GEOTECHNICAL & GEOPHYSICAL INVESTIGATIONS
FOR
OFFSHORE AND NEARSHORE DEVELOPMENTS

International Society for Soil Mechanics and Geotechnical Engineering

GEOTECHNICAL & GEOPHYSICAL INVESTIGATIONS FOR OFFSHORE AND NEARSHORE DEVELOPMENTS

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CONTENTS

Page

CONTENTS (CONTINUED)

ABBREVIATIONS USED IN THE TEXT

AUV	Autonomous Underwater Vehicle
(D)GPS	(Differential) Global Positioning System
BH	Borehole
BPT	Ball Penetration Test
CID	Consolidated Isotropically, Drained triaxial compression
CIU	Consolidated Isotropically, Undrained triaxial compression
CPT	Cone Penetration Test
DMT	Dilatometer test
DP	Dynamic Positioning
GBS	Gravity Based Structure
GPS	Global Positioning System
HSE	Health, Safety and Environmental
LBL	Long Baseline
PCPT or CPTU	Piezo-cone Penetration Test
PMT	Pressuremeter Test
PROD	Portable Remotely Operated Drill
ROV	Remotely Operated Vehicles
ROTV	Remotely Operated Towed Vehicles
RQD	Rock Quality Designation
SBL	Short Baseline
SPS	Standard Positioning Service
SPT	Standard Penetration Test
SWL	Safe Working Load
TBT	T-bar Penetration Test
USBL	Ultra Short Baseline
UTM	Universal Transverse Mercator
UU	Unconsolidated, Undrained triaxial compression
UUV	Untethered Underwater Vehicle
VST	Vane Shear Test

PREFACE

Two of the objectives of 2001-2005 Technical Committee 1 “Offshore and Nearshore Geotechnical Engineering” of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) were:

- Provide support to ISSMGE member countries requesting dissemination of offshore/nearshore geotechnical expertise from other countries.
- Prepare documentation that gives practical information on executing nearshore and/or offshore geotechnical projects.

In view of these objectives, Technical Committee 1 (TC1) members agreed that industry would be served with a handbook giving an inventory of geotechnical and geophysical data acquisition techniques for characterising offshore and nearshore soil conditions. This should include recommended planning schedules for offshore and nearshore projects. Thus, TC1 members supported by numerous other colleagues prepared this handbook and made this available to attendees of the two September 2005 Geotechnical Conferences:

- 16th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE) in Osaka, Japan.
- International Symposium on Frontiers in Offshore Geotechnics (ISFOG) in Perth, Australia.

This handbook was also published on the web site of the ISSMGE at about the same time.

Members of TC1 during the 2001-2005 term were:

H.J. Kolk (Netherlands),	chair
M.B. de Groot (Netherlands),	secretary
A.R. Koelewijn (Netherlands),	co-secretary
K.H. Andersen (Norway)	core member
J.P. Iorio (France)	core member
A. Amr Darrag (Egypt)	core member
T. Tsuchida (Japan)	core member
M. VandenBroeck (Belgium)	core member

M. Achmus (Germany)
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N. Smith (United Kingdom)
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M. Sweeney (United Kingdom)
M. Werno (Poland)
P.I. Yakovlev (Ukraine)
K. Zen (Japan).

Numerous non-TC1 members contributed to this document. In particular, R. Hobbs and R. Salisbury (both from the UK), A.H. Nooy van der Kolff, L.A. Paassen, M.Th. van Staveren, A.J. Wegerif and G.L. van der Zwaag (all from The Netherlands) gave a significant amount of useful comments and suggestions. The support of all the colleagues worldwide is deeply appreciated.

While every care has been taken in preparing this handbook, it should not be regarded as either definitive or necessarily complete, and it is for guidance only. This information should be used with caution and neither its authors nor the International Society for Soil Mechanics and Geotechnical Engineering accept any liability for the consequences arising from its use.

1. INTRODUCTION

This review of the aspects and techniques of marine site investigation has been produced by Technical Committee 1: Offshore and nearshore geotechnical engineering, of the International Society for Soil Mechanics and Geotechnical Engineering, with the aim of providing guidance and good practice examples for the collection of site investigation data for offshore and nearshore structures.

Knowledge of seabed soils and rocks is essential if offshore and nearshore structures are to be properly and safely designed and built. A large part of the commercial and operational risk involved in these works relates to uncertainties about the properties of soils and rocks at the site. It is therefore necessary to perform sufficient investigations to evaluate these risks thoroughly. Many geophysical and geotechnical techniques are available to the engineer to perform such investigations. However, offshore and nearshore site investigations involve special problems raising the question - what is sufficient?

The answer largely depends on the situation. For offshore platform design, the information required on the soils is different to that, say, for a pipeline and the requirements for a dredging program are different again. Further, the geotechnical information needed for a feasibility study or a site selection is quite different from that needed for detailed design. The equipment and techniques for site investigations in deep water differ significantly from those for shallow water; those for calm water differ from those for harsher environments. It is to assist with the answer as to what is sufficient, that the authors of this booklet aspire.

Many parties are involved in the planning and decision-making process of a site investigation, including the owners and clients, designers, contractors, investigators and surveyors. Rarely has any one person all the experience and expertise needed for planning the optimal programme.
This document provides useful information for these construction professionals and includes information on:

- Soil and rock properties and their consequences for engineering design.
- Typical techniques and equipment for marine site investigation.
- The relevance of different methods of data acquisition.
- Guidance on the planning and scopes of work for geophysical and geotechnical investigations, and interpretation of the results.
- The foundation engineering issues surrounding different sorts of structures, schemes and working methods.
- Examples and case histories to illustrate special situations, difficulties and common problems.

Although hydrographic surveys and other data collection of the water column are required for proper design, the requirements and techniques for such surveys and investigations are not covered in detail in this document.

There are many existing international, national and industry codes and guidelines on offshore and nearshore geotechnical and geophysical investigation techniques and operations. These codes and regulations are subject to regular review, modification and improvement, and expert advice should always be sought. This booklet does not in any way purport to be a definitive or thorough dissertation on the state of industry practice, rather it is hoped that it will assist, in some measure, all those engaged in these activities by having to hand a useful practical guide to good practice.

References to achievable soil and rock penetration, production rates and weather limitations and the like, are for general guidance only. What is achievable will always be governed by a combination of factors such as geology, water depth, environmental conditions and vessel capabilities. Every project and every situation is different. the subject itself is highly technical. Moreover, a project's successful outcome depends on securing the services of highly competent contractors and technical advisors.

Invariably, a program of offshore work will require permits from the maritime authorities and from the various departments having jurisdiction over operating areas such as offshore oil and gas fields and their associated infrastructure of pipelines and work zones. All marine activities are subject to international and/or national regulations as well as industry operating standards. A number of the international regulations, such as those of the International Maritime Organisation (IMO), have not necessarily been ratified by all participating nations although they may, in whole or part, have been adopted by, or have become accepted practice of, individual nation states. Many of the more common operational and technical facets of geophysical surveying and geotechnical investigations are included together with references to various standards and codes of practice; a list of some of these is included in Section 13.

2. INVESTIGATION, PLANNING AND OVERVIEW OF TECHNIQUES

This section provides an overview of the site investigation process, its purpose and the normal chronological order for planning the works. The importance of a desk study (also known as a desktop study) is discussed together with a brief look at the two key sciences involved in the site investigation process: the geophysical survey and the geotechnical investigation.

2.1 SITE INVESTIGATIONS

Site investigations for offshore structures, nearshore structures and dredging works are necessary to acquire data that will facilitate successful foundation design, site or route selection, choice of foundation type, dimensioning, installation and operational integrity of the proposed structure. Success depends on a well-prepared budget, good planning, and attention to quality and safety to develop an acceptable risk profile.

The data required include site-specific information on:
- Seabed topography and morphology such as rock outcrops and boulders.
- Nature of the soils and rocks, their stratification and variability.
- Soil strength, deformation and consolidation characteristics.
- The influence of specific factors such as cyclic loading, rate of loading, soil sensitivity and thixotropy.
- The possibility of scouring.

Information may also be required on regional influencing factors such as:
- Slope instability.
- Earthquake susceptibility.
- Presence of shallow gas or hydrates.

The type and quantity of data required will depend upon factors that include:
- Type of structure planned.
- Installation/construction methods proposed.
- Water depth.
- Existing site data.
- Project phase, e.g. feasibility study or final design.
- Acceptable risk to people and the environment.
- Type of foundation loads.

2.2 PLANNING

The level of information required on a site’s soil and rock properties will doubtlessly change during the course of a project. In the early stages, the information should be at least sufficient to demonstrate the feasibility and suitability of the design concepts. The data should also be adequate to select the best site or route. At later stages, the information should be sufficiently detailed and site-specific to allow contractors to provide optimised pricing for provision of design, supply and installation works. A final investigation stage may be necessary to resolve any specific issues that arise as the design and construction works progress.

A site investigation programme moves forward through progressive stages. Planning for each stage is reliant on previous findings in order to optimise the scope of work. The geotechnical investigation considers many factors including vertical and horizontal uniformity of the seabed soils, their geological history, the dimensions of the proposed structure and the design concepts.

It is important that the geophysical and geotechnical components are planned together as integrated parts of the same investigation. Data analysis should be considered as a single exercise drawing together the results of geological, geophysical, hydrographic and geotechnical work, perhaps performed by specialists, in an integrated manner into one final report.

Increasingly there is a requirement for environmental baseline surveys and environmental impact assessments for offshore construction projects. Whilst the detail of such surveys is outside the scope of this document, these may involve the collection of seabed samples for chemical, physical and biological analysis, as well as seabed photography and sediment distribution studies. There will thus be some overlap with the data collected in conventional geophysical and geotechnical surveys. It is important that survey planning takes account of this overlap to ensure maximum efficiency of overall data collection. This extends to the data analysis stage where, for example, grain size data is shared between environmental and geotechnical specialists and seabed photographs are used to enhance the interpretation of seabed conditions.

The sequence for the investigation programme should be:
- Desk study.
- Topographical and geophysical survey.
- Geotechnical survey and laboratory testing.
- Additional geophysical and/or geotechnical surveys and/or laboratory testing as required.

Depending on the size of a project and/or the complexity of the geotechnical context and associated risks (geohazards), additional intermediate stages may be necessary.

Whatever the number of stages, it is important that the geotechnical analyses take account of the survey reports, knowing with confidence that the data gathered at different stages are complementary. Any contradictory data regarding seabed features, the stratigraphy, or the soil descriptions, must be resolved. The resolution may require new analyses and interpretation of the survey data, or require additional, site-specific, survey tasks.

The geotechnical design and the associated investigation depends strongly on factors such as the structure’s function, or the engineering activity, the general design concepts, types of environmental load (wave load magnitude and period, wave load composition, currents, loading from icebergs and ice sheets, probability of earthquakes, etc) and design criteria (limits to settlement and displacement). To focus and optimise the geotechnical investigation, it is important to clarify these factors early in the investigation programme while leaving options open should the investigations lead to unexpected results. Success also depends on establishing and maintaining good communications between all parties, including oceanographers, wave load specialists, seismologists, structural engineers and other marine professionals. A structured, risk-avoidance approach is the best way to set the right priorities and focus for the geotechnical investigation.

2.3 DESK STUDY

The desk study is the first phase of a site investigation, bringing together existing, or researched information, and identifying potential areas of information conflict or deficiency. The desk study needs to consider a broad range of issues, all of which may affect a project both practically and logistically.

The desk study should include a review of all sources of appropriate information, and collect and evaluate all available relevant data for the site including, for example:

- Bathymetric information.
- Geological information.
- Information and records of seismic activity.
- Existing geotechnical data and information.
- Previous experience with foundations in the area
- Meteorological and oceanographic information (metocean) including tides, currents, wind and wave regimes.

Some desk studies, for example for cable routes, wind farms and dredging sand searches, may include additional, non-technical data such as seabed congestion, restricted areas, shipping movements, fishing or military activity, permitting, etc.

In any desk study of seabed conditions, a qualitative and quantitative assessment of existing data is mandatory. Potential sources for information and data sets include companies with proprietary data, national geological survey organisations, academia, other maritime operators and contractors. Internet sites contain metadata for some offshore regions but sources need to be checked and the data verified. Invariably, the sources for this information cannot be held liable for the accuracy, or relevance, of their information and therefore it should be used with discretion at the engineer’s (or user’s) risk. Much third party information will have copyright or other restrictions applied to its use and these should be properly researched, and where necessary the owners’ permission sought, before being cited.

A desk study alone is not sufficient for detailed engineering purposes, but should be sufficient for conceptual engineering to move forward in a focussed manner and provide the basis upon which to design and plan subsequent site investigation work.

2.4 GEOPHYSICAL SURVEY

A geophysical survey is required to understand the nature or characteristics of the seabed. The term is generic and comprises various individual objectives including:

- Establishing bathymetry.
- Identification and location of significant seabed features, obstructions and hazards.
- Determination of the geometry of the subsurface layers (thickness, dip).
- Extrapolation of local geotechnical data across the entire site.

Typically, the information is acquired using a combination of techniques:

- Seabed bathymetry and topography:
  - Echosounding or swath echosounding (particularly in areas of uneven seabed, outcrops, corals, pockmarks, sand waves, etc).
- Seabed features and obstructions:
  - Traditionally by sidescan sonar. Modern mosaicing systems will provide an acoustic “photograph” of the seabed in which prominent features can be more easily understood and interpreted. Increasingly these are being augmented with the backscatter and seabed discrimination information from swath echosounders.
  - Magnetometer to identify metallic objects, such as pipeline and cable crossings, metallic debris and ammunition, at or just below seabed.
- Geological (sub-bottom) information:
  - Usually by means of reflection seismic systems. Digital data capture is common, which facilitates processing, and can lead to enhanced resolution. Depending on the system and method employed, seabed penetration to 50 m or so is typical for geotechnical purposes.
  - High-resolution seismic refraction can provide useful complementary data for shallow strata definition (<10 m soil depth). Seismic refraction is also suitable for shallow water depths (<15 m) where low-frequency seismic reflection methods may reach their operational limits.
  - Electrical resistivity surveys can provide some indication of hard materials at, or near, the seabed (in contrast to softer materials like clay, silt or sand). However, distinguishing strata from electrical resistivity data is generally unreliable.

Section 4 discusses various types of geophysical survey techniques. These techniques need 'ground truthing' to associate the profiles with the true character of the seabed constituents. Ground truth is obtained from geotechnical surveys, including in-situ testing, sampling and laboratory testing.

2.5 GEOTECHNICAL SURVEY AND LABORATORY TESTING

The geotechnical survey and laboratory testing programme is designed to acquire reliable information on the stratification, the geological characteristics and the geotechnical properties of the different soils and rocks found on site. The geological characteristics are listed in Table 2.5-1. The values of the geotechnical properties, expressed in soil and rock parameters, should be known with sufficient accuracy to meet the engineering requirements of the structure design. This requires a site-specific investigation and interpretation of the soil and rock properties by geotechnical experts, geologists and geophysicists.

Table 2.5-1 BASIC GEOLOGICAL CHARACTERISTICS REQUIRED

SOIL	ROCK
Identification of the soil units Identification of the principal and minor constituents Homogeneity Colour, shape & angularity of the particles Structure (bedding, fissuring)	Identification of the rock units (rock name) Weathering Homogeneity Colour Bedding (thickness and orientation) Fracturing (spacing and orientation) Structure characteristics such as infilling, openness etc.

Frequently, a limited geotechnical survey and some laboratory testing are carried out at the same time as the geophysical survey, primarily for aiding interpretation of the geophysical data. The main geotechnical survey is normally performed some time after the geophysical survey and often after site, or route, selection has been formalised. This allows effective targeting of sample and test locations to better identify soil strata changes, clarification of any apparent anomalies, or investigation of specific seabed features identified from geophysical data. The same experts should be involved at all stages in preparing the scope of work.

It is recommended that a second, independent, interpretation of the geophysical data is performed at the end of the laboratory testing stage to crosscheck the initially assumed geometry of the subsurface layers (thickness, dip).

Geotechnical data acquisition uses a combination of techniques:

- Coring and sampling methods for material identification, description and subsequent laboratory testing where engineering parameters are determined.
- In-situ testing for accurate stratification and determination of engineering parameters.

Section 5 discusses the wide range of available equipment for each geotechnical method.

3. VESSELS, SURVEY PLATFORMS AND DEPLOYMENT SYSTEMS

The choice of vessel and deployment systems depends partly on the type of information needed, partly on the environment, and on availability of suitable equipment. The information required determines, for instance, whether a survey over a long track is necessary or a test at a single location, and whether just seabed surface information is needed, or whether penetration information to a certain depth is required. The environmental considerations that may affect and/or constrain operations include water depth, tidal variation, wave, current and weather conditions.

If the water depth is less than about 20 m, geotechnical operations may be carried out as onshore by using an ordinary drilling or cone penetration test rig from a jack-up platform. Where wind and wave conditions are benign (sheltered areas), it can be acceptable to operate similar equipment in these water depths from anchored barges although barge motion may affect the geotechnical quality. In greater water depths, or if wave, current or wind conditions are severe, it is necessary to employ vessels fitted with anchoring or dynamic positioning systems and heave compensating systems.

Geotechnical site investigations can be either in seabed mode (where the sampler or in-situ testing tool is deployed directly from seabed) or in drilling mode (where the tool is deployed from the bottom of a borehole), In the seabed mode, sampling and in-situ test penetration depth is limited, depending on soil type and tools used. In-situ testing in the drilling mode achieves greater depths as the borehole progresses.

A recent development has been a portable, remotely operated drill. This robotic seabed device operates in water depths to 2,000 m and is able to drill, take core, piston or thin-walled push samples, and conduct cone and ball penetration tests to 100 m below the seabed.

3.1 SHIPS AND BARGES FOR GEOPHYSICAL AND GEOTECHNICAL SURVEYS

It is normal to conduct major offshore geophysical and geotechnical surveys from specialised survey vessels specifically fitted with equipment for deploying and handling geophysical and geotechnical systems. Surveyors, geophysicists and other onboard specialist personnel are provided with laboratories, workshops and processing software. These vessels can remain at sea for many weeks.

Most vessels equipped with an A-frame, or another suitable crane handling system, can undertake geotechnical surveys. Where office or cabin space is at a premium, temporary special containerised workshops and laboratories can be installed, for example, on the back decks of workboats.

Figure 3-1 *Geophysical survey ship*

Inshore and nearshore geophysical surveys are normally conducted from launches, or from small vessels such as fishing boats. The smaller geotechnical apparatus, such as grab samplers, gravity corers, vibrocorers and lightweight cone penetration test (CPT) systems, can be deployed from survey ships or similar size vessels.

The best solution when handling heavy or specialist geotechnical systems is using specialist geotechnical vessels fitted with heavy duty A-frames, cranes and winches. The suitability of non-specialised ships and barges depends on:

- Capability to keep track, or maintain position.
- Deck space around a moonpool or along the vessel's side.
- The capability of the equipment to accommodate deck movements relative to the seabed, or the possibility of installing a marine riser system (using a heavy seabed footing) with the geotechnical equipment installed on its platform.
- Cranes and winches capable of handling the necessary equipment.

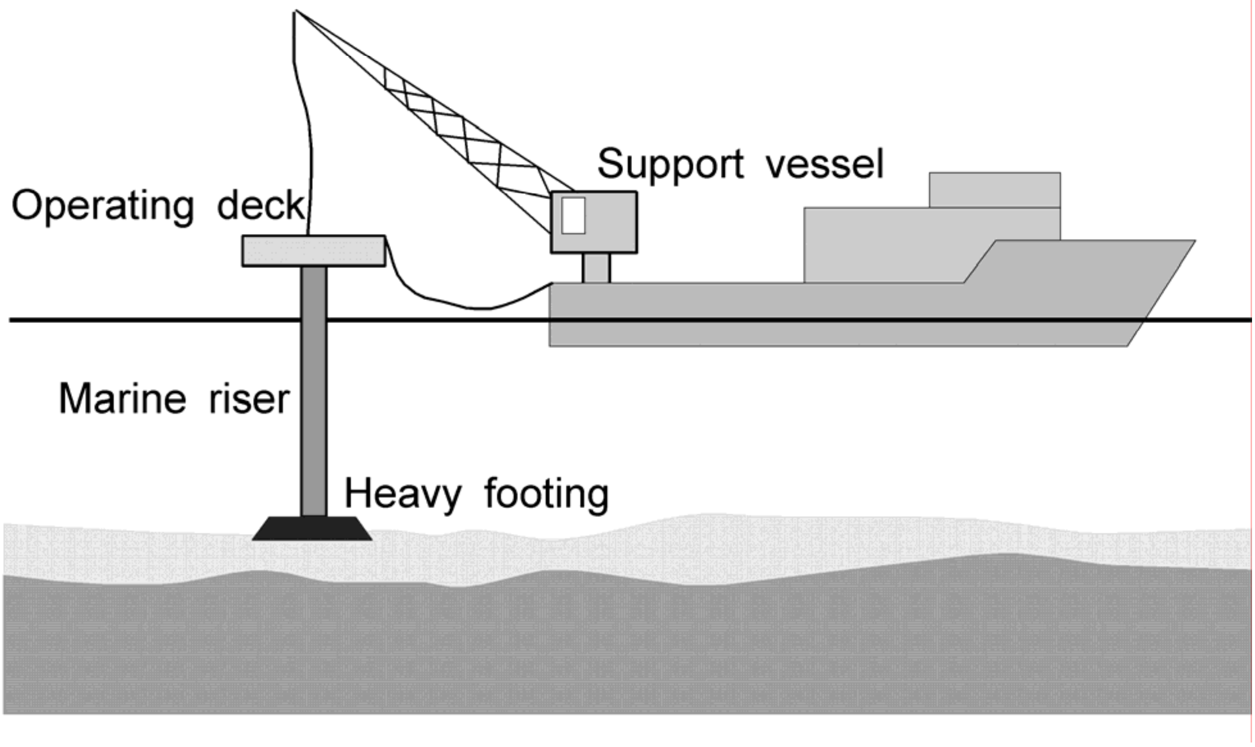

Figure 3-2 *Marine riser system to cope with vessel movements*

Calculating the size of cranes, A-frames and other facilities, is the province of the marine engineer. Safe working loads (SWL) are calculated based on the mass of the tool and its tow or lifting cable, together with the maximum dynamic stresses likely to be encountered when retrieving the tool from the seabed. For example, some tools, such as corers, have to be pulled out of the seabed, while the mass of grab samplers increases threefold when filled with a large sample. Other tools, such as deep-towed bodies, or refraction seismic systems that are towed across the seabed, impose considerable stresses on tow cables and systems. Upward reaction forces have to be countered when penetration tests, such as Cone Penetration Tests (CPTs), are performed.

Ships conducting coring, or in-situ testing operations, have to maintain station vertically above the core/test site. This is best achieved when the vessel has a dynamic positioning system or joystick-controlled thrusters. Alternatively, a multi-point anchoring system may suffice, although this can increase operational times and is usually impracticable in deep water. Further, anchoring may be restricted by shipping activities in the work area. Where water depths are limited and the sea is moderately calm, spuds may be suitable for keeping a barge in position.

When selecting a vessel, attention to detail is required. A low-cost vessel can easily turn into a financial liability and seriously jeopardise a project. A vessel's ability to work in bad weather is vital in harsher environments, where sea-state can easily terminate an operation when using an unsuitable ship. A vessel's capacity for deploying and recovering geotechnical and geophysical systems requires closest attention, especially if the ship or its crew are new to the work. Where cranes, or A-frames, are fitted, the ship's structure has to be surveyed to ensure its integral strength is adequate and that the vessel's stability will not be compromised.

Any survey vessel must meet modern health & safety requirements and have fully up-to-date certification for its lifesaving aids, communications and navigation systems, and for its deck machinery such as cranes, winches etc.

For most geotechnical investigations requiring seabed penetration greater than 10 m, drilling methods will be required. The exceptions are the use of long piston corers, of 20 m to 30 m length, used in soft, deep water clay deposits, and the bigger seabed penetration test systems, both of which require large vessels with specialist deployment equipment and sufficient deck space, and facilities, for safe operations.

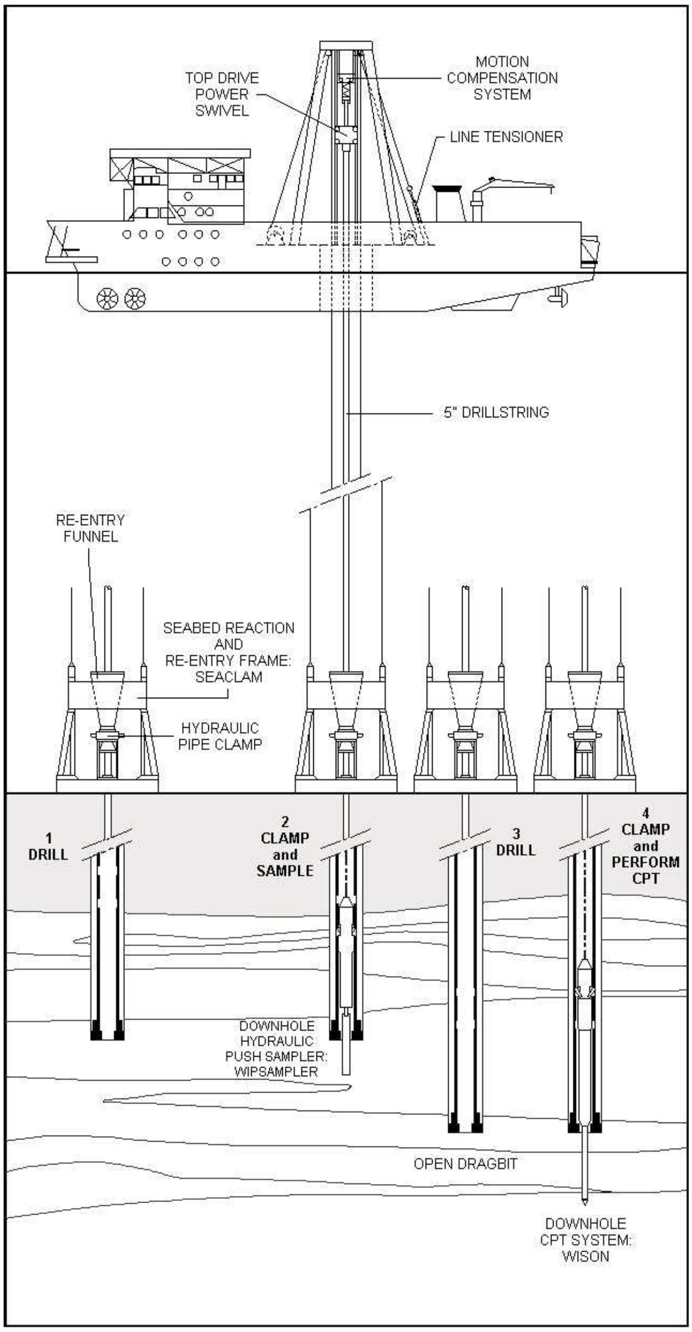

Figure 3-3 *Typical procedures for drilling, push sampling and in-situ testing*

A detailed description of geotechnical drilling, penetration test systems and operations is outside the scope of this document, but a brief summary of the main methods is shown in Figure 3-3**Error! Reference source not found.**.

