THE ROLE OF THE ROV WITHIN INTEGRATED GEOTECHNICAL AND HYDROGRAPHIC SITE INVESTIGATION

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THE ROLE OF THE ROV WITHIN INTEGRATED GEOTECHNICAL AND HYDROGRAPHIC SITE INVESTIGATION

by

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The role of the ROV within integrated geotechnical and hydrographic site investigation

The acquisition of marine survey data is traditionally undertaken from surface vessels including boats and temporary rigs. Translation of these techniques to the nearshore zone is a complex task and requires equipment adaptation and often the sacrifice of data coverage. The remotely operated vehicle (ROV) offers the potential for overcoming some of the standard nearshore survey concerns, providing remote intervention and data acquisition in areas of restricted access.

In situ testing is the most efficient and reliable method of acquiring data with minimal sediment disturbance effects. Research has been undertaken into the viability of nearshore cone penetration testing (CPT) which has shown the T-Bar flow round penetrometer to be a possible solution. Data could be acquired in sediments with undrained shear strengths of up to 300 kPa from a bottom crawling ROV weighing 260 kgf and measuring 1 m in length by 0.6 m in width. The collection of sediment cores may be necessary in areas requiring ground truthing for geophysical or *in situ* investigations. A pneumatic piston corer has been designed and manufactured and is capable of collecting sediment cores up to 400 mm in length, 38 mm in diameter, in sediment with undrained shear strength of 17 kPa. To ascertain additional sediment characteristics *in situ*, a resistivity sub-bottom profiling system has also been designed and tested and allows for discrimination between sediment types ranging in size from gravel to silt.

The integration of equipment and testing procedures can be further developed through the use of integrated data management approaches such as geographical information systems (GIS). An off-the-shelf GIS, ArcInfo 8, was used to create a GIS containing typical nearshore data using the Dart estuary as a case study location.

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Nomenclature

AC - Alternating current

ACOP - Approved Code of Practice

AUV - Autonomous underwater vehicle

BMS - Benthic Multicoring System

BP - British Petroleum

CAUC - Anisotropically consolidated undrained triaxial compression tests

CD – Chart datum

CEC - Crown Estates Commission

CL – Centre line

CPT – Cone penetration system

CPTU – Piezocone penetrometer

CRS - Constant rate of strain

CTD - Conductivity-temperature-depth

DC - Direct current

DGPS - Differential GPS

DBMS - Database management systems

EEZ - Exclusive economic zone

EP - Electrical profiling

ESRI - Environmental Systems Research Institute

FICUS - Formation imaging and coring for unconsolidated sediments

GIS – Geographical information system

GPR - Ground probing radar

GPS - Global Positioning System

HSC - Health and Safety Commission

ICA - Inside cutting-edge angle

ICR - Inside clearance ratio of sampler

ICZM - Integrated coastal zone management

ID – Internal diameter

IHO - International Hydrographic Organization

IRTP - International Reference Test Procedure

LBL - Long baseline

LIDAR - airborne Light Detection and Ranging

MBARI - Monterey Bay Aquarium Research Institute

MBMGIS - Monterey Bay Marine GIS

MCS - Multiple-Barrel Coring System

MHWN – Mean high water neaps

MHWS – Mean high water springs

MLWS – Mean low water springs

MLWN – Mean low water neaps

NOAA - National Oceanic and Atmospheric Administration

OBC - Ocean bottom cables

OCA - Outside cutting-edge angle

OD – Outside diameter

OS – Ordnance Survey

OSIRIS - Ocean Survey Integrated Research Information System

PAT – Point attribute table

PSA - Particle size analysis

QC - Quality control

RCPTU – Resistivity piezocone

RDGPS - Relative differential GPS

RIDDOR - Reporting of Injuries Diseases and Dangerous Occurrences Regulations

ROV – Remotely operated vehicle

RT-GIS - Real-time geographical information system

SBL - Short baseline

SCUBA – Self contained underwater breathing apparatus

SS - Simple shear

STRATAFORM - STRATA FORmation on the Margins

TIN - Triangular irregular network

TX – Triaxial

UKHO – United Kingdom Hydrographic Office

USBL - Ultra short baseline

UTM - Universal Transverse Mercator

VES - Vertical electrical sounding

VRU - Vertical reference unit

WADGPS - Wide area GPS

WGS – World Geodetic System

A_c - Cone base area

A_s - Sleeve surface area

B - Outside diameter of core tube

B_q - Ratio between excess pore pressure and the net bearing pressure

c_v - Coefficient of consolidation

D - Diameter of cone

D_d - Degree of disturbance

f_s - Sleeve friction

F_s - Total force acting on sleeve

H_1 - Height relating to inside-cutting edge angle

H_2 - Height relating to outside-cutting edge angle

I_P - Plasticity index

k - Shear strength constant

M_s - Dry mass solids

M_w - Mass water

N_b - Bar factor

N_c - Cone factor

Q_b - Total force on bar

Q_c - Total force acting on cone

q_b - Measured bar resistance

q_c - Cone resistance

q_{cnet} - Net bearing resistance

R - External core radius

R_1 - Internal core radius at inside cutting edge

R_2 - Internal core radius

S_u -Undrained shear strength

t - Core tube wall thickness

u_o - Change in ambient pore pressure - relative to depth at which cone was zeroed

v - Speed of penetration

z - Depth

α - Area ratio

Δe - Change in void ratio

e_0 - Initial void ratio

σ - Overburden pressure

ρ_s - Density solids

σ'_v - Vertical effective stress increase - relative to depth at which cone was zeroed

ρ_w - Density water

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Noli nothis permittere te terere

AUTHOR'S DECLARATION

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award.

