GUIDANCE NOTES
ON
GEOTECHNICAL INVESTIGATIONS
FOR
SUBSEA STRUCTURES

FULL DRAFT FOR DISCUSSION

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Offshore Soil Investigation Forum

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Dear Colleague

RE: GUIDANCE NOTES ON GEOTECHNICAL INVESTIGATIONS FOR SUBSEA STRUCTURES

We are pleased to provide herewith a copy of the first Full Draft of the above referenced Guidance Notes.

This document is now being distributed widely throughout the offshore industry, for use as a working document and also to obtain comments and suggestions from potential users. The aim will be to collate and incorporate this input during the remainder of the year 2000 and then issue the Final document early in 2001.

We will be very pleased to receive any comments or suggestions you might wish to make, so please send them to either:

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Please also pass on a copy to any colleagues or acquaintances you think may be interested.

Yours faithfully
for the Offshore Soil Investigation Forum

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FOREWORD

FOREWORD

This document is aimed at offshore engineers, who are not geotechnical specialists, but may have the responsibility for assessing the appropriate level of geotechnical data required for successful design and installation of small subsea structures.

This document has been produced by the 'Offshore Soil Investigation Forum', (OSIF) an informal grouping of oil company geotechnical departments, geotechnical contractors, consultants and operators of geotechnical drilling vessels, that has been meeting annually since 1983.

The OSIF primary objectives are fourfold, namely :

- Improving communications between clients and geotechnical service providers,
- Exchanging experience and ideas in the field of offshore geotechnics,
- Standardising procedures, equipment, and tendering process for offshore soil investigations,
- Continuously improving all aspects of offshore soil investigations, particularly those related to technical quality, health, safety and the environment.

Key OSIF participants include :

BP-AMOCO	**FUGRO**	**NOTEBY**
COFLEXIP STENA OFFSHORE	**TOTALFINA ELF**	**NORSK HYDRO**
DNV	**LLOYD's Register**	**SAGE ENGINEERING**
DSND	**NGI**	**SHELL**
STATOIL		

The present Guidance Notes have been developed with the support of all the above parties.

The UK, Society for Underwater Technology (SUT), Offshore Site Investigation and Geotechnics (OSIG) Committee, are also active supporters of this document.

CONTACTS

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1. INTRODUCTION

The present document has been produced to provide simple guidance on acceptable good practice in the collection of geotechnical data for the purpose of design, installation, and operation of small subsea structures, with the intention of providing a useful aid to the planning, specification, and execution of geotechnical investigations.

The principal contents of this document include:

- Guidance on which soil properties are of importance for particular aspects of design and installation.
- Reference to the relevant regulations and guidelines.
- Information on the available methods of data acquisition, such as corers, samplers, and in situ testing systems, and their applicability and/or relevance for the structures considered.
- Guidance regarding the planning and scope of work of geotechnical investigations.
- Suggestions regarding the interpretation, integration and presentation of geotechnical data.

2. RELEVANT REGULATIONS AND GUIDELINES

2.1 RELEVANT REGULATIONS AND GUIDELINES

The two main relevant regulations and guidelines are:

- ISO/DIS 13628-1 **'Draft International Standard for Design and Operation of Subsea Production Systems - Part 1 General Requirements and Recommendations'** (1997).
- API RP 17A **'Recommended Practice for Design and Operation of Subsea Production Systems'** (2nd ed., 1996).

The guidance provided is very limited and the relevant sections from each document are reproduced in Appendix I of this document.

3. SOIL PARAMETERS REQUIRED FOR DESIGN AND INSTALLATION

3.1 GENERAL

Geotechnical investigations for subsea structures are performed in order to acquire data that will facilitate successful foundation design, installation and the operational integrity of the structure. To this end, site specific information is required on:

- soil type and variability
- strength, deformation and consolidation characteristics
- seabed topography
- the influence of cyclic loading
- scour potential

Data may also be required on regional factors of influence such as:

- slope instability
- earthquake susceptibility
- presence of shallow gas or gas hydrates

The type and quantity of data required will depend upon factors such as:

- type of structure
- type of foundation
- installation method
- water depth
- site data already available

3.2 TYPES OF STRUCTURE

There are many types and form of subsea structure, the most common of which include the following:

- subsea production, and pre-drilling templates
- wellhead protection covers
- pipe bridges/crossing structures
- mid-water arch anchor structures
- pipeline end manifolds (PLEMs)
- pipeline support structures
- spool pieces

All the above are “permanent” or semi-permanent structures. There are, however, many different types of temporary subsea structure that may require site specific soil data, including:

- Temporary riser bases (seabed support for drilling riser)
- Pipeline ‘Hot-tap’ or repair frames
- Pipeline tow and lay-down heads (can also be permanent)

3.3 TYPES OF FOUNDATIONS

The support for subsea structures may be provided in numerous ways, including:

- Gravity Base Foundation (relying solely on the natural base contact area of the structure)
- Mud Mats (discrete ‘pad’ footings – usually at each corner of the structure)
- Skirts (usually continuous steel plates around the full base or mudmat perimeter)
- Suction Caissons (typically in the form of skirted circular mudmats or short piles – that are installed with the aid of suction pressure)
- Piles (tubular steel piles installed through guides in the base and then connected to it)

Some subsea structures also obtain their long term support by means of mechanical connection to the well conductor(s).

3.4 FOUNDATION PROBLEMS TO BE DESIGNED AGAINST

Site specific and regional geotechnical data is required at the proposed locations of subsea structures in order to ensure:

a. the structure can be successfully installed without incurring very expensive delays
b. the seabed will support the structure without incurring excessive, immediate, deformations or long term settlement
c. there will be sufficient uplift and sliding resistance to overcome vertical and horizontal loading from externally-applied forces such as trawl board impact and snagging.
d. liquefaction or scour of the seabed does not remove support during operations
e. drilling operations and/or escape of shallow gas does not undermine the structure
f. mass seabed movement due to earthquakes and/or slope instability does not cause excessive displacements of the structure.

3.5 TYPICAL PROBLEMS EXPERIENCED

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

3.5.1 Bearing capacity failure during installation due to lack of touchdown control, which is not uncommon at deepwater sites with soft soil. Associated with excessive penetration and/or increased subsequent susceptibility to sliding failure due to prefailure of soil.

3.5.2 Excessive initial penetration of structures during installation due to lack of expected thin surface sand layer.

3.5.3 Failure to penetrate skirts or suctions caissons because of denser surface sand, greater gravel/cobble content, or stiffer clay, than expected.

3.5.4 Differential settlements preventing correct flowline alignment and connection by ROV.

3.5.5 Undermining of structures due to scour, drilling wash-out or gas escape.

3.5.6 Unacceptable stresses on conductors due to seabed movement.

3.5.7 Inability to drive piles to target penetration due to harder strata being encountered.

3.5.8 Pile driving resistance much lower than expected due to encountering weaker strata; resulting in piles of insufficient length to give sufficient axial capacity (compression or tension.)

3.5.9 Unacceptable inclination of structure due to presence of pockmark not detected by conventional bathymetric survey.

3.5.10 Problems related to carbonate soils, such as possible hard caprock, cemented layers and low bearing capacity of piles in carbonate sands.

3.6 PARAMETERS REQUIRED

To address all of these issues the following basic soil parameters need to be determined.

Table 3.1 Basic Soil Parameters Required

Clay	Sand
Grain size	Grain Size
Atterberg(plastic/liquid) limits	Relative Density
Water content	Max / Min Density
Total unit weight	Total Unit Weight
Undrained shear strength	Friction Angle
Remoulded Shear Strength	

Table 3.2 Additional Soil Parameters for Specific Applications

Application	Additional Soil Parameters
On bottom stability	Sensitivity (clay), base-soil interface friction
Scour / erosion	Permeability (sand / silt)
Slope stability	Strain rate effects, cyclic behaviour of soil, permeability (sand / silt), strength anisotropy
Liquefaction	Cyclic behaviour of soil, compressibility, relative density
Settlements	Constrained modulus and consolidation characteristics
Corrosion	Electrical resistivity, geochemical tests, bacteriological analysis
Thermal considerations / frost	Thermal conductivity, heat capacity, salinity
Spool pieces / tie-in etc.	Constrained modulus and consolidation characteristics
Piles	Elastic modulus

4. DATA ACQUISITION METHODS

4.1 SITE WORK

4.1.1 General

The main methods of geotechnical data acquisition (geophysical surveys are referred to in Chapter 5 under Planning and Scheduling) fall into two categories:

a) Seabed techniques
b) Borehole techniques

These techniques and their relative merits are discussed below and more detailed descriptions of equipment and systems are provided in Appendix III.

4.1.2 Seabed Techniques

The “primary” methods of acquiring shallow seabed soils data for marine projects have traditionally involved relatively simple coring and sampling equipment such as:

a) Vibrocorer
b) Gravity Corer
c) Grab Sampler

and in-situ testing by means of the:

d) Cone, or Piezocone, Penetration Test (CPT/PCPT or CPTU).

There are also more specialised or complex sampling, or in-situ testing, systems that can be used to resolve a particular design issue or measure a specific parameter. Methods in this category include:

a) Box Corer
b) Rock Corer
c) In-situ Vane Test (for high accuracy measurement of shear strength in very soft clays)
d) In-situ Model Tests (using scaled model of the structure or its foundation)
e) Plate load test (pushes in flat plate, whilst measuring load and penetration, in order to determine settlement and bearing capacity for small structures and footings.).