3.2 GEOTECHNICAL DRILL SHIPS

Most deep penetration geotechnical investigations for offshore developments are performed from dedicated, purpose built, or converted, vessels. Since drilling operations can take several days per borehole, and verticality of the drill string is critical, the use of dynamic positioning, or a multi-point anchoring system, is essential. The size and favourable station-keeping characteristics of such vessels can also make them cost-effective for shallow penetration investigations.

A heave-compensated, rotary drilling technique, typically utilising a 5-inch OD steel drill string and an open-faced dragbit, is used. In ultra deep water, aluminium drill pipes may be used. Sampling and in-situ testing is generally performed via wire-line operated down-hole tools. The highly controlled nature of the sampling and testing operations means that, for the majority of ground conditions, this will provide the highest achievable quality of samples and test data.

Figure 3-4 *Geotechnical drill ship*

3.3 GEOTECHNICAL JACK-UP PLATFORMS

In favourable circumstances, drill ships can operate in water depths as shallow as 20 m. In extreme circumstances, shallow-penetration investigations may be feasible in water depths of 10 m. However, the primary method for drilling boreholes in water depths between 20 m and the shore – including the inter-tidal zone – is with a jack-up drilling platform. Such platforms are typically capable of both rotary and percussive drilling techniques, high-quality sampling and in-situ testing.

When selecting a jack-up unit, consideration should include predicting leg penetration, to ensure that the rig has sufficiently leg length, and that the legs will not punch through during installation. This is of particular importance in areas where soft soils or thin, hard layers overlying softer soils are anticipated.

3.4 OTHER PLATFORMS

Temporary or permanent platforms can be suitable for geotechnical investigations depending on:

- Space available for a drill rig and associated equipment and/or the possibility of installing a penetration test rig and providing sufficient reaction for a penetration test.
- Availability of cranes capable of handling the investigation equipment.

Figure 3-5 *Geotechnical jack-up rig*

3.5 HIGH-WHEELED VEHICLES AND OTHER TRUCKS

High-wheeled vehicles and other land trucks can sometimes be used where the seabed dries at low tide. For soft, muddy terrains, wide tracks and low-pressure wheels, air cushions, or other systems, may be needed. The weight of such a vehicle may be an issue if penetration tests are required - while a low weight (mass) vehicle allows access to a muddy foreshore, its reaction mass may be insufficient, or limit the achievable penetration depth.

3.6 REMOTELY CONTROLLED SYSTEMS

Remotely controlled systems, managed from ships can also be used for geotechnical investigations. These are discussed in Section 5.3.2.

3.7 POSITIONING

Offshore and nearshore geophysical or geotechnical investigations require accurate positioning systems, such as differential global positioning system (DGPS), and heading sensors such as gyrocompasses. Close to shore, or when operating near an offshore platform, traditional land survey systems such as lasers and Total Stations can be used.

Where underwater positioning is required, acoustic positioning systems such as Ultra Short Baseline (USBL), Long Baseline (LBL) or special variations of these, are the typical methods employed.

3.7.1 Global Positioning System

The US Department of Defence’s Global Positioning System (GPS) is a satellite based system providing positioning anywhere on the globe. Primarily designed for military applications, GPS has become the chief positioning system for most civil applications at sea. The GPS system is divided into three segments:

- **The Space Segment** is a constellation of, nominally, 24 satellites arranged in six orbital planes.
- **The Control Segment** consists of tracking stations located around the world to monitor the satellites and compute their precise orbits (ephemeris) and clock corrections, and uploads these from a Master Control Station.
- **The User Segment** consists of the GPS receivers and the user community.

GPS receivers convert signals into position, velocity, and time. Four satellites are required to compute X, Y, Z (position) and Time. Civil users have free access to the Standard Positioning Service (SPS), which, typically, provides accuracy better than 37 m. The measurements, together with the satellites broadcast position, are used to compute position and height in X, Y, Z terms or latitude and longitude in terms of the World Geodetic System 1984 (WGS84).

Differential Global Positioning System (DGPS) techniques correct bias errors at one location with bias observations measured at a known position. A reference receiver, or base station, computes corrections for each satellite signal, which are then applied in the user’s receiver.

Differential corrections may be used in real-time or in post-processing. Real-time corrections can be transmitted by radio, such as the free-access IALA beacon network, or more commonly, over radio or satellite links of DGPS vendors such as Fugro and Veripos. Nominally, standard DGPS corrections can provide accuracy of 1 m to 3 m. Satellite broadcast DGPS are available that allow positioning with an accuracy up to 0.1 m.

3.7.2 Underwater Acoustic Positioning

Only a brief overview of the chief underwater acoustic positioning systems is given here due to their complexity.

Long Baseline (LBL) positioning requires an array of seabed transducers installed at known points around a work area. Accuracy depends upon the frequency and power transmitted; lower frequency is normally less accurate than high frequency, but has a longer range. The coded acoustic signals from the transponders are interrogated by a transceiver deployed from a vessel, or other work platform, from which position is then determined by trilateration. A variation on the theme is the Short Baseline (SBL) that functions as an inverted LBL, where the ‘array’ is fixed, for example, to the under-keel of a ship.

Ultra Short Baseline (USBL) positioning is a range and bearing system typically used to locate an underwater vehicle, or structure, from a mother ship at a known position using, for example, DGPS. The system can be very accurate and is particularly useful as a position input during Dynamic Positioning (DP) operations.

3.7.3 Geodesy

All positions and depths are expressed in terms of either:

- Grid co-ordinates – eastings, northings and depths / heights.
- Geographical co-ordinates – latitude, longitude and depths / heights.

Geodetic computations and data manipulation is complex and fraught with the potential for serious error and should be left to experts.

The chief aspects are:

Spheroid

The spheroid is a figure of the earth, or earth model, upon which positions are referred. There are many spheroids in use and they are normally nominated by a national mapping or charting agency. Internationally accepted spheroids include GRS80 used by the GPS system's WGS84 earth model.

Coordinates expressed on the spheroid are latitudes and longitudes (and occasionally earth-centred X,Y, Z) and their associated heights are referenced to the geoid.

Geoid

The geoid is an equipotential surface analogous to sea level (on an imaginary world without land). Every point on the geoid is normal to the direction of gravity; it is the plane that a common surveyor's level assumes.

Projection

A projection is a mathematical method of converting the curved surface of the earth to the flat plane of a map or chart. There are many projections and the choice determines the properties of the map or chart. The key parameters defining a projection's constants are:

- Central Meridian – a longitude (or latitude) forming one direction of the Origin of the projection.
- A latitude (or longitude) associated with the Central Meridian that defines the second ordinate of the Origin.
- False eastings and northings of the Origin – Cartesian grid coordinates chosen such that negative numbers do not occur at the southwest extremity of the projection's limits.

Projection example: Universal Transverse Mercator projection (UTM)

The UTM is an internationally accepted projection whose main parameters are constant. The system comprises of 60 Zones each of 6 degrees longitude. The Zones are numbered from 1 beginning at 180 degrees west (or east), and extend from the equator to 80 degrees north and south; each zone is subdivided into 8 degree latitudinal bands numbered alphabetically.

- Central Meridian: the longitude for the centre of a particular zone, e.g. 3 degrees east.
- Latitude of Origin: the equator, 0 degrees north / south.
- Scale factor on the Central Meridian: 0.9996.
- False eastings (of the Central Meridian): 500000 m E.
- False northings (of the Origin) – 0 m N for the northern hemisphere, and 10000000 m N for the southern hemisphere.

3.7.4 Grid

The common grid is a Cartesian representation on the projection. It should be noted that Grid North is only coincident with True (geographical) North on the Central Meridian. To the west of the Central Meridian, True North is east of Grid North and vice versa to the east.

3.7.5 Heights

Heights (and depths) are probably the most difficult concepts to grasp and offer great scope for error. The following is a brief overview:

Land heights (and 'depths' for shallow inland waterways) are normally referenced to a national vertical datum, while sea depths are referenced to Chart Datum.

Chart Datum is a local vertical datum below which the tide will normally not fall. The definitions are wide and varied. A port's Chart Datum should be referenced to the land levelling system, but in some regions of the world, this is the exception rather than the rule. Depths measured by echosounders etc, are reduced to Chart Datum by applying corrections for tide.

Tides are measured by tide gauges operated either by a local authority or by a contractor.

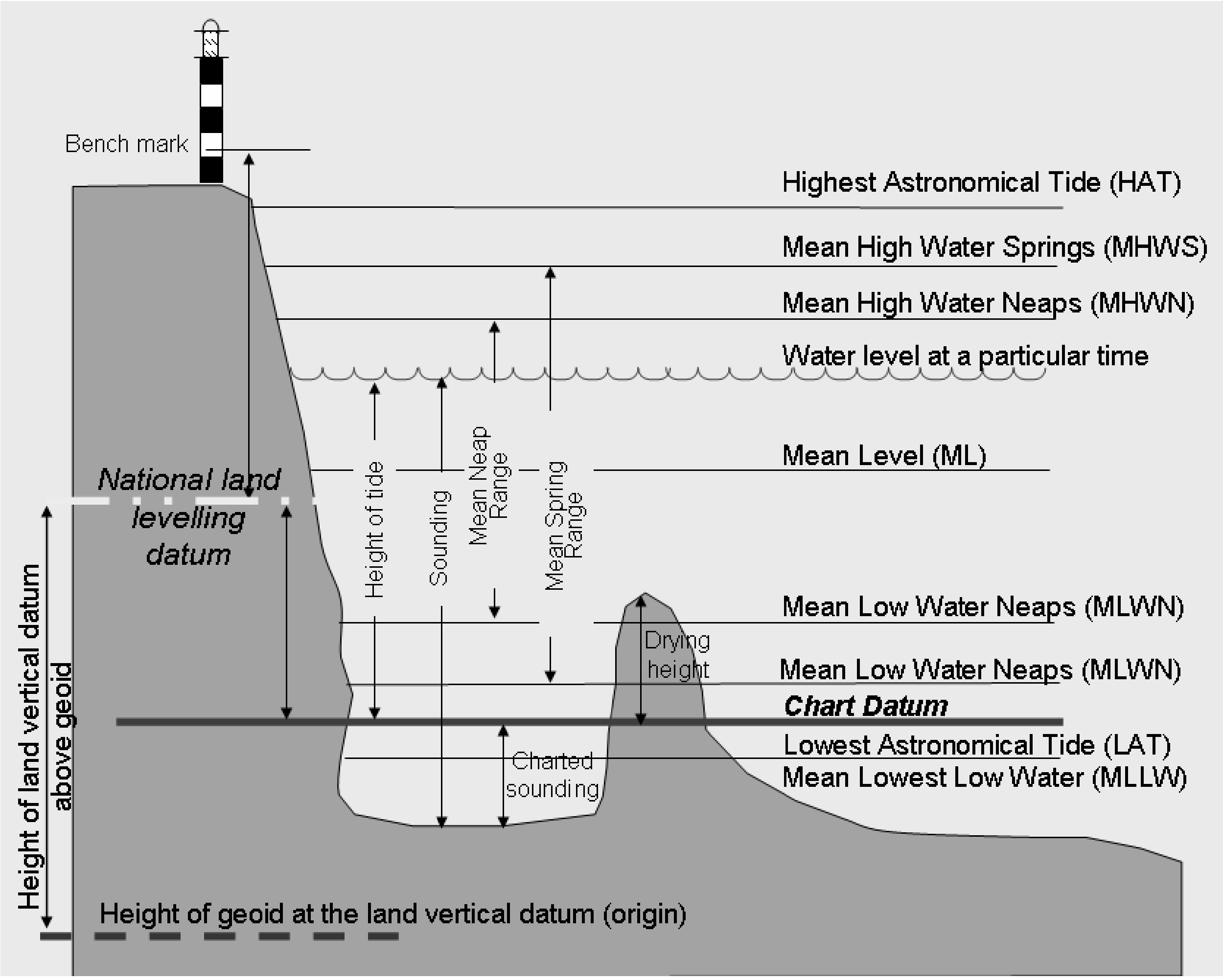

Figure 3-6 *Chart Datum and height / depth relationships*

A note on GPS heights: heights derived from the GPS are heights above the WGS84 spheroid at the point of position. Individual receivers handle heights in different ways and the methods used, and datum quoted, should be verified from the manufacturers literature. The heights provided from DGPS systems should be discussed with individual service providers.

Converting a GPS (or any height referenced to a spheroid) to Chart Datum requires knowledge about:

- Height of the geoid above / below the spheroid at the point of observation.
- Relationship between the geoid and the national height datum.
- Relationship between the national height system and Chart Datum.

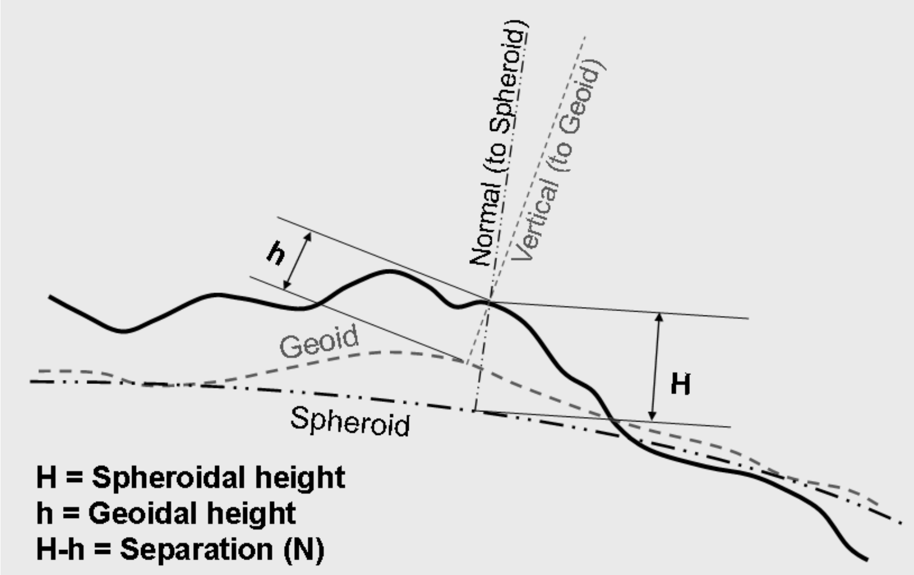

Figure 3-7

Geoid - spheroid separation

3.8 COMMUNICATION AND ACCESSIBILITY

Specialist geophysical and geotechnical investigation vessels are provided with office facilities, computer and communication systems that allow data processing, evaluation and reporting to be completed shortly after acquisition. These systems are generally linked to onshore facilities, allowing optimal evaluation and (if required), adjustment of the survey programme.

3.9 SAFETY REQUIREMENTS AND ENVIRONMENTAL FACTORS

Health, Safety and Environmental (HSE) issues and controls are key components of a successful investigation. All parties (principals and investigation contractors) should work towards managing their businesses in such a way that they minimise the risk to the safety and health of employees and sub-contractors. Environmental controls should also be in place to manage environmental risks.

Companies should take account of safety issues in all operations and provide a safe working environment for employees. This should include provision of appropriate equipment and training to enable employees to carry out their duties safely. Key components of a sound HSE Management System are:

- As a minimum, compliance with all statutory laws and regulations concerning occupational health, safety and the environment.

- Acting proactively to prevent injury or damage from operations.
- Ensuring that HSE issues are considered at appropriate points throughout the processes.
- Continuing efforts to reduce the environmental and health impact of operations by reducing waste, emissions, and discharges and through efficient energy use.
- Continuing reviews to improve processes and practices with the goal of zero accidents.
- Thorough investigation and prevention, endeavouring to prevent recurrence of incidents.
- Emphasis on communication and cooperation, encouraging personnel to take part in the improvement process.
- Awareness and understanding of all employees towards their responsibilities in the HSE process.
- Ensuring competence at all levels through continued information, instruction and training.
- Maintaining necessary knowledge of relevant standards, legislation, Codes of Practice and other material relating to project activities and to ensure this material is made available to all.
- Ensuring suppliers and sub-contractors have HSE Management Systems appropriate to their activities.
- Conducting HSE audits on a regular basis to ensure compliance and effectiveness.
- Preparing project-specific Health and Safety Plans when planning site investigations.

4. GEOPHYSICAL TECHNIQUES

The range of modern geophysical instruments available to surveyors and engineers is extensive and their capabilities manifold. Only the briefest treatment of the more common systems is given here and the reader is referred to the many excellent textbooks and other sources of information available.

In broad terms, these instruments are categorised as:

- High-resolution reflection systems – using sound (acoustic energy) and measuring where the energy is ‘reflected’ from a geological horizon or seabed.
- Seismic refraction systems – using sound energy and measuring where the energy is ‘refracted’ along geological horizons.
- Electrical resistivity systems – using electrical energy and measuring the resistance of a bulk of near-seabed soil.

This section also provides an overview of remotely operated platforms, seabed classification methods and underwater cameras.

4.1 HIGH-RESOLUTION REFLECTION SYSTEMS

Function and applications

Geophysical survey systems use sound or, at close quarters, laser light, to make measurements of the seabed and the sub-seabed. The sensors tend to fall into three categories:

- Seabed measuring systems, e.g. echosounders, multibeam sounders.
- Imaging sensors, e.g. sidescan sonar, laser-scan, acoustic scanning systems.
- Sub-bottom profilers, e.g. pingers, boomers etc.

Information from high-resolution reflection systems requires the interpretation of reflections from the top of sub-soil geological formations (reflectors). It is important to note that these systems define the boundaries between geological formations, but provide more qualitative than quantitative information on soil characteristics, hence the need for calibration information, e.g. from boreholes and sampling, for complementary geotechnical assessment in a process known as ‘ground truthing’.

The most common combinations of system sensors for engineering applications are:

- Echosounder – for measuring the water depth directly beneath a vessel.
- Swath bathymetry – for surveying a wide swath of seabed soundings either side of a survey vessel.
- Sidescan sonar – for generating a scaled image of the seabed morphology and features.
- Sub-bottom profiler – for determining the stratification of soils beneath the seabed.

System technology and science

Acoustic energy (sound) is the most common source for underwater measuring and sensing systems. In operation, an acoustic energy source generates a pulse of sound that travels through the water column and, where powerful enough, penetrates into the seabed. The sound energy is reflected back, as an echo, to a receiver system and the lapse in travel time from transmission to reception is converted into distance.

The media through which the sound passes affect the acoustic signal in various ways. The denser a medium, the faster is the speed of sound; hence, as the wave front passes through different material densities, its rate of progress varies. At the interface between media, a change in the properties will cause some energy to be reflected; this is most prominent at the water/soil interface and occurs between soil strata.

The two fundamental characteristics of the acoustic wave used in geophysical survey systems, are amplitude and frequency. Different acoustic and seismic tools operate within different amplitude and frequency ranges, and provide information on different aspects of the physical environment. In the simplest terms, high frequency, low amplitude signals provide high-resolution information in the water column, shallowest sub-seabed depths, and have a shorter range. A low frequency, high amplitude signal will travel further into the ground, but has lower resolution.

To generate different frequencies and amplitudes of acoustic energy, transducers of many types are used. Electro-mechanical transducers generate acoustic pulses in echosounders, sidescan sonar, pingers, boomers and chirp sonar. Electrical discharges generate acoustic energy in sparker systems. Air gun systems convert compressed air pressure into high-energy acoustic pressure waves in seismic sources. Returning signals are detected using pressure sensitive transducers and hydrophones. The pressure pulses are converted to electrical energy for measurement.

4.1.1 Bathymetry systems

Echosounders

The echosounder measures water depth from the two-way travel time of a high frequency pulse emitted by a transducer. The system must be calibrated to eliminate errors introduced by temperature and salinity and other factors that affect sound velocity. The choice of echosounder depends on factors including accuracy requirements, depth of water and achievable resolution. Typical frequencies range from 10 kHz to 200 kHz.

Until the introduction of swath instruments, echosounders were single beam devices, operating vertically below the survey vessel to gather a single line of soundings.

Swath echosounders

Multibeam, or interferometric swath echosounders, have become increasingly common and provide the geophysicist with a powerful seabed-modelling tool. Each transducer produces a fan of acoustic beams (or energy) to provide sounding information either side of a vessel’s track. The high-performance systems have wide-angle swaths that cover an area up to 10 times water depth; more typically, the swath width is 2 to 4 times the water depth. As water depth increases, range increases, but maximum range becomes limited due to acoustic energy depletion at the outer beams.

The accuracy of swath systems is critically dependent on the corrections applied to remove vessel motion (heave, pitch, roll, yaw etc); consequently, a swath system is integrated with many other specialist sensors within the ship or sub-sea vehicle.

The chief advantage of swath bathymetry systems is the high rate of productivity and excellent data sample density, especially in deeper water. Swath systems can be hull mounted, installed in a towed body (tow-fish), or mounted on a remotely operated platform. While hull mounted systems are easier to calibrate than towed systems, towed systems offer more portability and operate closer to the seabed. Many swath bathymetry systems also record backscatter (reflected energy) from the seabed, similar to sidescan sonar images.

The depth measured by single beam and multibeam echosounders is normally referenced to ambient water level. To relate the depth of the soundings to a reference surface (Chart Datum) such as Lowest Astronomical Tide, it is necessary to apply a correction for tide. Tide corrections are obtained from recording tide gauges, and either applied during the survey or afterwards in the post-processing phase. There are also DGPS systems that can measure geodetic height with accuracy better than 0.3 m and this information can be used to derive an ‘absolute’ vessel height (i.e. dispensing with the need to observe tides by removing the air/sea interface from the observations). However, the relationships between Chart Datum and geodetic surfaces is complex, and to avoid introducing large errors, tidal and geodetic heighting solutions should be left to the expert surveyor. (See also Section 3.7.5)

LiDAR

In shallow, clear waters (typically less than 30 m to 50 m deep and with relatively low concentrations of suspended solids), air-borne, laser scanning systems known as LiDAR are becoming increasingly common. Two laser frequencies are used; red light for reflecting from the sea surface, and green light to penetrate to the seabed. The difference between the two measurements is the water depth (after adjusting for refraction). Typically, the more modern LiDAR is as accurate (if not more so) than multibeam. For areas of significant extent, these systems are very efficient and, despite their apparent high-costs, can be very cost-effective in the coastal zone.

Advantages and limitations

Excluding the more sophisticated deep water systems, echosounders can be fitted to most vessels either by an over-the-side mount or through a special opening in the ship’s hull.

Multibeam echosounders come in a wide variety of sizes depending upon their function. The deep water and oceanic systems require large transducer arrays (4 m to 7 m long) that have to be purpose built into a ship’s hull (an expensive procedure) hence are restricted to specialist survey ships. For water depths less than, say, 200 m, multibeam systems on over-the-side mounts are common. Shallow water (1 m < depth <100 m) systems, being more compact, are normally fitted as temporary attachments.

All echosounders require careful installation to avoid sources of interference such as cavitation, or other acoustic noise. Echosounders require calibration which, in the case of the multibeam, is a complex procedure requiring several hours to complete; time must be allowed for this critical procedure. Frequent measurements of seawater column temperature, density and salinity are also needed to determine the ever-changing speed of sound. These are performed underway using disposable SV (sound velocity) probes, or by stopping the vessel at intervals to make readings of temperature, salinity, pressure and/or conductivity.

4.1.2 Sidescan sonar

Sidescan sonars provide an acoustic, oblique, photo-like image of the seafloor. By ensonifying a swath of seabed and measuring the amplitude of the back-scattered return signals, an image is acquired of objects on the seabed and information on the morphology (the different materials and features comprising the seabed surface).

High-frequency sonar (c. 500 kHz) provide high-resolution images, but with short (< 100 m) ranges. Lower frequency systems (c. 60 kHz) provide longer ranges, but with lower resolution. Sidescan sonar tow-fish can be towed deep or shallow depending on requirements. Alternatively, the systems can be mounted in steerable ROTVs (Remotely Operated Towed Vehicles), ROVs (Remotely Operated Vehicles) or AUVs (Autonomous Underwater Vehicles).

In deeper water, tracking a towed sidescan fish is problematic because acoustic tracking systems are typically limited to a range of approximately 3 to 4 kilometres; in 1500 m of water, at least 5 km of cable is required to keep the fish at the required depth. Developments to overcome this problem include using a second vessel (chase boat) to track the fish directly from above (costly) or deploying the sidescan on a remote platform.