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Signed. [signature]

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Chapter 1

Introduction

Nearshore engineering surveys are undertaken for the purpose of gathering information pertaining to the bathymetry and morphology of the seabed, along with the geotechnical characteristics and geophysical profiles of the sub-stratum. Standard practice tends to involve a low resolution bathymetric and sub-bottom survey of the approximate area of interest, followed by a higher resolution, site specific investigation entailing detailed analysis of the location and form of the materials present. The traditional survey technique in the nearshore region is to use surface towed equipment and jack-up rigs, with diving teams and ROVs (Remotely Operated Vehicles) acting as support systems, performing very basic investigation tasks. However, the potential for expanding the capabilities of these supplementary systems is vast, with the possibility of offering the opportunity to acquire high-resolution survey data in their own right.

The importance of nearshore surveys has been recognised by large survey companies such as Fugro UDI Ltd:

> *"Inshore areas can present a difficult environment in which to conduct hydrographic and geophysical surveys. Yet these surveys are increasingly important in providing essential data for the safe landfalls of subsea cables and pipelines and for site surveys for offshore renewable energy projects."*
>
> (Oceanspace, 2001a)

Pipeline landings, sewage outfalls, land reclamation, coastal engineering construction and hydrographic charting are just some of the examples of the requirements for nearshore surveys. The problems associated with survey in this region are addressed in this thesis.

1.1. Aims

The aims of this research are:

1. To assess the feasibility of using a remotely operated vehicle (ROV) to acquire geotechnical and hydrographic site investigation data.
2. To investigate the importance of equipment and data integration in geotechnical and hydrographic site investigation.

1.2. Objectives

In order to fulfil the aims of this research the objectives are:

1. Investigation into current survey techniques
2. Development of new ROV based tools for investigation in the nearshore zone
3. Comprehensive testing of designed systems
4. Review of integrated data management systems
5. Application of integrated management system to field site of the Dart estuary

1.3. Project overview

This research consists of a literature review of current marine survey techniques, chapters describing the development of new systems and a case study of the Dart estuary with reference to the suitability of geographical information systems (GIS) as a data management system in the nearshore zone.

The Marine survey techniques chapter describes a range of current survey and site investigation techniques and through a review of the literature highlights three techniques not as yet fully operational in the nearshore zone. Chapter three describes the proposed nearshore survey ROV and includes suggestions as to the fundamental design criteria. The cone penetration testing (CPT) chapter draws together many sources of literature for the design of a system capable of operation from the proposed ROV. Chapters five and six, Sediment coring and Resistivity testing, describe two systems designed, built and tested as part of this research and how they compare with current investigation techniques. Chapter seven, The Dart estuary a case study, investigates the suitability of GIS as a solution to the data management issues faced during a marine survey in a typical nearshore environment. Finally a discussion and summary chapter indicates the main findings of the research and includes some suggestions for further study.

Chapter 2

Marine survey techniques

2.1. Introduction

Hydrographic, geophysical and geotechnical survey techniques, have in the main, been developed for use in the offshore environment where the largest spatial extent needs to be surveyed in the shortest possible time. Many of these techniques have been further adapted to overcome the problems faced when acquiring data in deep water. The nearshore environment poses an alternative set of problems, to the surveyor, based on restricted manoeuvrability and water depth. To optimise survey in the nearshore zone, allowing high-resolution data acquisition, current techniques need to be adapted to fit the location constraints. This chapter examines the current survey techniques and investigates the reasons why these methods may not always be the most appropriate or efficient in the nearshore environment.

2.1.1. Surface techniques

Traditional surface based survey techniques are based either on boats or on temporary platforms such as jack-up rigs. In some instances surveys can also be undertaken from the land or from marine structures such as pontoons. The primary concern in any surface based operation is the ability to provide a stable platform. Wave and tidal action, inherently prevalent in nearshore or shallow water create instability in the water column that must be overcome if reliable data is to be acquired. The movement of a side scan fish in the water column creates noise in the recorded data and the vibration of a cone penetrometer (CPT) as it penetrates the sediment adversely affects the quality of the data being collected.

The techniques employed for acquiring survey data in the nearshore zone are hindered by many difficulties inherent to the location. Unless a steep drop off is present at a site, the first problem encountered is that of water depth. However steep the seabed gradient, there will always be a transition zone between the sea and the land in which water based craft cannot operate and to which land techniques cannot extend. The standard approach would be to overlap the land and marine data by extending the land based techniques as far seaward as is possible at low water. This method of splicing data cannot, however be achieved in areas where the seabed gradient is very shallow, the foreshore comprises materials with very low bearing capacity and obviously cannot be applied in areas such as cliff bases where there is little or no land platform.

The second problem encountered is that of manoeuvrability in the potentially congested nearshore zone. Engineering investigations are often required to be undertaken in harbours and marinas, thus facing the problem of limited accessibility due to the presence of structures such as jetties, the vessels themselves and the numerous associated buoys, anchor chains, etc. Thirdly, environmental parameters including tidal fluctuations, strong currents and the associated sediment transport can also pose difficulties when investigating in these regions. It is also possible that in this age of strong environmental policies that it would be thought undesirable to take a motor vessel into protected nature areas such as wetlands, thus leaving another gap in the survey zone.

The surface vessel is potentially limited in its access to the entire survey site although it offers the ability to obtain large volumes of data relatively quickly. The restrictions in coverage occur due to the draught of the vessel and the layback of the equipment in the water. Running survey lines parallel to the seabed contours can help to reduce these problems, however, the success of this method is very much dependent on the tidal movements and the strength of water currents. Alternatively, hull mounted equipment can be utilised to increase accessibility, although this can require the use of complex mounting structures which may take a long time to fit and calibrate, thus adding substantially to the cost of the spread.

The vessels used for offshore survey are by necessity large and have many specialist modifications including large lifting frames and moon pools. The Skandi Carla (Plate 2.1) is Fugro-UDI's multi-purpose ROV survey and construction support vessel. It is 83.85 m long, 19.70 m wide and has a draught of 6.1 m. The vessel has a helideck, a moon pool and three deck cranes. It has an endurance of 40 + days and a maximum speed of 15 knots (Fugro UDI b).

the area covered is very much time dependent. The fluent movement of divers is also crucial in maintaining the state of the seabed, disturbance of which may distort subsequent geotechnical analysis.

