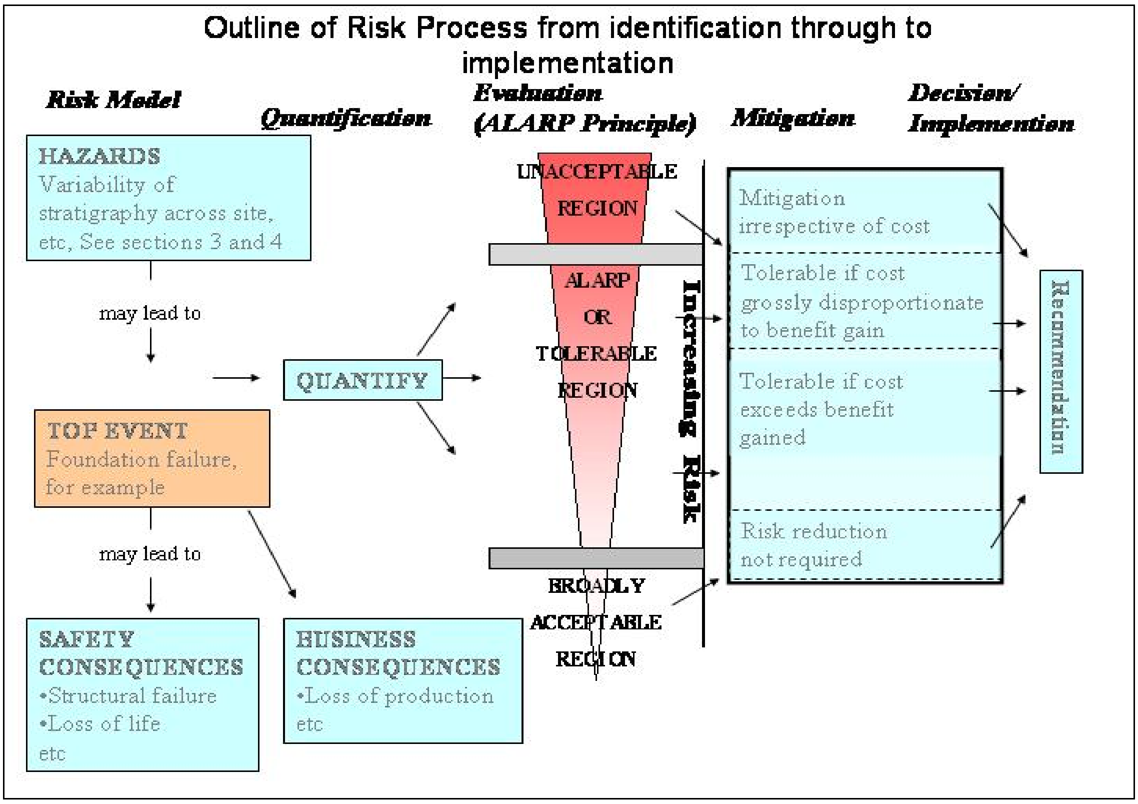


Figure 20 Geotechnical risk model

Clayton, C.R.I (2001) states in *'Managing geotechnical risk: time for change?'*: *'In geotechnical risk management the first and most important step is the identification of the hazards and their associated risks. In the UK, a great deal can be found from the existing information (such as topographical and geological maps, books and journal papers, air photographs and satellite images) that is used for the traditional desk study.*

However, hazard identification is a fundamentally different process. Rather than using data to predict the likely ground conditions, the purpose is to speculate about unfavourable conditions that might be encountered, and to use the experience to catalogue the risks that must be tackled in order to achieve relative certainty during construction. Hazard identification is therefore the starting point for effective geotechnical risk analysis.'

He goes on to state that hazard identification requires the creation of an expert team to review the existing information to brainstorm potential hazards which should be recorded on a Risk Register (which records the identified hazard together with its likelihood, consequences, possible mitigation and residual risk and other risk management information).