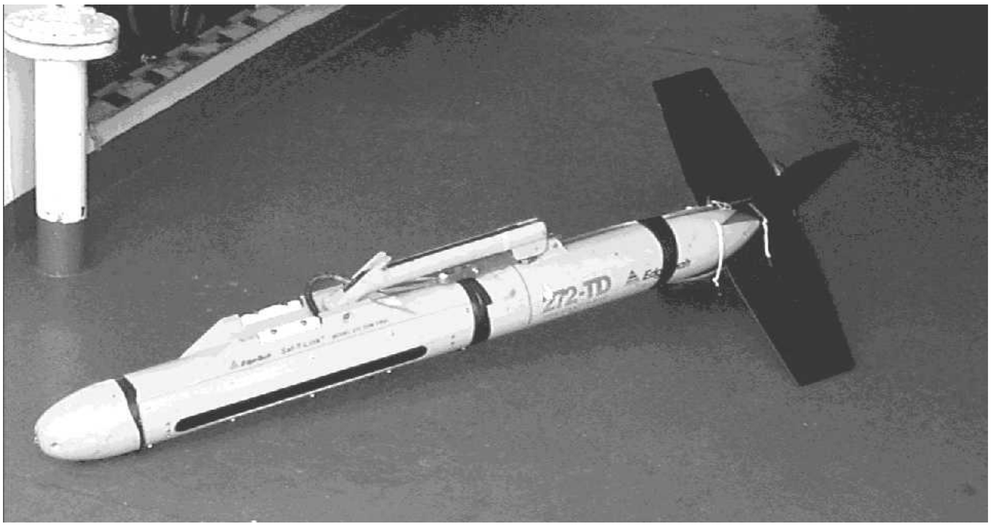

Figure 4-1 *Edgetech sidescan sonar*

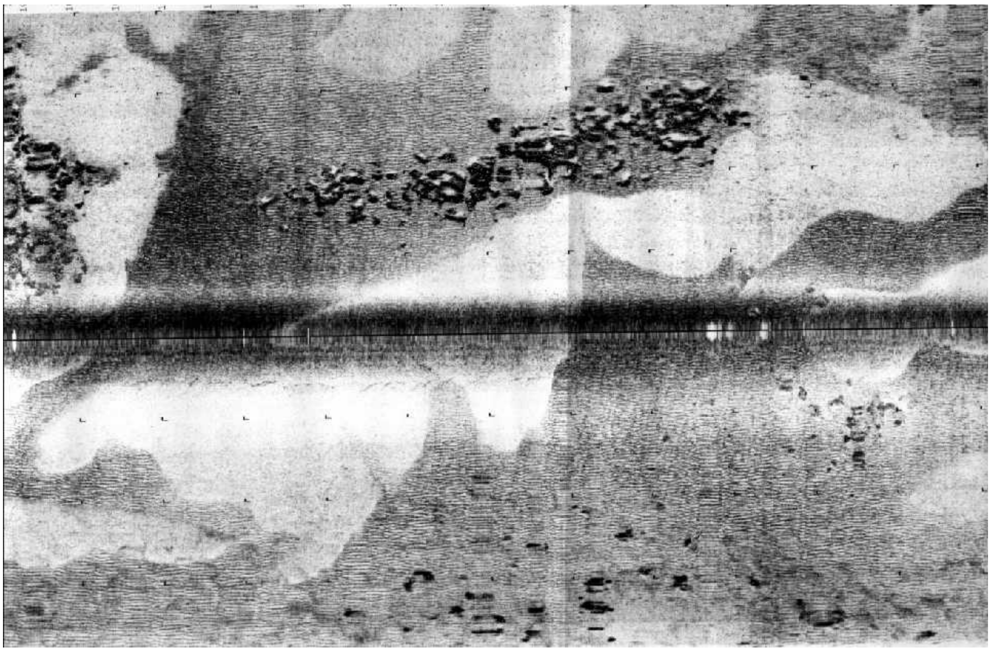

Figure 4-2 *Sidescan sonar image of seabed*

Advantages and limitations

Sidescan sonar is probably one of the most useful tools for imaging the seabed. The clarity of the image, especially from the latest systems, is extraordinary. Developments in sonar imaging continue to move forward rapidly. Its use in seabed classification systems is discussed in Section 4.5.

The smaller, shallow water systems can be deployed from most vessels. The deeper towed systems require a powered winch and a suitable system for running out the cable, normally an A-frame. If operating at, say, 1000 m depth, a cable some 5000 m long is required necessitating a large and heavy winch. The so-called 'deep-tow' systems are very large tow-fish, 4 m or 5 m long, and heavy. They require a large, powered winch and special launch and recovery systems and therefore are restricted to specialist survey vessels. The normal tow speed for a sidescan survey is about 4 knots; however, as operating depth increases, so the drag and strain on tow cables increase. A deep-tow system operating at 2000 m will reduce tow speed to 1 or 2 knots, greatly adding to the time required for a survey.

Because of the long length of the tow cable, surveyors have to allow for a 'run-in' and 'run-out' equivalent to the length of the tow, to ensure the required area is covered. Turning times with long cables increase such that a deep-tow can take several hours to complete a line turn. These factors must be taken into consideration when planning and costing an operation.

4.1.3 Sub-bottom profilers

Sub-bottom profilers, sometimes referred to as single channel systems, are used throughout the industry for the shallowest sort of seabed profiling.

Pingers

So-called because of their high frequency acoustic 'pings', pingers operate on a range of single frequencies between 3.5 kHz and 7 kHz, and can achieve seabed penetration from just a few metres to more than 50 m. They are capable of resolving soil layers to approximately 0.3 m. These high-frequency profilers are particularly useful for delineating shallow lithology features such as faults, gas accumulations and relict channels.

Boomers

These instruments have a broader band acoustic source, between 500 Hz to 5 kHz, and can typically penetrate the seabed to between 30 m and 100 m with resolution of 0.3 m to 1.0 m. Boomers make excellent general-purpose geophysical profilers.

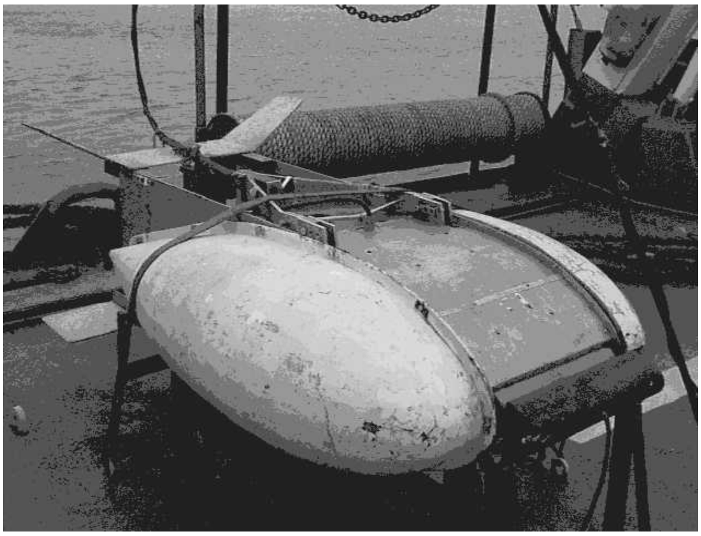

Figure 4-3 *Pinger sub-bottom profiler*

Sparkers

These very powerful instruments can penetrate soils and rocks to 1000 m+, but because of their unstable pulse waveform, are not in such common use as formerly.

CHIRP

The CHIRP sub-bottom profiler is a recent introduction to geophysical survey. Designed to replace the pingers and boomers, CHIRP systems operate around a central frequency that is swept electronically across a range of frequencies (i.e. a ‘chirp’) between 3 kHz to 40 kHz and can improve resolution in suitable near-seabed sediments.

Advantages and limitations

The single channel acoustic systems provide an excellent range of tools for remotely imaging near-surface soils and rocks. Care is needed not to overreach their capabilities; for example, as the depth of soil penetration increases, so the single channel systems begin to suffer from decreasing signal-to-noise ratios and from multiple reflections. These multiple reflections are the result of acoustic energy reflected between pairs of horizons before returning to the receiver and become superimposed on real data causing masking and making interpretation difficult. The problem is particularly acute within the water column because the sea surface and seabed interfaces are strong acoustic reflectors.

The same factors that affect sidescan cables apply, although the length-depth ratio is less. A limitation with the higher frequency profilers is that, in the presence of gas or hard soils, or biologic colonies, acoustic penetration can be severely reduced or even arrested.

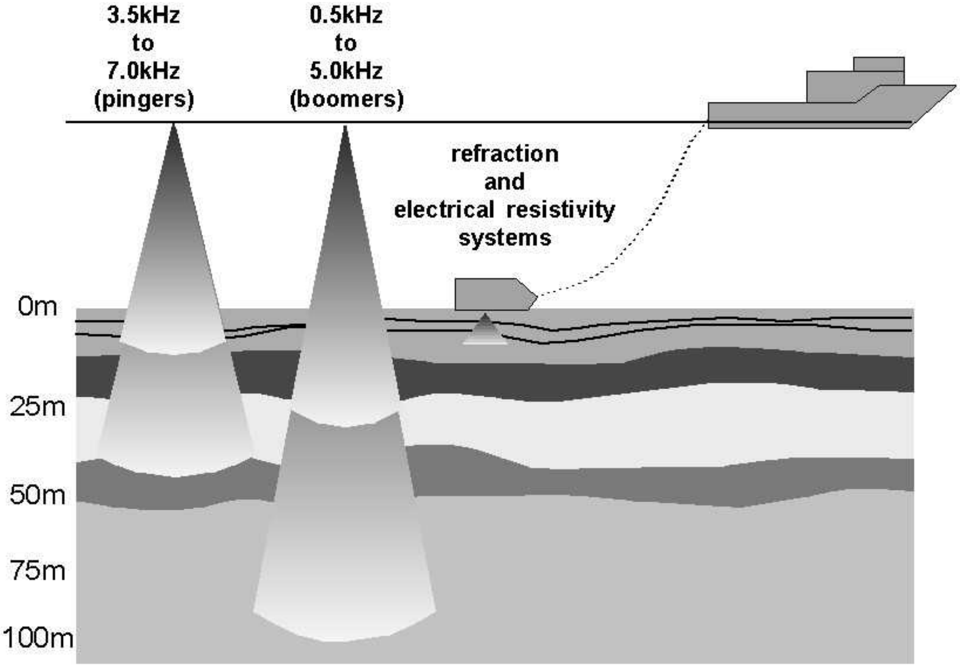

Figure 4-4

Typical seafloor penetration ranges of geophysical systems

4.2 SEISMIC REFRACTION SYSTEMS

Seabed refraction seismic is a method of acquiring high-resolution information of soil sedimentary structures. Refraction systems are typically employed where fine detail is required of the first 3 m of the seabed, and especially the topmost 1 m. The most common application is as a burial assessment tool for submarine cable installation and for pipeline route investigations. Other applications include site investigations for harbours and coastal developments and pre-dredge areas.

System technology and science

Seismic refraction has been used for many years on shore as an exploration reconnaissance tool and for civil engineering applications. In recent years, the technique has been applied with great success to shallow marine soil investigations.

A seismic source at the seabed is used to induce an acoustic pressure wave into the soil. In shallow water (typically <250 m), an airgun is used. As the pressure wave passes through the soil layers, some of its energy is refracted along sedimentary boundaries before returning to the soil surface, where a hydrophone streamer picks it up. The length of the streamer and the number of hydrophones determine the depth of recorded penetration and the resolution of the information – the longer the streamer the greater the depth of penetration recorded, but the lower the resolution. For detailed imaging of the topmost 3 m to 5 m of the seabed, a typical streamer is 24 m to 30 m long and contains some 48 hydrophones.

By plotting the first time of arrival (first break) of the refracted waves versus distance from the seismic source, time-distance curves are produced. The analysis of the slope of these curves provides a direct determination of the depth of the various soil layers. The compression wave velocity (Vp) provides the geoscientist with information that can be used to characterise each soil layer.

The refraction method can measure seismic velocities to better than 50 metres per second with soil penetration accuracy of about 10% of depth, for example, a soil layer at 2 m depth could be resolved to ± 0.2 m. The main weakness of the method is that it falls short in resolving inversion velocity problems, for example, in situations where a softer layer underlies a stronger one.

The seismic refraction method provides quantitative data (compressive wave velocities) of individual soil layers, unlike seismic reflection. Soil sections with similar seismic velocities are normally compared with geotechnical information from CPTs and/or cores taken at, say, 1 km to 3 km intervals. Thus, soils can be classified based on seismic velocity and strength properties, and can be assessed by correlation with geotechnical data. This is particularly useful for estimating burial conditions (achievable burial depth and magnitude of towing forces of seabed ploughs) and for assessing dredgeability and rippability of soils and rocks respectively.

System description

The most widely used high-resolution seismic refraction system, GAMBAS®, comprises a steel reinforced instrument sled dragged across the seabed. Within the sled are housed the seismic source, attitude sensors, pressure/depth and temperature sensors, tension meters for the tow cable and the multiplexing electronics for passing the data to the support vessel. The sled is navigated using acoustic positioning such as an ultra-short baseline (USBL) system. Trailing behind the sled is the hydrophone streamer for receiving the refracted signals. Depending on depth configuration, the sled system can weigh from 0.2 to 1.0 tonnes.

To tow the system across the seabed, a composite tow and power/communications cable connects the sled to the surface support vessel’s winch system. Each refraction-measuring cycle requires the sled to be stationary while the vessel continues to steam ahead at 3 to 4 knots. This is achieved by using a stop-go, or yo-yo, device mounted on the vessel’s deck and which pays out cable while the sled is stopped and pulls in cable (faster than the ships motion) to bring the sled to its next observing location.

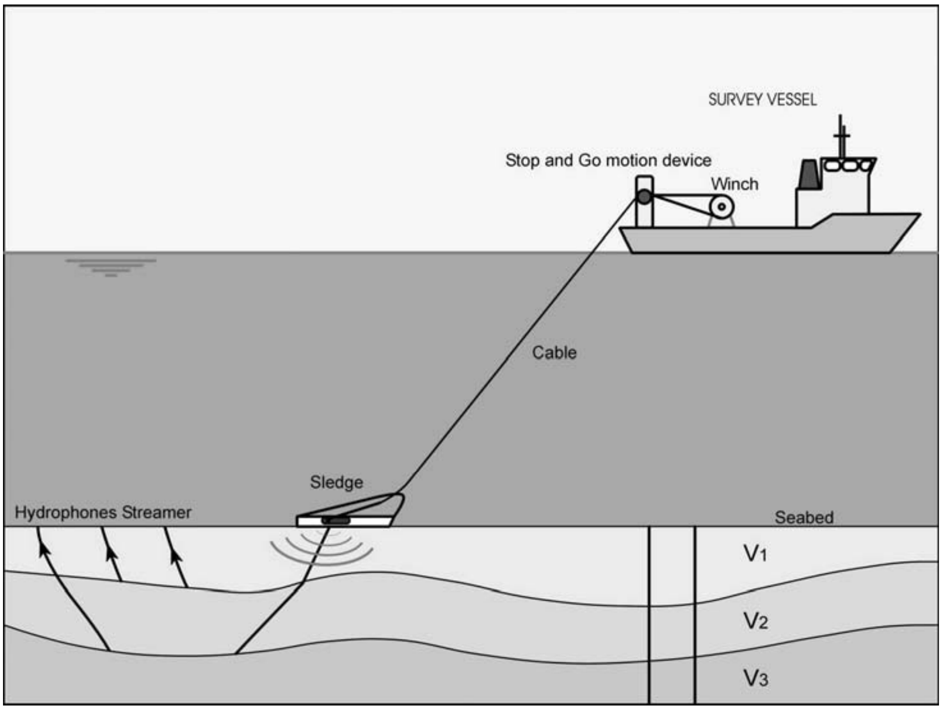

Figure 4-5 *GAMBAS® operating principles for seismic refraction*

Figure 4-6 *GAMBAS® seabed tow sled for seismic refraction*

An alternative system is CRISP, which uses a lightweight canister at, or above, the sea bottom. Compared to GAMBAS®, this system is more suitable for rough seabed conditions and for high contrast soil strata.

For deployment and tow, refraction seismic systems require ships equipped with 1.5 to 5 tonne SWL A-frames. Deck space of about 100 m^2 is needed for handling the system, for the heavy cable winch and, possibly, an air-line winch, and for storage. Usually, refraction systems are deployed from specialist survey or geotechnical vessels, or from large workboats. For inshore surveys, smaller boats are used.

Advantages and limitations

High-resolution seismic refraction is an efficient technique for acquiring detailed information in the top metres of the sub-surface. The technique provides an accurate, quasi-continuous, profile of sub-seabed sediments giving, simultaneously, a high-resolution definition of the soil layering and a quantitative characterisation of their materials.

Information acquired in real-time can be used to define the subsequent geotechnical programme and optimise the number and locations of samples, e.g. seabed samples, in-situ testing or boreholes. Detailed analysis is performed during office interpretation where integrated alignment charts are compiled showing lithology and soil characteristics along the profile.

High-resolution seismic refraction is a valuable tool for burial assessment purposes. The continuous profile aids in minimising geotechnical uncertainties that, in turn, reduce the risk of ploughing downtime. Closely spaced grids of refraction lines provide reliable information for assessing volumes of soils and rocks that can be removed by standard dredging techniques, or that require specific treatment, for example by cutter-dredger or blasting.

Seismic refraction surveys in water depths beyond 350 m are not yet feasible due to limitations of the seismic source.

4.3 ELECTRICAL RESISTIVITY SYSTEMS

Function and applications

Seabed electrical resistivity profiling is a semi-continuous method of measuring the bulk resistivity of a volume of soil near the seabed. The technique uses a towed sled from which is towed a multi-electrode streamer cable.

For surveys requiring soil penetration depths of 3 m to 5 m, for example cable burial assessment, streamer lengths are typically 20 m. For deeper penetration and other applications, such as drilling site surveys, pre-dredge surveys or harbour / coastal investigations, a longer streamer is required.

System technology and science

By injecting an electrical square wave current into the seabed through a pair of electrodes (A and B in Figure 4-7) an electrical potential is created that can be measured between the reference electrode (N) and, typically, 13 electrodes (M1 …. M13).

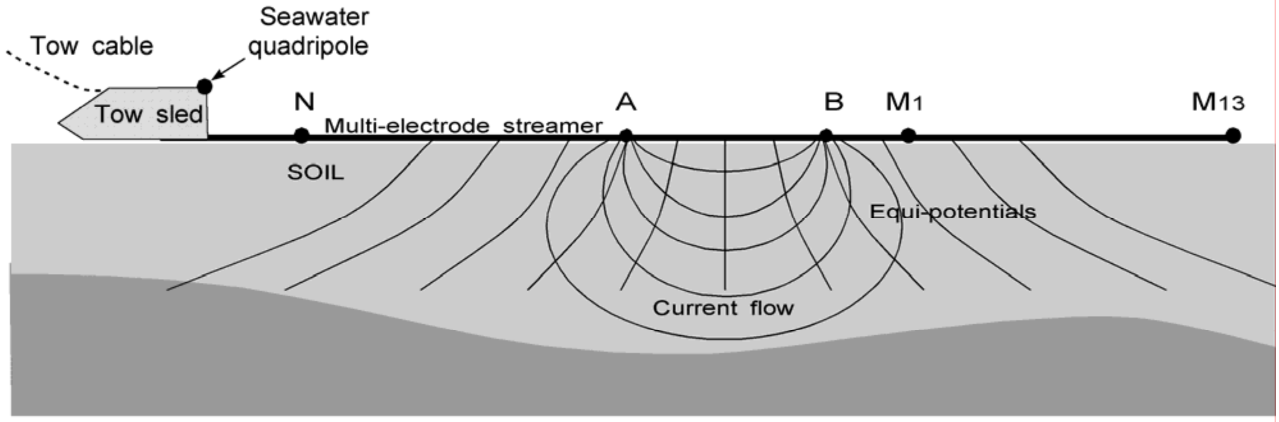

Figure 4-7 *Electrical resistivity principles*

To compensate for the self-potential effects of the soil, the polarity of the injected current is alternated at 1 Hz. The resistivity of the ambient seawater is measured using a short, low-intensity, square wave injected into the sea by a short quadripole antenna. The ratio of seabed resistivity to that of the seawater is called the formation factor. The potential difference is measured at each of the 13 electrodes at a sampling rate from 1 Hz to 10 Hz. The depth of investigation is a function of the electrode separation; short spacing produces values associated with the upper part of the soil mass, while increasing separation provides information on progressively deeper sediments.

The formation factor in saturated marine sediments is linked directly to the material's porosity. Its value provides qualitative information on soil type and the state of consolidation.

Obtaining layered resistivity versus depth is theoretically possible by implementing inverse modelling techniques. However, inverse modelling is time consuming and the resolution of the technique is insufficient to discriminate between all possible geological conditions. Hence, this approach has yet to provide convincing results.

Interpretation of resistivity measurements should always be supported by geotechnical information obtained from cone penetration test and/or sample data..

System description

A seabed resistivity system comprises a steel reinforced sled in which are housed the electronics, acquisition unit, power unit, attitude sensors, temperature and pressure sensors, and the cable tension meters. Behind the sled is towed the 24 m to 30 m long multi-electrode streamer in which is housed two 24 V 10 amp current injection electrodes (A and B in Figure 4-7). The sled is hauled across the seabed by a tow/power/ communications cable attached to a surface support vessel. Some systems are fitted with a yo-yo device that permits the sled to halt during measurements, thus improving the signal to noise ratio.

Typically, resistivity systems can operate down to 2000 m water depth and can be towed at 2 to 3 knots. Soil penetration depths are in the order of 5 m, although it is possible to get greater depth (c. 30 m) using wider spacing for the electrodes and sacrificing resolution and accuracy. The sled, which is similar to, but lighter than, the refraction sled, is deployed and towed from an A-frame fed by a 2000 m to 6000 m capacity cable winch.

Advantages and limitations

As results depend on water depth and salinity, great care should be taken when calibrating the system and attention to detail is required in the operating procedures and interpretation methods.

Resistivity surveys provide continuous profiles and fill gaps where normal acoustic systems are unreliable, for example in gas-charged sediments, and between CPTs in more homogenous soils. They can be employed in conjunction with refraction seismic surveys as an augmentation / bulk sampling system.

The technique tests a bulk sample of a volume of soil rather than discrete elements. In common with reflection seismic, resistivity requires ground truth data in order to provide meaningful soil type information. Marine resistivity techniques cannot reliably differentiate between discrete soil layers.

4.4 REMOTELY OPERATED GEOPHYSICAL PLATFORMS

4.4.1 Remotely Operated Vehicles (ROV)

ROVs have been used for may years to carry geophysical sensors. Linked to the mother vessel via an optical and electric umbilical, survey and inspection ROVs are frequently fitted with sidescan sonar and multibeam echosounders. These vehicles have the advantage of great manoeuvrability under direct human control, and a constant source of power and, hence, endurance.

Typically, in shallower water an ROV can operate at 2 or 3 knots, but in deeper water the drag of the long umbilical reduces velocity considerably. ROVs are ideal for inspection, but can have some disadvantages for geophysical survey, such as noise generated by their propulsion systems and other acoustic interference sources. Because they require substantial handling systems, ROVs capable of carrying geophysical sensors are limited to specialist ROV vessels.

Figure 4-8 *Sea Demon ROV*

4.4.2 Autonomous Underwater Vehicles (AUV)

Although autonomous underwater vehicles have been in use since the early 1980s, their introduction into the commercial world in 2000 has heralded new opportunities for geophysical surveying. These vehicles operate autonomously, without on-line command and control intervention, by following a pre-programmed work scope and failsafe procedure uploaded to their on-board computers. The larger of these vehicles can be equipped with swath echosounders, sidescan sonars and high-frequency sub-bottom profilers. Some AUVs can also carry, or tow, a magnetometer and many other sensors, making them extremely flexible and powerful tools.

A special variant of the AUV is the UUV, or Untethered Underwater Vehicle, that requires an acoustic ‘tether’ for its command and control.

Powered by special battery technology (typically lithium) or fuel cells, AUVs have mission endurance ranging from 12 to 60 or more hours and some can reach depths of 6000 m.

Typically, AUVs operate at 3 to 4 knots (independent of depth) and eliminate the time required for costly line turns or deviations associated with deep tow systems. The smaller AUVs (< 2.5 m long) can be deployed from any vessel that has a suitable handling system. For the larger vehicles, which can reach lengths of 6m or more, special launch and recovery systems are needed and hence these vehicles are generally restricted to larger vessels.

AUVs produce, and store, very high-quality data because, unlike towed systems, they are capable of operating continuously at optimum sensor heights above the seabed.

Figure 4-9 *AUV retrieval on survey vessel*

4.5 SEABED CLASSIFICATION SYSTEMS

Function and applications

A capability to classify seabed material without the need for costly sampling devices has obvious advantages. Seabed classification systems exist and their effectiveness is improving; however, they are not yet a panacea.

System description

Seabed classification is a processed solution requiring a proprietary software and electronics package. The measures of roughness and hardness combined can provide quantitative information on seabed types, but will not be reliable enough to determine detailed soil characteristics.

Sidescan sonar can identify seabed morphological boundaries very well. By combining the bounding attributes of a sidescan with the roughness-hardness ratios of a seabed classification system, areas with similar properties can be identified with high reliability. The final step is to use seabed sampling, say with a box corer or grab sampler, to recover examples of the topmost soils and correlate these to the roughness-hardness ratios. In this way, a reliable model of the seabed topsoil is possible.

Advantages and limitations

Seabed classification using remote sensing is a rapid method that does not require additional in-sea equipment. However, sidescan or multibeam backscatter data is necessary to detect seabed objects, determine the morphological boundaries and, if reliable seabed interpretation is required, ground truth seabed samples are required.

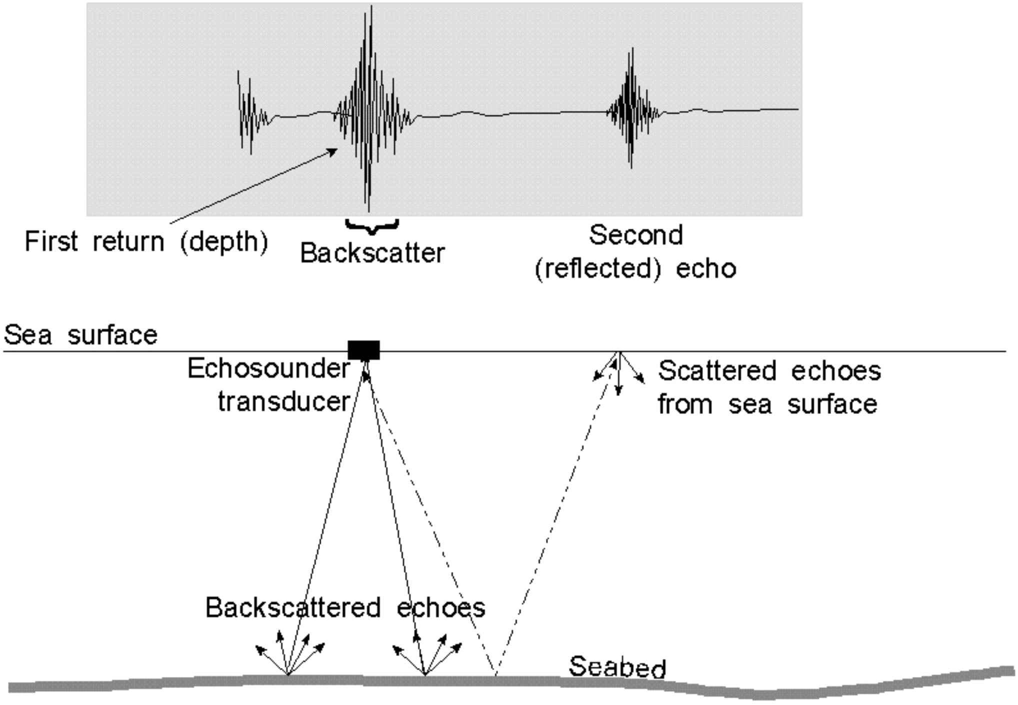

Figure 4-10 *Basic principles of a seabed classification system*

4.6 UNDERWATER CAMERAS

Function and applications

The visualising systems used for structural inspection can often assist in solving remotely sensed ambiguities. In-situ examination of uncontaminated soil colour, condition and context provide valuable information to the geologist or benthic scientist for environmental assessment and impact studies.