There are three main limitations of diver surveys: equipment, safety and cost. The equipment that can be carried by a diver is restricted in terms of payload and type. Buoyancy can be altered to increase the payload capacity of a diver but ultimately the feasible payload is low. The type of equipment that can be carried is limited due to the practicalities of swimming with it and the physical effect on the diver's health e.g. the inherent dangers of using electrical equipment underwater. This point links in to the other major limitation relating to diver surveys, that of health and safety.

The Health and Safety Commission (HSC) have prepared an approved code of practice for commercial diving projects inland/inshore (Health and Safety Commission, 1998). The introduction and scope of the Code sets out the areas covered:

> *"This Code applies to all diving projects conducted in support of civil engineering or marine-related projects:*
> *(a) inshore within United Kingdom territorial waters adjacent to Great Britain (generally 12 nautical miles from the low water line);*
> *(b) inland in Great Britain including in docks, harbours, rivers, culverts, canals, lakes, ponds and reservoirs"*
>
> (Health and Safety Commission, 1998)

This means that any nearshore engineering works have to comply with the regulations set out by following the Approved Code of Practice (ACOP). The Code includes many areas that may be of concern when costing a survey, for example the minimum number of personnel required:

> *"Regulation 6 (3) (a) 77 ACOP: The minimum team size normally required to conduct a dive safely within the scope of this Code is four – a supervisor, a working diver, a standby diver and a tender for the working diver."*
>
> (Health and Safety Commission, 1998)

The time that divers can spend in the water is dependent upon the maximum required dive depth and the air supply methods in place e.g. divers with air tanks are limited by the capacity of the tank. The deeper the dive, the shorter the length of time available 'in water' (Table 2.2) leading to the requirement for more divers. This increase in personnel is more than likely to lead to variability in the data acquired if manual recording techniques are employed. Furthermore, the working performance of a diver is subject to variation with submersion time due to fatigue, placing a question mark over the reliability of data acquired.

Depth (m)	Depth (ft)	Time (min)	Time (Hours & mins)
3.0	10	unlimited	unlimited
4.6	15	unlimited	unlimited
6.1	20	unlimited	unlimited
7.6	25	595	9 – 55
9.1	30	405	6 – 45
10.7	35	310	5 – 10
12.2	40	200	3 – 20
15.2	50	100	1 – 40
18.2	60	60	1 – 0
21.3	70	50	0 – 50
24.4	80	40	0 – 40
27.4	90	30	0 – 30
30.5	100	25	0 – 25
33.5	110	20	0 – 20
36.6	120	15	0 – 15
39.6	130	10	0 - 10
42.7	140	10	0 - 10
45.7	150	5	0 - 5
48.8	160	5	0 - 5
51.8	170	5	0 - 5
54.9	180	5	0 - 5

Table 2.2: Diver time table (U. S. Navy, 1999)

The physical well being of divers also affects the running of a survey operation as addressed by

> *Regulation 13 (1) (b) 146 ACOP:*
> *People who dive in a diving project and who consider themselves unfit for any reason, for example, fatigue, minor injury, recent medical treatment, must inform their supervisor. Even a minor illness, such as the common cold or a dental problem, can have serious effects on the diver under pressure, and should be reported to the supervisor before the start of a dive."*
> (Health and Safety Commission, 1998)

Emergency situations such as decompression sickness, must be given due consideration beforehand and the provision made for treatment:

> *"Regulation 6 (3) (b) 110 ACOP: The diving contractor has a responsibility to ensure the provision of facilities so that a diver can be recompressed in an emergency, should this be necessary."* (Health and Safety Commission, 1998)

Regulation 6 goes on to set out the minimum standards for the location of treatment centres in relation to the specific type of dive being undertaken, for example:

> *"Regulation 6 (3) (b) 111 ACOP*
> *(b) for dives over 10 and up to 50 metres with either:*
> *- no planned in-water decompression; or*
> *- with planned in-water decompression of up to 20 minutes,*

a suitable two-person, two-compartment chamber should be no more than 2 hours travelling distance from the dive site;"

(Health and Safety Commission, 1998)

Although these codes of practice are complex and numerous, they are generally fairly straight forward to adhere to when working in the nearshore zone as a direct result of the shallow water and the proximity to the coast. However, they restrict the flexibility of the survey team, i.e. moving into deeper water or further offshore to follow up interesting data is not a straightforward change of location. The Health and Safety Executive, maintain a record of diving incidents, an example of which can be seen in Table 2.3:

RIDDOR category	01/04/2000 – 31/03/2001
Public non-fatal	2
Over 3 day	2
Major injury	5
Fatality	5
Dangerous occurrence	22

(RIDDOR: Reporting of Injuries Diseases and Dangerous Occurrences Regulations 1995)
Table 2.3: Diver incidents (inshore) (Health and Safety Executive, 2001)

An example of the seemingly harmless environment in which serious incidents can occur is illustrated by one of the above fatalities:

"08/11/2000 - Working at a depth of 3 m on a construction project in Canary Wharf using Surface Supplied Equipment. Communications were lost and the diver was recovered unconscious from the water and died."

(Health and Safety Executive, 2001)

One might assume that a dive of 3m in an inshore waterway would be one the 'safest' environments in which a survey could be undertaken. The above example illustrates that accidents can and do happen in routine dive operations. Personal communication with a commercial offshore diver, (Limbrick, 2001), has highlighted the dangers associated with submerged survey. In correspondence, he emphasised the simple fact that most diving incidents occur in 'normal' circumstances i.e. at the surface or during standard diving procedure. Offshore diving is generally regarded as more dangerous than inshore diving due to the depth of water and therefore the saturated diving techniques employed. However, these operations are by default more closely supervised with a vast array of technical staff and equipment close at hand.