4.1.3 Borehole Techniques

Boreholes will normally be drilled from a dedicated geotechnical drilling vessel, using heave-compensated rotary techniques. Sampling and in-situ testing will be performed by means of downhole tools operating through an open drilling bit.

Alternatively, geotechnical boreholes can be drilled from conventional industry MODUs (mobile offshore drilling units) should they be operating at the site. Specially modified downhole geotechnical sampling and testing tools are available for operations of this type.

Further details are provided in Appendix III.

4.1.4 Specialist In-situ Probes

Specialist In-situ probes, which can be used with seabed equipment or in "downhole mode, include:

- thermal conductivity cone/heat flow probe, (for determining the thermal conductivity/heat capacity of virgin soil and/or trench backfill)
- electrical conductivity cone, (for determining electrical conductivity of virgin soil and/or trench backfill)
- temperature cone, (for measuring the in-situ temperature of virgin soil and/or trench backfill)
- seismic cone, (for determining shear wave velocities, shear moduli and soil density)
- nuclear density probe, (for determining the bulk density of virgin soil and/or trench backfill)

4.2 LABORATORY TESTING

4.2.1 Offshore laboratory testing

a) <u>Non-dedicated vessels</u>

Whenever possible, basic soil classification and testing should be performed on samples as soon as they are recovered. Cores are normally cut into sections of a convenient length for storage and transport. Exposed surfaces of core should be visually classified and simple shear strength tests performed, on cohesive soils, with tools such as hand-operated shear vanes or "pocket" penetrometers. If facilities permit, moisture content and soil unit weight determinations will provide useful additional information. A preliminary core log should be produced, in a format similar to that presented in Appendix II.

All samples to be transported to an onshore laboratory should be carefully sealed and labelled, stored in the correct vertical orientation and packaged so as to minimise moisture loss and disturbance during transit. Soft clay samples to be tested for mechanical properties in the onshore laboratory should be stored in sample tubes or tube liners properly sealed at both ends.

b) <u>Dedicated Geotechnical Drilling Vessel</u>

Dedicated geotechnical drilling vessels are normally equipped with a basic soils testing laboratory. This will facilitate the extrusion and description of samples, sub-sampling of specimens for immediate testing and water proof re-sealing of the remaining sample. Testing performed would typically include the determination of:

- Moisture content
- Wet and dry density
- Undrained shear strength, by means of:
  - pocket penetrometer
  - hand shear vane
  - mechanical shear vane
  - fall cone
  - Unconsolidated, undrained (UU) triaxial compression test.

Effective re-sealing of samples for transport to the onshore laboratory is typically achieved by means of:

1. Removing surface moisture/drilling mud
2. Wrapping in clear plastic wrap (“cling film”)
3. Overwrapping in aluminium foil
4. Placing in a cylindrical cardboard carton which is subsequently filled with molten paraffin wax, which, when cooled and hardened, provides a very effective water-tight seal.

4.2.2 Onshore laboratory testing

Laboratory testing of samples, onshore, should be performed in a suitably accredited laboratory, and in accordance with appropriate national or international standards such as:

British Standards Institution (1990)
BS1377 : Methods of tests for soil for civil engineering purposes.
American Society for Testing and Materials,
Annual Book of ASTM Standards (1999)
Volumes 04.07 and 04.08, Soil and Rock; Building stones.
or the:
Norwegian, NORSOK Standard, series for individual tests, such as:
NORSOK Standard, NS8005, Geotechnical testing. Laboratory methods. Grain size analysis of soil samples.

4.3 SELECTION OF SUITABLE EQUIPMENT AND METHODS

This section evaluates the suitability of different in-situ and laboratory tests for determining the required parameters. The evaluation has been divided into conventional tests which are normally used in standard investigations and special tests which may be considered for specific design topics. Conventional tests and special tests are presented in Tables 4.1 and 4.2 respectively. **The level of suitability/applicability is indicated on a scale of 1 to 5, where 1 is Poor and 5 is Very Good.**

Similarly, an evaluation of sampling equipment is presented in Tables 4.3 and 4.4.

Table 4.1 Conventional Testing Methods

	In-Situ Testing			Laboratory Testing		
Soil Parameters	Type of Tests	Applicability		Type of Tests	Applicability	
		Sand	Clay		Sand	Clay
Interpolation of soil layering in between cores borings / (P)CPTs	Seismic reflection, (sub-bottom) profiling	2	2	N/A	N/A	N/A
Soil classification	Seismic reflection profiling CPT/PCPT*	1 4	1 4	Grain size, Water content, Atterberg limits.	5 2 N/A	3 3 5
Soil density	CPT/PCPT*	3 to 4	2	Unit weight and water content measurement	1 to 2	5
Soil strength (Undrained shear strength)	CPT/PCPT* In-situ Vane	N/A N/A	3 to 4 4 to 5	Unconsolidated triaxial compression, Consolidated triaxial compression, Fallcone, pocket penetrometer, Torvane, Labvane, Direct Simple Shear	N/A 5 N/A	3 to 4 5 3
Friction angle (Drained shear strength)	CPT/PCPT*	3 to 4	2	Consolidated triaxial compression, Direct Shear (Shear box), Direct Simple Shear	5(c) 4	5 1
Sensitivity	CPT/PCPT* In-situ Vane	N/A N/A	2 3	Fall cone, labvane	N/A	5
Consolidation characteristics and permeability	PCPT*	1	3(d)	Oedometer	2(c)	5
				Grain size, porosity and moisture content	2(c)	2

* Note: The abbreviation CPTU is sometimes used in place of PCPT

Table 4.2 Special Testing Methods

Soil Parameters	In-Situ Testing			Laboratory Testing		
	Type of Tests	Applicability		Type of Tests	Applicability	
		Sand	Clay		Sand	Clay
Interpolation of soil layering in between borings/CPT's	Instrumented plough Seismic refraction profiling Electrical resistivity profiling	3 (e) (e)	3 (e) (e)	N/A	N/A	N/A
Soil density	Electrical resistivity probe Nuclear density probe Seismic cone	2 to 3 1 to 2 3 to 4 (f)	1 2 to 3	Triaxial with bender elements	3 to 4 (f)	1
Soil strength and deformation	Pipe model test Plate load test	3 to 4	3 to 4	Direct simple shear	4 (c)	5
Rate effects / cyclic behaviour				Direct simple shear - static/cyclic Consolidated triaxial – static/cyclic	4 (b) 5 (c)	5 5
Permeability	PCPT* - dissipation tests BAT probe Piezoprobe	1	4	Special permeability tests	5 (c)	N/A
Thermal conductivity	Heat flow probe	4	4 to 5	Transient method Steady state method Mineralogy and porosity	5 (c) 5 (c) 4	5 5 4
Corrosion potential	Electrical resistivity cone	4	4	Electrical resistivity	4 (c)	4
Gas content	BAT/DGP (Deep Gas Probe)	4	4	Geochemical	5	5

* Note: The abbreviation CPTU is sometimes used in place of PCPT.

Table 4.3 Seabed Sampling Equipment

Type of Equipment *	Sample Quality		Recovery (relative to length of sample tube)	
	Sand (g)	Clay	Sand	Clay
Gravity Corer/Piston Corer	2	3	1	3 to 4
Vibro Corer	2 to 3	2 to 3 (h)	3 to 4	2 to 3
Grab Sampler	1 to 2	1	1 to 2	2
Box Corer (i)	1 to 2	5	1	5

* Note: These represent the main generic equipment types. Enhanced variants of some are available and discussed in more detail in Appendix III

Table 4.4 Downhole Sampling Equipment

Type of Equipment	Sample Quality		Recovery (relative to length of sample tube)	
	Sand (g)	**Clay**	**Sand**	**Clay**
Hydraulic Piston Sampler	3 to 4	5	3	5
Hydraulic Push Sampler	3 to 4	4 to 5	3	5
Hammer Sampler	2 to 3	2 to 3	3 to 4	3 to 4
Rotary Coring (j)	1	2 (j)	1	3 (j)

Key:

Suitability Scale

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

Notes:

a) Good if calibrated against site specific laboratory tests

b) Consolidated Drained Triaxial, if in-situ density is known

c) If in-situ density is known

d) If dissipation tests are performed

e) Potentially good – still to be proven, resistivity in particular requires very careful correlation with samples and/or in-situ testing

f) If in-situ shear wave velocity and laboratory shear wave velocities for different densities are available.

g) It is normally not possible to take undisturbed samples in sand

h) Poor in Soft clays (but can be improved if controlled self-weight penetration of barrel is achievable, i.e. no vibration used.)

i) Recovery is limited to 0.5m and suitable only for very soft to firm clays and loose Clayey/Silty Sands

j) Normally used in rock or very hard clay only

5. PLANNING AND SCOPE OF WORK

5.1 OBJECTIVE

The objective of the site investigation for a subsea structure is to obtain sufficient reliable information to permit the safe and economic design of installation and permanent works. The investigation should be designed to verify and expand upon any information previously collected.

Experience shows that unexpected or poorly defined ground conditions are one of the most commonly occurring causes of construction project delays and cost escalations. Subsea projects can be particularly exposed to such because of their reliance on satisfactory seafloor soil properties for trouble-free installation and operation.