Clayton and Power (2002) present the following model to identify geotechnical risks:

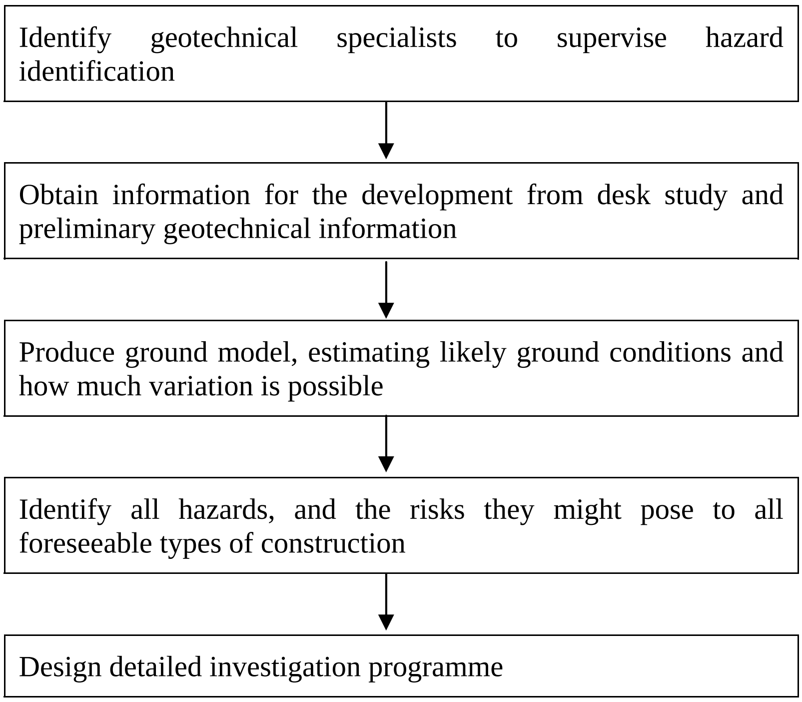
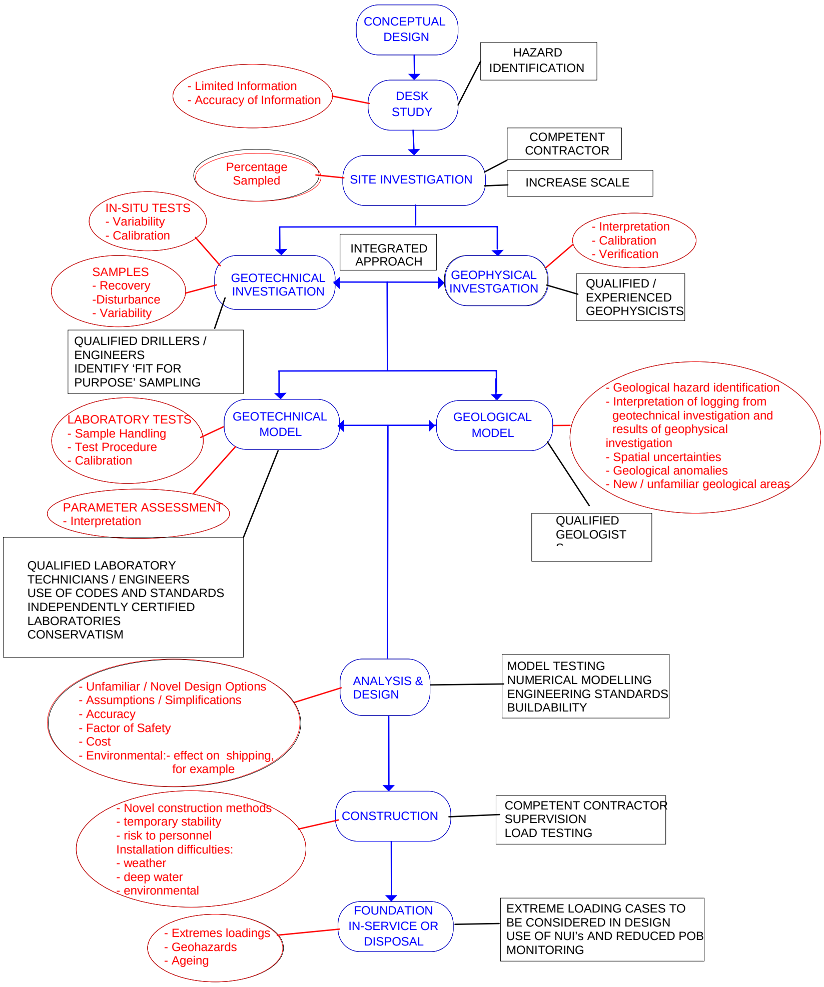


Figure 21 Identifying geotechnical risk

Figure 22 presents a life cycle perspective on risk related to offshore geotechnics. This shows some of the stages of offshore geotechnical engineering through the entire life cycle of the offshore development (in blue uppercase) with the hazards and uncertainties present at each stage (in red lowercase) and the reasonable mitigation measures (in black boxes in uppercase). Furthermore, mitigative measures of general applicability to the whole process are also highlighted. Between each of the geotechnical process stages there are also potential communication or interface hazards, which are not shown explicitly.