Due to the high personnel, equipment and safety issues, which are part and parcel of diving surveys, the cost can be high. Pricing structures are commercially sensitive and thus it is difficult to provide a comparison between techniques. However, two price guidelines have been obtained to give an indication as to the extent of the financial commitment (Tables 2.4 & 2.5).

	Cost per day
Saturation system with hyperbaric lifeboat	£1300
Diving consumables	£200
Superintendent	£500
Supervisor	£475
4 Divers	£500 each
Life Support Technicians	£360
Sub total	£5195
Overhead and profit (35%)	£1820
Total (excluding mobilisation / demobilisation and diving gas)	**£7015**

Table 2.4: Cost of 50 m saturation dive survey

	Cost per day
Four divers (Superintendent, Diver, Dive tender, Supervisor)	£650
Boat hire (£40 per hour)	£320
Total (excluding mobilisation / demobilisation and diving gas)	**£970**

Table 2.5: Cost of Scuba dive survey

It must once again be noted that the cost per day is based on an 8 hour timescale and not a full 24 hour day. In this instance continuous survey would become an expensive option due to the personnel requirements.

The amount of equipment a diver can carry is limited by his payload capacity and this stretches to even the most basic survey instruments such as positioning systems. There are products on the market which allow for the positioning of divers via miniature acoustic devices (Desert Star Systems, 2002) thus overcoming this problem. In terms of acquiring geotechnical engineering data, the diver offers some advantages but is also faced with limitations. Many of the difficulties that will be discussed relating to the remote acquisition of data are not an issue to a diver. For example, the diver can use a simple hand held and operated shear vane at the desired location, take a reading, move on to another location and repeat the measurement with the maximum of ease. However, coping with depth, time and speed of survey and the ability to carry and operate many pieces of equipment simultaneously are all issues which the diver based survey needs to address. In summary, the diver's main competitive edge is that he/she offers the ability to utilise very simplistic methods, which obviously come much cheaper and are more mechanically reliable than the more complex methods employed elsewhere, but at a significant cost.

2.1.2.2. ROVs

The investigation/eyeball ROV has enormous potential as a survey tool that at present is being largely overlooked in nearshore engineering applications. Offshore pipe laying operations are monitored by an ROV as standard practice to ensure that acceptable touchdown is achieved. Subsequent inspections of the pipelines to check for corrosion or free-span are frequently carried out by ROVs as an alternative to or in conjunction with side scan sonar. Further developments of the ROV in these areas of activity are discussed below but it is important to acknowledge the relevance of the ROV in its current underdeveloped state in the nearshore environment.

The three main advantages of using an ROV for any type of survey are the acquisition of a permanent record, the option of utilising an additional wide range of equipment and the negligible risk to human safety. The ROV always carries a video camera with a real time surface link to allow the pilot to navigate the survey site, thus creating a permanent record of the area. In addition to this, further equipment such as manipulator arms and remote sensing devices can be utilised, allowing the acquisition of supplementary information.

In terms of the safety element, the ROV obviously becomes a more attractive solution with increasing water depth, as there is no associated risk to human health. In the nearshore environment this is unlikely to be a consideration, but with further development, this advantage may promote the ROV as a serious alternative to the techniques currently employed in deeper water.

Three issues are faced when using an ROV; the umbilical, the control mechanism, and equipment downtime. An umbilical tether is attached to the ROV for the input of power and for surface control purposes. This can restrict manoeuvrability and access into areas with complex structures such as piers or jetties. The control mechanism, which consists of three orthogonal thrusters can also inhibit access, again due to the possibility of entanglement. For example, it would be unwise to fly the ROV too close to a seaweed bed. Downtime due to equipment failure must be a consideration when planning an ROV based survey. Unless a complete set of spare parts or indeed even a spare ROV are held by the operators on site, there is the possibility of delay in acquiring parts as well as the time required for repair.

The ROV is often confined to use in deep water and advancements with regard to the specific application of the ROV in these circumstances is continuous, for example the advent of remote electromagnetic weld inspection techniques (Raine, 1996). However, a variety of applications and locations are being investigated in order to increase its scope, including:

- looking at seafloor disturbance caused by anchor movement utilising video and still cameras and a laser ranging device (Hardin et al., 1992).
- studying marine pollution using equipment including LIDAR (airborne Light Detection and Ranging) and acoustic sensors for measuring acoustic impedance (Gereit et al., 1998).
- working in midwater collecting samples using a suction sampler and a detritus sampler (Robison, 1992).
- adding a platform and a wave compensating system to the ROV to aid movement along the bottom in poor weather (Edwards, 1991).

A large number of the ROVs being utilised in the offshore survey industry at present have been designed /adapted specifically for the intended role although many are off-the-shelf systems with adaptations made as necessary. The dimensions of these ROVs varies according to the task in hand (Table 2.6), however the majority may be regarded as large pieces of equipment requiring specialist vessels for deployment and recapture (Plates 2.4, 2.5, 2.6).

Defining the cost of an ROV survey is complicated by the large range of vehicles and the fact that they may or may not be equipped to perform the required task. For the purpose of comparison with the cost of a diver survey, in terms of simple visual inspection, a rough estimate can be provided. A day rental of a Benthos Minirover MK II, pilot and tender would cost approximately £600, excluding mobilisation and demobilisation (Seascape, 2002). The ROV would be fitted with basic equipment including a tracking system, a still camera, and a manipulator arm (Seascape, 2002). As a simple visual inspection tool the ROV is £370 a day cheaper to hire than a diving team (Table 2.5). However, as the potential capabilities of the two approaches varies so considerably this price comparison must remain a simple comparison and not be taken as a definitive guide.