5.2 PLANNING AND SCHEDULING

The required level of information about soil properties at a subsea site may change during a field development project. In the early stages the data available should be sufficient to demonstrate the feasibility and suitability of preferred design concepts. At later stages the data 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 which can arise as the design and construction works progress.

The site investigation programme for a subsea project should therefore be undertaken in progressive stages. Planning for each stage should be based upon previous findings in order to optimise the scope of work. Factors such as: vertical and horizontal uniformity of soil profiles, geological history, and structure size and concept, should be directly reflected in the design of the site investigation.

The ideal sequence of the site investigation programme should therefore be as follows:

- Desk Study
- Geophysical Survey
- Geotechnical Investigation

Each of these stages is discussed below.

5.3 DESK STUDY

The desk study should incorporate a review of all appropriate sources of information and the collection and evaluation of all relevant available types of data, for the area of interest, including:

- geological
- bathymetric
- geotechnical
- metocean (tides, currents etc)
- seismicity
- performance of existing structures.

In any desk study of seabed conditions an assessment of existing data should be made. Potential sources include national geological surveys, academia and other operators and contractors. Internet site www.eu-seabed.net contains metadata for offshore Europe. Globally selected academic data is stored by NOAA in Boulder, Colorado www.ngdc.noaa.gov/mgg/aboutmgg/wdcmgg.html.

The performance of a desk study alone is not sufficient for detailed engineering purposes but should enable conceptual engineering to progress in a more focussed manner. It also provides the ideal basis upon which to design and plan subsequent survey work.

5.4 GEOPHYSICAL SURVEY

A geophysical survey will usually be performed at the site to collect information on;

- Seabed topography – by echo-sounding or swathe bathymetry. The latter is particularly important in “pockmark” or sand wave areas or other areas of generally uneven seabed.
- Seabed features and obstructions –by methods such as side scan sonar
- Sub-bottom profiling of uppermost 50m, or so, of seabed - usually by means of reflection seismics, but recent developments in towed resistivity and seismic refraction methods are providing useful complementary data for shallow strata definition. Digital capture of data is now available and facilitates processing and the achievement of enhanced resolution.

As a general rule, the size of the survey area will be of the order: 1000m x 1000m.

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

The performance of a geophysical survey alone or in addition to a desk study is not sufficient for detailed engineering purposes unless site geotechnical data is already available.

5.5 GEOTECHNICAL INVESTIGATION

The geotechnical investigation will normally be performed on completion of the geophysical survey, and after the preferred site has been determined, either from the same vessel or as a completely separate operation from a different vessel. This allows for sample and test locations to be more effectively targeted to identify soil strata changes, clarify apparent anomalies or investigate specific seabed features.

A competent geotechnical engineer should be involved in preparing the scope of work and specification.

Suitable equipment

The primary data acquisition methods used in most geotechnical investigations will be:

- Coring and Sampling for material identification, description and subsequent Laboratory Testing
- In-situ testing for accurate stratification and determination of key engineering parameters.

There is a wide range of available equipment for each method. They are described briefly in section 4.0 'Data Acquisition Methods' and in more detail in Appendix III.

The suitability of each tool for use in the Geotechnical Investigation should be assessed by reference to section 4.0. This should be carried out in conjunction with knowledge of the engineering objectives of the selected concept(s) and the results of the desk study and geophysical survey phases. Guidance on data acquisition requirements for specific engineering objectives are provided in section 3.0, 'Soil Parameters Required for Design and Installation'.

Suitable vessels and supervision

The geotechnical investigation can be performed either from the geophysical survey vessel, provided it has the capabilities, or from a separate vessel with suitable deployment or drilling capabilities. The work should be supervised by a competent geotechnical engineer who is aware of the objectives of the investigation.

5.6 TYPICAL SCOPES OF WORK FOR GEOTECHNICAL INVESTIGATIONS

The following suggested scopes of work are offered as minimum prudent programmes which should be reviewed in the light of structure-specific factors, such as: weight, dimensions, installation method and purpose.

5.6.1 Small Unpiled Structure (GBS or Mudmats)

One CPT plus One Core (Vibro or Gravity) to 5-6m at each structure location.

5.6.2 Skirted or Caisson supported Structures

One CPT at each corner plus one or two cores or boreholes (depending upon skirt or Caisson depth).

5.6.3 Large Unpiled Structures

Programmes as above, depending upon foundation support type, but depth of penetration governed by structure size. Penetration depth should be at least equivalent to the largest dimension of the structure and preferably 1.5 x this dimension.

Penetration requirements in excess of 5 to 6m will typically require boreholes to be drilled from a specialist vessel. However, in deepwater and with very soft soils long gravity/piston-corers may be used to recover cores of 20 metres in length, and more. In shallow waters and stiffer/denser soils, specialist high performance vibrocores can sometimes recover cores of up to 8 or 9 metres in length.

5.6.4 Piled Structures

At least one borehole with downhole sampling and CPTs to the expected pile penetration, plus 4 x pile diameter. E.g. for a 1.0 metre diameter pile to be driven to 20 metres, drill a borehole to 24 metres. The required pile penetration should be reassessed on site, on the basis of soil conditions encountered, in order to ensure the borehole depth is great enough. Additional short cores or CPTs may be required in order to ascertain the variability of near surface strata, should this be expected to have an impact on design, installation or operation.

5.6.5 Other Considerations

If cyclic loading/liquefaction is expected to be a potential problem, consideration should be given to performing “seismic” cone testing. Additional good quality soil samples should be recovered from critical strata for ‘cyclic’, laboratory testing, (i.e. tests that investigate the effect of cyclic loadings, on material characteristics such as: strength, stiffness and internal pore pressure).

The drilling of production wells through subsea templates and other structures can often lead to wash-out and undermining of the structure’s foundations. The drilling of a geotechnical borehole to around 100 metres can provide information to allow for the design of a more effective and controlled well conductor installation procedure.

Consideration should also be given to the regional context of a structure’s location, particularly in deep water, and the potential for slope instability and other geohazards, which may adversely influence the integrity of a structure.

Table 5.1 Summary of Typical Scopes of Work

Structure	Scope of Work	Penetration (m)	Comment
1. Small unpiled structure	1 No. Core plus 1 No. CPT	5m to 6m	
2. Skirted or Caisson supported structure	1 No. CPT per corner, plus 1 No. or 2 No. Cores or Boreholes	To depth of Skirt plus 1m to 1 x diameter	Penetration distance below skirt or caisson tip, depends on loading and other design factors [1]
3. Large unpiled structures	1 No. Borehole with CPTs, plus 1 No. Borehole with samples only	1.5 x largest horizontal dimension of structure	Additional shallow cores and CPTs to be added if variability of surface strata has significant consequences.
4. Piled Structure	1 No. Borehole with CPTs and Samples	Pile penetration plus 4 x pile diameter	Additional shallow cores and CPTs to be added if variability of surface strata has significant consequences.

Notes:
1. a) For horizontal loading and shearing : 1m
   b) Scour prevention : 1m
   c) Vertical loading or pull-out : 1 x D
   d) Combined loading : To be judged by a competent geotechnical engineer.

2. If cyclic loading/liquefaction is expected to be a potential problem, consideration should be given to: the performance of “Seismic” cone tests, and the collection of additional high quality samples, in critical strata, for subsequent cyclic laboratory testing and dynamic moduli determination.

6. INTERPRETATION, INTEGRATION AND REPORTING

Introduction

To maximise the value of the data acquisition exercise it is essential that all field and laboratory data are:

- evaluated critically
- presented clearly
- summarised succinctly

To achieve this it is important that a minimum standard of data presentation is adopted. The following sections describe proven good practice and recommend some minimum standards. All interpretation and reporting should be subject to Quality Assurance procedures to the standards of ISO 9000 or equivalent.

For more comprehensive guidance, reference can be made to NORSOK standard : “Common Requirements – Marine Soil Investigations”. Ref. G-CR-001 Rev. 1, May 1996.

Core and sample and borehole logs

These should clearly show the soil type variation with depth and include as a minimum:

- a graphical soil symbol column
- a detailed written description of the soil type, its strength or density, constituent parts and any structure or inclusions and how these characteristics vary with depth. (Descriptions should adhere to terminology laid down in the relevant national or international standards).
- moisture content, wet and dry density test results
- undrained shear strength measurements in clay
- internal friction angle for sands
- Atterberg (liquid and plastic) Limits for clays

Typical core and borehole log formats displaying most of these requirements are included in Appendix II.

CPT/PCPT (CPTU) results

Measured and derived parameters should be plotted graphically against depth at a convenient scale such as 1cm to 1m and include:

- cone resistance
- sleeve friction
- excess pore pressure
- friction ratio (ratio of sleeve friction to cone resistance)
- pore pressure ratio (ratio of excess pore pressure to cone resistance)
- q_{net} (cone resistance corrected for pore pressure effects).

In addition, an interpreted log of the CPT or PCPT should be presented in a format similar to a core log in order that it might be clearly understood by non-geotechnical engineers. The interpreted log should incorporate:

- a graphical soil symbol column
- a detailed description of the interpreted soil types (using the same standard terminology as the core logs).
- a graphical plot of interpreted shear strength for cohesive soils
- estimated values of relative density and friction angle for cohesionless soils.