CONSERVATISM



KEY

- Geotechnical Process
- Uncertainty/ Hazards in Geotechnical Process
- Risk Mitigation Measures

Note:
1. Interface and communication hazards present between each stage. These can be mitigated through clear and unambiguous objectives and communication, by working in teams / collaborations with an open, friendly work culture
2. Throughout the stages key features that must be in place are competent qualified personnel, quality assurance and risk management

Figure 22 Key geotechnical engineering risks and mitigation measures for stages over the entire life cycle of an offshore development

5.4.3 Assessment of likelihood of hazard / uncertainty

After identification of the hazards the likelihood is assessed. Typical methods of assessment of likelihood used by industry include:

- Qualitative or risk matrix approaches
- Fault tree modelling using software such as FaultTree+
- Use of historical data
- Expert opinion, brainstorming and the Delphi Technique

Probabilistic Approaches involving Risk Modelling (Whitman 1984, Chowdhury, 1992) and Monte Carlo Simulations are yet to be widely accepted by industry but show promise for the future (Clayton and Power, 2002). These approaches attempt to derive a probability of failure of a structure based on the use of distributions rather than single point values in the input data and carrying out a Monte Carlo Analysis to determine the probability of failure.

5.4.4 Assessment of consequences of hazard / uncertainty

The risk is determined as the likelihood of occurrence of a failure hazard multiplied by the consequences of the failure hazard.

The consequences of failure hazards depend on the nature of the hazard, of the failure and the type of nature of the structure involved and the effect on and number of POB and third parties. The nature of the failure can be:

- excessive settlement/heave
- excessive lateral displacement or rotation
- foundation failure leading to structural collapse including failure as a result of a geohazard

Generally consequences can be classified as:

- Health and Safety
- Environmental
- Commercial
- Or a combination of the above

The type and nature of a selection of structures and a suggested ranking of possible Health and Safety consequences to the POB of severe geotechnical failure are summarised in Table 14.

Table 14 Type and nature of structures

Type of structure	*Nature of structure and foundations*	*Relative safety consequences of geotechnical failure to POB (high/medium/low/negligible)*
Jacket platforms and concrete gravity base structure(GBS)	Fixed/self supporting	High
Tension Leg Platforms (TLP)	Floating attached by tensioned legs	Medium
FPSO (Floating Production Storage Offloading)	Floating anchored	Low
Normally Unoccupied Installations	(Sub-type of others)	Negligible
Semi-submersibles	Floating attached by anchors	Medium/Low
SPARs	Floating attached by anchors	Low/Negligible
Pipelines	Resting on sea floor	Negligible
Sea-bed assets, etc	Resting on/under sea floor	Negligible

As this report mainly considers Health and Safety risks, the commercial and environmental consequences have not been included in Table 14 but should be considered at the same time. This is because the first level consequences will generally impact on all three consequence types and, likewise, mitigative measures, may mitigate against all three types of consequence. Therefore, in order to make a case for implementing a mitigative measure, all three types must be considered together, as individually, the case for implementation of further for risk reduction measures may be insufficient.

5.4.5 Risk evaluation

Risk Evaluation comprises consideration of the calculated or estimated level of risk in order to determine priority of or need for mitigation. Health and Safety risks are evaluated with respect to the ALARP Principle as discussed in Section 5.3.2, to determine whether the risks to which the POB and third parties are exposed are as low as reasonably practicable.

It is good practice to consider as far as possible the calculated risk in terms of Individual Risk and Societal concerns as well as overall risk. For a full ALARP evaluation it is necessary to consider the total risks from all hazards to the POB and third parties and the part that geotechnical risks play.

Furthermore, it is industry practice to take into consideration the UKOOA Framework to determine which approach or combination of approaches is most applicable.