Autonomous underwater vehicles (AUVs) offer an alternative solution to remote intervention. The term AUV is often applied to vehicles that are controlled remotely without the use of an umbilical. In the strictest sense AUVs do not have an umbilical and therefore by definition act autonomously i.e. they follow commands set prior to survey. If an operator is controlling the vehicle in real time then it should be referred to as an ROV.

AUVs offer an alternative to diver and ROV survey, with their primary advantage being the autonomous collection of data. They have been designed predominantly for work in deep water where some ROV characteristics, for example the prerequisite for an umbilical, might be problematic:

> *"The key area of concern is the extra payload created by tethers up to 10,000 ft long – not just on the submerged ROV, but also the attendant surface vessel."*
>
> (Offshore, 2002)

The HUGIN UUV (untethered underwater vehicle) is 4.8 m in length, weighs approximately 700 kgf in air and carries a Simrad EM3000 multibeam echosounder (Størkersen et al., 1998). It has been specifically designed for *"cost effective mapping of seabed topography down to 600 m water depth"*. The Theseus AUV was designed to lay fibre-optic cable in water depths ranging from 50 to 600 m, has a survey speed of 3.7 knots and a range of 920 km (Ferguson et al., 1999). The AUV is 10.8 m in length, 1.28 m in width, and with the maximum payload of 220 km of cable weighs 8,600 kgf.

The detection of very shallow mines was the design incentive for the Mopheus Ultramodular AUV (Smith et al., 2001). In order to satisfy the requirement for survey in shallow water the AUV design goals included a weight limit of 40 – 100 kgf and an outside diameter of less than 50 cm. The Alistar AUV measures 3.5 m in length, 1.4 m in height, 1.35 m in width, weighs 1000 kgf and is capable of speeds of up to 9 knots (Offshore, 2002). The AUV has four horizontal thrusters and two vertical thrusters, which combined with the unique shape, allows the unit to hover, a capability not normally associated with AUVs.

The AUVs briefly described above are just a sample of many systems being utilised in the offshore industry as an alternative to surface vessel and ROV surveys. It is likely that the AUV will become more commonplace and may, in time, replace the ROV. However due to tight design constraints related to the hydrodynamics of the AUV the addition of testing equipment can be problematic.

ROVs appear to offer solutions to some of the difficulties faced when surveying in the nearshore zone. Although not directly comparable, divers, ROVs and AUVs have many similarities and individual advantages and disadvantages. The move towards survey in deeper waters has led to rapid developments in ROV/ AUV technology and brought an associated move away from diver activities. Although this study concentrates on survey in the shallower waters the ability to transfer the techniques investigated to deep water sites is not possible with diver based methods. This flexibility in design approach and the current awareness of the future increase in ROV and AUV development is the basis for this study. The complex design features of AUVs make them slightly less adaptable and certainly not an off-the shelf option. The current equipment adaptations and possible future uses of ROVs will therefore be investigated in this thesis in preference to the use of divers or AUVs.

2.2. Hydrographic

Hydrographic data in this context will include bathymetry (seabed depth data) and morphology (seabed structure) information. Both of these processes are well practised and the techniques have evolved over the years so that highly accurate and reliable data may be obtained from a range of environments and platforms. The International Hydrographic Organization (IHO) (1998) has published 'Standards for Hydrographic Surveys' which define the acceptable limits for surveys undertaken in a range of areas. The two orders that relate to surveys of the nearshore zone are summarised in Table 2.7:

Order	Special	1
Examples of typical areas	Harbours, berthing areas and associated critical channels with minimum underkeel clearance	Harbours, harbour approach channels, recommended tracks and some coastal areas up to 100 m
Horizontal accuracy (5% confidence level)	2 m	5 m +5% of depth
Depth accuracy for reduced depths (95% confidence level)	a = 0.25 m b = 0.0075	a = 0.5 m b = 0.013
100% bottom search	Compulsory	Required in selected areas
System detection capability	Cubic features > 1 m	Cubic features > 2 m in depths up to 40 m; 10% of depth beyond 40 m
Maximum line spacing	Not applicable as 100% search compulsory	3 x average depth or 25 m whichever is greater

Where a = constant depth error; b*d + depth dependent error

b = factor of depth dependent error; d = depth

$\pm\sqrt{[a^2 + (b*d)^2]}$

Table 2.7: Summary of minimum standards for Special order and order 1 Hydrographic surveys (International Hydrographic Organization, 1998)

These standards provide a regulated method of ensuring that hydrographic surveys meet the advised accuracy, precision and coverage criteria and take into account the specific location based requirements and restrictions.

2.2.1. Bathymetry

The bathymetry of the seabed can be acquired using a variety of different techniques (see below) although the majority operate on the principle of acoustic propagation. An acoustic beam transmitted from a transducer on the surface vessel, is reflected from the seabed surface, and the return detected by the same transducer. The total travel time of the signal can then be used in conjunction with the speed of sound in water to calculate the depth of water:

$$\text{Distance} = \frac{\text{Speed} * \text{Time}}{2}$$

Note: This distance (depth) value needs to be corrected for height of tide and the vertical position of the transducer face and thus eventually provides a depth referenced to chart datum.

Simple bathymetric surveys are undertaken using a single or dual frequency echo sounder, hull mounted on an inshore survey vessel. Survey lines are established at the required intervals (Table 2.7) and the vessel acquires normal incidence depth data whilst moving along these lines. High frequency echo sounding transducers allow for high resolution depth measurements but have lower depth penetration due to signal attenuation (Table 2.8). In coastal waters where water depth is limited, higher frequency systems are employed to offer high-resolution bathymetry.

The advantage of echo sounding is that data can be acquired quickly with a relatively simple piece of equipment, which requires limited calibration. The primary disadvantage is that data are only collected directly below the echo beam therefore necessitating the use of interpolation techniques in order to acquire useful charts. Although echo sounders use normal incidence reflections for acquiring depth data, the return is actually composed of a seabed insonification footprint (Fig. 2.1), which varies in size depending on water depth and beamwidth.