System technology and science

For operations in shallow depths during daylight, there is a range of off-the-shelf cameras. However, daylight tends to become totally absorbed in seawater below 300 m to 500 m; even at 100 m the amount of light available is often barely perceptible. Two options are available, a) camera lighting systems, b) low-light cameras.

Lighting systems are housed in pressure housings and a variety of light emission types are available. Low-light cameras depend on light-enhancement systems (like night-vision glasses), while in extreme dark, solid-state photon detectors are used to collect any available light.

System description

The common sorts of cameras for sub-sea visualisation are:

- Television (real-time) colour or black & white.
- Video cameras (self-recording / digital).
- Movie film (now uncommon but special sensitive films are occasionally used).
- Stills cameras (film), normally 35mm format.
- Digital stills cameras.
- Low light cameras.

The most common form of deployment for lightweight cameras (stills, video) is by diver. For prolonged excursions, for real-time visualisation and in hazardous or remote locations, cameras and lighting systems are commonly installed on an ROV. Either a small observation class vehicle or full size survey vehicle can be used. Cameras can also be lowered to the seafloor using a reinforced power and control cable.

Advantages and limitations

Seabed visualisation is a valuable tool providing high-resolution and discriminatory information. Colour, texture and benthic life forms can all be studied in great detail. Diver deployment in shallow water is relatively inexpensive, but deeper water requires saturation diving and costs become extremely high. The alternative is to use an ROV; the small observation class can be operated relatively inexpensively from most vessels but the larger survey class ROVs are limited to specialist survey vessels or large workboats.

Visual sampling with an ROV in deep water, say 2000 m, is a time consuming process; a dive to the seabed can take over four hours and a similar time to return to the surface. Once at the seafloor, an ROV can operate for many hours, or even days, and therefore it is more cost-efficient to combine visualisation with other remote sensing operations.

5. GEOTECHNICAL TECHNIQUES

Geotechnical investigations can be done in either seabed mode (where the sampler or in-situ testing tool is deployed directly from the seabed) or in drilling mode (where the tool is deployed from the bottom of a borehole). In seabed mode, penetration depths are normally limited to between 20 m and 60 m, depending on type of soil and capacity of rig. In drilling mode, great depths are achievable. Drilling is normally done from vessels or platforms in which case all penetration depths of geotechnical interest can be investigated. Some coring and drilling equipment exists which operate from the seabed. These allow investigations up to 100 m below seabed.

In soft to stiff clays, soil sampling should preferably be performed with piston samplers. When piston samplers are impractical, thin walled push-samplers should be tried or, in dense sand, hammer samplers may have to be used. In some cases, such as in boulder clays and cemented soils, rock coring techniques may be necessary.

Routine in-situ testing methods include (piezo) cone penetration tests ((P)CPT) with pore pressure measurements. Additional tests in soft clays include field vane, T-bar and ball probe tests.

5.1 OVERVIEW OF GEOTECHNICAL TECHNIQUES

Table 5.1-1 gives an indication of water depths and sampler penetration depths that can be achieved with various drilling, sampling and coring systems. Descriptions of these systems are presented in Section 5.2.

Table 5.1-1 WATER DEPTH AND PENETRATION CAPABILITIES DRILLING, SAMPLING AND CORING SYSTEMS

Equipment Description	Maximum Water Depth (m)*	Penetration (m)*
Drill mode borings from vessels	Unlimited**	Unlimited**
Rock corer (seabed unit)	200 m	2 m to 6 m
PROD™ seabed drilling/coring	20 m to 2,000 m	2 m to 100 m
Basic gravity corer	Unlimited**	1 m to 8 m
Piston corer	Unlimited**	3 m to 30 m
Vibrocorer	1000 m	3 m to 8 m
Box Corer	Unlimited**	0.3 m to 0.5 m
Seabed Push-in Sampler	250 m	1 m to 2 m
Grab Sampler (mechanical)	Unlimited**	0.1 m to 0.5 m
Grab Sampler (hydraulic)	200 m	0.3 m to 0.5 m

* These figures should be used for general guidance only.

** Water depth is limited by the deployment winch and handling capabilities.

Table 5.1-2 and Table 5.1-3 present comparisons with respect to sample quality and recovery of seabed samplers and down-hole sampling equipment respectively. The numbers refer to a qualitative assessment of suitability according to the following schedule:

1: Poor or inappropriate
2: Acceptable for non-critical analyses
3: Moderately good
4: Good
5: Very good

Table 5.1-2 SEABED SAMPLING EQUIPMENT

Type of Equipment	Sample Quality			Recovery (relative to length of sample tube)		
	sand	**clay**	**rock**	**sand**	**clay**	**rock**
Gravity / Piston corer	2	3	1	1	3 to 4	1
Vibrocorer	2 to 3	2 to 3	1	3 to 4	2 to 3	1
Grab sampler	1 to 2	1	1	1 to 2	2	1
Box corer	1 to 2	5	1	1	5	1
Rotary corer	1	2	3 to 4	1	3	3 to 4

Table 5.1-3 DOWN-HOLE SAMPLING EQUIPMENT

Type of equipment	Sample quality			Recovery (relative to length of sample tube)		
	sand	**clay**	**rock**	**sand**	**clay**	**rock**
Hydraulic piston sampler	3 to 4	5	1	3	5	1
Hydraulic push sampler	3 to 4	4 to 5	1	3	5	1
Hammer sampler	2 to 3	2 to 3	1	3 to 4	3 to 4	1
Rotary coring	1	2	3 to 4	1	3	3 to 4

Table 5.1.4 gives an indication of water depths and test penetration depths associated with various types of in-situ testing equipment. Descriptions of these testing systems are presented in Section 5.3.

Table 5.1-4 WATER DEPTH AND PENETRATION CAPABILITIES OF IN-SITU TESTING SYSTEMS

Equipment Description	Water Depth (m)*	Penetration (m)*
Deck- or frame-operated penetration tests	20 m	2 m to 60 m
Seabed wheeldrive penetration tests	500 m to 3000 m	2 m to 60 m
Drilling mode downhole penetration tests	Unlimited**	Unlimited**
PROD™ seabed penetration tests	20 m to 2,000 m	2 m to 100 m
Light weight wheeldrive penetration tests	2000 m	2 m to 5 m
ROV penetration tests	300 m to 2000 m	1 m to 2 m
Minicone penetration tests	250 m to 2500 m	5 m to 6 m
Seabed vane test	250 m to 2500 m	5 m to 25 m

* These figures should be used for general guidance only
** Water depth is limited by the deployment winch and handling capabilities

5.2 SAMPLING SYSTEMS

5.2.1 Borehole samplers

Samplers used in the bottom of the borehole can be installed by pushing or hammering. Push sampling provides higher quality samples. The push force is generally obtained using a wireline system or from pressurized drilling fluid inside the drill string. Occasionally, the drill string may be used to push a sampler into the borehole bottom. In soft to stiff clays, it is preferable that sampling is done with piston samplers. When piston samplers cannot be used, thin walled push-samplers should be tried. When this is not possible, as in dense sand, hammer samplers may be used. Installation by hammering in a shallow water environment may use rods and be combined with Standard Penetration Tests (SPTs). Caution is needed when using such SPT data since the results may be highly affected by energy losses in the freestanding SPT rods. Wire-line down-hole hammers can be used in greater water depths. Sample hammer blow-counts from such samplers generally do not correlate with SPT data largely due to energy losses. In some cases, such as in boulder clays with stones, and in cemented soils, rock-coring techniques may be necessary.

Above sampling/coring methods apply for boreholes drilled from vessels or platforms. An alternative method of drilling and coring/sampling/testing is used by the lightweight PROD^{TM} (Portable Remotely Operated Drill) unit. It is an 85 kN (8.5 tonnes) submerged weight seabed unit which houses a self-contained coring and testing system powered by an electrical umbilical from a support vessel . The PROD^{TM} unit is designed to operate in a maximum water depth of 2000 m and to sample/core/test to 100 m penetration below seabed.

For high quality sampling in relatively soft soil and in very shallow water depths, a continuous boring/sampling system such as the Begemann system may be used.

5.2.2 Underwater rock coring systems

Function and applications

Underwater rotary rock corers are used to recover undisturbed core samples of harder soils and rock, usually in shallow water. They are particularly well suited for:

- Pre-dredging investigations.
- Engineering developments in ports and harbours.
- Long sea-outfall, pipeline and cable landfall investigations.
- Mineral prospecting.

System technology and science

In order to recover a high quality and undisturbed core sample, the core tube has to be static. Rotary rock corers are designed as double or triple tube devices where the innermost tube acts as a core liner, the middle tube, if present, acts as a holder and the rotating outer tube carries the hollow drill bit. As the bit cuts down through the soils and rock, the core created passes into the liner in a relatively undisturbed state.

Figure 5-1

Sorotel rock corer

System description

Seabed rock corers come in a variety of shapes and sizes, typically recovering cores from 25 mm to 150 mm in diameter and 2 m to 6 m in length.

Most rock corers comprise some form of coring tower mounted on a base plate, or tripod footing, with dimensions and weights usually within the ranges:

- Height: 4 m to 8 m
- Maximum base width: 2 m to 6 m
- Weight in air: 1 tonne to 8 tonnes.

Rotary drilling mechanisms can be electrically or hydraulically driven via umbilical cables to the surface. Some systems incorporate a video camera on the seabed frame to improve operational monitoring and control. The drilling fluid used to lubricate and cool the drilling process can be either water or a ‘mud’ flush.

Since coring can take one or two hours per hole, the deployment vessel needs to have good station-keeping capabilities. Dynamic positioning, joystick controlled thrusters, or a multi-point anchoring system will normally be required.

Advantages and limitations

The primary advantage of the seabed rock coring systems is their ability to core harder soils than other seabed sampling devices, and the ability to core rock that would otherwise require a surface operated drilling rig.

Most systems are designed to operate in water depths of 200 m or less, close to the coastline where seabed rock outcrops are most likely to be found. Coring depths are usually limited to a few metres. The percentage recovery and core quality may also be lower than for surface operated systems.

5.2.3 Basic gravity corer

Function and applications

Gravity corers provide a rapid means of obtaining a continuous core sample in water depths of a few metres down to several thousand metres. Depending upon their deployment and operating systems, gravity corers can be operated from a wide range of vessels.

Gravity coring applications cover nearly all facets of seabed soils investigation including:

- Dredging and inshore engineering.
- Offshore oil & gas engineering.
- Route surveys for pipelines and cables.

Gravity core samples are useful for providing soil type control for geophysical surveys.

System technology and science

One of the simplest geotechnical devices, the impetus of gravity acting on the heavy, free-falling device is the motive force that drives the corer into the soil.

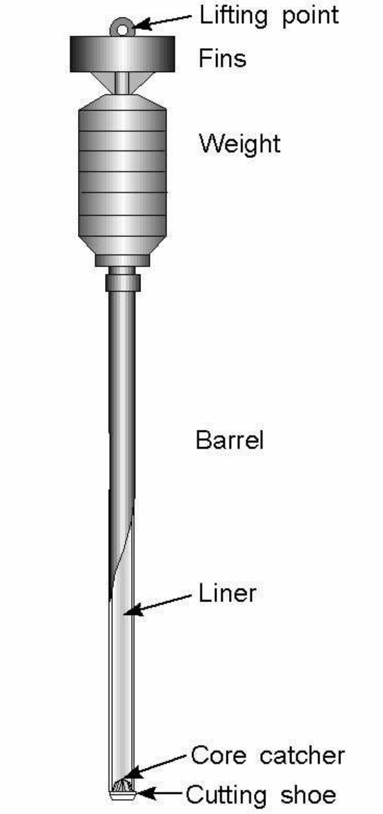

Figure 5-2 *Gravity corer*

System description

A gravity corer consists of a steel tube in which is inserted a plastic liner to hold the core sample. The penetrating end of the tube is fitted with a cutter and a concave spring-steel core-catcher to retain the sample when the corer is retracted from the soil.

A set of heavy weights, up to 750 kg, is attached at the top end of the tube above which is a fin arrangement to keep the corer stable and vertical during its fall to the seabed. A deployment and recovery line is attached to the top of the corer. Normal practice is to lower the device to within 10 m of the seabed before releasing. Gravity core tubes range in length from 1 m up to 8 m. The standard tube is 102 mm external diameter with a 90 mm external diameter plastic core liner.

Deployment is normally from a deck crane, up to 2 tonnes SWL (depending on size of the corer) with a free-fall winch capability.

Advantages and limitations

Gravity corers are only appropriate for use in very soft to firm clays, as penetration in stiffer clays or sands is usually limited. The penetration depth is between 1 m and 8 m.

5.2.4 Piston corer

Function and applications

For improved recovery and higher quality gravity core samples in soft soils, the liner of the core barrel is fitted with a stationary piston. Samples from piston corers allow for more detailed soil sequencing and more accurate strength analysis.

Applications for piston corers include:

- Anchor holding assessments.
- Suction caisson design.
- Seabed structure foundation and installation studies.
- Slope stability analysis.

System technology and science

The suction caused when withdrawing a core barrel from a soft soil such as clay, can pull the sample from the barrel, or in other ways disturb its homogeneity. By inserting a piston above the sample, the partial vacuum caused above the piston, when the barrel is withdrawn, keeps the sample from being pulled out of the tube.

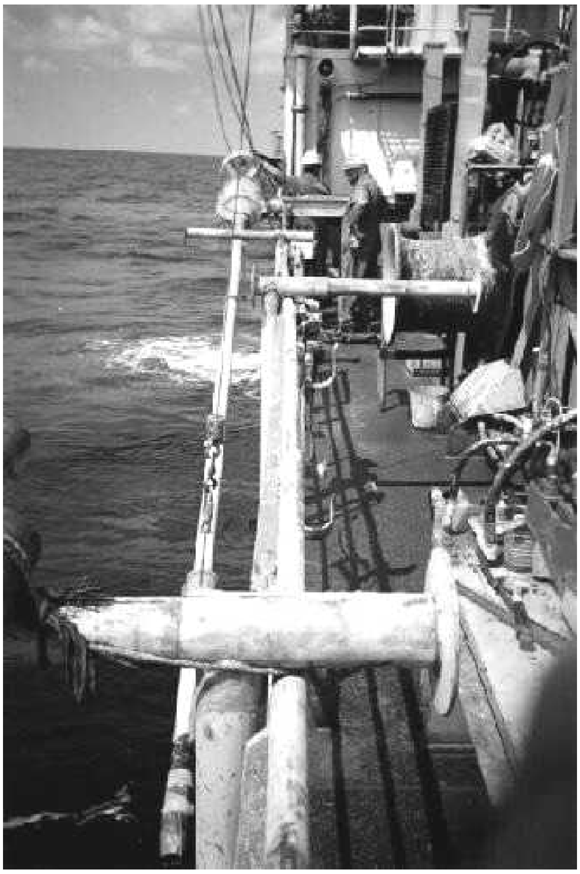

Figure 5-3 *Preparing a long piston corer for deployment*

System description

Piston corers can have barrels up to 30 m long. Handling such a long device requires (optionally) a Kullenberg-type trigger mechanism and a purpose-built deployment and recovery system. The barrel of the device is recovered to the horizontal and must be supported at points along its length to prevent buckling. The operating water depth of the system is solely a function of its deployment winch and cable capacity.

Advantages and limitations

The piston corer, when correctly designed and operated, can produce good quality samples in soft soils. The penetration depth can be from 3 m to 30 m. The long, deep water piston corers can, in some instances, eliminate the requirement for a drilling vessel, and in theory be deployed from a wide range of vessels. However, the realisation of a safe and efficient operation requires the use of large, well-equipped vessels, and usually the mobilisation of a high capacity deployment winch and handling system together with structural modifications to the vessel.

5.2.5 Kullenberg device for piston corer

Function and applications

Gravity corers are typically released at a height of 10 m above the sea floor. To ensure optimum free-fall, the Kullenberg release device is used.

The device is most appropriate when handling long piston corers and in deep water, or other circumstances, where a controlled free-fall distance is required.

System technology and science

The Kullenberg device is a simple release mechanism activated by the weight coming off a trigger line.

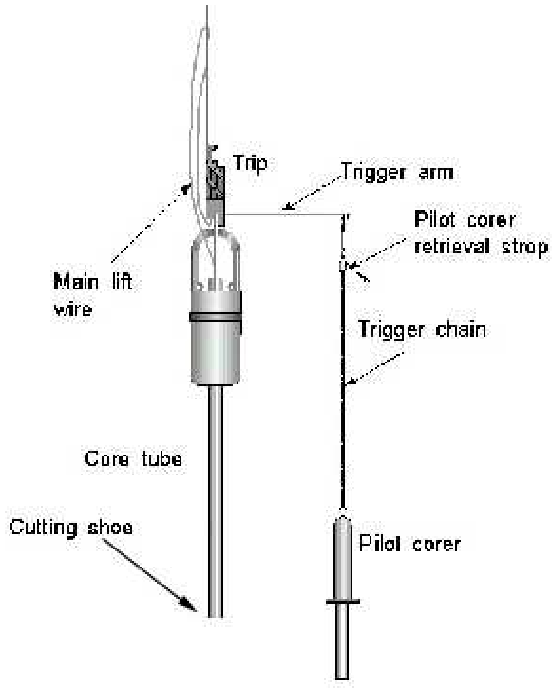

Figure 5-4 *Kullenberg device*

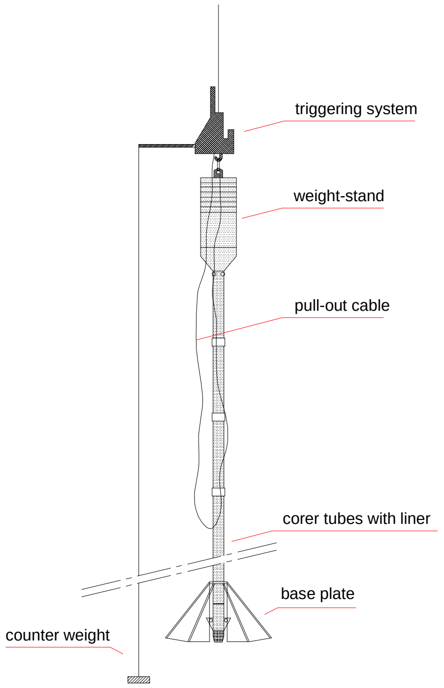

Figure 5-5 *STACOR® layout*

System description

The device comprises a latch which retains the gravity corer, and a boom attached to the lift line from which is suspended a weight (sometimes another sampling tool) holding the latch closed. The trigger chain is made to equal the length of the corer plus the desired free-fall distance. When the weight touches the seabed, the tension comes off and the latch released, allowing the gravity corer to fall to the seabed.

Advantages and limitations

The Kullenberg-type device eliminates the need for a deployment winch with free-fall capability. It also allows for a controlled variable free-fall distance to suit the prevailing soil conditions.

The release mechanism, however, is a temperamental arrangement and requires skilled operatives to function satisfactorily and safely. It is used chiefly for sampling in deep water. A further improvement to the Kullenberg system is to provide the piston corer with a base plate (STACOR®**Error! Reference source not found.**). This reference system ensures that the piston remains effectively stationary at the sediment surface during corer penetration, thus significantly improving core recovery and sample quality.

5.2.6 Vibrocorer

Function and applications

Vibrocorers are used wherever soil conditions are unsuited to gravity corers or where greater penetration of the seabed is necessary. The Aimers McLean type is one of the standard industry designs and is for use in sands and denser/stronger soils: it is the next step down from the rotary rock corer.

Used widely throughout the site investigation industry, vibrocorers can be deployed in water depths down to 1000 m, chiefly to recover samples for:

- Pre-dredge soil investigations.
- Offshore oil & gas pipeline investigations.
- Mineral and aggregates prospecting.
- Environmental impact studies.
- Civil engineering for ports and harbours.
- Inshore geotechnical investigations.

On occasion, vibrocorers are used for cable route investigations.

System technology and science

To penetrate soils such as dense sands and gravels, or to reach deeper into stiff clays, rather than depending on a gravity free-fall, the corer's barrel is vibrated, thus facilitating its penetration into the soil. In other respects, the barrel and sample retention systems are similar to gravity corers.

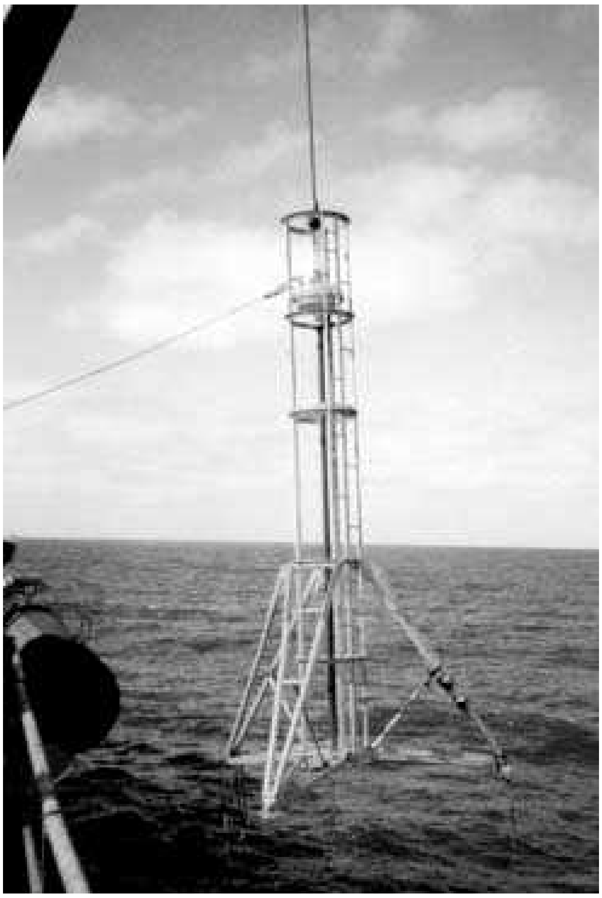

Figure 5-6 *Aimers McLean type vibrocorer*

System description

The typical vibrocorer consists of a tall steel frame and tripod support. Within the frame is a standard 102 mm steel coring barrel in which is inserted a 90 mm PVC liner to contain the sample. A spring steel core-catcher is fitted to the cutting shoe, as with the gravity corer.

Two linear electric motors enclosed in a pressure housing provide the vibratory motion; the core barrel is attached directly to the motor housing. Power (415 VDC) is fed to the motors via an electrical control line from the surface support vessel. Once in motion, the heavy motor housing provides the mass to drive the core barrel into the seabed. A typical 6 m vibrocorer will weigh nearly two tonnes and requires a crane for deployment and recovery. Power is normally provided from a separate generator installed on deck. Vibrocorers come with barrel lengths of 3 m, 6 m and 8 m; a normal coring operation in 100 m water depth will take about one hour.

Advantages and limitations

Vibrocorers provide valuable information for laboratory testing for soil classification purposes. Shear strength measurements must be interpreted with caution due to sample disturbance caused by the shaking motion. Because of vibrocorer equipment size and power demands, substantially sized ships are required. Further, because coring is a protracted process, the ship must be capable of remaining on station and will preferably have either DP or good joy-stick control, otherwise excessive position excursions may cause the core barrels to bend, which may lead to a total loss of the system and other financial loss through downtime. The penetration depth can be from 3 m to 8 m.

5.2.7 Box corers

Function and applications

The seabed box corer is used to recover relatively undisturbed block samples of seabed in soft, cohesive sediments.

System technology and science

The box corer is a very simple device that envelops an area of seabed then seals the base of its box to retain the sample from further disturbance during recovery.

System description

The standard box corer consists of a steel frame incorporating the sample box surmounted by a 200 kg to 300 kg mass. When activated by a self-release trigger system, the box is closed at the bottom by a swivelling base. The total mass of a box corer is in the order of 1.5 tonnes and the sample volume is about 25 to 30 litres.

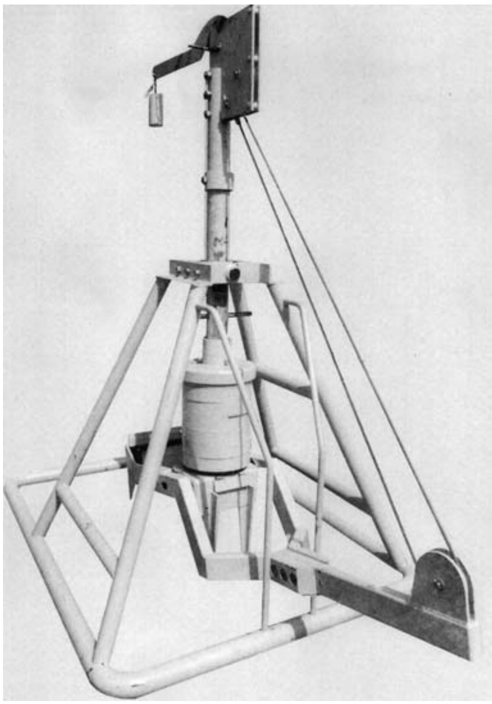

Figure 5-7 *Box corer*

In operation, the box corer is lowered to the seabed and, on contact, the self-release trigger is primed. The sample box is then pushed 400 mm to 500 mm into the seabed by the action of the weight. The trigger mechanism releases a latch that allows the swivel base to close off the captured sample before recovery to the surface where the sample is removed for examination.

Advantages and limitations

The great advantage of these devices is that they can recover a large, relatively undisturbed and high quality sample for study and for laboratory testing. Their value in environmental assessments is that they preserve well any benthic life forms and habitants, and facilitate visual examination of a portion of the seabed surface.