5.4.6 Approaches to risk mitigation

Introduction to risk mitigation

The optimum approach to risk mitigation depends on the risk evaluation as discussed in the section above. Options for risk mitigation should be considered together with their benefit (in terms of risk reduction and the resulting residual risk) and the cost, time and trouble. The effort put into identifying risk mitigation options should be commensurate with that for identifying risks.

From a number of possible options (which will include a 'Do Nothing' option) an optimum risk mitigation option (or combination of mitigative measures) is chosen for implementation. Furthermore, synergies between mitigative measures should be taken into account; often one measure can mitigate various risks. The residual (i.e. remaining) risk and cost of the mitigative measure should be taken into consideration.

Risk mitigation methods are normally considered to fall into the following categories:

- Avoid (i.e. do something else, or avoid by novel design, for example floating platforms)
- Transfer (e.g. insure, sub-contract, transfer to another party in the contract, etc. Note that the duty holder cannot transfer Health and Safety or environmental risks)
- Retain (hold accept i.e. do nothing)
- Mitigate by:
  - Reduce the Likelihood of occurrence (e.g. use greater Factor of Safety)
  - Reduce the Impact if failure occurs (e.g. reduce POB)
- Rescue (e.g. emergency planning)

Note: in general avoiding the risk followed by reducing the likelihood tend to be the most (cost) effective strategies.

Figure 22 shows the key stages of offshore geotechnical engineering processes with the potential hazards and the place of different mitigative measures. These mitigative measures are discussed here in greater detail.

It is generally accepted that overall Risk Mitigation Strategies include:

- Effective use of risk management techniques. For further guidance refer to:
  - '*Reducing Risk, Protecting People*', HSE (2002)
  - OTO 2001/063 '*Marine risk assessment*', HSE (2001)
  - '*Managing geotechnical risk: Time for Change*', Clayton, C.R.I, (2001)
  - '*Managing Geotechnical Risk in Deepwater*', Clayton, C.R.I, and Power, P (2002)
  - *PRAM Guidelines*, Association for Project Management (1998)

- Adequate use of expert geotechnical advice. Refer to:

  '*Control of Uncertainty in Geotechnical Engineering'*; Muir Wood, A.M. This paper suggests that a 'geotechnical conductor' should oversee the whole project process from conception to construction in order that communication errors are minimised. Furthermore, Muir-Wood recommends different levels of geotechnical expertise depending on the geotechnical complexity. In other words, a complex project should not be managed by an inexperienced geotechnical engineer or by someone without suitable geotechnical training.

- Quality Assurance through the project life-cycle

Industry views on reducing the likelihood of geotechnical failure include:

- *Increasing scale of site investigation*
- *Increasing the Factor of Safety (deterministic approach) or reducing the Probability of Failure (probabilistic approach).*
- *Adopting a more robust design - a robust design is either tolerable (can tolerate unexpected/unforeseen ground conditions or is adaptable (can be adapted during construction to cope with unexpected/unforeseen ground conditions) - this latter requires consideration of the Observational method*
- *Field trials and load testing*
- *Ensure good practice and latest thinking is used in in-situ and laboratory testing and interpretation of test results*
- *Adopting methods which have lower geotechnical uncertainty (see Section 3)*

Industry views of aspects which reduce the consequences of geotechnical failure include but are not limited to:

- *Use of floating rather than fixed structures*
- *Reducing the POB and use of NUI's*
- *Effective emergency planning*

Discussion on risk mitigation strategy

The aim of risk mitigation should be to reduce the risk to ALARP and in a way such that is acceptable as far as possible to all stakeholders. This can be achieved by:

- ensuring the Individual and Societal Risks to the POB and third parties are not intolerable (as defined in the ALARP Principle)
- ensuring the sum of the cost of risk mitigation and the (residual) risks are minimised - both considered in Net Present Value terms. This involves a consideration of the Value of a Statistical Fatality (or Value of Fatality Prevented) and should take into consideration any operational benefits or disbenefits and environmental and commercial risks or issues

- taking into consideration factors outside a Risk Assessment: such as environment, social, political factors and societal values (refer to the UKOOA framework)

Risk mitigation is achieved through a reduction of the likelihood and consequences of that risk. This can also be achieved through avoiding risks and through transferring risks, as described earlier in this section. The other way to deal with risks other than mitigation is to ‘do nothing’ by accepting the risk. This may be possible in circumstances where the consequences or likelihood of the risk are deemed to be as low as reasonably practicable (ALARP) without further action.