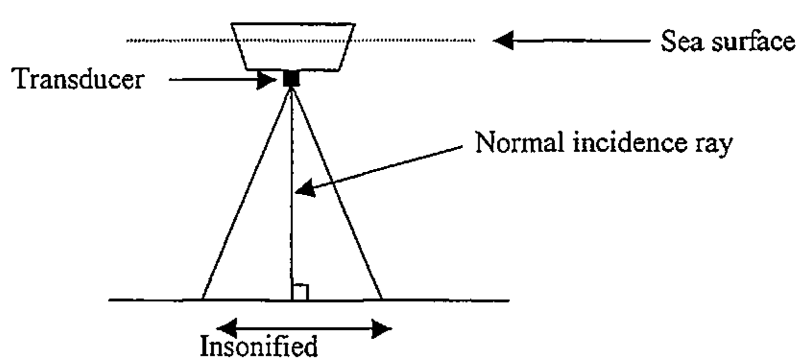


Figure 2.1: Echo sounder footprint
Note: A correction for the vertical position of the transducer in relation to the sea surface should be applied to the water depth calculations.

In low resolution surveys this footprint does not usually pose a problem, however, in high-resolution surveys, data can be affected by earlier returns from part of the footprint other than the normal incidence ray-path (Fig. 2.2).

Make	Model	Frequency	Depth range	Accuracy	Resolution	Reference
Oceandata	Bathy-1500	12 kHz, 24 kHz, 33 kHz, 40 kHz, 100 kHz, 200 kHz	0-5000 m	0-40 m = ± 2.5 cm 40-200 m = ± 5.0 cm >200 m = ± 2.5 cm	1 cm <= 99.9 units 10 cm > 99.9 units	(Oceandata, 2001)
Oceandata	Bathy-500MF	33 kHz, 40 kHz, 50 kHz, 200 kHz	0-640 m	+ 0.5%	0.01 units depth < 100 m 0.1 units depths > 100 m	(Oceandata, 2001)
Navitronic	Navisound 100PC	28-35 kHz 190-225 kHz	0.5-640 m	7 cm at 33 kHz 1 cm at 210 kHz	1 cm	(Navitronic, 2001)
Simrad	EA 500	12 kHz, 18 kHz, 27 kHz, 38 kHz, 49 kHz, 120 kHz, 200 kHz, 710 kHz	0 – 13000 m		cm < 1000 m dm > 1000 m m > 10000 m	(Kongsberg Simrad, 2001)

Table 2.8: Echo sounders

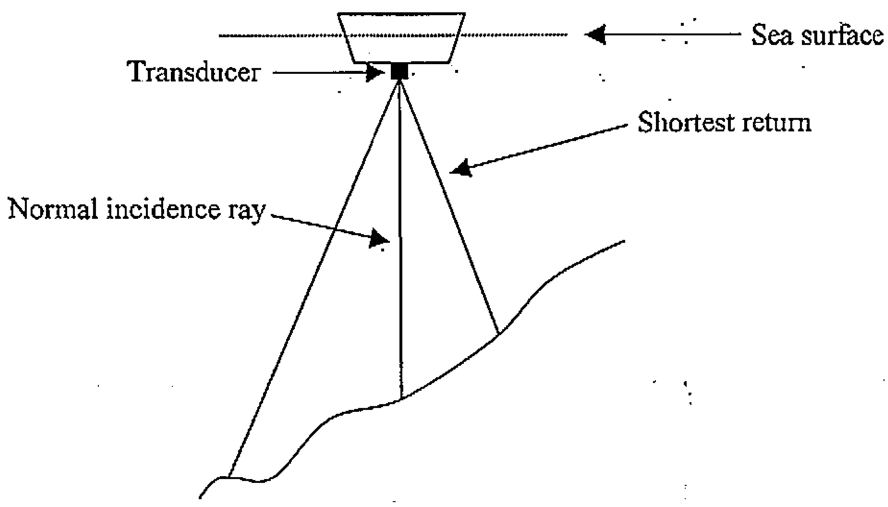


Figure 2.2: Echo sounder footprint returns

In a high-resolution survey this anomalous return would introduce significant error to the bathymetric chart, where the depth obtained actually represents a different location. In nearshore applications this problem is reduced as a result of the limited water depth i.e. signal divergence is narrow but may be observed where steep channels are being surveyed.

The acquisition of bathymetric data under permanent and floating structures may be fundamental to nearshore investigations; the build up of sediment around pontoon legs and at outfalls are just two examples of regions of possible interest. In these situations the ROV offers the ability to enter previously inaccessible areas, thus providing the opportunity to acquire bathymetric data. Depth measurement from an ROV can take two forms: echo sounding and depth sensing. An echo sounding survey would be undertaken by acquiring depth via the standard echo technique, but by supplementing this information with a value for the depth of the ROV in the water at the same instant. This depth value would most likely be obtained from a pressure sensor on the ROV. The alternative technique is to fly the ROV at a constant height above the seabed via an altimeter system, and then combine this value with the pressure derived depth value from the ROV.

Unfortunately ROV depths derived from pressure sensors are subject to variation as a direct result of wave oscillation (Fig. 2.3). Variations due to pitch, roll and heave also need to be taken into account and thus a motion compensator would be required.