Examples of a typical PCPT result format are presented in Appendix II.

Special in-situ test results

The results of non-standard tests should be presented in a clear and simple format, preferably including graphical representation, together with an explanation of the results and their implications.

Laboratory test results

Each individual laboratory test result should be presented graphically where appropriate, and in a format that complies with the relevant National or International standard. All results should also be summarised in tabular form.

Interpretation and design parameters

The interpretation and correlation of laboratory and In-situ test data should be performed by competent geotechnical engineers and the results presented as ranges of recommended geotechnical design parameters for each location or section of route.

Integration of results

It is essential that the results of any geophysical survey and the geotechnical data are carefully integrated by suitably qualified personnel. Only in this way can the full value of these two components of the site assessment be fully realised, and misleading interpolation between individual sample and test locations avoided.

Report formats

Geotechnical Report formats should be designed for ease of assimilation by non-geotechnical engineers. Wherever possible the data should also be summarised graphically.

The depth, below seabed, to the top or base of critical near surface strata should be presented in the form of contour (isopach) plots if sufficient data are available.

The variation of critical design parameters should be plotted, against depth below seabed, to show actual values, upper and lower bound envelopes and recommended mean.

A suggested geotechnical investigation report layout, based upon the NORSOK Standard, is presented in Table 7.1 below, but other formats can be adopted to suit the requirement of a particular project.

Table 7.1 Suggested Report Structure

Subsea Geotechnical Investigation 1999 Executive summary A short presentation of the project, the task and the results (main points from Parts A, B and C)

Part A Soil parameters for design * Summary Part A	Part B Geotechnical data * Summary Part B	Part C Field operation *Summary Part C

A1 Summary of soil conditions	B1 CPTs/PCPT Results and Interpretations	C1 Log of activities
A2 Basic soil parameters	B2 Core Logs	C2 CPT/PCPT Operations
A3 Recommended soil Parameters for pipeline design and installation	B3 Classification tests	C3 Sampling/Coring Operations
A4 Interpretation and Evaluation of geotechnical Data	B4 Triaxial tests	C4 Field Laboratory testing
A5 List of symbols and Classification system used	B5 Consolidation tests	C5 Water depth and tidal Measurements
A6 References	B6 Direct shear tests (shear box)	C10 List of co ordinates
	B7 Other geotechnical tests	C11 Positioning System
	B8 Corrosion tests	C12 References
	B9 Chemical tests	
	B10 Geological tests	
	B11 Description of laboratory test procedures	
	B12 List of symbols and classification system used	
	B13 References	

For minor investigations a simpler report structure can be considered to avoid too much repetition.

(This format follows the recommendations of the NORSOK Standard: Common Requirements – Marine Soil Investigations. Ref: G-CR-001 Rev. 1, May 1996).

APPENDIX I

EXTRACTS FROM RELEVANT REGULATIONS AND GUIDELINES

APPENDIX I

EXTRACTS FROM RELEVANT REGULATIONS AND GUIDELINES

ISO/DIS 13628-1 'Petroleum and Natural Gas Industries - Draft International Standard for Design and Operation of Subsea Production Systems - Part 1: General Requirements and Recommendations' (1997).

5.2 Design criteria

5.2.1 Environmental data

The following environmental data are typically required for the installation site of the subsea installation and applicable along the pipeline route to the processing facility :

5.2.1.1 Oceanographic data

- water :

- currents :

- seabed : *soil description, friction angles, soil shear-strength-depth profile and load bearing capacity, pockmarks, presence of shallow gas, earthquake data, seabed topography, stability under cyclonic conditions, resistivity, density, marine growth.*

API RP 17A 'Recommended Practice for Design and Operation of Subsea Production Systems' (2nd ed., 1996).

2.2.3 Subsea Wellhead System Design Considerations

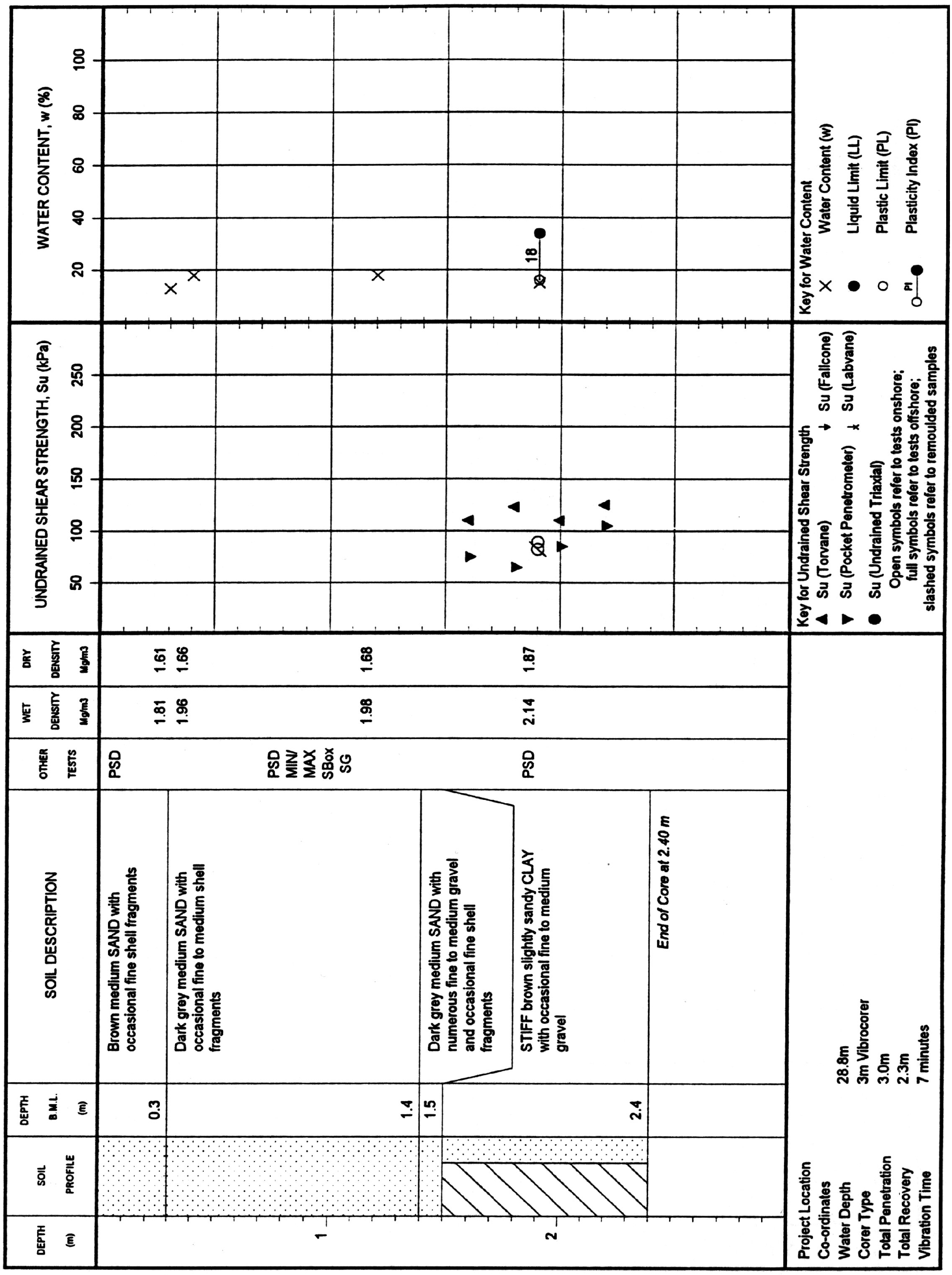
2.2.3.1 Structural Integrity. *The wellhead system is the structural foundation for a subsea completion. It must transfer applied loads to the casing strings and into the surrounding soil...*

a. Geotechnical Investigation. *The starting point for an investigation of structural integrity is a geotechnical investigation of the intended location. If data is not available, a shallow hazard survey and/or soil borings will provide soil data near the seabed. If a planned well-site is in an area that is subject to massive soil movements, special soil borings will be required to assess the extent of the geohazard. API RP 2A provides more information on soil sampling techniques.*