Any mitigation strategy should encompass a risk assessment document so that the various strands of inter-related activities and mitigation measures are assessed together so that their interdependencies are also evaluated. This document should be prepared at the commencement of the project and should also identify the key stages throughout the project where a risk and mitigation re-assessment is to be performed. This re-assessment is aimed at identify new risks and mitigation measures which, for example, could arise from the following:

- changes in the law during the duration of the project which may impact working practices, e.g. implications of changes in law with regards to material disposal
- risks that have not been identified as part of the initial review
- development of new technologies which allow improved methods of mitigation

Throughout the risk and mitigation assessment it is considered that paramount importance is placed on the need for qualified, and where necessary, experienced personnel and that quality assurance systems are in place. These measures are considered to be fundamental for ensuring risks are understood, properly accounted for and mitigation measures are properly implemented.

6. SUMMARY AND THOUGHTS FOR THE FUTURE

The offshore industry is technically sophisticated and has risen to the challenges posed by working in new environments. It has been apparent that as this study progressed, many of the issues raised by industry were being investigated and problems solved by the use of new techniques and approaches. Examples include the adoption of the integrated investigation, the exploitation of geophysics and the use of autonomous underwater vehicles.

There is an active and knowledgeable set of organisations and people who are working hard to solve the new problems brought about by deeper water, marginal field development and offshore renewables. A number of pointers came from this study, namely the importance of:

- Awareness
- Training
- Skill development
- Integration
- Process and procedure

There is a need for wider understanding of the specialist technologies of geophysics, engineering geology and geotechnical engineering. This will make more widespread the integration and optimisation of the instigation/design/installation process.

The development of an accurate terrain (ground) investigation requires careful planning and relies on the use of a variety of information including desk study, sampling and an understanding of geological and seabed processes. Ground model development is an engineering geological skill, a resource that is relatively rare in the offshore industry.

The collection of data sets is already underway and should be further encouraged. It is through selfless sharing of information that the whole industry can benefit. Sharing information has generally been a feature of the offshore industry and they should be applauded for it.

The sustainability of the offshore industry and its safe operation depends upon new people entering the range of professions that comprise it; without this replenishment the knowledge, skills and enthusiasm that have made the UK offshore industry highly successful will decline. Already there are strong indications that young people do not view the sector as providing the interest or lifestyle that they would like. This is common to many occupations founded in science and engineering and must be regretted. The current generation who commenced their careers in the early seventies, when the UK oil industry was rapidly developing are now approaching retirement. Every effort should be made to gather the experience they have, particularly the ability to manage multi-disciplinary specialists – the key factor in achieving successful and safe project outcomes.

It has become apparent through the course of this study that individual and group competence is pre-requisite. Without this, the best processes and procedures will not be effective.

This study has demonstrated there is still a wealth of ideas and enthusiasm meeting new challenges in offshore engineering. The awareness of what each group can bring to bear on the problems and the importance of managed integration must continue to be worked on.

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APPENDIX A
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QUESTIONNAIRES

Name and Position:	
Name of organisation:	
Main areas of business:	

Please comment on any or all of the following issues, in particular with regard to studies in deeper water *(examples provided are not intended to lead views):*

1. The concept of a single field investigation integrating geophysics and geotechnics – i.e. "one pass", *e.g. is more reliance being placed on geophysics for near-surface ground characterisation and will this increase?*

2. The interaction of human factors and new technology – e.g. technicians rather than engineers or geologists becoming responsible for ground characterisation? Can the use of increasingly sophisticated software tools compromise engineering judgement?

3. The reduction in the amount of physical soils samples being obtained in deeper water sites and the consequent risks of overprocessing of limited data sets and/or missing critical features with wide spaced sub-bottom profiles.

4. Consideration of the degree of confidence in input data in comparison with the accuracy of analytical methods. Are these being quantified in a rational way?

5. Development and applicability of structural reliability (probabilistic) methods for offshore foundation engineering, *e.g. for a sparse data set, is a probabilistic approach justified or should a higher factor of safety be used to cater for uncertainty?*

6. The application of new and more advanced methods of design and analysis, e.g. the MTD approach for pile design in comparison to "tried and tested" API methods.