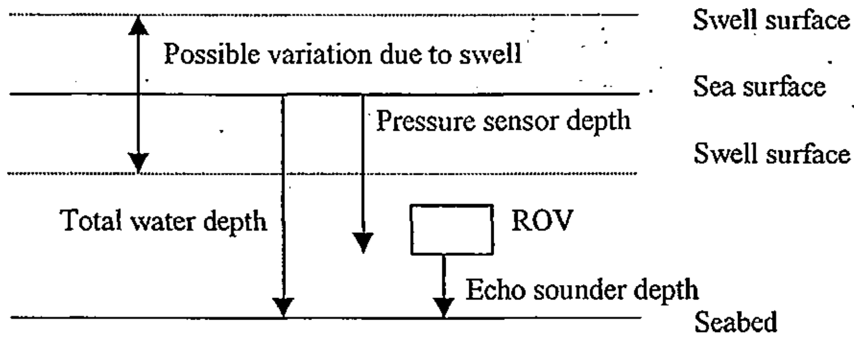


Figure 2.3: Variation of depth reading resulting from wave oscillation

For higher resolution seabed representations, seabed depth data are acquired over a swath width by using many beams simultaneously, a technique called multibeam survey (Fig. 2.4). If line spacing is determined such that the distance between lines is less than the swath width of the system, then overlap occurs. This technique ensures that a much larger percentage of the seabed is directly measured, thus a higher resolution contour chart can be created. Furthermore, if adjacent survey lines are run in opposite directions, then anomalous depth returns can be detected and eliminated.

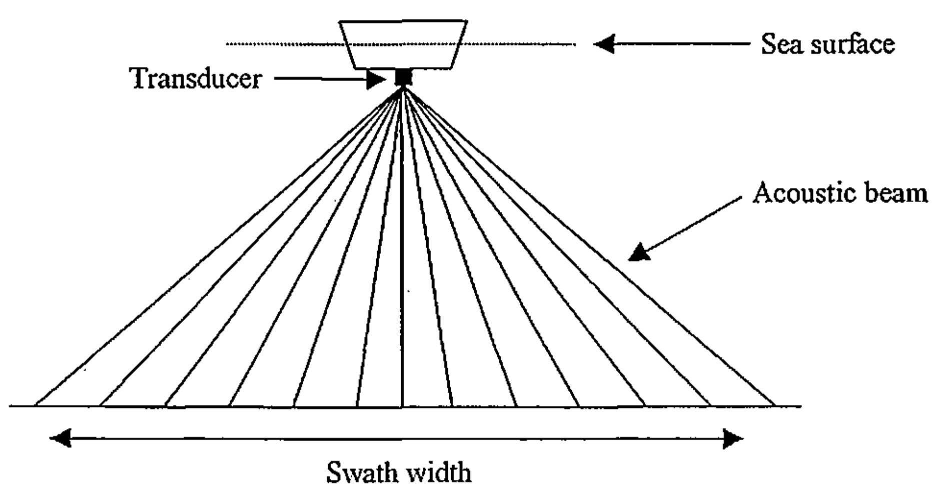


Figure 2.4: Multibeam echo sounding

One of the most useful features of the multibeam system is the ability to acquire data over a wide swath of seabed. In congested areas, the surveyor may be able to acquire depth data from locations inaccessible by vessel due to this feature (Fig. 2.5). It is important to recognise, however, that structures may interfere with the signal giving a distorted view of the seabed and thus an element of caution must be applied to data in these regions.

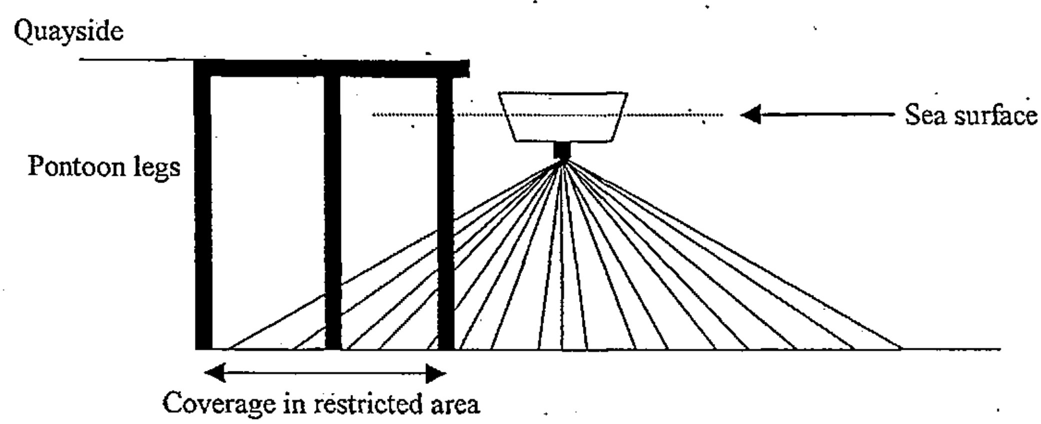


Figure 2.5: Acquiring inaccessible depth data using multibeam sonar

Multibeam surveying does however, have disadvantages, which are particularly problematic in inshore survey. At a meeting of the Southern Branch of the UK Hydrographic Society in February 2001 it was felt that:

> *"swathe bathymetry is NOT accepted as the standard for inshore hydrography"*
> (Heaps, 2001)

The primary reasons for this view are summarised below:

- *"Too expensive. The small operator will only use such expensive systems when the client pays.*
- *Too bulky and power hungry for small craft.*
- *Mobilisation and calibration considered to be rather long compared to traditional methods"*

(Heaps, 2001)

The unease surrounding multibeam survey was further vocalised at a training workshop held by Octopus Marine where:

> *"many delegates felt that they did not use the multibeam more was because it was just too complex and they didn't trust the results."*
> (Oceanspace, 2001b)

The Ross Mini-Sweep system has been designed specifically for use in shallow water and can be mounted on vessels small enough to be transported by road (Oceanspace, 2001c). However, even this system has its disadvantages when surveying in congested areas:

> *"Two 20-foot booms mounted on either side of the vessel will provide a 50-foot overall swath width."* (Oceanspace, 2001c).

Flying ROV survey systems allow bathymetric data to be collected from a wide area in a similar manner to those utilised in standard surveys. The Reson SeaBat 6012 is an example of a system that can be ROV mounted (Table 2.9).