APPENDIX II

PRESENTATION FORMATS

CONTENTS LIST

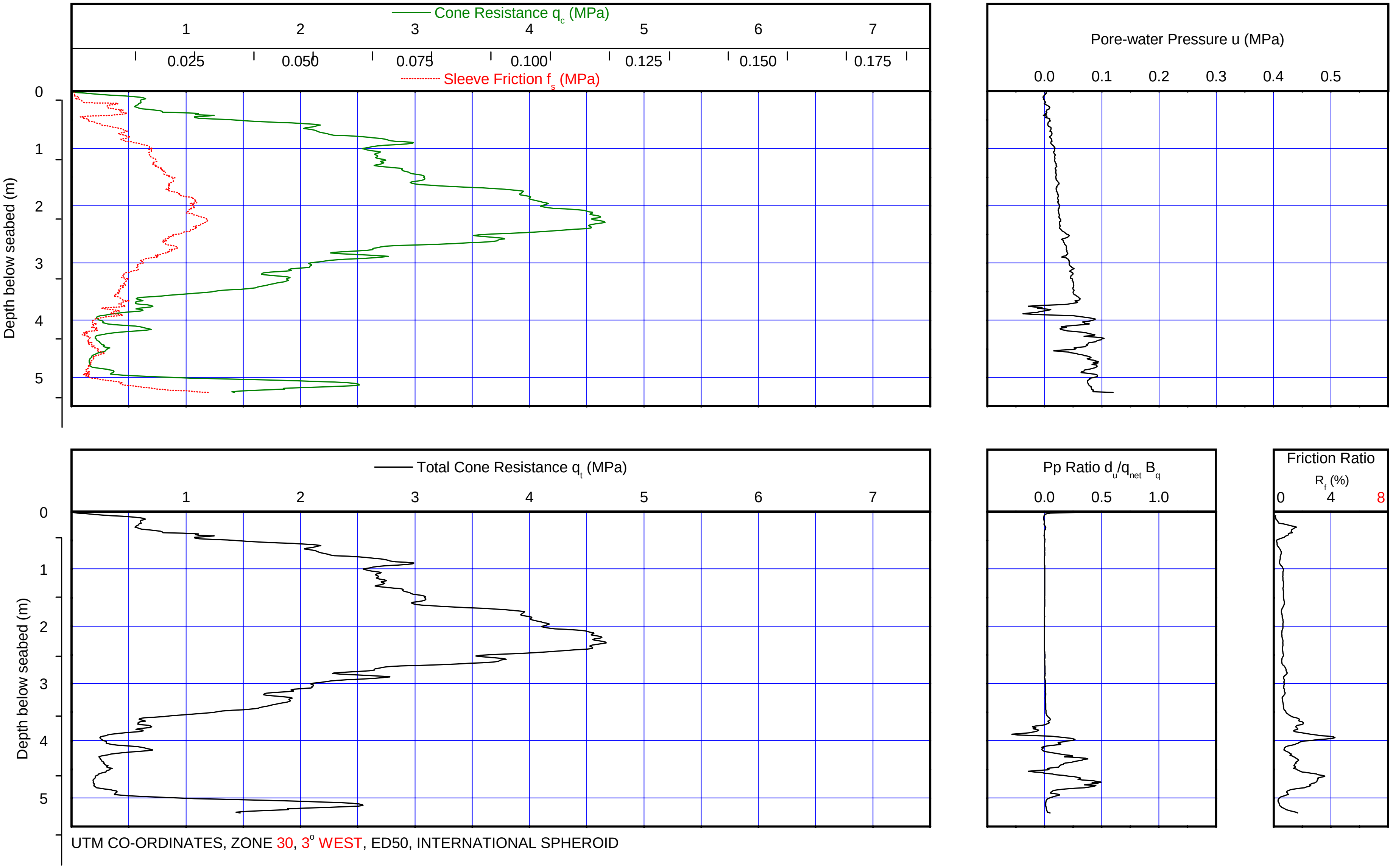


EXAMPLE OF A GRAVITY / VIBROCORE CORE LOG

Figure II-1

Checked by: Date : Filename : / / Drawn by: Date:

Approved by: Date :

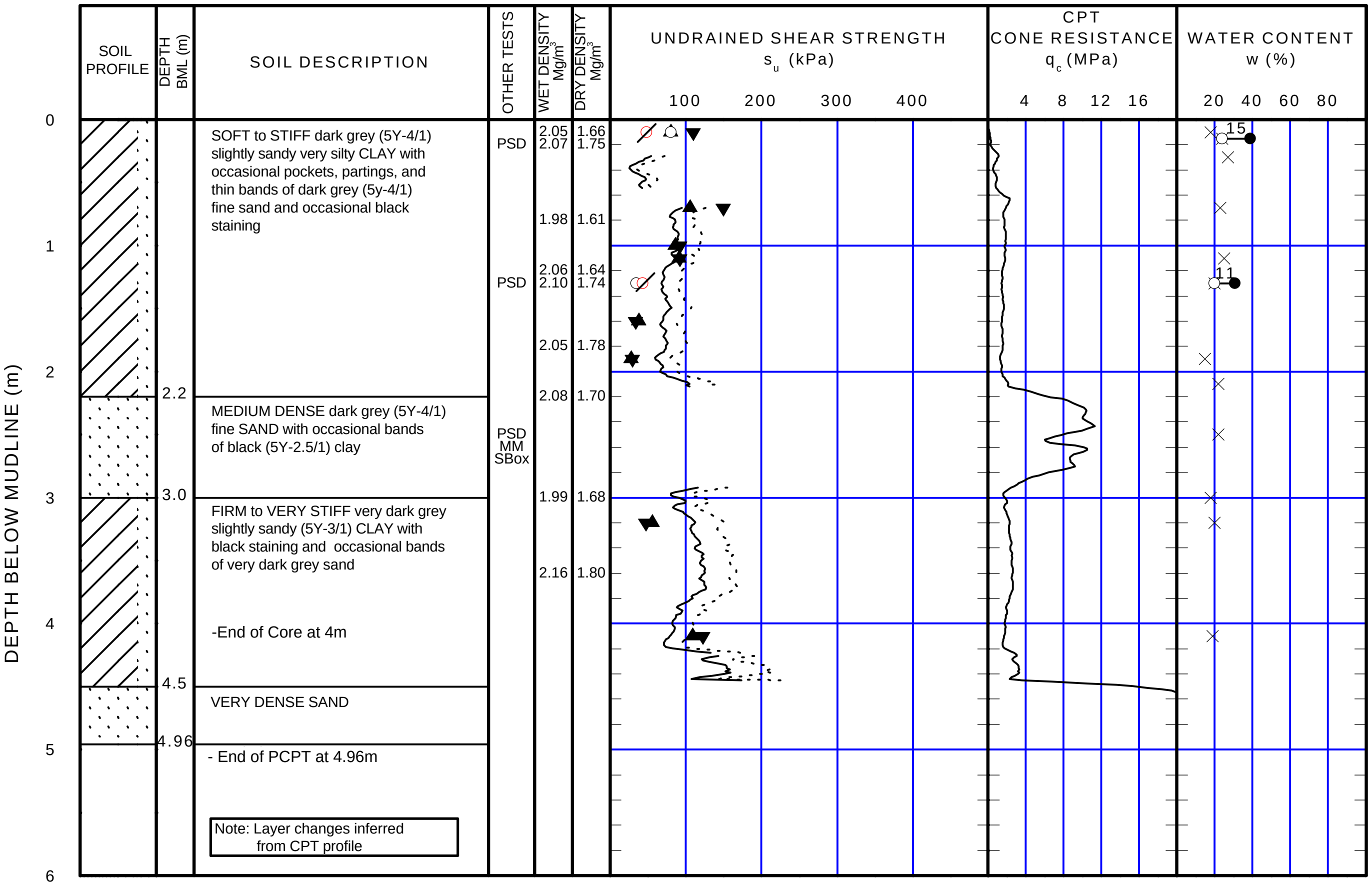


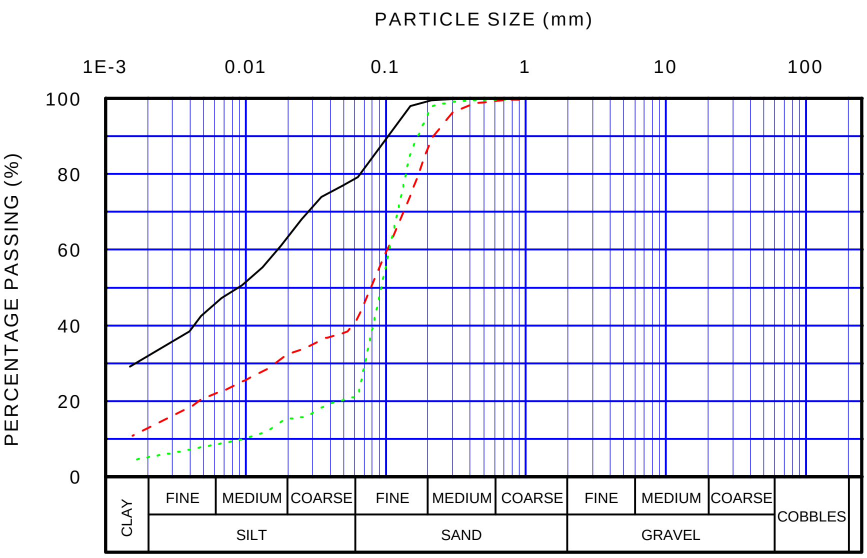
UTM CO-ORDINATES, ZONE 30, 3° WEST, ED50, INTERNATIONAL SPHEROID

Co-ordinates	: mE mN	Date of testing	:
Approx. Water Depth	: m	Cone used	:
CPT Final Penetration	: m	Location	:

EXAMPLE OF SEABED CONE PENETRATION TEST

Figure II-2





Key for Undrained Shear Strength

- ● s_u (UU) ■ s_u (FC) ▼ s_u (PP)
- ▲ s_u (TV) — s_u (LV) ⊗ s_u (CAU)
- - - - - s_u (Interpreted from PCPT data, N_{kt}=15)
- ——— s_u (Interpreted from PCPT data, N_{kt}=20)

Open symbols refer to tests onshore;
Full symbols refer to tests offshore;
Slashed symbols refer to remoulded samples

Key for Water Content

- × Water Content (w)
- ● Liquid Limit (LL)
- ○ Plastic Limit (PL)
- PI ○—● Plasticity Index (PI)