7. The risks associated with introducing too many ideas simultaneously, e.g. new, less conservative, methods for foundation design in conjunction with reduction in wave loading on the basis of probabilistic considerations.

8. In your experience, what effect, if any, is the recent change from a certification regime to a verification regime having on the independent checking of foundation design? What effect will there be in future?

9. Is foundation design adequately addressed in Safety Case submissions?

10. Are there adequate numbers of experienced geotechnical engineers/engineering geophysicists in the industry and are the experienced personnel who are leaving the industry being replaced?

11. For what type of structures, if any, and how often, is foundation design not performed by geotechnical engineers?

Name and Position:	
Name of organisation:	
Main areas of business:	

1. For the following site investigation tools, please comment on:

- Frequency of use (1 never used, 2 rarely used, 3 sometimes used, 4 usually used, 5 always used)
- Measurement uncertainty: (1 assumed correct, 2 medium accuracy – treat with some caution, 3 unreliable / wide scatter)

Tool	Familiarity (%)	Frequency of use (1-5)	Measurement uncertainty (1,2,3)	Additional comments (Value to S.I., usefulness in deep water, likelihood of being phased out, etc)
Cone Penetration Test				
Piezocone				
Seismic cone				
Lateral stress cone				
Pressuremeter cone				
Small diameter seabed cones				
T-bar penetrometer				
Shear vane				
Hydraulic fracture Probe				
Temperature probe				
Nuclear density Probe				
Thermal Conductivity Sensor				
Electrical conductivity sensor				
Pressuremeter				
Instrumented Plough				
Vibrocorer				
Long Corer				
Push Corer				
Box Corer				
Pressurised Corer				

Push Sampler				
Hammer Sampler				
Piston Sampler				
Grab Sampler				
Deepwater Gas Sampler				
Rotary Coring				

2. Please describe any new site investigation tools that you are aware of and classify them as state of the art or state of practice.

3. For the following methods of delivering site investigation tools to the seabed, please comment.

Tool	Familiarity (Yes / No)	Frequency of use (1-5)	Please comment on new developments, concerns over use or other pertinent issues.
Downhole tools			
Light seabed frames			
Heavy seabed frames			
ROVs			
AUVs			

4. Please describe any new or alternative methods of delivering site investigation tools to the seabed that you are aware of and classify them as state of the art or state of practice.

5. There are many challenges associated with site investigation in deep water. Could you please comment on the following issues and indicate what you consider the state of practice is. Please also indicate any new developments.

a) Overcoming the weight of the drill string or umbilical

b) The delivery of power to the tools/seabed frames.

c) Limited penetration of probes from seabed frames

d) Comparison of the results from obtained from different tools.

e) Improving the accuracy of determining stratification

f) Minimising sample disturbance, particularly in very soft soils.

g) Limitations of site investigation tools to large (expensive) ships.

6. Please comment on any other issues that you feel are relevant to the current state of practice in site investigation in the offshore industry.

7. For the following items, which do you think contribute most to the uncertainty in assessing the capacity of offshore foundation systems? What do you believe is the most rational way of assessing and/or quantifying such uncertainties and risks in the measurement of geotechnical parameters?

	Uncertainty High/Med/Low	Comments
Natural Variability		
Sample Acquisition		
Sample Treatment		
Sample Testing		
Other (State which)		

Questionnaire C: Foundation Analysis
Offshore Risk and Safety Study

Name and Position:	
Name of organisation:	
Main areas of business:	

1. For the following foundation types, please comment on:

   - How frequently do you consider they are used at present (1 never used, 2 rarely used, 3 sometimes used, 4 usually used, 5 always used)
   - How frequently do you consider they will be used in the future (1 never used, 2 rarely used, 3 sometimes used, 4 usually used, 5 always used)
   - In your experience, what methods are used to design these foundation systems at present. What new developments are predicted for the analysis of these foundation types.