5.2.8 Seabed push-in samplers

Function and applications

Push-in samplers were originally developed as down-hole tools for geotechnical drilling operations to reduce the high level of sample disturbance common to the older type of percussion driven samplers.

Seabed versions have been developed that allow higher quality samples to be recovered in softer soils. Typical applications include:

- Offshore oil & gas pipeline and small structure investigations.
- Civil engineering studies for ports and harbours.
- Inshore site investigations.

System technology and science

The standard down-hole push-sampling technique involves latching the sampler behind the drill bit and inserting it into the soil in a controlled manner through the application of hydraulic pressure or the weight of the drill string.

Most standard push-sampling tubes are fabricated from stainless steel and are 1m long with an internal diameter of about 75 mm. The wall thickness is around 1.5 mm and the tube has a sharpened cutting edge. The tube is attached to a sample head and incorporating a one-way valve system. As soil enters the tube, the water trapped above the valve is expelled. When the tube is extracted from the soil, the valve closes and creates suction above the sample to ensure its retention.

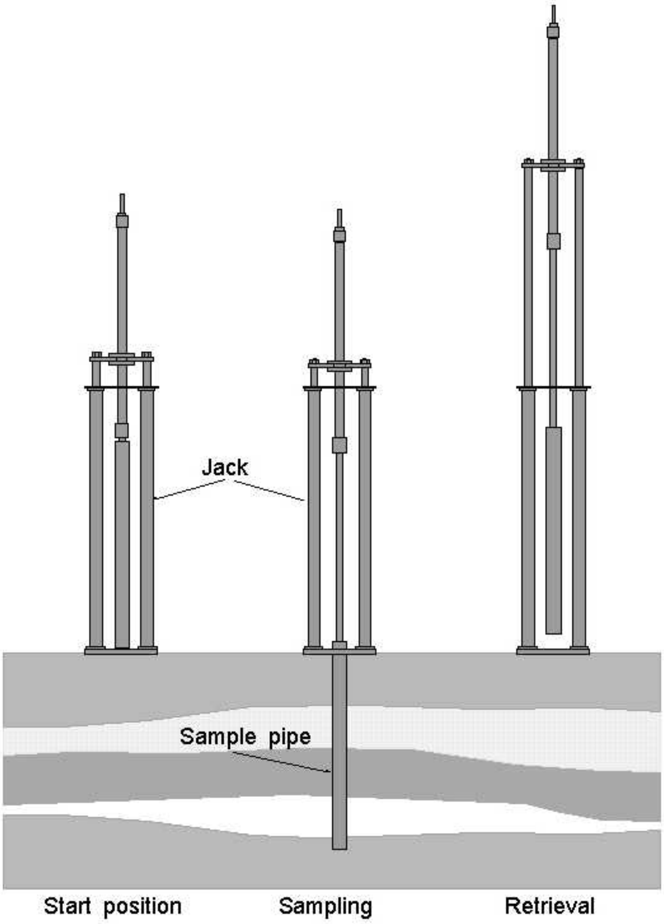

Figure 5-8 *A stand-alone seabed push-in sampler*

System description

Seabed push-samplers are usually incorporated in a seabed frame, either as a stand-alone tool, or in tandem with a CPT device. Most are capable of pushing in a sample tube between 1 m and 1.5 m long and having a diameter of between 72 mm and 100 mm. The seabed frame can weigh from 10 kN, or if a CPT unit is incorporated, from 20 kN up to 50 kN.

Advantages and limitations

The advantages of these devices are, a) they provide higher quality samples in soft soils than other seabed coring devices, and b) if incorporated with a CPT system, they reduce deployment time and provide samples directly adjacent to CPT tests for correlation. The limitations are the limited penetration depth of 1 m to 2 m. They are unsuitable for non-cohesive soils.

5.2.9 Grab samplers

Function and applications

Grab samplers are one of the most common methods of retrieving soil samples from the seabed surface. The information they provide, although coarse, can be applied in a number of applications such as:

- Bulk sampling for seabed minerals.
- Marine aggregate prospecting.
- Environmental sampling.
- Pre-dredge investigations.
- Ground truth for morphological mapping and geophysical survey.

Grab samplers can be used to recover samples of most seabed soils, although care is needed in selecting the right size unit for the task.

System technology and science

The grab sampler is a device that simply grabs a sample of the topmost layers of the seabed by bringing two steel clamshells together and cutting a bite from the soil.

System description

The grab sampler comprises two steel clamshells acting on a single or double pivot. The shells are brought together either by a powerful spring (Shipek type) or powered hydraulic rams operated from the support vessel.

In operation, the grab is lowered to the seabed and activated either automatically or by remote control. The shells swivel together in a cutting action and remove a section of seabed. The sample is then recovered to the surface for examination.

Geotechnical investigations normally require large samples and favour the bigger hydraulic clamshell grabs. These systems can retrieve samples of 0.35 m^3 or 700 kg mass. A typical hydraulic grab will weigh around half a tonne and can operate in water depths to 200 m. Typical performance rates are between three and four samples per hour.

Advantages and limitations

The smaller Shipek type grab sampler is only useful for ground truthing geophysical surveys for the surface layer, and in basic hydrography. Sampling is to about 0.1 m below the seabed. The more massive hydraulic grabs are capable of recovering relatively intact samples of consolidated soils to a depth of about 0.5 m.

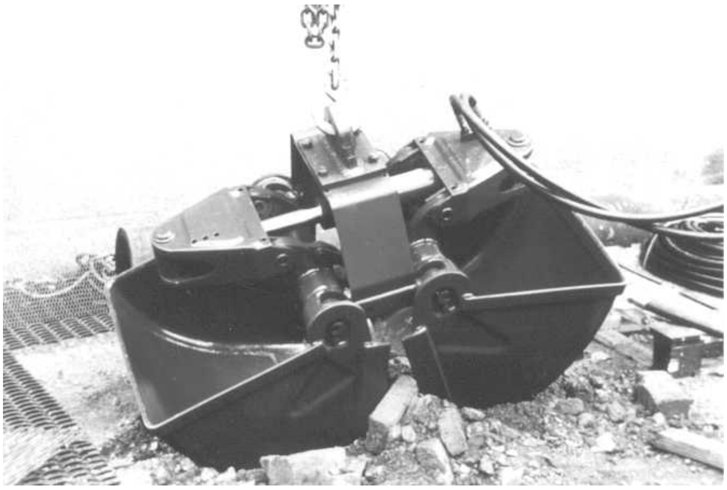

Figure 5-9 *Hydraulic grab sampler*

In areas of large cobbles or boulders, grabs can become jammed open and their contents washed away during recovery to the surface. However, the hydraulic grab is more likely to recover cobbles and small boulders than any other system, and in this respect is invaluable.

Small grabs can be operated from virtually any sort of vessel. The large hydraulic grabs require at minimum a 25 kN SWL crane, 10 kVA, 415 VDC generator, and a 210 bar hydraulic power pack, and therefore demand the use of a large vessel.

The geotechnical value of soil samples obtained by grab sampler may be limited due to the washing out of finer cohesionless materials during recovery, and the level of disturbance imparted to cohesionless soils.

5.2.10 Handling and testing of samples

Opening of sample tubes and laboratory testing on board a vessel may be required for checking the quality of the soil samples and for guiding the extent of drilling and sampling. Pictures should be taken of rock cores and a preliminary boring log should be produced on board.

For offshore developments, a field laboratory should be provided, where soil samples can be opened, visually inspected, and tested. The field laboratory should be supervised by a qualified geotechnical engineer, and as a minimum have equipment to perform index testing (water content, unit weight, identification of carbonate material, and simple undrained shear strength measurements).

For nearshore developments, often no field laboratory and qualified geotechnical laboratory engineer is available on the vessel or rig, and all testing must be done in an onshore laboratory.

Sealing, handling and storage of the samples onboard, and transport of the soil samples ashore must be performed in such a way that their condition is affected as little as possible. For example, it may be preferable to store tube samples of loose sand or very soft clay in an upright position.

All testing should be done in accordance with recognised international standards or codes.

5.3 IN-SITU TESTING SYSTEMS

The greatest advantage of in-situ testing is that it permits the evaluation of important physical characteristics of soil, and sometimes rock, in its natural state. In cohesionless soils, it is often the only means of determining certain engineering parameters such as the relative density of sands.

A secondary, but extremely valuable, benefit is the immediate availability of results with most types of test, allowing decisions to be made on site without having to wait for the results of laboratory testing.

A disadvantage is that most techniques do not measure engineering parameters directly, but instead require empirical correlations to derive them.

The following subsections describe in-situ testing systems where units resting on the seabed are used to push in-situ testing probes into the soil. An alternative test method consists of pushing a probe into the bottom of a borehole using a unit which latches into a drill string. Such units exist for drilling systems operated from vessels or platforms and for the PROD^{TM} seabed drill.

5.3.1 Seabed cone penetration tests

Function and applications

The Cone Penetration Test (CPT) is the most widely used in-situ test for marine engineering applications. Its prime use is providing information on soil type and stratification as well as on undrained shear strength in clays, and relative density and angles of shearing resistance in sand.

CPTs have a wide range of applications that include:

- Offshore oil & gas pipeline route investigations, trenching and stability studies.
- Geotechnical investigations for seabed structures and anchors.
- Geotechnical investigations for nearshore structures.
- Submarine cable route surveys and burial assessment studies.
- Inshore civil engineering studies.
- Pre-dredge investigations.
- Ground truth for geophysical survey and morphological mapping.

System technology and science

The cone penetration test provides an empirical assessment of seabed soils based on the resistance of the soil to a cone-tipped probe, or penetrometer, as it is pushed into the seabed at a rate of penetration that is as constant as possible, usually 20 mm per second. Standard cones have a tip angle of 60° and a cross-sectional area between 500 mm^2 and 2000 mm^2, with 1000 mm^2 and 1500 mm^2 cones being the most common. Minicones with cross-sections of 100 mm^2 or 200 mm^2 are also available and are discussed below (see Section 5.3.3).

Electrical strain gauges within the cone assembly measure the resistance on the cone tip, which is expressed as the average pressure (q_c) and unit friction (f_s) and friction on a sleeve behind the tip. In a piezocone penetration test (PCPT), an additional parameter, soil pore water pressure, is measured via a porous element in the cone face or at the shoulder between cone tip and friction sleeve. (NB: the PCPT is sometimes referred to as the CPTU, the U being geotechnical shorthand for pore pressure). Data are transmitted in real-time to the surface support vessel for recording and analysis. The measured cone resistance needs to be corrected for pore pressure acting behind the conical tip. In clays, the net cone resistance (q_{net}) obtained by subtracting the overburden stress from the corrected cone resistance, provides a better indication of the undrained shear strength.

Soil types are determined by reference to a graph of cone resistance (q_c) against the friction ratio. Friction ratio is the sleeve friction (f_s) divided by cone resistance (q_c) (in clays, a friction ratio of f_s divided by the net cone resistance (q_{net}) is preferable). Important information is also provided by the ratio of excess pore pressure to the net cone resistance. Other empirical relationships are used to estimate shear strength in clays and the relative density and internal angle of friction in sands.

Measuring the pore pressure provides valuable additional information on a soil's stratification, permeability and stress history, i.e. whether it is "under"-, "normally" or "over"-consolidated.

Wheel-drive penetration test unit

The wheel-drive unit comprises a seabed reaction frame, containing the wheel-drive mechanism, electronic control and data acquisition systems. Each wheel-drive unit consists of four steel wheels clamped tightly against the penetrometer's push rod. 440 VAC electrical power for the hydraulic or electric wheel-drive motor is supplied via an umbilical cable from the support vessel. The string of thrust rods can be up to 65 m long and is either kept under constant tension or supported by a guide attached to the lift lines to prevent the string buckling in the water column. As the wheels are rotated against the rod, the penetrometer is pushed into the soil at a constant rate of 20 mm per second. The outputs from the strain gauges within the cone assembly are passed up the umbilical to the ship.

Typically, wheel-drive units weigh between 6 and 13 tonnes and deliver a thrust of up to 100 kN. The largest wheel-drive CPTs weigh some 25 tonnes in air and have a thrust capacity of 200 kN. In dense sands and hard gravely clays, typical penetration ranges are about 20 m and for softer, normally consolidated clays, between 30 m and 60 m.

These large wheel-drive devices require sizeable handling systems capable of up to 40 tonnes SWL, plus adequate deck space, and hence can only be operated from relatively large vessels. They can be used in water depths to 1800 m (at the present time) but systems capable of operations in 3000 m are under development.

Alternative seabed penetrometer rigs are available where hydraulic rams, rather than a wheel-drive system, are used to push the rods into the sea bottom.

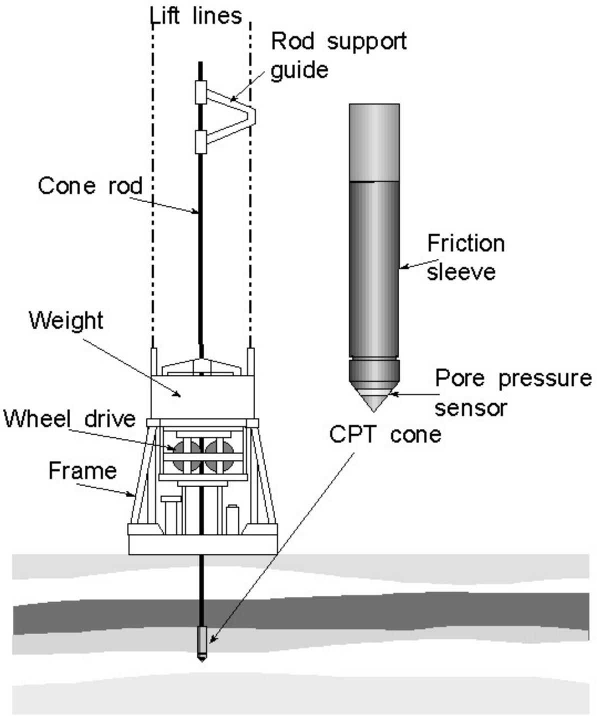

Figure 5-10 *Wheel-drive penetration test unit*

Lightweight wheel-drive penetration test unit

The lightweight CPT unit is the most popular model for submarine cable and pipeline route investigations, ploughing assessment and for trenching studies. The unit typically comprise a 4 m tall frame mounted on a 4m diameter seabed base-frame and weigh about 2.3 tonnes. The drive motors, wheel-drive and sensor systems are mounted on the base-frame.

The lightweight wheel-drive operates in the same way as the larger version, applying a thrust of up to 15 kN to the 1000 mm^2 cone, but uses only two steel wheels. The cone rod can penetrate 2 m into the seabed. Electrical power for the motors is supplied via an armoured umbilical cable which is also used to deploy and recover the device from the surface support vessel. Lightweight wheel-drive units normally include an array of ancillary sensors and samplers and can be deployed in water depths down to 1500 m. Some battery-powered versions can be operated in water depths greater than 2000 m.

The lightweight wheel-drive systems can be operated from most vessels fitted with 5 tonne SWL cranes, or from A-frames having sufficient reach. Adequate deck space is needed to accommodate the 20 kVA generators, 1500 m wire winch and for storage/handling. The design is particularly robust to maintain high productivity rates.

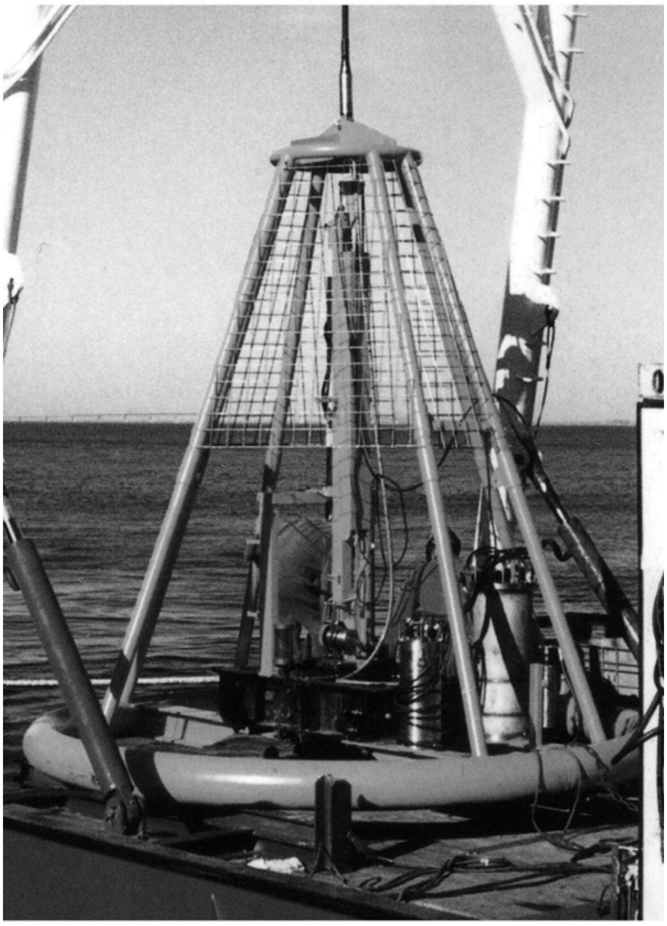

Figure 5-11 *Lightweight wheel-drive penetration test unit*

It is noted that various other types of lightweight seabed CPT units are available with different configurations, weights and penetration capabilities. These have a lower production rate compared to the above type, but may be better suited for other geotechnical purposes than cable and pipeline surveys.

Advantages and limitations

The two wheel-drive type units described above are probably the most versatile and well-proven of the in-situ seabed testing systems available. The high productivity and reliability of most systems means they provide a very cost-effective method for geotechnical data acquisition. The ability to evaluate results in real time provides for greater programme flexibility and minimises the possibility of leaving site with insufficient data.

The lightweight systems can be deployed from most geophysical survey vessels and a wide range of other, suitably equipped, vessels of opportunity. The largest wheel-drive systems require vessels with heavy deployment capabilities, such as drill ships, diving support vessels and other construction support vessels, but their penetration capability is unsurpassed and can reduce the requirement for borehole data.

Maximum penetration achievable with seabed systems is in the order of 50 to 70 m. Penetration tests at greater depth can be performed using downhole penetration units. The penetration force is obtained using a wireline system or from pressurized drilling fluid inside the drill string. Reaction for insertion of the test probe is obtained from drill string weight and/or a seabed unit clamping the drill string.

5.3.2 ROV penetration test units

Function and applications

Where a CPT is required at a precise location in deep water, or where a series of continuous tests are needed along, for example, a cable route or pipeline trench, the ROV penetration test unit provides a useful option.

Applications of this unit include:

- Offshore oil & gas pipeline and control cable route investigations.
- Soil temperature gradients for pipeline heave and buckling assessments.
- Trench backfill investigations.
- Submarine cable route studies, real-time plough assessment studies.
- Ground truth for morphological mapping and geophysical survey.
- Environmental and geotechnical assessments, of drill cutting mounds for example.

System technology and science

Instead of deploying a penetration test unit from a vessel, the ROV based system can be precisely placed for optimum results. The advantage of mobility allows the CPT operator to select areas based upon visual inspection and to conduct a rapid series of tests.

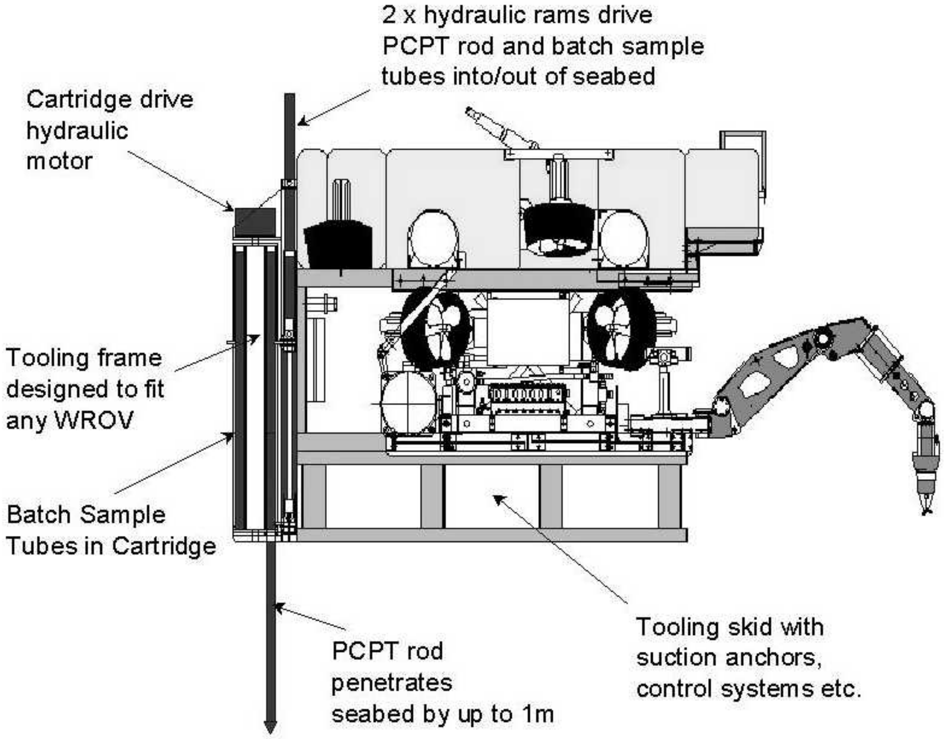

Figure 5-12

ROV mounted CPT unit

System description

The penetrometer test device and its peripheral systems are mounted on a standard ROV tooling skid. A work-class ROV is then attached to the skid and the penetrometer and its sub-systems take their power from the vehicle's supply.

The 1m-long push rod is thrust into the soil by a hydraulic ram. Due to the limited reactive force provided by an ROV, the CPT's cone area is reduced to 500 mm^2.

The water depth capability of ROV CPTs is often only limited by the capacity of the vehicle, hence deployment down to 3000 m is quite feasible although 1500 m is more normal.

Advantages and limitations

The ROV penetration test unit can be operated from any vessel equipped for ROV operations. For deep water pipeline route assessments, the unit is a useful quantitative instrument. Its great advantage is the precision with which it can be placed, for example right alongside a pipeline or structure. Operated in advance of a configurable cable plough, ROV CPTs can provide real-time ploughing assessment information.

5.3.3 Minicone test

Function and applications

Minicones do not conform to international standards, which set a range of 500 mm^2 to 2000 mm^2 for the cone tip area. They were developed in order to facilitate improved stratigraphic profiling and soil parameter definition from vessels that, because of limited handling capability, could previously deploy only coring and sampling devices. The primary application for this technology was on pipeline and cable route surveys, but this has subsequently expanded to include investigations for small subsea structures, anchors and dredging assessments.

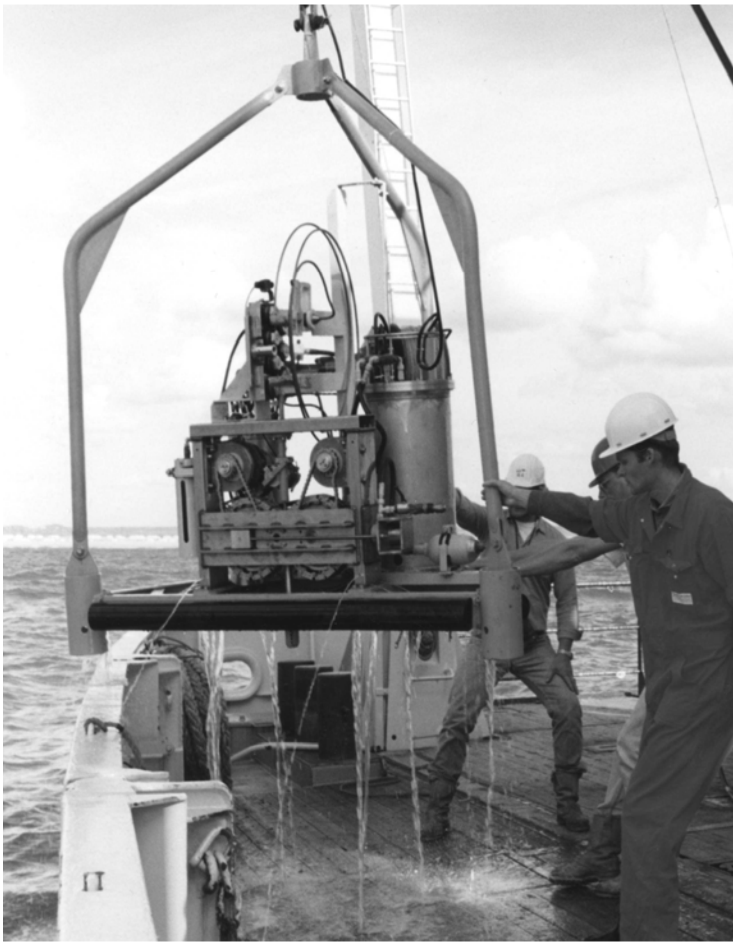

Figure 5-13 *SEASCOUT with minicone system*

System technology and science

The cone tip of a minicone system is typically 100mm^2 or 200 mm^2 ($^1/_{10}$ that of a standard cone) and its push rod, instead of being one length of rigid steel, is a coil that must first pass through a straightening device. Cone tip resistance and sleeve friction are measured as in the CPT but pore pressure measurement is less common.

The rate of penetration is usually higher than the CPT, typically twice as fast, at around 40 mm per second. Interpretation of minicone tests should take account of the smaller size, and higher penetration rate, which change the degree of consolidation occurring during the test and also the strain rate in the soil, both of which may affect the penetration resistance. Minicones capable of measuring soil temperature and/or thermal conductivity are also available.

System description

The minicone and its peripheral systems are mounted on a seabed frame that comprises a thrust machine, electronic data acquisition unit, hydraulic power pack, coiled push rod and straightener. Power for the hydraulic power pack is provided by an umbilical cable to the support vessel, or batteries mounted on the seabed frame. The minicone test can penetrate 5 m to 6 m into the seabed with a thrust of 1 tonne. The water depth capability of the minicone systems is usually in the range 1500 m to 2500 m.