PSD Details

- ——— at 0.05 m 9.2/9.5
- - - - at 1.3 m 9.2/9.5
- ····· at 2.5 m 9.2/9.5

Tested in accordance with the following clauses of BS 1377 : Part 2 1990
- 9.2 Wet Sieve
- 9.3 Dry Sieve
- 9.4 Sedimentation by pipette
- 9.5 Sedimentation by hydrometer

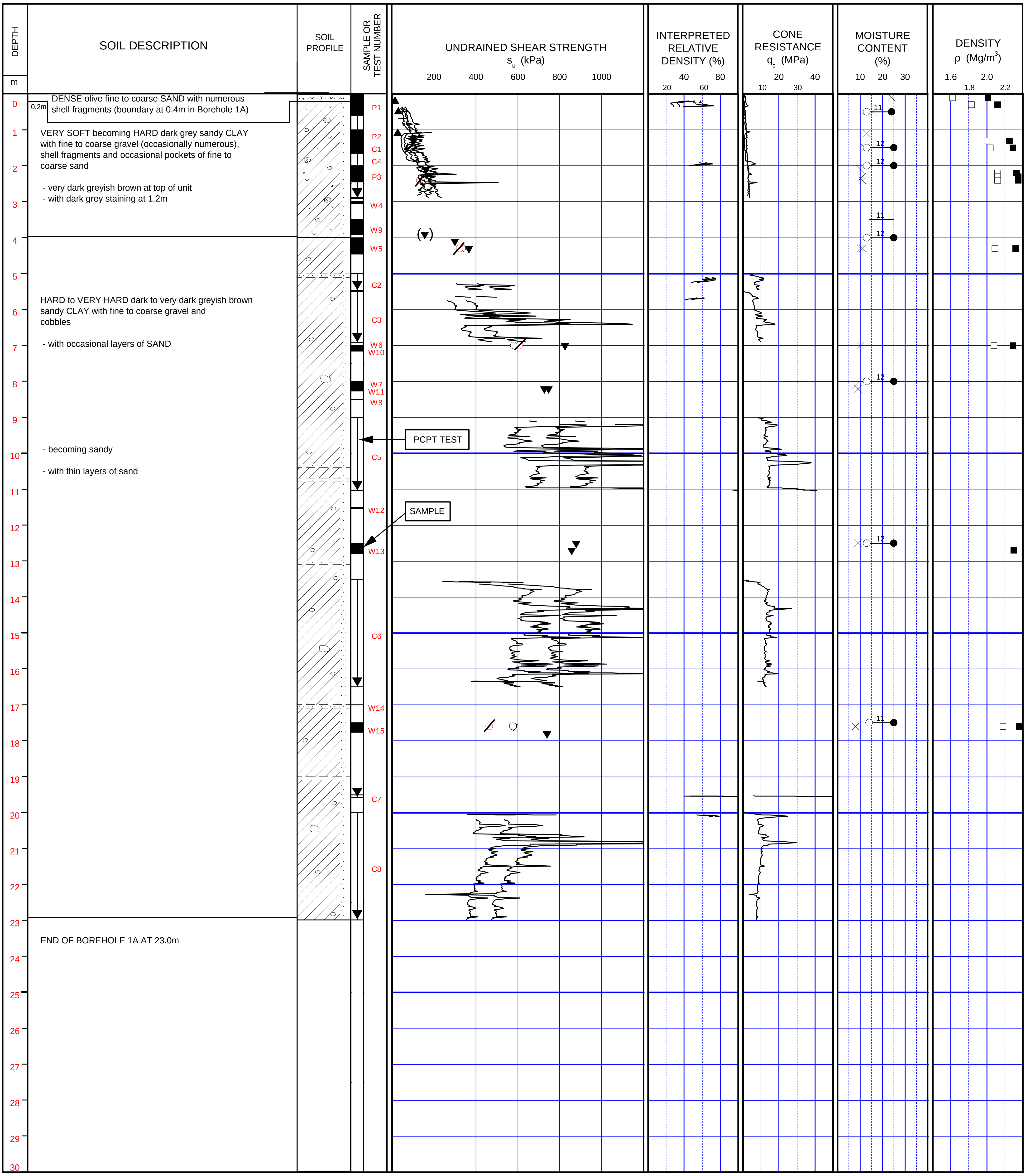
Log Details

Location	:	Approx. Water Depth	: m
Co-ordinates	:	PCPT Final Penetration	: m
	:	Recovery	: m
Core Type	:		

EXAMPLE OF A COMBINED CORE / CPT LOG

Figure II-3

Approved by: Date: Checked by: Date: Created by: Date: Drawn by: Date:



DRILLING REMARKS:

Type of Bit

Type of Mud

Notes

KEY FOR UNDRAINED SHEAR STRENGTH:

- ▲ s_u (Torvane)
- ■ s_u (Laboratory Vane)
- ▼ s_u (Pocket Penetrometer)
- ● s_u (Undrained Triaxial)
- — s_u (Fallcone)
- ⊗ s_u (CAU_c)
- ⊕ s_u (CAU_e)
- ⊠ s_u (DSS)
- × s_u (In-situ Vane)
- ✳ s_u (Remoulded In-situ Vane)
- ——— s_u (Interpreted from CPT data)

Open symbols refer to tests onshore; full symbols refer to tests offshore; slashed symbols refer to remoulded samples

KEY FOR MOISTURE CONTENT:

- × Water Content (w)
- ● Liquid Limit (LL)
- ○ Plastic Limit (PL)
- ○—PI—● Plasticity Index (PI)

KEY FOR DENSITY:

- □ Natural Dry Density (ρ_d)
- ■ Natural Wet Density (ρ_w)

LOCATION : , ,

CO-ORDINATES : - mE mN

: - mE mN

DATE :

WATER DEPTH : m

Filename : J:/ / / .OPJ

EXAMPLE OF A BOREHOLE LOG

Figure II-4

APPENDIX III

INFORMATION ON GEOTECHNICAL EQUIPMENT

CONTENTS LIST

FIGURES

APPENDIX III

INFORMATION ON GEOTECHNICAL EQUIPMENT

1. SEABED TECHNIQUES (Primary Methods)

1.1 Vibrocorers

a) Description

The vibrocorer, as the name suggests is a method of driving a sample tube into the seabed by vibratory means. Typical systems comprise a steel core barrel of between 75mm and 100mm in diameter and 3m to 6m in length. Inside the core barrel is a tightly fitting plastic tube or "core liner", which is preferably transparent but may be opaque. This is held in place by a 'cutting shoe' at the end of the barrel which also incorporates a sprung steel "core catcher" sample retention device. On top of the barrel is a vibratory motor, incorporating a contra-rotating asymmetrical weight, driven electrically or hydraulically. The motor and core barrel are usually encased in a tubular steel deployment frame with a tripod or oblong base to ensure stability and verticality.

The equipment is deployed on a single steel lifting cable with an associated electric or hydraulic umbilical cable. Once on the seabed the vibratory motor is activated typically for between 5 and 10 minutes and the barrel penetrates under the combination of the vibratory effect and the weight of the motor.

On recovery to the surface the core barrel is removed and replaced by another, ready for redeployment. The internal core liner is extruded and usually cut into sections for core description, testing and/or sealing for transport to an onshore laboratory.

System enhancements that are available include higher frequency motors to improve penetration in sands and percussion attachments, usually comprising a spring and reciprocating weight arrangement between the motor and core barrel, to improve penetration in stiff clay.

b) Advantages

The main advantages of this method is that the equipment is relatively simple, inexpensive and lightweight (around 0.75 tonnes to 1.25 tonnes in air typically, although lifting capacity must allow for barrel retraction forces and the self weight of cored soil) and can be a very cost effective method of recovering some material in most types of soil.

c) Disadvantages

The main disadvantages include :

i) Penetration may be limited in dense cohesionless strata or very stiff clays and thus fail to recover samples of critical strata that may, for example, give rise to trenching difficulties.

ii) Accurate definition of soil, stratification may be impaired by plugging, compaction or core loss, causing sections of the soil profile to be missed or misinterpreted. In 'soft' soils for example the corer may penetrate say up to 0.5 metres before any material enters the barrel. During subsequent penetration the barrel may periodically plug and prevent the entry of soil and on extraction of the core barrel, suction or gravity may pull part of the core from the barrel causing it to be left on or in the seabed. The net effect may then be that despite achieving 3 metres penetration the true stratification of the recovered material within the 3 metre section cannot accurately be determined.

iii) The vibratory method induces disturbance in the soil with the effect that subsequent laboratory tests for parameters such as shear strength and consolidation characteristics may produce unrepresentatively low values. This effect will be more predominant in softer soils rendering the method unsuitable for accurate engineering evaluations in soft to very soft clay for example.

iv) For some vessels the equipment can prove cumbersome to handle particularly for the longer barrelled models. For example some “6 metre” vibrocorers have a total height of around 7.5 metres and a maximum base width of 5 metres.

1.2 Gravity corers

a) Description

The standard gravity corer normally comprises a core barrel, liner and cutting shoe, very similar to those used with vibrocorers; on top of which is a single large weight or a series of adjustable smaller weights usually totaling between 0.5 tonnes and 1.0 tonnes. They are deployed on a single steel lifting cable and penetration is achieved by allowing the unit to free fall the last 5 - 10 metres to the seabed.