Foundation	Familiarity (%)	Frequency of use (1-5)	Future frequency of use (1-5)	Methods used for design and additional comments
Drag anchors				
Driven piles				
Suction-installed piles				
Drilled and grouted piles				
Plate embedment anchors				
Suction caissons				
Spudcan footings				
Shallow foundations				

2. Please describe any new foundation types that are not listed above and comment on the design approaches used.

3. For the following types of structures, please comment.

- Familiarity with structure type (Yes / No)
- How frequently do you consider they are used at present (1 never used, 2 rarely used, 3 sometimes used, 4 usually used, 5 always used)
- How frequently do you consider they will be used in the future (1 never used, 2 rarely used, 3 sometimes used, 4 usually used, 5 always used)
- What future developments are predicted for these structures.

Structure	Familiarity (Yes / No)	Frequency of use (1-5)	Future frequency of use (1-5)	Future developments and additional comments
FPSO				
Jacket				
Gravity base				
Spar or TLP				
Subsea				

4. Please comment on the following issues related to the design of offshore foundation systems:

h) The industry approach to dealing with cyclic loading.

i) The industry approach to incorporating the effects of ageing in foundation capacity.

j) The role of 3D finite element analysis now and in the future.

k) The role of model or small scale testing.

l) The role of empirical design methods now and in the future.

m) In general terms, what are appropriate factors of safety (or resistance factors) now and in the future.

n) Should these factors be changed where there is less direct soils data, or where, for example, cone data are used without corresponding sampling for correlation purposes.

o) The merits or otherwise of "tried and tested" more empirical approaches to design vs. more advanced fundamental techniques.

p) For how many structures have you used the MTD/Imperial College pile design method? In clay? In sand?

q) What factors of safety (or partial factors) should be used with this method (in clay/sand/compression/tension)? What equivalent factors of safety are achieved using API calculations for piles designed by the MTD method?

r) Does standard site investigation yield sufficient data to perform these MTD calculations with confidence? Do you consider that special tests are necessary? If less site investigation data were available in future, would this affect your confidence in the MTD calculations?

s) Are the risks of soil disturbance from adjacent (including previously drilled) conductors/wells adequately taken into account in foundation design and well planning? Are these risks greater for present day or future structure designs than those for previous ones?

t) Please describe any other issues related to the design of offshore structures and foundation systems that you consider are important with particular emphasis on the challenges of deeper water and harsh environments.

5. What uncertainty is there in assessing foundation capacity for the following items? Is this uncertainty due to soils data or design methods? What do you believe is the most rational way of assessing and/or quantifying such uncertainties and risks?

	Uncertainty High/Med/Low	Comments
Drag Anchors		
Driven piles		
Suction installed piles		
Drilled and grouted piles		
Plate embedment anchors		
Suction caissons		
Spudcan footings		
Shallow foundations		

Name and Position:	
Name of organisation:	
Main areas of business:	

1. Please comment on future trends in the use of geophysical data for ground characterisation with respect to:

a) Geomorphology	
b) Stratigraphy	
c) Geometry of units	
d) Composition	
e) Strength	
f) Compressibility	

2. Please comment on the adequacy of conceptual geological models based on data obtained from new technologies (e.g. geophysical methods)

3. There are changes in the relative proportions of "ground truth" (CPT's, boreholes, observations from ROVs, etc.) and information obtained from geophysical methods. Please comment on the following:

a) Is there a move towards increasing reliance on geophysics? (Yes / No)	
b) What do you consider are the changes in the use of "ground truth"	
c) What will be the effect of these moves / trends?	

4. What do you consider to be future trends in the identification and quantification of geohazards in terms of technological and conceptual models?

5. Please comment on what you consider to be the present and future availability of regional and site specific data for desk studies of UK offshore areas.

6. What do you consider to be the possibilities today and in the future for 3D deep seismic data and bathymetry in investigating and characterising the sea-floor and shallow deposits?

7. The stages of work for a site investigation are summarised below. Please indicate on a scale of 1– 4 (1 most important, 2 next most important, etc.) the relative importance of each stage. Indicate where you think more effort should be placed in the future (1 most effort, 2 next most effort, etc.). Please justify these rankings.