Advantages and limitations

The minicone system can be operated from a wide range of vessel types equipped with cranes or A-frames capable of 2.5 to 5 tonnes SWL and which have limited free deck space. The test is very rapid, requiring as little as 10 to 15 minutes on the seabed, and results are immediately available for evaluation. Minicones are more sensitive to the presence of thin laminae within soil layers compared to CPT cones. This enables, for example, the detection of thin sand layers within a soft clay formation that may dramatically affect the drainage and settlement characteristics of that formation. Greater care needs to be exercised when using the minicone to derive engineering design parameters because of less experience with such smaller cones and the effects of partial consolidation and higher strain rates referred to previously. This is particularly pertinent for areas where there is little existing geotechnical knowledge. In such areas, site and regional specific correlation may be required.

5.3.4 Vane shear test

Function and applications

The vane test is one of many tools that can be deployed in boreholes, from wheel-drive machines or stand-alone test rigs. The vane test is a rapid and accurate means of assessing the in-situ undrained shear strength of cohesive soils, e.g. soft clays.

System technology and science

The vane test requires pushing a cruciform steel vane into a clay soil and applying torque. The torque resistance is measured until the soil fails at its natural shear strength.

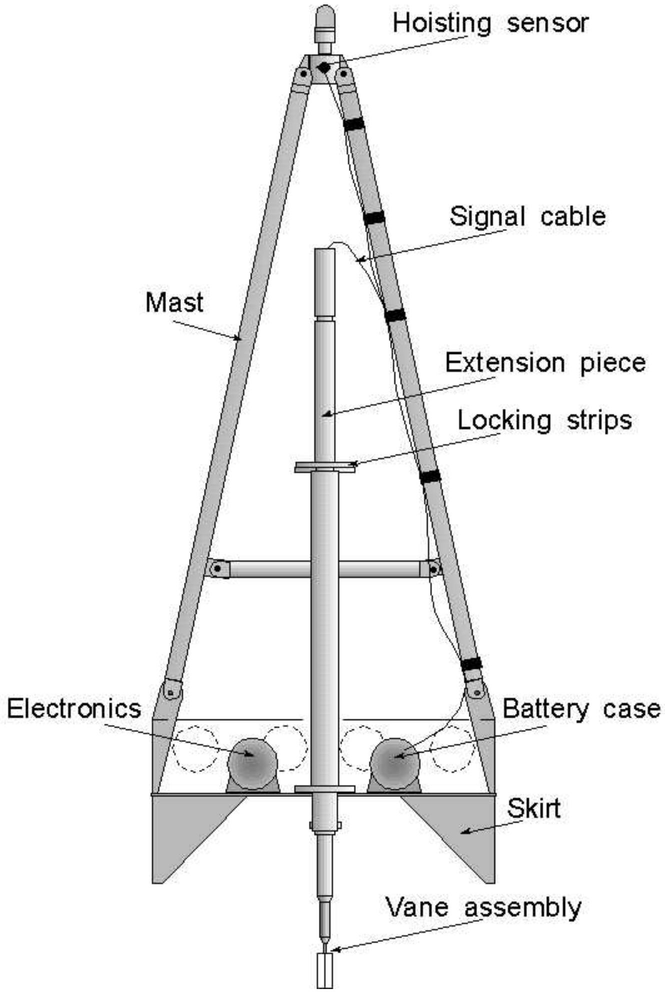

Figure 5-14 *Stand-alone vane test*

Figure 5-15 *A Halibut vane test rig during recovery*

System description

The vane test consists of a steel vane, typically between 38 mm and 65 mm in diameter and 75 mm to 130 mm high. The vane is attached to a shaft that turns at a constant rate between 6º and 12º per minute. After the soil fails, the rate of rotation can be increased to around 60° per minute and a measurement of remoulded strength obtained. The measurement of torque versus rotation is transmitted to the surface support vessel through an umbilical link or can be stored in a solid state memory on the seabed frame.

In operation, the vane test is pushed into the soil, typically 0.5 m, before being activated. At the end of each test, the vane can be pushed in further and the procedure repeated at a different elevation. Vane tests can be attached to wheel-drive penetrometer rods, as wire-line deployed sensors within a borehole, or deployed to the seabed in a purpose built frame.

Advantages and limitations

The main advantage of the vane shear test is that it provides a direct measure of undrained peak (and eventually remoulded) shear strength. The main disadvantages compared to penetration tests, is that it gives discontinuous strength profile data and that it takes relatively more time to obtain a strength profile.

5.3.5 T-bar and ball penetration test

Function and applications

The T-bar and ball penetration tests are similar to the CPT but designed to provide a more accurate assessment of shear strength in very soft soils. The T-bar is generally deployed using seabed penetration systems only, whereas the ball penetrometer can be deployed from both seabed and borehole based systems.

System technology and science

As with the CPT, the T-bar and ball penetration tests (TBT and BPT respectively) provide an empirical assessment of seabed soils based on the resistance of the soil as the T-bar or ball probe is pushed into the seabed. The T-bar comprises a short cylindrical bar that attaches perpendicularly to the penetrometer rods. As it is pushed into the soil, a load cell situated immediately behind the bar measures the resistance. The higher resistances generated in very soft soil, combined with an improved interpretation procedure, enables shear strengths to be determined with greater confidence compared to (P)CPTs. The ball probe is based on the same principles as the T-bar, except that the bar is replaced by a ball.

System description

The standard T-bar, used with wheel-drive seabed penetration systems, is 250 mm long and has a diameter of 40 mm. In addition to the resistance load cell, two pore pressure transducers may be incorporated in the bar and an inclinometer in the 36 mm diameter shaft. The standard penetration rate of 20 mm per second is the same as for the CPT. A smaller version has been developed for down-hole deployment.

Figure 5-16 *T-bar and ball probe*

A typical ball penetrometer has a diameter of 60 mm to 80 mm and is followed by a 20 mm to 25 mm diameter shaft. Pore pressure may be measured at some point within the ball (e.g. at the leading edge, or at the maximum diameter), or on the shaft behind the ball. The actual transducer is normally housed in the shaft, which also houses an inclinometer and the resistance load cell.

Advantages and limitations

Both the T-bar and the ball probe have similar advantages to the cone penetrometer with respect to ease of deployment and high production rates. Due to the larger areas, the TBT and BPT are restricted to soft sediments, although offshore tests have been conducted in silts and silty sands with penetration resistance up to 5 MPa. Shear strength interpretation from T-bar and ball tests is more straightforward compared to the cone, since there is less correction for the overburden stress, and the correlation factors between penetration resistance and shear strength appear to lie in a narrower range than for the cone.

5.3.6 Additional sensors applied with conventional CPT technology

A range of additional sensors deployable both nearshore and offshore by means of conventional cone penetrometer technology, include:

Thermal conductivity probe – for measuring a soil's heat dissipation characteristics. Especially important in deep water site investigations where the insulating characteristics of soils are important considerations for designing anti-waxing solutions in pipelines.

Electrical conductivity cone – the electrical conductivity of a soil depends on the soil type, porosity, water content and pore water composition. Primary applications for this measurement are in determining corrosion potential for pipelines and structures, detecting pore water pollutants and assessing changes in porosity.

Seismic cone –incorporates a triaxial geophone in the cone shaft. Used with a shear wave generator on the seabed reaction frame, it provides information on the low strain stiffness of a soil - particularly useful in analysing earthquake hazards and foundations subject to dynamic loads. The shear wave velocity profile it provides is also useful for analysing deep seismic data. The in situ shear wave velocity measurements can be compared to shear wave velocity measured in laboratory specimens to provide a means of assessing the applicability of the laboratory test data to the field behaviour of the soil.

Natural gamma – a sensor for detecting the natural gamma radiation of a soil as a means of ascertaining soil type and density.

Dilatometer – for measuring horizontal soil stiffness and stress at a selected depth. Pushed to this depth in a similar manner to the CPT. The strain range is more limited than in a pressuremeter test

5.3.7 Other in-situ tests

Other in-situ tests which are occasionally applied in nearshore investigations include:

Standard Penetration Test – providing a measure of static and cyclic (liquefaction) soil strength at the bottom of a borehole.

Pressuremeter – for measuring horizontal soil stiffness and strength at a selected depth. Borehole (Menard), push-in (cone) pressuremeters and self-boring pressuremeters are available.

5.4 LABORATORY TESTING

Laboratory techniques for offshore site investigations essentially do not differ from those applied to geotechnical investigations for onshore developments and generally follow the same standards.

Laboratory tests should be carried out on representative samples. The quality of the samples for testing in the laboratory has a large influence on the reliability of the test results. The quality is determined by the sampling method and environment (Section 5.1), and the transport and storage conditions.

Strength tests may require samples to be consolidated to estimated in-situ stresses. A SHANSEP consolidation procedure should be considered to reduce sample disturbance effects caused by sampling and sample handling. Sample disturbance may be estimated from the void ratio change when consolidating the samples back to the in-situ stresses.

For preparation of sand specimens for (cyclic) strength testing, consideration should be given to including cyclic pre-shearing of the samples.

5.5 SUITABILITY OF IN-SITU AND LABORATORY TESTS

The suitability of different in-situ and laboratory tests for determining soil parameters is assessed in this section. The review is divided into conventional tests that are normally used in standard investigations and special tests that may be considered for specific design topics. Table 5.5-1 and Table 5.5-2 list the conventional tests and special tests respectively. The level of suitability / applicability is indicated on a scale of 1 to 5 where:

1 = poor or inappropriate	4 = good
2 = acceptable for non critical analyses	5 = very good
3 = moderately good	

Table 5.5-1 CONVENTIONAL TESTING METHODS

Soil parameters	In-situ testing			Laboratory testing		
	Type of test	Applicability		Type of test	Applicability	
		Sand	Clay		Sand	Clay
Interpolation of soil layering	Seismic reflection profiling	2	2			
Soil classification	Swath bathymetry,	1	1	Grain size distribution	5	2
	sidescan sonar			Grain size + hydrometer		4
	CPT	2	2	Water content	2	3
	(P)CPT	4 to 5	4 to 5	Atterberg limits		5
Soil density	CPT, (P)CPT	2	2	Unit weight and water content	1 to 2	5
Soil strength	CPT, (P)CPT		3 to 4	Triaxial shear strength		3 to 4
	VST		4 to 5	Triaxial CIU	4	4
(undrained shear strength)	PMT or DMT		2 to 3	Simple shear		3 to 4
	T-bar, ball probe		4 to 5	Fall cone, torvane,		3
				Pocket penetrometer		2
Angle of shearing resistance (drained shear strength)	CPT, (P)CPT	3 to 4	2	Triaxial CIU, CID (a)	5 (a)	5
				Simple shear	4	1
Sensitivity	CPT, (P)CPT		2	Fall cone, lab vane		3 to 4
	VST		3 to 4	Triaxial shear strength (intact/remoulded)		
	T-bar, ball probe		3 to 4(b)			3 to 4

Soil parameters	In-situ testing			Laboratory testing		
	Type of test	Applicability		Type of test	Applicability	
		Sand	Clay		Sand	Clay
Consolidation characteristics and permeability	(P)CPT	1	3	Oedometer	3 (a)	5

(a) if in-situ density is known. Triaxial tests may be required for reloading modulus of very dense sand and for permeability of coarse sand.
(b) 5 if cyclic tests performed.

Table 5.5-2 SPECIAL TESTING METHODS

Soil parameters	In – situ testing			Laboratory testing		
	Type of test	Applicability		Type of test	Applicability	
		Sand	Clay		Sand	Clay
Interpolation of soil layering	Seismic refraction profiling Electrical resistivity profiling	3 to 4(a) 2 to 3(b)	3 to 4(a) 2 to 3(b)			
Classification of carbonate soils	CPT,(P)CPT	4(c)	3	Carbonate content	5	5
Compressibility of carbonate sands				Oedometer Crushability	4 3	
Shear strength anisotropy (clay)				Triaxial CAUc, CAUe Simple shear		5
Rate effects, cyclic response				Consolidated triaxial, simple shear (static, cyclic)	5	5
Thixotropy				Thixotropy tests		4
Interface behaviour (piles, caissons)				Ring shear tests (soil/soil and soil/steel) Shear box(soil/soil and soil/steel)	3 to 4 3 to 4	3 to 4
Initial shear modulus	Seismic cone	4 to 5	4 to 5	Resonant column (d) Bender elements in triaxial simple shear and oedometer tests	4 to 5 4 to 5	4 to 5 4 to 5
Corrosion potential	Electrical resistivity cone	4	4	Electrical resistivity	4	4
Liquefaction potential	CPT, (P)CPT Electric resistivity cone	3 4		Electrical resistivity	4	

(a) 4 if reasonable calibration on samples/in-situ testing is done
(b) this technique needs extensive calibration on samples/in-situ testing
(c) CPT data are highly sensitive to degree of cementation (e.g. friction ratio)
(d) may also give damping at low strain levels

6. EVALUATION OF DATA AND REPORTING

6.1 GEOTECHNICAL QUALITY

Usually, geotechnical data are acquired for part of a specific phase of a construction project. To ensure that geotechnical data are properly incorporated in the whole project, it is important to assure a continuous thread of responsibility for the geotechnical input from the feasibility study to project completion. Adequate designation of responsibility for geotechnical aspects of the construction project helps to avoid misinterpretations of the data by design and construction professionals (Figure 6-1).

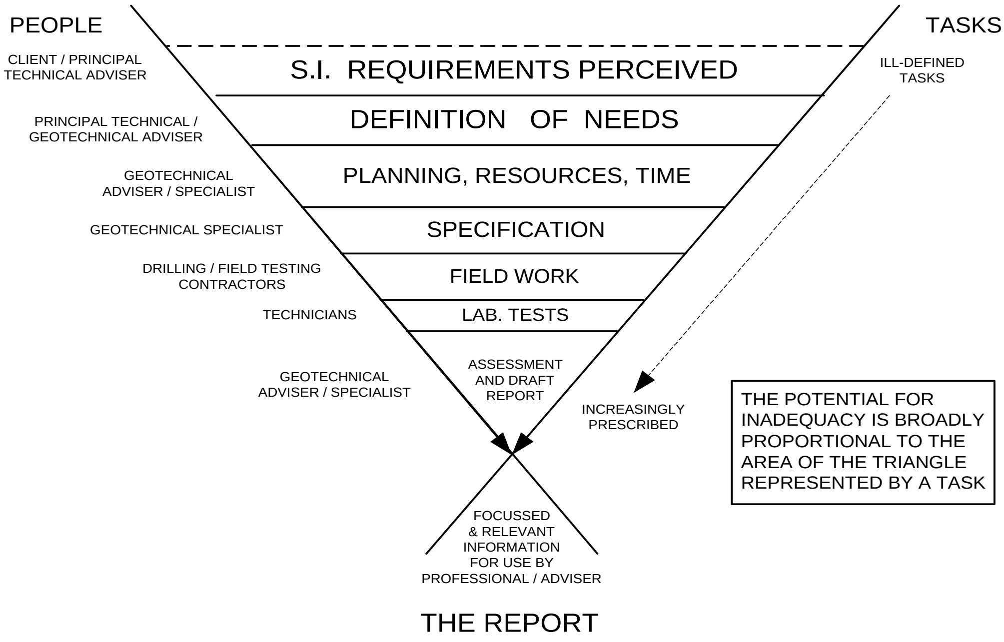

Figure 6-1 : Geotechnical Quality for Site Investigation (adapted from SISG).

In the diagram, the potential of acquiring inadequate data is greatest when errors are made in the initial phase of the investigation; the definition of requirements and needs, planning, resources and timing.

It is important that the design of an investigation (or a monitoring programme) suits the actual site conditions and construction characteristics. The investigation programme should be flexible so that adjustments to the programme can be made during the investigation when necessary. The cost associated with redoing part of the investigation at a later stage, or the design of alternative construction methods, is generally far greater than the cost of the original investigation.

6.2 PROJECT SPECIFIC INFORMATION

The geotechnical data and recommendations resulting from an investigation are usually tailored to the requirements of a unique construction project. Project-specific factors include:

- Location and soil conditions.
- Size and configuration of the structure.
- Nearby facilities.

It has to be taken into consideration that if any of these factors change, the validity of the investigation results may be affected as well. Also, project-specific data and recommendations are usually for the express purpose of a specific customer. Certain limitations imposed by the customer, such as project-specific limits to the investigation programme and agreed resources, may result in limitations on the use of the data. It is therefore important to realise that data acquired for a specific purpose and a specific customer may not necessarily be valid for a different purpose.

6.3 DATA ACQUISITION AND EVALUATION

A geotechnical investigation only provides information at the specific test location. With geotechnical knowledge and experience, information may be extrapolated between test locations. However, interfaces between ground materials may be more abrupt or gradual than expected and actual conditions in areas not tested may differ from predictions. Therefore, it is not realistic to expect that a geotechnical investigation can predict ground conditions entirely. Nevertheless, a properly planned and conducted geotechnical investigation can reduce the residual risk associated with unforeseen conditions to an acceptable level.

Geotechnical data must be carefully evaluated. Frequently, there will be some data that may not be representative of the soil conditions. Problems with data, for example, could be related to disturbance of samples, or parts of a sample, or in the malfunctioning of data acquisition equipment. Incidents during the offshore operation that could affect data must be recorded and accounted for in the evaluation.

For a safe and economical design of a structure, it is necessary to understand the behaviour of the ground for which the structure is destined. It is also important to be aware that the ground may be complex and can be changed by natural forces such as earthquakes, floods, seabed scour and ground water fluctuations. Additionally, construction at, or near, the site may affect ground conditions. In general, data acquired during an investigation is valid for a period of approximately 2 years after acquisition. After this period, the data may become inaccurate or unreliable.

6.4 REPORTING

Because geotechnical engineering requires extensive judgement and opinion, it is less exact than other design disciplines. Reporting of the field operation, in-situ and laboratory tests, and the interpretation of the test results, should include a level of detail that enables the reader to follow each step of the interpretation. The interpretation should, in addition to the geotechnical data, draw upon the available geological and geophysical data.

The reported data should be in digital form to facilitate further use and interpretation.

7. OFFSHORE PLATFORMS

The petroleum industry uses fixed offshore platforms for various purposes, such as drilling, production, living quarters and storage. The recent increase in demand for LNG terminals has led to these structures being located offshore, but closer to shore than traditional offshore platforms. LNG terminals share many similarities with offshore platforms, with respect to both loading and foundation design, and most of what is discussed here also applies to LNG terminals.

Permanent, fixed offshore platforms may be piled or suction foundation supported steel structures, or gravity platforms (GBS = ‘Gravity Based Structure') that rest on the seabed. Piles are usually tubular, open-ended and driven. On occasion, piles are grouted into carbonate or rock formations. A small number of steel platforms are supported by steel suction caissons rather than driven piles. The gravity platforms are steel or concrete structures equipped with skirts that penetrate into the seabed. The tallest GBS to date, which is located in the Troll field in the North Sea in about 330m water depth, is equipped with concrete skirts that penetrate 36 m into normally consolidated clay, whereas the Ekofisk Oil Storage Tank, located in about 60 m water depth, has short skirts that only penetrate about 0.6m into very dense sand. This all goes to demonstrate that the geotechnical conditions of a site are critical to the design of any structure.

Commonly, offshore platforms carry heavy deck loads and, in exposed locations, will experience severe storm loads. In some areas, earthquakes impose high dynamic loads and may reduce the soil strength. These loads, carried by the foundation, mean that foundation engineering is a critical element in the design process.

Jack-up platforms are restricted to shallow waters and are normally installed for a limited duration (i.e. months rather than years), and are typically supported on spudcans.

Recent developments for oil & gas exploitation in deep water involve the installation of various types of large floating structures. Anchoring systems for such structures are discussed in Section 8.

An offshore oil & gas field generally has a limited amount of structures. This is unlike an offshore wind farm, which consists of several separately founded wind energy turbines distributed over the wind farm area. Foundation types for wind energy towers are gravity-type, monopile, jacket-pile, tripod and suction caissons.

7.1 FOUNDATION DESIGN ISSUES

Some major foundation design issues for offshore platforms include:

- **Bearing capacity**. Whatever the structure, the subsoil must have sufficient capacity to carry the static and cyclic loads with an adequate safety margin against excessive displacements or failure. The capacity under cyclic loading may be different from the capacity under monotonic loading. The soil capacity under cyclic loading is an important design consideration.
- **Permanent displacements** (e.g. settlement). The static load will cause initial displacements as well as displacements caused by consolidation and creep in the soil beneath and outside the platform. The cyclic loading from waves and/or earthquakes will cause additional permanent displacements due to increased shear strains and dissipation of cyclically induced pore pressure. The permanent

displacements will reduce the freeboard between the platform deck and the sea surface, and may cause stresses to structural elements in the soil and to mechanical connections to items such as oil wells, risers and pipelines connected to the platform.

- **Cyclic displacements**. Cyclic loads cause cyclic displacements of the soil and the platform. Cyclic platform displacements may be a serviceability problem for people and equipment on board the platform. In common with permanent displacements, cyclic displacements may cause stresses in structural elements in the soil and in any connections to the structure.
- **Foundation stiffness**. Equivalent soil spring stiffness measurements are necessary for structural dynamic analyses from wave and/or earthquake loading. For platforms in deep water, the resonance period may approach the wave load period giving rise to significant wave load amplification. It is therefore important to ensure that the resonance period is far enough away from the wave load period, or to calculate and design for the wave load amplification factor.
- **Soil reaction stresses**. GBS structures must be designed for the stresses from the soil due both to static and cyclic loads. If the seabed is uneven and consists of dense sand, the soil reaction stresses may locally be very high. The soil reaction stresses may also redistribute with time due to creep and cyclic degradation of the soil modulus.
- **Penetration of skirts**. For GBSs with skirts, the skirt penetration resistance must be calculated to be certain that they will reach the designed penetration depth.
- **Pile drivability**. To ensure that adequate penetration depth is obtained and that the pile can withstand the driving stresses, the choice of pile driving equipment needs to be carefully assessed.
- **Punch-through**. Jack-up rig footings (spudcans) are normally installed by preloading the legs with ballast water. These will penetrate into the seabed from the increasing ballast load. Rapid, uncontrolled penetration may occur in soils where there is limited soil strength increase with depth, and in soils where a strong layer of limited thickness overlies a weaker layer.
- **Liquefaction potential analyses**. This is required for sites where sands or silty sands are present either in seismically active areas or where heavy wave loading can be expected.
- **Scour and erosion**. Wave and currents may cause scour and erosion around offshore platforms. The potential for scouring is greater in sand than in clay, and the potential typically increases as water depth decreases. Gravity platforms installed on sand may require a graded gravel fill around the periphery for erosion protection. Skirts along the periphery will help prevent scour underneath the base. In case of piles, scour may be accommodated by allowing for a certain scour depth in the design.

7.2 PARAMETERS REQUIRED

To address these issues, the geotechnical and geological information, discussed in Sections 2.1 to 2.5 need to be collected. Table 7.2-1 and Table 7.2-2 list the basic and specific soil and rock parameters needed for a typical offshore platform's foundation design.

Table 7.2-1 REQUIRED BASIC SOIL AND ROCK PARAMETERS

CLAY	SAND, SILT OR GRAVEL	ROCK
– General description – Layering – Grain size distribution – Water content – Total unit weight – Atterberg (plastic and liquid) limits – Indicative shear strength (miniature vane, torvane, pocket penetrometer, fall cone, UU, etc.) – Remoulded shear strength – Sensitivity – Soil stress history and over-consolidation ratio – Organic material content	– General description – Layering – Grain size distribution – Water content (silt) – Maximum and minimum densities – Relative density – Drained angle of shearing resistance – Soil stress history and over-consolidation ratio – Angularity – Carbonate content – Organic material content	– General description – RQD – Water absorption – Total unit weight – Unit weight of solid blocks – Unconfined compression strength – Mineralogy – Carbonate content

Table 7.2-2 ADDITIONAL PARAMETERS FOR SPECIFIC DESIGN ISSUES

Design issue	**Parameter**
Bearing capacity	– Monotonic shear strengths under different stress paths – Cyclic shear strength under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Undrained angle of shearing resistance (sand).
Permanent displacements	– Compressibility. – Permeability. – Permanent shear strain and pore pressure under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Compressibility after cyclic loading.
Cyclic displacements	– Cyclic shear strain as function of cyclic shear stress under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Initial shear modulus.
Foundation stiffness	– Cyclic shear strain as function of cyclic shear stress under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Initial shear modulus. – Damping.

Design issue	Parameter
Soil reaction stresses	– Monotonic and cyclic shear strengths. – Compressibility under virgin loading and reloading. – Cyclic and permanent shear strains and permanent pore pressure under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Seabed topography, objects on the seafloor.
Liquefaction potential	– Initial shear modulus. – Cyclic shear modulus degradation curves. – Damping. – Coefficient of reconsolidation (sand).
(For all the above)	– Cyclic shear strain and permanent pore pressure (sand) contour diagrams for at least one representative average shear stress (e.g. simple shear tests with τ_a=0). – Coefficient of reconsolidation (sand).
Skirt penetration	– Undrained anisotropic monotonic shear strengths. – Remoulded shear strength (or sensitivity). – Drained angle of shearing resistance (sand). – Residual interface angle of shearing resistance (sand). – CPT resistance (sand). – Seabed topography and objects on the seafloor. – Boulders in the soil within the skirt penetration depth.
Pile capacity and drivability	– Axial and lateral response. – Shear strength. – Soil modulus or strain at 50% ultimate strength – CPT cone resistance
Scour / erosion	– Permeability.

7.3 TYPICAL SCOPE FOR SITE INVESTIGATION

A geophysical survey for offshore platform projects at minimum has to achieve the general requirements described in Section 2.4. The geotechnical survey and laboratory testing need to meet the general requirements described in Section 2.5.

Table 7.3-1 and Table 7.3-2 are examples of typical investigation programmes and these require review and adaptation for project-specific factors.