The “stationary piston corer” (or Kullenberg-type corer) operates with a ‘trip-release’ mechanism and differs from a standard corer in having the core barrel closed at the bottom by a piston which is connected to the main lift wire and remains approximately stationary as the core barrel penetrates the seabed. The presence of the piston can create a partial vacuum between it and the top of the soil core thus resulting in improved recovery in some soil conditions.

b) Advantages

Quick, inexpensive and simple, and does not cause as much sample disturbance in soft clays as a vibrocorer.

c) Disadvantages

i) Poor penetration is stiff clays or granular soils

ii) A “free fall” winch is required

or

iii) If a “trip-release” mechanism is used, this can be cumbersome to handle on deck and potentially dangerous because of the possibility of inadvertent triggering.

1.3 Long Gravity/Piston Corers

a) Description

These corers, which are typically 20 metres to 30 metres in length, are developments of the “stationary piston corer” described above. They evolved for use in deepsea oceanographic research and are now being adopted by the oil and gas industry for use in deepwater and ultra deepwater geotechnical investigations.

b) Advantages

They provide a means of obtaining soils data to 20m or 30m below seabed that is usually less-expensive than using drilling methods.

c) Disadvantages

i) The samples obtained in this manner may be more disturbed and of lower quality than is achievable with drilling methods.

ii) The method is only suitable for “soft” cohesive soils.

ii) Penetration depth and recovery length cannot be guaranteed.

iv) Vessels with adequate space and deployment capabilities are limited.

1.4 Grab sampler

a) Description

The grab sampler is, in simple terms, an articulated bucket which closes when it comes into contact with the seabed and in so doing collects a sample of the surface deposits. These samplers can range in enclosed volume from a few litres to a cubic metre and closure is activated by a simple trip mechanism or by hydraulics in the case of some larger units.

b) Advantages

Usually relatively small, simple, inexpensive and easy to operate, although less so in the case of larger hydraulic units, which however have the advantage of greater and more consistent recovery.

c) Disadvantage

i) Sample recovery tends to be hit and miss
ii) Very shallow penetration
iii) Very disturbed sample
iv) Potential for wash-out of finer fraction of recovered sample thus rendering particle size distribution analysis unreliable.

1.5 Cone/Piezo Cone Penetration Test (CPT/PCPT or CPTU)

a) Description

Cone Penetration Testing involves the measurement of the resistance to the controlled penetration into the ground of a steel rod with a conical tip. Standard electrical cone penetrometers incorporate internal load cells that measure resistance on the cone tip and side friction on a 'sleeve' behind the tip. The 'Piezocone' version also measures excess pore water pressure in the ground generated by progress of the cone. This is achieved via a porous disc set in, or close to, the tip, which is connected to an internal pore pressure cell. Standard cones have a cross sectional area of $1000mm^2$ or $1500mm^2$ although some new systems are using cones with an equivalent area of $100mm^2$.

As a test proceeds, usually at a standard penetration rate of 20mm/sec, continuous measurements of tip resistance, sleeve friction, excess pore pressure and penetration distance are transmitted to the surface in real time via an umbilical cable.

Parameters such as soil type, relative density, shear strength and stress history can then be derived from the direct measurements and calculated ratios using empirical correlations.

b) Advantages

The CPT/PCPT has many advantages over conventional coring techniques including :

i) Usually guarantees greater penetration.
ii) Provides a complete stratigraphic profile (continuous measurement)
iii) Gives data in real time allowing almost immediate interpretation of ground conditions.
iv) Can reduce the amount of time-consuming laboratory testing.
v) Provides the only reliable method of determining the relative densities of cohesionless soils.
vi) Testing is very rapid and, depending on test spacing, the seabed unit may be left outboard between tests.

c) Disadvantages

The primary disadvantages are :

i) Weight - typically 5 tonnes to 15 tonnes to ensure sufficient reaction force to achieve the desired penetration in dense sands/stiff clays
(Mini Cone Test (MCT) systems, weighing only 1 to 2 tonnes, are available but may not provide the penetration capability or data quality required for foundation design.)
ii) Cost - the technical complexity and precision engineering involved in many of the components inevitably makes it a more highly priced item of equipment and requires well trained personnel to operate.

iii) A competent geotechnical engineer is normally required to process and interpret the test data

2. SEABED TECHNIQUES (Secondary Methods)

These systems generally represent an addition to the primary spread of equipment and not a replacement for any of its components. However, they often have the advantage of providing more accurate and/or relevant data for the solution of a specific problem, reduce conservatism in design and hence may deliver significant longer term cost benefits.

2.1 Seabed rock corers

There are a variety of these available in the market place ranging in size from around 1 tonne to 13 tonnes and theoretically capable of taking cores with diameters ranging from 25mm to 150mm, to penetrations of up to 9 metres. Most incorporate a rotary drive mechanism and diamond or tungsten carbide impregnated drilling bits plus an inner core barrel. Their main advantage is to be able to take cores of rock outcropping at or near seabed without recourse to a floating or fixed drilling platform. Their primary disadvantage is the variability in performance and recovery. The lack of direct control over, and ability to vary, drilling parameters such as bit pressures, flushing fluid flow rates, rotation speeds and drive rates on many systems, means core recovery can be very variable. The presence of unconsolidated sediments, gravel and cobbles over rock head, and weathered, and heavy fractured zones within the rock can also result in poor core recovery. The size and weight of some systems can also be a disadvantage.

2.2 Box corer

This is a relatively lightweight sampling system originally developed for oceanographic research purposes, it is designed to push a metal box about 0.5 metres into the seabed and, on retraction, seal in the sample by means of a blade-like door which closes beneath the box. Sample volumes are typically in the range 10 litres to 50 litres.

Its main application is in the retrieval of good quality block samples of soft clay in a manner that also permits inspection of a relatively undisturbed section of the seabed surface. Its main disadvantages are: its limited penetration capability and poor performance in granular soils.

2.3 In-situ vane test

The in-situ vane test is a very well established method, both onshore and offshore, for measuring the undrained shear strength of cohesive soils in-situ. The test basically comprises the insertion of a cruciform vane into the soil (either directly from the seabed or within a borehole), and rotating it at a constant speed, whilst measuring torque and deflection, until the soil shears. The undrained shear strength of the soil can be directly back-figured since the area of the sheared cylindrical surface is known from the vane dimensions. Continued rotation can also provide a value for residual or remoulded shear strength.

Units are usually lightweight (less than 1 tonne) and relatively easy to handle.

The major advantage of such systems is the ability to measure in-situ the undrained shear strength of soft to very soft soils at a high level of accuracy to penetrations of around 3m into the seabed. The main disadvantages are currently the speed of the operation - separate deployments are necessary for each penetration level at which tests are required - and that it is effectively a tool for investigating one soil type only, i.e. soft to very soft clay.

2.4 In-situ model tests

As the description implies in-situ model tests comprise equipment that attempt to reproduce the behavior of a structure or component on or in the seabed by using a model of it and, by means of instrumentation, measure desired parameters as it is placed on, pushed into or pulled along the seabed. Examples include model instrumented pipeline ploughs which are designed to make a trenchability assessment of a pipeline route and a Model Pipe Settlement Tester which is designed to investigate the initial self embedment of surface laid pipelines with a view to improving the accuracy of axial and lateral stability analyses.

A variation of the Model Pipe Test is the Plate Load Test which is regularly performed onshore but less frequently offshore. It is essentially a bearing capacity test in which a circular or rectangular steel plate is placed horizontally on the ground or seabed or within an excavated pit and is loaded vertically until foundation "failure" occurs or deformation exceeds an acceptable limit. Load and deformation are constantly measured throughout the test and the results extrapolated to predict full size foundation behavior.

The primary advantage of these tests is in providing direct indications of likely behavior in-situ and thus enabling reductions in design conservatism. Disadvantages can include size and cost of deployment for some systems and the fact that they are generally designed to provide information on one or two specific design parameters only.

2.5 Specialist in-situ probes

There is a wide variety of probes available, mostly designed for use with conventional CPT/PCPT systems. Measurements that can be made include important design parameters such as thermal conductivity and electrical resistivity. The additional cost of adding such probes to a spread is often insignificant.

Another, is the 'seismic' cone penetrometer which incorporates one or more geophones within the cone and test rod. An energy source, at seabed or within the water column generates one or more shockwaves and the sensors in the cone detect the arrival time of shear and/or compressional waves. From these measurements shear and compressional wave velocities can be measured and various dynamic moduli for the soil calculated. The additional equipment and time required for such testing can make it relatively expensive but, where specific dynamic risks exist, such as those posed by earthquakes or severe storm conditions, the data provided can be invaluable.

The Nuclear Density Probe is designed to give a direct measurement of bulk density in-situ and involves the use of a radioactive source and a detector to measure the porosity of a fixed volume of soil in-situ. The results are then compared with a series of laboratory control tests to arrive at a bulk density value. The advantage of the system is that it is possibly the only, currently available, method of performing this measurement in-situ in the marine environment. The disadvantages include the need for special permits and handling procedures for the radioactive source and the time consuming onshore control test and calibration programme.

3.0 BOREHOLE TECHNIQUES

a) Description

Drilling boreholes and using downhole sampling and in-situ testing tools is the conventional means of performing geotechnical investigations for the foundation design of fixed offshore production platforms. The work is usually performed from a dedicated geotechnical drilling vessel that is either dynamically positioned or uses a 4 to 6 point anchoring system.