Stage	Importance now (1 – 4)	Effort in the future (1 – 4)	Justification
Desk study and reconnaissance			
Preliminary ground investigation			
Detailed ground investigation			
Ground investigation during fabrication			

8. For the following statements, please state if you agree or disagree and explain why.

Statement	Agree?	Why?
Recent and near-future advances in geophysics will reduce the amount of ground truth required for the interpretation of the ground conditions.		
Specialist Quaternary and engineering geologists and geomorphologists must be involved in the final stages of interpretation of geophysical data.		
In the future, the accessibility to existing data from previous studies will be increasingly difficult.		
The study of potential geohazards in an area should be regulated in a similar manner to the environmental issues.		
In the future, data will have to be collected from many varied sources, not just oil and gas exploration and production companies.		
As developments move into deep-water environment, the time span needed for the acquisition of desk-study / reconnaissance data will need to be increased.		
For individual projects the quality and quantity of geophysical data about the sea-floor and shallow geology will increase.		
In the future there will be a need to increase the quality of sampling and testing carried out during site investigations.		
There is at present (or will be in the near future) an increasing tendency to only partially interpret the available geotechnical and geohazard data (due to lack of time; lack of accessibility)		

9. Please comment on any other issues that you feel are relevant to the current state of practice and future of ground characterisation, geological modelling and geohazard assessment in the offshore industry.

Name and Position:	
Name of organisation:	
Main areas of business:	

1. Use is now being made of the shallow part of conventional 3D exploration seismic data and the first arrival to identify shallow geo-hazards and provide seabed maps. Do you feel:

a) This is a substitute for site specific hazard studies? Yes / No / Maybe

b) Analytical methods will improve sufficiently in time to replace site specific seabed studies?
Yes / No / Maybe

c) Conventional Seismic vessels could be equipped with additional high resolution tools?
Yes / No / Maybe

2. Higher resolution seismic with lighter sources has proved effective in obtaining good 3D data on site specific studies in deep water with a surface vessel. Do you believe there will be:

a) An increasing utilisation of this approach? Yes / No / Maybe

b) Benefits in undertaking more 3D site studies? Yes / No / Maybe

3. Wavelet processing/data extraction is moving forward fast for reservoir characterisation and visualisation. Would your company support:

a) A similar concept for sea-bed engineering? Yes / No / Maybe

b) Developments in extracting soil parameters? Yes / No / Maybe

c) The use of such data without ground truth? Yes / No / Maybe

4. Swathe Bathymetry uses are increasing in all areas of seabed studies. Do you believe that:

a) Lithology signatures will identify sea floor lithology? Yes / No / Maybe

b) Could such systems in AUV/UUV's replace side scan sonars? Yes / No / Maybe

5. Bottom towed sensors and sources are being used in conjunction with other hardware for pipeline and cable route surveys. Do you consider:

a) Such instrumented units can be a substitute for samples? Yes / No / Maybe

b) Sledge systems could be used for deep water site studies? Yes / No / Maybe

c) These systems can be relied on for engineering purposes? Yes / No / Maybe

6. Use of AUVs is being promoted as the future way to acquire site survey data. Do you believe this is realistic:

a) Within the next five years? Yes / No / Maybe

b) This approach will replace surface vessel systems? Yes / No / Maybe

c) Positioning systems are robust enough to accept data? Yes / No / Maybe

7. Which of the above (or any other) hold the greatest promise in reducing uncertainty in quantification of Geological and Geotechnical Characterisation through Geophysics and why?

8. Do you anticipate an improvement in quantification of uncertainty with Geophysical Characterisation will be achieved through:

a) Better interpretation training? ____

b) Use of Sub-surface modelling? ____

c) Improved Spatial Correlation? ____

9. By which year and through which technical approach do you consider it will be possible to produce quantified Geotechnical parameters using Geophysical methods for:

a) Stratigraphy__________________________________/_______________________________

b) Soil type____________________________________/_______________________________

c) Soil Properties_______________________________/_______________________________

d) Field models for soil data______________________/_______________________________

10. For the following items, which do you think contribute most to the uncertainty in assessing the capacity of offshore foundation systems through geophysics? What do you believe is the most rational way of assessing and/or quantifying such uncertainties and risks?

	Uncertainty High/Med/Low	Comments
Development of Geological Models		
Experience of Geologist		
Identification of Stratigraphy		

	Uncertainty High/Med/Low	Comments
Identification of Area/volume of each Soil Type		
Identification of Soil Types		
Measurement of Soil Properties		
Inference of Geotechnical Parameters from Geophysical survey		
Human Factors, such as Experience of Geophysicist		

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RR 286

£25.00

ISBN 0-7176-2924-4

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