Table 7.3-1 TYPICAL SCOPE OF GEOPHYSICAL SURVEY FOR PLATFORMS

Survey purpose	Minimum survey area	Minimum depth	Means of survey
Seabed topography	Usually 1 km x 1 km in shallow water, 2 km x 2 km in deep water. Possible extension to 5 km x 5 km in areas with geohazards to incorporate possible platform location shifts etc.		Swath bathymetry, preferably multibeam
Seabed features			Sidescan sonar, line spacing 100-200 m depending on water depth, with sonar range set to provide 200 % coverage from line overlap.
Subsurface information		See geotechnical recommendations below	High-resolution / ultra high-resolution seismic survey for shallow geology and fault offset analysis. Line spacing: 100 m to 200 m depending on water depth. May be performed simultaneous with sidescan sonar. Also, 3D exploration seismic data (where available) to approximately 1.5 milliseconds for regional geohazard analysis and drilling hazard analysis to approximately 1000 m depth

Table 7.3-2 TYPICAL SCOPE OF GEOTECHNICAL SURVEY FOR PLATFORMS

Platform type	Scope of work	Penetration (m)	Sample testing
Gravity Platform	1 no. BH with continuous sampling down to 15 m, thereafter sampling with less than 0.5 m gaps to 0.5 x to 0.7 x platform diameter, followed by alternate sampling and CPT (preferably (P)CPT) with less than 0.5 m gaps.	1.5 x platform diameter	Index testing, (see basic parameters Table 7.2-1). Triaxial tests Oedometer tests. Permeability tests. Simple shear tests and anisotropically consolidated compression and extension triaxial tests, monotonic and cyclic. Shear wave velocity measurements by bender elements to determine initial shear modulus. Resonant column tests. X-ray photographs to determine soil layering within the tube, inclusions, sample quality. Radioactive core logging (optional).
	3 nos. BHs with continuous sampling to 15 m, thereafter sampling with less than 0.5 m gaps.	50 m	
	10 nos. continuous (P)CPTs	50 m or 1.5 x platform diameter	

Platform type	Scope of work	Penetration (m)	Sample testing
Piled platform	1 no. BH with samples every metre down to 15 m, thereafter sampling with less than 0.5 m gaps to 30 m, followed by alternate sampling and CPT (preferably (P)CPT) with less than 0.5 m gaps or 2 nos. BHs: one with sampling only and one with near-continuous CPT.	At least to pile penetration + 4 pile diameters or pile penetration plus pile group, diameter, whichever is the greater *	Index testing, (see basic parameters Table 7.2-1). Testing for pile capacity and drivability, and for (static mudmat) bearing capacity (Table 7.2.-2).
	Continuous (P)CPTs at a location 5-10 m from the main borehole .	30 m	
Jack-up rig	1 no. BH with samples at every metre down to 15 m, and thereafter gaps less than 0.5 m.	30 m or anticipated spudcan penetration + 1.5 x spudcan diameter, whichever is deeper.	Index testing, (see basic parameters Table 7.2-1). Testing for static bearing capacity (Table 7.2-2)
	1 no. Continuous (P)CPT at a location 5 to 10 m from the main borehole and/or at each leg location.	20 m	

* Typical required penetrations may vary from 70m for sand and/or over-consolidated clay sites to 150m for normally consolidated clay sites. The borehole depth may also have to take into account aspects of well design, for example required conductor setting depth.

The above scopes of work are indicative for typical platforms and fairly uniform soil conditions. The number of boreholes depends upon the size of the platform and the soil variability over the platform footprint. One should also allow for possible changes in the size (or even exact location) of this footprint. It is also possible that the type of platform might change, once design starts. The number of test sites also depends on the proposed platform’s purpose and the consequences of risk analysis for possible poor performance of the structure or the soil.

The number of borings, (P)CPTs and other in-situ tests, also depend on the ground variability across a site as determined from initial geophysical surveys. Extra borings or (P)CPTs are particularly necessary near geophysical anomalies or near discontinuities in the soil / rock layering.

Thus, for a GBS, depending on size and soil variability, one or two deep boreholes may be required, together with shallow boreholes/CPTs. More shallow boreholes are likely to be specified for a larger structure.

For piled structures, between one and four deep boreholes may be required, depending on size and soil variability. Extra CPTs or sample borings may be required for mudmat design and the assessment of horizontal soil resistance on piles. Near-continuous CPT profiles are required for axial pile design at sand sites using current CPT-based design methods. It is noted that more axial capacity is gained at deeper elevations for piles, so it is important to characterise these deeper soils accurately. In a dense sand, one would not want to miss bands of clay, for example, at the proposed tip elevation.

The general practice for offshore wind farms supported by foundations in sand and/or clay, is to perform one (P)CPT per foundation location and sample borings, of which the total number varies from 4 per site to 1 per 5 foundations, depending on wind farm size and soil heterogeneity. Rock coring at each wind turbine location, rather than (P)CPTs and sample borings, may be required in case rock is encountered.

Site investigations are preferably conducted in stages. In the early stage of a project the amount of in-situ testing may be limited to the information necessary for deciding the feasibility of different types of structure. In this instance, additional testing will be required for the detailed design stage. The site investigation should consider the likelihood of the platform location changing during the detailed platform design process because of changes in field layout, platform properties, and mooring leg properties.

In addition to sample borings, penetration tests (cone, T-bar or ball), vane shear tests and pressuremeter tests would contribute to a more reliable assessment of in-situ strength and stiffness parameters.

8. ANCHORED STRUCTURES

There are many types of anchored structures and these are conventionally classified according to two criteria:

- Duration of the anchoring: temporary versus semi-permanent or permanent.
- Water depth.

Temporary anchored structures are chiefly floating platforms used for drilling offshore wells, e.g. semi-submersible platforms, or for marine construction works such as crane, dredging and, pipelay barges. Temporary anchoring is restricted to relatively shallow water depths (typically < 300 m).

Permanent (or semi-permanent) anchoring applies to a large variety of structures, mostly associated with the production, storage and transportation of oil and gas. The water depth has a direct effect on the loading mode of the anchoring system. In shallow water, structures are anchored in catenary and the mooring force at the seabed is mainly horizontal. In deep water, taut anchoring, involving inclined loading at the seabed, is preferred to limit the extent of the anchor pattern and the length of the anchoring lines. The structures known as tension leg platforms (TLPs) generate vertical to near-vertical loads.

This guideline considers all types of anchoring systems capable of resisting significant tensions at seabed level (typically more than 1 MN). These are:

- Marine (drag) anchors.
- High holding power (HHP) drag anchors.
- Vertically loaded anchors (VLAs).
- Anchor piles.
- Gravity anchors, possibly equipped with skirts.
- Suction caissons.

8.1 DESIGN ISSUES AND INSTALLATION CONSTRAINTS

Site specific and regional geotechnical data are required at the proposed locations of the anchor points in order to ensure that, as a minimum:

- The anchor systems can be successfully installed without incurring costly delays.
- The seabed is able to resist the loads imposed by the foundation system without incurring excessive immediate deformations or long term movements.
- Specific instability processes (e.g. scour, liquefaction, mass seabed movements) cannot impair the long term safety of the anchoring system.

The following list of examples, based upon actual experience, serves to illustrate the potential impact of inadequate site investigation:

- Inability of drag anchors to penetrate hard seabed materials (stiff clays, cap rocks).
- Over-dragging of anchors due to presence of a hard horizon below seabed.
- Structural damage to anchor flukes due to tipping in an undetected rock outcrop.
- Interaction with man made objects including wrecks, debris and sub-sea structures including pipelines and cables.

- Failure to drive piles to target penetration owing to encountering harder than expected strata.
- Pile wall collapse caused by hard driving conditions in cemented formations and too large D/t (pile diameter/wall thickness) ratios.
- Problems related to carbonate soils, such as hard cap rock and cemented layers, limiting resistance on drag anchors and providing low skin friction along driven piles.
- Hole instabilities during drilling due to softer than anticipated layers.
- Failure to penetrate skirts or suction caissons into the seabed because of denser surface sands, greater gravel/cobble content or stiffer clay than expected, clay layers interbedded in sand deposits, or sand layers interbedded in clay deposits.
- Lower than expected resistance to suction caisson penetration which may be indicative of insufficient short-term holding capacity and delays to anchor line tensioning.

8.2 PARAMETERS REQUIRED

To address all design issues, the geotechnical information (including geological information) discussed in Section 2.1 to Section 2.5 needs to be collected. Table 8.2-1 and Table 8.2-2 respectively list the basic and specific soil and rock parameters that need to be determined.

Table 8.2-1 BASIC SOIL AND ROCK PARAMETERS REQUIRED

CLAY	SAND, SILT OR GRAVEL	ROCK
– General description – Grain size distribution – Organic material content – Mineralogy – Total unit weight – Atterberg (plastic/liquid) limits – Water content – Undrained shear strength – Remoulded shear strength – Sensitivity – Over consolidation ratio – Carbonate content	– General description – Grain size distribution – Maximum and minimum densities – Relative density – Water content (silt) – Carbonate content – Organic material content – Angularity – Angle of shearing resistance – Soils stress history and over-consolidation ratio	– General description – RQD – Water absorption – Total unit weight – Unit weight of solid blocks – Unconfined compression strength – Mineralogy – Carbonate content

Table 8.2-2 ADDITIONAL PARAMETERS FOR SPECIFIC APPLICATIONS

APPLICATION	ADDITIONAL PARAMETER
Scour / erosion	Permeability (sand / silt)
Slope stability	Strain rate effect, cyclic response, permeability, strength anisotropy
Liquefaction	Cyclic response, coefficient of (re)consolidation
Earthquake design	Strain rate effect, shear modulus, cyclic response
Settlements	Constrained modulus, consolidation, ageing and creep characteristics
Corrosion	Electrical resistivity, geochemical tests, bacteriological analyses
Suction anchor installation in clay, skirt penetration	Undrained anisotropic shear strength
Suction anchor installation in sand, skirt penetration	Permeability, cone resistance, drained angle of shearing resistance
Suction anchor capacity	Anisotropic monotonic and cyclic , shear strength, thixotropic regain, consolidation characteristics
Long term holding capacity of suction anchors in clay	Strain rate effects, cyclic response
Soil-pile friction in carbonate sands	Sand compressibility, crushability
Anchor piles	Elastic modulus

8.3 TYPICAL SCOPE FOR SITE INVESTIGATION

The chief design criterion for a geophysical survey for anchoring, is to achieve the general requirements described in Section 2.4. The geotechnical survey and laboratory testing have to achieve the general requirements described in Section 2.5. Table 8.3-1and Table 8.3-2 present typical scopes of works for these investigations. These are the minimum prudent programmes that should be reviewed and adapted in the light of project-specific factors.

Table 8.3-1 TYPICAL SCOPE OF GEOPHYSICAL SURVEY FOR ANCHORING

Survey purpose	Minimum survey area	Minimum depth	Means of survey
Seabed topography	Full extent of anchor spread		Swath bathymetry, preferably multibeam
Seabed features	Full extent of anchor spread		Sidescan sonar, line spacing 100 – 200 m depending on water depth and reliability of positioning, with sonar range set to provide 200% coverage from overlapping lines.
Subsurface information	Full extent of anchor spread	In excess of depth recommended for geotechnical data (see Table 8.3-2)	Sub-bottom profiler (shallow depth depending on soil conditions) or high-resolution seismic survey. Line spacing: 100 - 200 m. With caution, may be performed simultaneously with sidescan sonar survey.

Table 8.3-2 TYPICAL SCOPE OF GEOTECHNICAL SURVEY FOR ANCHORING

Anchor type	Scope of work	Penetration	Sample testing
Drag anchor	1 no. BH/core and/or 1 No. (P)CPT per anchor point A) B)	Sand: typically 5-10 m Soft clay: to 20 m	Anchor designs are generally not sensitive to displacements. Hence, emphasis in laboratory tests is generally on determination of static soil strength (peak and remoulded) and anchor-soil interface frictional resistance
Vertically Loaded Anchor (VLA)	1 no. BH and/or 1 No. (P)CPT per anchor point A)	Soft clay: to 50 m Other soils: to depth of fluke + 5 m	
Pile	1 no. BH and/or 1 No. (P)CPT per anchor point A) C)	Pile penetration + 4 pile diameters	
Gravity base	1 no. (P)CPT per corner + 1 or 2 nos. BH/core D)	1.5 x width (unskirted) or depth of skirt +1.5 x width	
Suction caisson	1 no. BH/core and/or 1 No. (P)CPT per anchor point E) F)	Depth of caisson + 1 diameter	

A) Continuous sampling BH and continuous (P)CPTs can be alternate every two locations or samples and (P)CPT strokes alternate in same BH.
B) Seismic refraction profiling can be useful along anticipated drag path in special circumstances.
C) In shallow water depths pressuremeter tests can be considered for obtaining pile lateral response.
D) Penetration distance below skirt depends on loading and other factors such as proximity of “hard” layer.
E) High quality samples required for advanced laboratory testing.
F) Other in-situ tests for assessing in-situ strength of clay: VST, TBT, BPT.

A finer geophysical survey grid may be required near the anchor point locations. Care should be taken that sufficient data/resolution are obtained in the zones of embedded anchor lines to verify that no rock outcrops or hard objects are present, and that there is a low risk of encountering boulders, which might damage or impede the anchoring system.

More boreholes or penetration tests may be needed near geophysical anomalies or near discontinuities in the soil layering.

Precise positioning of towed equipment is required because of the need to accurately map conditions across the relatively small footprint of most anchoring systems.

A geophysical survey alone (or in addition to a desk study) is not sufficient for detailed engineering purposes unless site specific geotechnical data are already available.

9. OFFSHORE PIPELINES

Offshore pipelines are used by the petroleum industry to transport gases or liquids at high temperature and pressure.

In general, design and construction of pipelines require an integrated approach covering factors such as:

- Pipeline size for the required product capacity.
- Pipeline strength related to external pressures, bending, torsion and buckling during installation.
- Pipeline strength related to external pressures (i.e. water depth) and internal pressures (i.e. pressurised fluids or gas).
- Pipeline stability against horizontal and vertical displacement during construction and operation.
- Effects from thermal expansion and contraction.
- In-place and in-service pipeline repair capabilities.
- Effects of salinity and corrosive soil and water conditions.

9.1 FOUNDATION DESIGN ISSUES AND INSTALLATION CONSTRAINTS

9.1.1 Interaction of pipeline and ground

The stress-strain-time response of ground is highly non-linear and often shows significant spatial variability (for example, due to stratigraphy). Geotechnical modelling invariably requires simplifying assumptions. In addition, pipeline installation and consequential ground disturbance will lead to differences between in-situ ground response and pipeline/ground interaction behaviour. Trenching and trench back-fill can increase further the complexity of pipeline interaction behaviour.

A particular consideration is the pipeline/ground response of an offshore pipeline supported on the seabed. Analysis of transverse pipeline loading may consider a conventional friction component and a passive resistance component. Mounding of soil due to pipeline penetration will increase transverse resistance.

9.1.2 Geotechnical hazards

The following section presents a summary of pipeline hazards. A hazard is the potential to cause damage to the pipeline and the main hazards with their potential consequences are summarised in Table 9.1-1.

Table 9.1-1 HAZARDS AND THEIR POTENTIAL CONSEQUENCES

HAZARD	POTENTIAL CONSEQUENCES													
	Slope failure and/or instability	Lateral instability	Vertical and/or lateral movement	Pipeline burial	Pipeline exposure	Pipeline spanning	Differential pipeline support	Gaseous and/or fluid emissions	Ground collapse	Sinking or floating of pipeline	Inaccessibility of pipeline	Abrasion of pipeline	Obstructions	Hampering of trenching
Slope movement	x													
Active faulting			x			x								
Liquefaction		x								x	x			
Sand waves		x		x	x	x								
Scour		x			x	x								
Rock outcrop, shell and coral banks						x	x							x
Drop stones and iceberg scars		x				x								x
Shallow gas							x	x						
Submarine channels and valleys				x	x							x		
Karstification									x					
Soil conditions and properties												x		
Human activities													x	

Those potential threats to pipelines that are related to soil conditions include:

- Soil type.
- High organic content, low pH, radio-active minerals.
- Presence of gas in pores.
- Stratigraphic and lateral heterogeneity.
- Seabed topography.

and/or are triggered by dynamic processes like:

- Seismic activity.
- Seabed currents.
- (Cyclic) wave action.
- Extreme meteorological conditions, such as hurricanes and tropical storms.
- Gradual changes in environment conditions, including man-induced changes.
- Construction activities.

9.2 SOIL PARAMETERS

The soil parameters listed in Table 9.2-1 are generally needed for foundation design of a typical pipeline.

Table 9.2-1 BASIC SOIL PARAMETERS REQUIRED

CLAY	**SAND**
General description	General description
Particle size distribution	Particle size distribution
Atterberg (plastic/liquid) limits	Relative density
Water content	Maximum and minimum densities
Bulk unit weight	Bulk unit weight
Undrained shear strength	Friction Angle

Additional soil parameters may be needed for particular design issues, as indicated in Table 9.2-2. Careful consideration should be given to the acquisition of project specific soil parameters.

Table 9.2-2 ADDITIONAL SOIL PARAMETERS FOR SPECIFIC APPLICATIONS

APPLICATION	**PERTINENT SOIL PARAMETERS (Properties required for S=sand, C=clay, R=rock)**														
	Shear strength	Friction angle	Relative density	Particle size distribution	Permeability	Compressibility	Sensitivity	Pipe-soil friction factors	Cyclic strength	Liquefaction resistance	Rock quality	Chemical analysis	Electrical conductivity	Thermal conductivity	Backfill properties
On-bottom stability	C	S	S	S			C	C/S		S					
Scour/ erosion	C	S	S	S											
Slope stability	C	S	S	S	S		C		C/S	S					
Liquefaction/ floating	C	S	S	S	S	S	C		C/S	S					
Settlements (rock berms)	C	S	S			C/S									
Upheaval buckling	C	S	S	S	S	C/S		C/S							
Free span assessments	C	S	S	S		S									
Dropped objects	C	S	S												
Shore approaches	C	S	S	S			C	C/S	C/S	S	R	C/S		C/S	C/S
Corrosion												C/S	C/S		
Thermal insulation														C/S	
Spool pieces/ tie-in/ PLEMs, etc.	C	S	S				C	C/S	C/S	S					
Start-up piles	C	S	S	S											
Ploughing	C	S	S	S	S	S	C			S					C/S
Jetting	C	S	S	S	S	S	C			S					C/S
Self bury potential/ natural backfill	C	S	S	S											
Sinkage	C	S	S				C			S					
Axial/ lateral resistance	C	C/S	S	S				C/S							

9.3 SITE INVESTIGATION

9.3.1 Desk study

It is important to integrate and interpret pipeline route information that can be extracted from a desk study. This is key to cost-effective and successful design of on-site data acquisition activities. Data sources can include specific geophysical, geotechnical, metocean and environmental data at some distance from the proposed pipeline route, as well as regional overviews and survey information and performance reports for existing pipelines.

In deep water areas (>450 m), the use of 3D exploration seismic data can provide good regional information on seafloor features, seabed and sub-seabed geology and geohazards. Seafloor images determined from high quality 3D seismic data may provide information on bathymetry and seabed features such as steep slopes, fault scarps, canyons, mobile sediments and pockmarks. The resolution of such images, however, is limited and cannot replace purpose recorded multibeam echo sounder data. Similarly, sub-sea information derived from exploration 3D data cannot replace ultra high-resolution seismic data for determining stratigraphy and geohazards in the foundation zone along a pipeline route.

Careful use of available data in many cases can be used for efficient planning of site specific studies and can reduce the scope of a dedicated site investigation.

9.3.2 Geophysical survey

A geophysical pipeline route survey is performed to collect information on 1) seabed topography and water depths; 2) seabed features and obstructions that may constrain pipeline route design; 3) sub-bottom features in the foundation zone to approximately 5 m to 10 m below seabed; and 4) the presence of buried cables and other metallic objects.

The width of a survey corridor is generally between 500 m and 1000 m, centred on the proposed pipeline route. The actual width of the corridor depends on factors such as water depth, seabed features and possible re-routing requirements.

In shallow water and shore approach zones, the corridor may be limited to 500 m, whereas in deep water, the survey corridor may need to be in excess of 1000 m to incorporate re-routing options necessitated by seabed features such as pockmarks, steep slopes and other geohazards associated with continental margins.

The suggested minimum requirements for a geophysical pipeline route survey are:

Survey line plan:
- 1x survey line along the centre line of the proposed pipeline route.
- 1x survey line at 50 m on either side of the centre line.
- One or more survey lines at 100 m spacing on either side of centre line to maximum corridor width.
- Cross-lines at 500 m or 1000 m spacing.

Data acquisition sensors:

- Echosounder bathymetry: preferably multibeam / swath.
- Sidescan sonar.
- Sub-bottom profiler (usually pinger) to approximately 5 m to 10 m below seafloor.
- Optionally: magnetometer, preferably two units in gradiometer mode, usually only along centre line.
- Optionally: refraction seismic or electrical resistivity profiling.

To reduce the loss of seismic signal in the water column, reduce geometric errors and obtain the highest resolution, it is preferred to use deep-tow or an autonomous underwater vehicle (AUV) for deep water surveys.

Notes:

1 Acquisition details, such as seismic sampling intervals and frequencies used etc, need to be determined on a site-by-site basis, as they are dependent on water depth.

2 A magnetometer or gradiometer must be used in case unidentifiable (ferrous) objects are observed on either sidescan sonar or sub-bottom profiler, or if there is a risk of buried cables or pipelines, ordnance or other hazardous metallic objects being present.

9.3.3 Geophysical burial assessment survey

GeoBAS (Geophysical Burial Assessment Survey) is performed where pipeline burial is an option or deemed necessary, especially for nearshore approaches where burial depth may be increased as a result of increased human activity (i.e. increased risk for pipeline damage, rupture).

The commonly used survey methods are seismic refraction, to determine a velocity profile of the soil, which is indicative for variations in soil density and strength (see Section 3.9), and electrical resistivity for indications of variations in soil porosity and hence soil strength.

9.3.4 Geotechnical survey

A geotechnical site investigation is performed to calibrate geophysical information and to determine design parameters for pipeline design and installation. Data acquisition methods for geotechnical site investigations along a pipeline route include:

- Cone penetration testing.
- Gravity/drop coring (very soft to firm clays).
- Vibrocoring (sand).
- Grab sampling (sand/gravel).

More specialist sampling and testing methods for a particular design issue or parameter may include:

- Box coring.
- Rock coring.
- Soil thermal conductivity measurements with a thermal conductivity probe.
- In-situ vane testing for accurate measurement of shear strength of clay.
- In-situ T-bar or ball penetrometer for accurate measurement of shear strength of clay.

- In-situ model testing (e.g. instrumented plough, pipeline section test).
- Seismic cone penetration testing for shear wave velocities and shear moduli.

The spacing of soil sampling and in-situ testing along the pipeline route will generally depend on the lateral variability of soil conditions, the presence of geohazards, and whether or not trenching is required.

Table 9.3-1 gives guidelines on the frequency and penetration of sampling and testing for common scenarios.

Table 9.3-1 GUIDELINES FOR TEST AND SAMPLE FREQUENCY AND PENETRATION

Pipeline Route Section	Average Spacing	Penetration	Remarks
Un-trenched sections	1 to 5 km*	1 to 2 m	Increase frequency and penetration in areas of very soft clay or potentially unstable slopes. Supplement with grab samples in areas of sand/gravel.
Trenched sections (offshore)	0.5 to 1 km	Trench depth + 1 m	If both cores and CPTs are performed, a percentage of the cores should be performed directly adjacent to CPTs, for correlation purposes.
Trenched sections (shore approach)	0.3 to 0.5 km	Trench depth + 1 m	
Soil transition zone	0.3 to 0.5 km	3 to 5 m	
Features such as pockmarks, iceberg scars, sand waves etc	3 per feature	to maximum height/depth of feature	Representative features may need to be selected for investigation rather than all of them
Pipeline or cable crossing or subsea structure (Ts, valve cover etc)	≥ 2 per structure	5 m	May need to be deeper for particularly large structures
Anchor support piles	≥ 1 per pile or pile group	10 to 20 m	Needs to be checked against required bearing capacity and soil type

* Average spacing greater than 1km should only be considered in areas of consistent geology where geotechnical conditions are already well known.

Minimum laboratory testing should consist of geotechnical classification testing for basic physical properties.

9.3.5 Data acquisition for cathodic protection

Specific data acquisition on both soil and water samples is recommended for cathodic protection analysis. Generally, the sampling frequency for these samples is the same as for geotechnical sampling. This typically consists of one box core sample and one water sample at each geotechnical testing location.

Typical testing for pipeline cathodic protection analysis on soil and water covers:

Soil:
- Electrical conductivity – either on samples, or in-situ, using electrical conductivity cone penetrometer.
- Temperature.
- Sulphate reducing bacteria (SRB).
- H_2S [hydrogen sulphide] content.
- Chemical composition, including metals, inorganic compounds, pH.

Water:
- In-situ electrical conductivity, salinity and temperature (CTD/STD probe).
- Chemical composition, including dissolved O_2 [oxygen] and CO_2 [carbon dioxide], metals, inorganic compounds, pH.

10. NEARSHORE STRUCTURES

Nearshore structures considered here are:

- Breakwaters (rubble mound, vertical and composite types).
- Seawalls (sloping and vertical).
- Jetties, dolphins and platforms (piled and gravity types).
- Quay walls (gravity and piled types, including sheet piles).

The main function of breakwaters and seawalls is to dissipate wave energy. Many of these structures consist mainly of bulk material, such as rock fill, and weight loads dominate the foundation engineering requirements. In seismically active parts of the world, sudden and extreme horizontal loads are important design considerations. In the case of vertical breakwaters and vertical faced seawalls, horizontal cyclic wave loads are significant.

The principal foundation design issues for many jetties, dolphins and platforms, are the horizontal loads created by waves and berthing vessels. Many jetties and platforms also carry relatively heavy loads from cargo handling machinery and cranes. In some situations, horizontal active earth-pressure and seismic loads will be the dominant consideration in the foundation design for quay walls.

Many nearshore structures share similar characteristics with offshore structures. Their dimensions are, in general, less, and consequently demand lower investments. The funds available for nearshore structure geotechnical investigations are often substantially less than those available for offshore structures. The very shallow water, energetic wave regime and the large influence of tides, means that many of the offshore site investigation tools are often not suitable.

10.1 FOUNDATION DESIGN ISSUES

Nearshore structures are, by their very nature, at the interface of the open sea and the land. In this zone, the marine environment exerts its extremes on these structures, demanding careful attention to their foundation design.

10.1.1 Rubble mound (or composite) breakwaters and sloping seawalls

The main design issues to be considered are:

- Slope failure (especially with soft soil in the upper layer of the seabed). With loose sand (e.g. dumped as soil improvement programme); wave induced liquefaction may contribute to slope failure.
- Weight induced settlement.
- Earthquake loading induced settlement and/or liquefaction-induced slope instability in case of loose sand.
- Filter instability, especially below the seaward toe. Upper soil layer only relevant.