The typical operational configuration is shown in Fig III-2. It comprises a motion-compensated rotary drilling system utilising 5 inch diameter API steel drill pipe and an open drag bit. A seabed frame is used to immobilise the drill pipe during sampling and in-situ testing operations and provide the necessary reaction force to push the sampling tube or probe ahead of the drill bit.

The downhole tools are normally deployed on an electro-hydraulic umbilical. Samples are taken in stainless steel thin-walled sample tubes typically of 30mm to 75mm diameter and 0.5m to 2.0m in length. CPTs, and the other in-situ probes described above, can be pushed into the soil up to 3.0m beyond the drill bit .

With conventional steel drill pipe, operations are limited to around 700m to 800m. This can be extended to nearly 2000m by using aluminium drill pipe and umbilical-less tools that are penetrated using drilling mud pressure. The downhole tools are deployed, at the required testing or sampling depth, by free-fall through the drillstring. They latch behind the drill bit and on completion of their operation are recovered with a wireline ‘overshot’ fishing tool. Test data are stored in a solid state memory and retrieved on return to deck.

b) Advantages

This method guarantees required penetration in almost all soil conditions and provides the highest quality samples and in-situ test data. Most dedicated vessels also have a fully equipped soils laboratory for onboard testing. The vessels are usually capable of high production rates with low weather sensitivity.

c) Disadvantages

Cost and availability, although with some forward planning both can be mitigated.

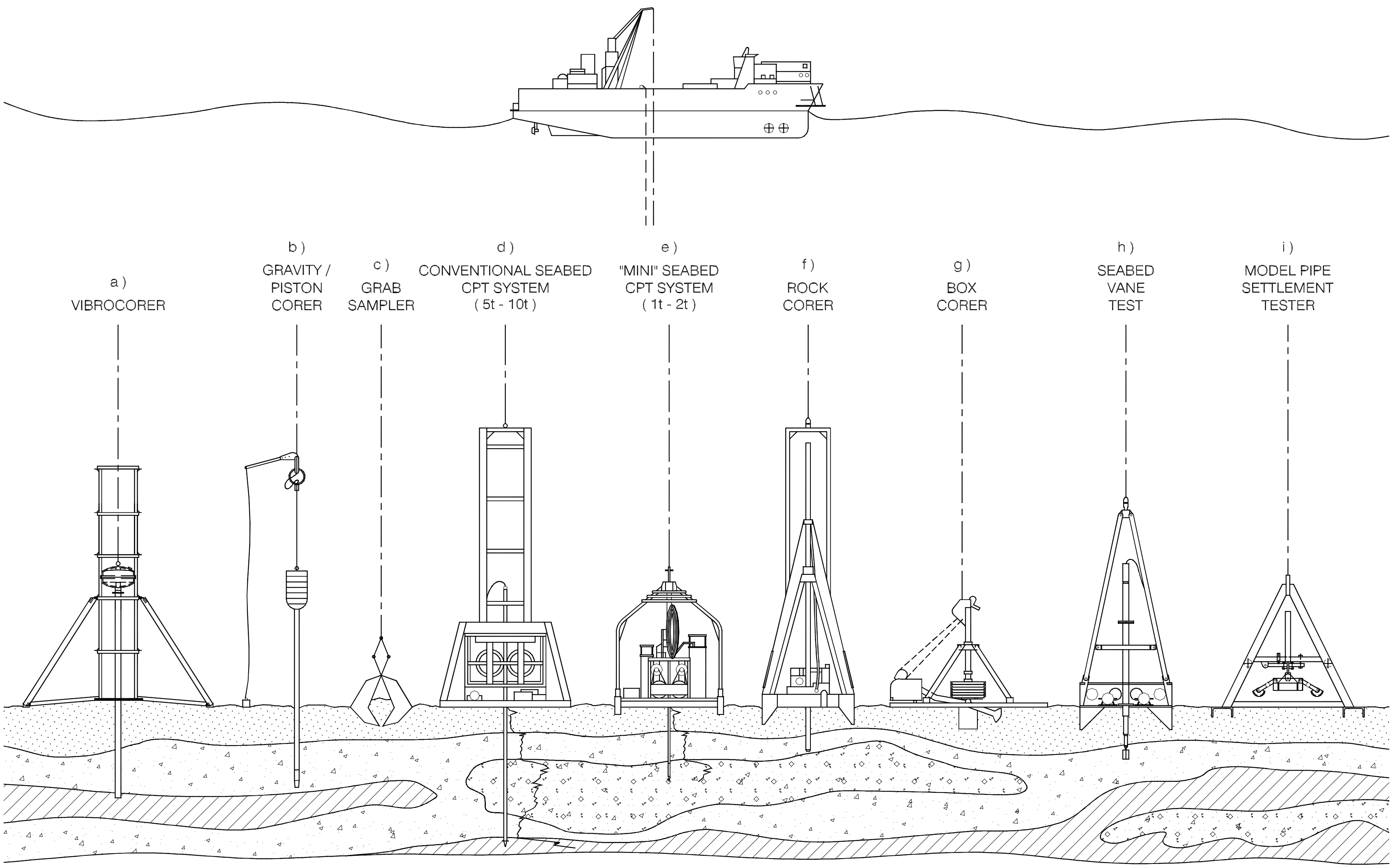


Fig. III –1

Examples of Seabed Sampling and In-situ Testing Systems

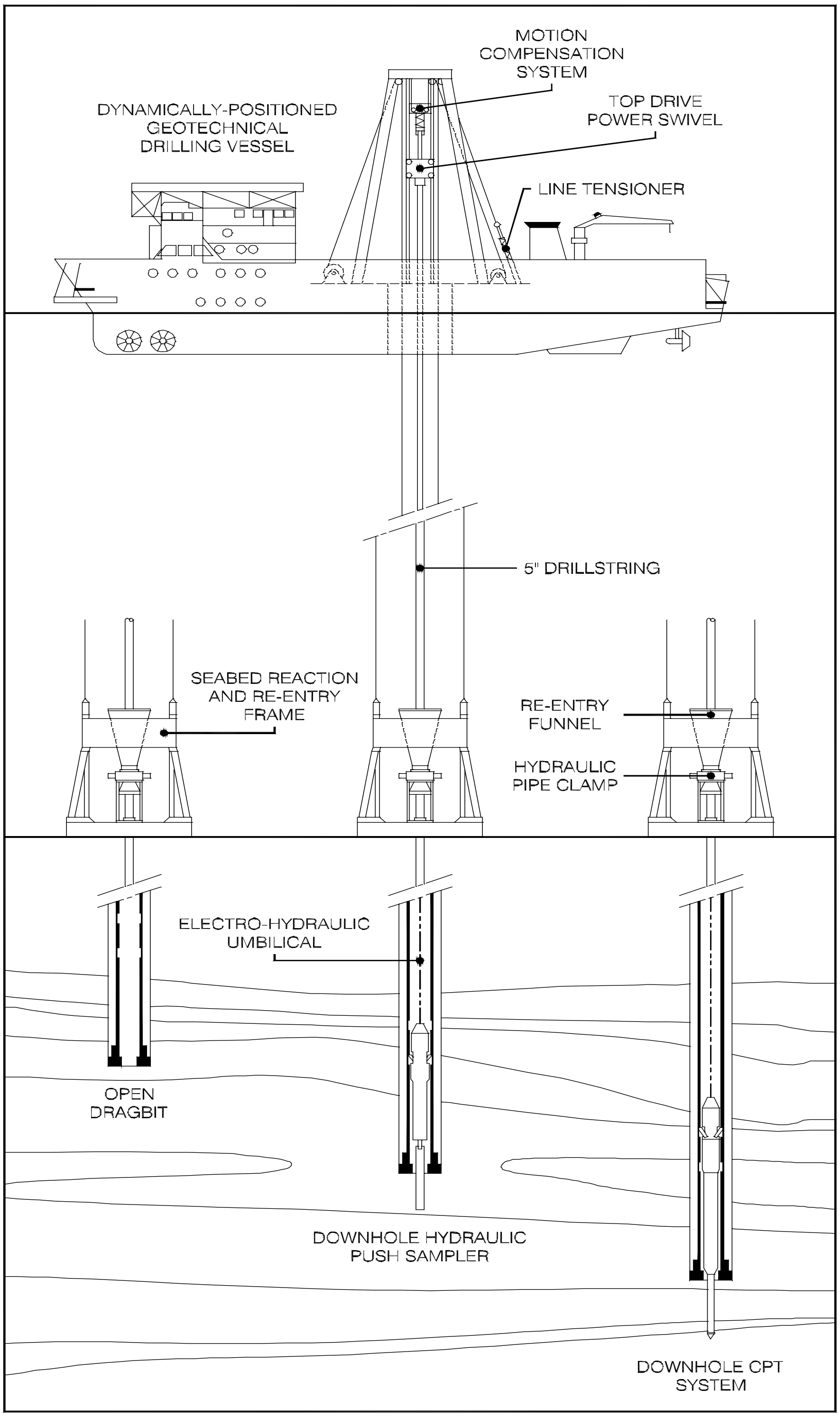


Figure III – 2

Typical Configuration for Offshore Geotechnical Drilling, Sampling and In-situ testing