10.1.2 Vertical breakwater with thin rubble bed

The same issues as with rubble mound breakwaters apply. Generally, higher soil strength and stiffness are needed to avoid bearing capacity failure (corresponding to slope failure) and unacceptable settlement. Vertical breakwaters experience a higher sensitivity to local ground variations than do rubble mound types.

Additional issues:
- Deformation or instability caused by wave induced cyclic loading.
- Tilting caused by insufficient soil stiffness and/or creep.

10.1.3 Vertical, gravity type seawall and gravity type quay wall

The main design issues to be considered are:
- Bearing capacity.
- Settlement and tilting (also due to creep).
- Earthquake loading induced settlement and/or liquefaction induced bearing capacity failure in case of loose sand.
- Filter instability.

10.1.4 Piled structure, including sheet pile wall

The main design issues to be considered are:
- Axial pile capacity.
- Thickness of sediment layers and their capacity to produce sufficient skin friction for axially loaded tension piles, even where the load has a strongly cyclic character. Cemented soils may yield special problems.
- Thickness of sediment layers and their capacity to produce sufficient horizontal resistance for horizontally loaded piles (including sheet piles), even where the load has a strongly cyclic character.
- Elasticity of foundation soil for short duration load in case of horizontally loaded piles for breasting dolphins.
- Drivability of pile. The presence of cap rock may yield large problems. The same applies for local rock-outcrops, especially for sheet pile wall.
- Friction forces developed on sheet piles surfaces.
- Scour around piles, especially with sandy sea beds, and the resulting reduction in capacity for tension loading or horizontal loading.

10.2 INFORMATION REQUIRED

To address the issues, the geotechnical and geological information discussed in Sections 2.1 to 2.5 is required. Table 10.2-1 and Table 10.2-2 list the specific soil and rock parameters to be determined:

Table 10.2-1 BASIC SOIL AND ROCK PARAMETERS FOR NEARSHORE STRUCTURES

CLAY	SAND, SILT OR GRAVEL	ROCK
– General description – Grain size distribution – Organic material content – Mineralogy – Total unit weight – Atterberg (plastic/liquid) limits – Water content – Undrained shear strength – Remoulded shear strength – Sensitivity – Over-consolidation ratio	– General description – Carbonate content – Organic material content – Grain size distribution – Maximum and minimum densities – Relative density – Water content (silt) – Angularity	– General description – RQD (Rock Quality Designation) – Water absorption – Total unit weight – Unit weight of solid blocks – Unconfined compression strength – Mineralogy

Table 10.2-2 ADDITIONAL PARAMETERS FOR SPECIFIC NEARSHORE STRUCTURES

Design issue	**Parameter**
Bearing capacity and slope stability	– Anisotropic monotonic shear strength. – Cyclic shear strength under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Drained angle of shearing resistance (sand).
Permanent displacements	– Compressibility (including creep characteristics with clay). – Permeability. – Permanent shear strain and pore pressure under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Compressibility after cyclic loading.
Cyclic displacements	– Cyclic shear strain as function of cyclic shear stress under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Initial shear modulus.
Foundation stiffness	– Cyclic shear strain as function of cyclic shear stress under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Initial shear modulus. – Damping parameters. – Creep parameters
Soil reaction stresses	– Monotonic and cyclic shear strengths. – Compressibility under virgin loading and reloading. – Cyclic and permanent shear strains and permanent pore pressure under combined average and cyclic shear stresses for triaxial and simple shear stress paths. – Seabed topography, objects on the seafloor.

Design issue	Parameter
(For all items above):	– Relative density of sand – Cyclic shear strain and permanent pore pressure (sand) contour diagrams for at least one representative average shear stress (e.g. simple shear tests with τ_a=0). – Coefficient of reconsolidation (sand).
Liquefaction potential	– Relative density of sand – Initial shear modulus. – Cyclic shear modulus degradation curves. – Damping. – Coefficient of reconsolidation (sand).
Pile capacity and drivability	– Shear strength. – 50% strain factor. – Cone resistance – Sand compressibility and crushability (in carbonate sands)
Scour / erosion	– Grain size. Permeability.

10.3 TYPICAL SCOPE FOR SITE INVESTIGATION

The geophysical survey for nearshore structures has to be designed to achieve the general requirements described in Section 2.4. The geotechnical survey and laboratory testing should meet the general requirements described in Section 2.5. As an example, a typical investigation programme for detailed design may comprise the investigations as given in Table 10.3-1 and Table 10.3-2. These suggested investigation programmes are offered as minimum prudent programmes for review and adaptation in the light of project-specific factors. It should be noted that the work scope for a feasibility study, or for preliminary design, is substantially less.

Table 10.3-1 TYPICAL SCOPE OF GEOPHYSICAL INVESTIGATIONS FOR NEARSHORE STRUCTURES

Survey purpose	Minimum survey area	Minimum depth	Means of survey
Seabed topography	Plan area of construction works		Swath bathymetry, preferably multibeam
Seabed features	Plan area of construction works		Sidescan sonar used in high frequency mode and short range, line spacing depending on water depth, with minimum 200% coverage from overlapping lines.
Sub-surface information	Plan area of construction works	In excess of depth recommended for geotechnical data (see Table 10.3-2)	Sub-bottom profiler or high-resolution seismic survey. Line spacing: 10 m. With caution, may be performed simultaneously with sidescan sonar. Seismic refraction may be favoured for complex sites; line or grid spacing depending on anticipated ground variations and associated risks.

Table 10.3-2 TYPICAL SCOPE OF GEOTECHNICAL SURVEY FOR NEARSHORE STRUCTURES

Type of structure	Scope of work	Penetration (m)	Sample testing
Rubble mound or composite breakwater	3 nos. borings (each with 10 samples & SPTs, with at least one in each layer) or (P)CPTs per 100 m	2 x maximum water depth for 1/3 of the number of borings / (P)CPTs and 0.5 x maximum water depth for 2/3 of the number of borings / (P)CPTs	Classification tests to find the basic soil and rock parameters as mentioned in Table 10.2-1. Additional laboratory tests depending on the need for additional parameters as mentioned in Table 10.2-2. Additional laboratory tests depend on the need for additional parameters as mentioned in Table 10.2-2.
Sloping seawall	2 nos. borings or (P)CPTs per 100 m	1 x maximum water depth for 1/3 of the number of borings / (P)CPTs and 0.5 x maximum water depth for 2/3 of the number of borings / (P)CPTs	
Vertical breakwater with thin rubble bed	3 nos. borings or (P)CPTs per 50 m	2 x maximum water depth for 1/3 of the number of borings / (P)CPTs and 1 x the maximum water depth for 2/3 of the number of borings / (P)CPTs	
Vertical, gravity type seawall and gravity type quay wall	3 nos. borings or (P)CPTs per 50 m	1.5 x maximum water depth for 1/3 of the number of borings / (P)CPTs and 0.5 x maximum water depth for 2/3 of the number of borings / (P)CPTs	
Piled structure	1 no. (P)CPT and / or boring per pile or pile group or per 30 m (sheet piles)	Conservatively assessed pile penetration + 4 pile diameters or at least the width of a pile group, whichever is the greater	

NOTES:

- For rubble mound (or composite) breakwaters and seawalls: preferably alternate borings and (P)CPTs.
- For vertical breakwaters, gravity type seawalls and gravity type quay walls: preferably most (P)CPTs and a few borings to get some representative samples in each relevant layer.
- For piled structures, preferably one (P)CPT per pile or pile group + a few borings to get some representative samples in each relevant layer.
- For piled structures at clay sites, samples are important. The number of boreholes required depends upon variability of the site. There should be flexibility in the site investigation programme.
- The required penetration depth depends on the dimensions of the proposed structure. Usually these dimensions are unknown at the time of the investigations. The dimensions, however, are strongly related to the water depth at the highest water level, which is why the maximum water depth is chosen as an indicator for required soil investigation depth. Alternatively, one should consider an investigation depth in the order of 0.8 to 1.2 times the structure height as per Eurocode recommendations.
- More boreholes or (P)CPTs may be required near anomalies or near discontinuities in the soil layering.
- In the event that the upper layers of the seabed consist of very soft soil, replacement of several metres of this soil with (clean) sand may be needed for the foundation of a nearshore structure. The geotechnical survey and laboratory testing required to find suitable sand are discussed in Section 11.
- In case of reconstruction of an existing structure, fewer geotechnical investigations may be needed if the soil or rock proves capable of offering satisfactory foundation behaviour over the predicted life of the structure.

11. DREDGING WORKS

11.1 CHARACTERISTICS OF DREDGING WORKS

Offshore or nearshore dredging programmes entail lowering of the seabed and disposal of the dredged material to another (approved) location. In some cases, seabed lowering is the main objective, such as for the creation of a harbour basin, an approach channel, or for a pipeline trench. In other cases, reclamation of soil is the main objective and seabed lowering is just a means of mining the material.

Geotechnical investigations are always needed at the seabed lowering site and often also at the disposal site. The seabed lowering site may sometimes be chosen at an earlier stage than the disposal site, or vice versa.

The area covered by a dredging project may be very large compared to the area required for offshore or nearshore structures.

The dredging process usually comprises four main stages:

1. *excavation*, comprising the loosening, fragmentation or cutting of the soil or rock
2. *raising* the excavated material to the surface by hydraulic or mechanical methods
3. *transport* of the excavated material to a reclamation or disposal area
4. *disposal* or use of the dredged material.

Each stage requires specific knowledge of the soil or rock properties of the site.

One of the following types of equipment is typically employed for the first and second stages:

- Trailing suction hopper dredger.
- Stationary suction dredger.
- Cutter dredger.
- Dredging mill.
- Grab on pontoon or on vessel (with or without hopper).
- Backhoe on pontoon or on vessel (with or without hopper).

If (hard) rock needs to be removed and cutting is not possible or suitable, the dredging activity may be preceded by breaking the rock with explosives.

The third stage (transport) does not require additional equipment when a hopper dredger, or other vessel capable to transport the dredged material, is used. In case of stationary dredgers, this stage may require separate (hopper) barges, berthing alongside the dredger, or pipelines in which the material is transported as a soil-water slurry.

The fourth stage (disposal) may be done using bottom doors (hoppers), pumps, specially shaped pipe-ends (sometimes onshore; sometimes attached to a special pontoon), grabs or other equipment.

The choice of dredger type, and other equipment, largely depends on the soil and rock characteristics and on the environmental conditions, such as water depth, current, sand transport and waves. Trailing suction hopper dredgers are virtually the only type of equipment capable of operating in the open sea. Heave compensators and floating pipelines may assist in facilitating the operation of other types of dredgers working at sea, but waves always seriously limit the choice of equipment.

11.2 GEOTECHNICAL DESIGN ISSUES

The main objectives of geotechnical investigations are to establish:

- The volumes and distribution of materials to be dredged.
- The physical and mechanical properties of the materials that influence the dredging and transport processes.
- The suitability of materials for land reclamation.

Additional objectives may include determination of:

- The physical and mechanical properties of the subsoil for future reclamation areas with respect to stability and settlement of the fill. (Note: investigations to verify the quality of the earthworks at the reclamed are beyond the scope of this document).
- The physical and chemical properties of the materials with respect to potential environmental effects of the dredging and transport processes and/or fill at the deposition.

Typical problems experienced:

- Presence of rock, especially if discovered at a late stage in the project.
- Soil or rock too hard for dredging with proposed equipment.
- Soil or rock too hard, or too dense, or too impermeable and adversely affecting production rates.
- Slope failure by uncontrolled breaching, liquefaction or shear failure, causing damage to structures, land or foundation ground.
- Quick refilling of dredged trench or basin by large sand/silt transport regimes.
- In-situ soil not meeting the specification for reclamation purposes; in particular the fines content of sand too large and leading to reclaimed sand being unable to densify under water and hence increasing sensitivity to liquefaction.
- Fine particles in suspension near the dredging operation, or near the disposal site, creating turbid water.
- Distribution of pollution into the marine environment from polluted dredged materials.

11.3 REQUIRED INFORMATION

Requirements for pollution or contamination assessment are not discussed here, but information on the investigation, evaluation, dredging and disposal of contaminated materials can be found in the literature.

For the remainder, the geotechnical information discussed in Sections 2.1 to 2.5 need to be collected. The geotechnical parameters listed in Table 11.3-1and Table 11.3-2 are specific for each stage of a dredging operation. It should be noted that a **safe estimate** of each strength parameter for dredging is a HIGH strength value for ground to be excavated, whereas it is a LOW value for nearly all other geotechnical activities, where stability is required.

Table 11.3-1 BASIC GEOTECHNICAL PARAMETERS REQUIRED FOR DREDGING

APPLICATION	CLAY	SAND, SILT OR GRAVEL	ROCK
Excavation (methods & production)	– General description – Grain size – Organic material content – Gas content – Total unit weight – Atterberg (plastic/liquid) limits – Water content – Undrained shear strength	– General description – Grain size – Angularity – Carbonate content – Maximum and minimum densities	– General description – RQD – Water absorption – Total unit weight – Unit weight of solid blocks – Unconfined compression strength – Mineralogy
Transport (methods & production)	– Organic material content – Gas content – Particle unit weight – Atterberg (plastic/liquid) limits – Water content – Undrained shear strength	– Grain size – Maximum and minimum densities – Particle unit weight – Mineralogy	– Unit weight of solid blocks – Unconfined compression strength – Mineralogy
Abrasion with excavation and transport	– Grain size of coarse-grained minor constituents – Mineralogy of coarse-grained minor constituents	– Grain size – Angularity – Particle unit weight – Mineralogy	– Unit weight of solid blocks – Unconfined compression strength – Mineralogy
Fill material	– Clay only for special purposes used as fill material; required parameters to be derived from special purpose	– Grain size – Angularity – Organic material content – Max/Min density	– Block size distribution – RQD – Water absorption – Unit weight of solid blocks – Mineralogy
Dredged slope stability and settlement and stability of future fill area	– Grain size – Organic material content – Mineralogy – Total unit weight – Atterberg (plastic/liquid) limits – Water content – Undrained shear strength	– Grain size – Angularity – Carbonate content – Organic material content – Maximum and minimum densities	– Block size distribution – RQD – Water absorption – Total unit weight – Unit weight of solid blocks – Unconfined compression strength – Mineralogy

Table 11.3-2 ADDITIONAL PARAMETERS FOR SPECIFIC DREDGING APPLICATIONS

APPLICATION	CLAY	SAND, SILT OR GRAVEL	ROCK
Excavation (methods & production)	– Rheological properties (very soft clays)	– Relative density – Permeability	– Elasticity
Transport (methods & production)	– Rheological properties (very soft clays)		
Abrasion with excavation and transport			
Fill material		– Compaction characteristics	– Compaction characteristics
Dredged slope stability	– Drained shear strength – Sensitivity – Over-consolidation ratio	– Relative density	– Drained shear strength of total mass
Settlement and stability of future fill area	– Consolidation parameters – Drained shear strength – Sensitivity – Over-consolidation ratio	– Relative density	

11.4 TYPICAL SCOPE FOR SITE INVESTIGATIONS

The geophysical survey for dredging works mirrors the general requirements described in Section 2.4. The geotechnical survey and laboratory requirements are described in Section 2.5. The required scope depends largely on project requirements and local circumstances. Table 11.4-1 and Table 11.4-2 provide typical investigation programmes and represent the minimum prudent programmes for review and adaptation in the light of project-specific factors. The work scope for a feasibility study or preliminary design is significantly less.

Table 11.4-1 TYPICAL SCOPE OF GEOPHYSICAL INVESTIGATIONS FOR DREDGING

Survey purpose	Minimum survey area	Minimum depth	Means of survey
Seabed topography	Slightly larger than plan area of works		Multibeam echosounder of appropriate operating frequency
Seabed features			Sidescan sonar, line spacing depending on water depth and reliability of positioning, minimum overlap of lines 20 - 30%
Sub-surface information		In excess of depth recommended for geotechnical data (see Table 11.4-2)	Sub-bottom profiler or high-resolution seismic survey. Line spacing: varying from 1 x maximum water depth to 200 m, depending on accuracy required and risks involved with ground variations. Seismic refraction may be favoured for complex sites (uneven rock within dredging depth); line or grid spacing depending on anticipated ground variations and associated risks.

Table 11.4-2 TYPICAL SCOPE OF GEOTECHNICAL INVESTIGATION FOR DREDGING

Application	Scope of work	Penetration (m)	Sample testing
Lowering sea bed	Number of boreholes strongly depends on risk involved with ground variations. Bates (1981) suggested 3 + $A^{0.5}.D^{0.33}/50$, where A is area in m^2 and D is average thickness of material to be removed in metres. Samples & SPTs every 2 m with at least one in each layer. Some (P)CPTs if undrained shear strength (clay) and/or relative density (silt and sand) is relevant.	Slightly deeper than level of required lowering of sea bed	Classification tests to find the basic soil and rock parameters as mentioned in Table 11.3-1 Additional laboratory tests depending on the need for additional parameters as mentioned in Table 11.3-2.
Slope stability	1 borehole (samples & SPTs every 2 m, with at least one in each layer) or (P)CPT per 100 m. (P)CPT especially relevant in case of silt or sand and relatively steep slope	0.5 x the slope height below required level of lowering of sea bed	
Fill material	Number of boreholes strongly depends on expected ground variations, with a minimum of three required	To depth of potential fill material	
Settlement and stability of subsoil of reclamation area	Number of boreholes or (P)CPTs strongly depends on risk involved with ground variations, e.g. one borehole (samples & SPTs every 2 m, with at least one in each layer) or (P)CPT per 1000 m^2 to a minimum of three per 10000 m^2.	1 x to 3 x reclamation height depending on risk involved with influence of deeper layers	

More boreholes or (P)CPTs may be required near anomalies or near discontinuities in the soil layering, especially if a type of rock or soil is present that cannot be excavated, raised or transported with the proposed dredging equipment, or if another high risk is involved.

12. GOOD PRACTICE

Good practice begins with the supervising project manager. It is critical to the success of a geotechnical investigation that field works are supervised, and directed, by experienced and qualified geotechnical engineers. Failure to follow this simple advice will inevitably lead to expensive disasters.

In order to ensure that the quality of the work is sufficient and to select the samples for laboratory testing, and to adjust the soil testing programme when necessary, an experienced geotechnical engineer is invaluable. Quality expertise is particularly important when the geological context of the site is not well-known and/or when the existing data are poor.

12.1 PRACTICAL SUPERVISION

12.1.1 Quality of the work

The purpose here is to ensure relevance, sufficiency and reliability of acquired data and, where appropriate, integrating this with data collected during other surveys of a site. The geotechnical supervisor has to ensure that all the data will constitute a satisfactory basis for the development of safe and optimised foundation design, for the analysis of all identified geohazards and, possibly, for the definition of appropriate equipment for construction / installation of offshore structures. Borings, sampling, and in-situ tests have to be performed in accordance with good practice and industry standards. It is vital that the appropriate sampling tools are used commensurate with a site's soil type, density and consistency.

12.1.2 Laboratory testing

The supervisor in charge has to:

- Select representative samples for laboratory testing and validate the programme of laboratory tests (taking into consideration the homogeneity of the soil encountered).
- Ensure that the quality of sample recovery is sufficient for the proposed tests (undisturbed sampling required for mechanical tests), and ensure the quality of conditioning for transportation.
- Define the programme of laboratory testing with due consideration for the objectives of the survey. Specific attention must be paid to the selection of representative samples.
- Define as appropriate, relevant adjustment to usual testing procedures (such as stress levels).
- Define the testing schedule to ensure that the entire foreseen programme develops without unacceptable delays, knowing that the laboratory testing process is on the critical path for the preparation of the final interpretative report.

12.1.3 Adjustment of survey programme

Preliminary interpretation of survey results in near real-time is necessary to identify doubtful results or geological singularities, and to define any necessary adjustment to the survey programme.

12.2 EXAMPLES OF GOOD PRACTICE

<u>Example 1</u>: Geotechnical survey for an offshore platform

The geological context of the site was not well-known and the original specification provided for only one deep borehole and two shallow boreholes at the location of the platform, with alternate sampling and cone testing.

The geophysical and geotechnical surveys were undertaken in parallel:

- Geophysical survey in order to define pipeline route.
- Geotechnical survey for the definition of pile foundation design of the offshore platform.

The geophysical survey was performed just before the geotechnical phase and revealed the presence of a fault at the precise location of the platform. The presence of this fault could not have been anticipated at the time when the specification was prepared.

The first action of the geotechnical supervisor was to adjust the programme to provide a minimum of two deep boreholes (one on each side of the fault), and provide specific testing (including dating of the sediments) to assess the potential activity of the fault. During the drilling, cemented (weak rock) layers were encountered.

The supervisor requested rock recovery and adjusted the programme of testing in order to assess the strength and the thickness of the cemented layers (information essential for the pile drivability analysis). The supervisor then ensured that the borehole depths were sufficient to allow for the expected penetration depths of the piles. This checking was made through evaluation in real-time of ultimate bearing capacity as a function of pile penetration, and by comparison with estimated design loads.

Furthermore, the supervisor ensured that the quality of all identification tests was performed on board the drilling vessel. Lastly, the supervisor prepared a factual report collecting all the findings of the geotechnical investigation. The information contained in this report was profitably used by the geophysical engineer to efficiently and reliably evaluate the potential activity of the fault.

<u>Example 2</u>: Geotechnical survey for offshore pipeline

The site is in a region of high seismic activity carrying a serious risk of liquefaction of sand sediments. The specification called for shallow boreholes (drop core or vibrocore), and CPTs at regular intervals along the proposed pipeline route. The geophysical survey revealed the presence of paleo-channels infilled with sand material and sensitive to liquefaction.

The supervisor ensured that sufficient cone testing was performed in these paleo-channels for a proper assessment of the liquefaction risk and to define relevant mitigation measures to avoid the possibility of pipe flotation.

Example 3: Geotechnical survey for maritime works

This site also lay in an active seismic context with a risk of liquefaction of silty sand sediments.

Firstly, the supervisor ensured that undisturbed samples were taken in the silty sand sediments and subjected these samples to mechanical (dynamic) tests. The supervisor also defined the procedure for performing these tests. Quality sampling was also acquired in the underlying weathered / fractured rock substratum.

To ensure the quality of the sampling, trial tests were performed at the beginning of the works in order to define the sampling procedure and the type of sampler to be used. The presence of a qualified engineer was essential to validate this procedure and to ensure the success of the investigation.

Another requirement of the supervisor was to define the location of boreholes and CPTs based on the analysis of seismic profiles from a geophysical survey, and boreholes were provided at the location of geological singularities (possible expression of ancient seismic faults).

12.3 PITFALLS TO AVOID

There is a adage: anyone who has never made a mistake has ever made anything. In the many years the authors have been practicing, they have witnessed many common (and not so common) mistakes. Some of the more common are listed below:

Weak organisation

- Late tender bidding leading to rushed proposal.
- Unclear tender requirements and / or specification.
- Poor contract specification and / or terms.
- Poor / inadequate communication between parties involved.

Facilities inadequate for rough environment

- Poor compensation for sea swell.
- Anchoring / mooring not capable of keeping position during drill-mode boring.
- Inadequate deck-space or crane capacity for handling equipment and soil samples.
- No solid casing available to obviate bending of drill string or CPT string, yielding overestimate of depth of operation.
- Inadvertently creating dangerous situations for deck hands.

Such situations may result in:

- Failing to perform the required investigation.
- Poor quality of information.
- Low production rate and consequently high costs.
- The temptation for the crew to imaginatively fill gaps in data.

Inexperienced crew and / or insufficient supervision

Offshore and nearshore site investigations require a crew experienced in working at sea, experience working with soils, and experienced with the specialised equipment.

Independent supervision is essential in view of the pressure under which a crew may labour to produce enough results in a limited time, possibly exacerbated by a lack of opportunity for those who need the geotechnical data to verify the correctness of the information.

Lack of experience in the crew and inadequate supervision may lead to poor quality and unreliable results.

Insufficient preparation, poor planning and unexpected results

Staging and planning of offshore or nearshore site investigations always require some compromise, as can be concluded from Section 2.2:

- Mobilisation for each stage of offshore or nearshore site investigation is expensive and time consuming. From this point of view, it would be ideal to have just one stage in which all relevant information is collected. However, unexpected characteristics may be found which suggest the need for additional, more detailed investigations and/or changes in the design of the proposed development.
- From the view of developing a project, it would be ideal to split the geotechnical investigations up into many stages. Each stage produces new knowledge about the soil and rock, which may lead to a change in the preliminary design and raise new questions about the properties of soil and rock, which can be studied at a further stage. In this way, a stepwise approach to the essential information and the corresponding best investigation scheme is possible.

A compromise between both points of view is needed and it is recommended to minimise the disadvantages of the compromise by trying to reach the following:

- A good preparation, including the desk study described in Section 2.3. Indeed, the use of geotechnical knowledge available from the past, and insight into the geological characteristics of the soil and rock studied, allows some degree of prediction to identify which anomalies, discontinuities and special properties might be expected and incorporated in the planning of the investigations.
- Flexibility in the programme and good communication lines between those who perform the investigations, those who need the information, and those who can make decisions about the investigation, such that the programme can be adapted quickly and efficiently during the investigation stage.

Incorrect positioning

Incorrect horizontal positioning during a site investigation may lead to attributing soil or rock properties to the wrong location. Further, tests performed at the same (apparent) coordinates on some other occasion, will appear to conflict with the results because of the position error. This will either lead to an incorrect interpretation of the geophysical data, or result in significant confusion and disputes, and demands for additional work (with associated costs).

Incorrect vertical positioning, e.g. by having incorrect information about the tide, may result in a wrong estimate of the seabed level at a site. Confusion may also result from the comparison of the water depth found from echosounding and the water depth found during deployment of the geotechnical tools; this is particularly relevant in the presence of thick layers of very soft sediment (mud) at the seabed. For example, echosounders tend to indicate a water depth corresponding to the top of the soft layer, whereas the apparatus lowered to the seabed indicates a greater depth corresponding to firmer layers beneath.

Incorrect interpretation of acoustic signals in shallow water

Upward propagating acoustic signals partly reflect at the air-water interface. These reflections often interfere with the reflections from the interfaces between soil layers or a soil-rock interface. This is a special handicap in shallow water and can lead to an incorrect interpretation of the layering or may result in failure to interpret.

13. REFERENCES

This section lists references for the subsequent sections of this document. These provide complementary guidelines on offshore and nearshore surveys and techniques.

1. INTRODUCTION

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