Property	Specification
Measurement range	0.2 to 200 metres
Range resolution	5 cm
Max. vessel speed	20 Knots
Max. update rate	30 complete updates per second
Depth ratings	350 m or 500 m
Frequency	455 kHz
Number of beams	60
Field of view	90° (horizontal) by 15° (vertical)
Beam size	1½° (horizontal) x 15° (vertical)
Transducer weight	16 kgf (dry), 5 kgf (wet)

Table 2.9: Reson SeaBat 6012 multibeam specifications (Reson, 2001)

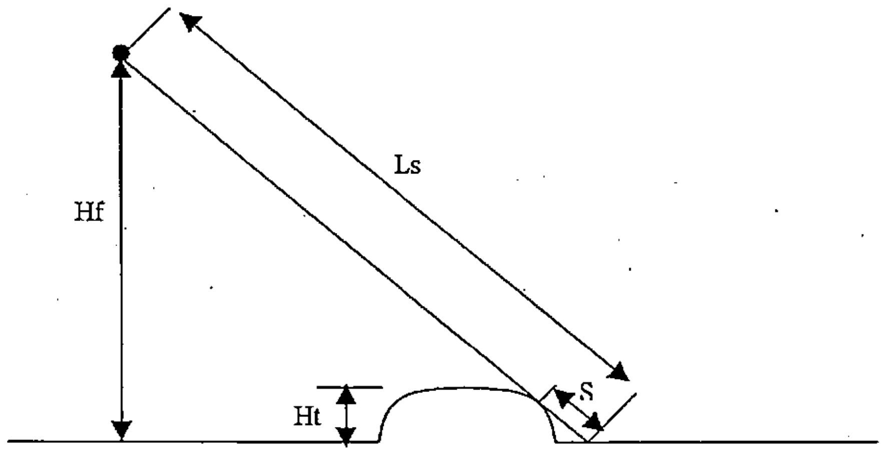
These units allow the user to acquire reliable high-resolution data in areas inaccessible to surface vessels and although are generally used offshore, are well suited to inshore survey.

2.2.2. Morphology

In addition to bathymetry, it is often useful to determine the morphology and sedimentological characteristics of an area of seabed. The distribution and variety of seabed material can provide important information with regards to the flux of sediment in an area resulting from meteorological, tidal and current activity. The two primary techniques used for this purpose are acoustic imagery (side scan sonar) and acoustic sediment classification (RoxAnn and Quester Tangent).

Side scan sonar provides the user with an image of the seafloor by recording the intensity of the acoustic returns as emitted and received by two oblique transducers (Fig. 2.6). Seabed slope and bottom materials dictate the strength of the return with normal incidence returns and 'hard' surfaces being the best reflectors. Records are usually displayed as a grey scale with strong returns represented by dark grey and with colour lightening as the signal decreases in strength. Acoustic shadows (areas which do not return signals) are therefore displayed as white areas on the record. Shade variation creates a virtual image of the seafloor, which can indicate variations in substrate, and the presence of man-made objects such as pipelines and sunken vessels (Plate 2.7).

The time taken for the signal to reach the seabed (measured as a slant range) may be used to indicate depth variations, although this is not as accurate as conventional depth sounding. A simple formula may then be used to calculate object height (Fig. 2.7).



$$Ht = \frac{S \cdot Hf}{Ls}$$

Ht = Height of object
S = Length of acoustic shadow
Hf = Height of fish above seabed

Figure 2.7: Side scan height calculation

As with echo sounders, higher frequency systems afford higher resolution and different systems may offer variations in the swath width and beamwidth. Side scan sonar can therefore provide not only an indication as to the morphology of the area with features such as ripples being easily recognised, but it can also provide detail as to the distribution of sediment groups. Ground truthing is required to calibrate the system, thus assisting the process of isopach mapping.

A slightly different approach is employed by systems such as Quester Tangent and RoxAnn whereby:

> *"The raw information collected is seafloor acoustic backscatter versus time and angle of arrival, and the character of these signals is dictated, for the most part, by the material properties of the substrate and by the micro-relief in the area insonified."* (de Moustier and Matsumoto, 1993)

The 'shape' of the seafloor is formed through small scale features such as individual grain characteristics including size and shape and larger scale features such as deposition patterns (e.g. ripples). The difference in simple echo sounder returns from a smooth and rough seabed surface is illustrated in Figure 2.8.

road transportable and can be assembled by two people utilising a 30 tonne crane (Seacore, 2002). This rig is just one example of the options open to engineers wishing to acquire *in situ* sediment information or samples; other larger rigs are also an option as are more traditional surface vessels. One of the limitations of small temporary rigs such as Skate 1 is the shallow draught. Due to this problem, transfer of personnel from launches to the rig and towing of the rig between sites is limited by wave conditions, in particular wave height. Wave heights of between 0.5 m and 1 m, frequently encountered in coastal locations, would limit if not halt survey operations and lead to an increase in standby time and consequently costs. Although in terms of location geotechnical testing is discrete and not continuous, the use of such large testing bases restricts the possible survey locations to those with sufficient space to house the platform. Testing in more restricted areas is more difficult to achieve and requires alternative solutions. A landing frame housing *in situ* testing equipment is one such alternative, as ROVs are another.

2.3.1. Sampling

Seabed sediment can be acquired through simple surface dredging or grab coring techniques, which allow a large volume of material to be collected quickly. However these techniques do not preserve the *in situ* characteristics of the material and can only be used for general classification purposes. Drill ships or rigs are often used in the offshore industry to obtain core samples utilising four primary techniques;

1. Gravity corers – penetrates sediment under force of gravity.
2. Piston corers – piston pushes tube into sediment. May be operated by pneumatic, hydraulic or mechanical systems.
3. Vibrocorers – rotational action vibrates the core into the sediment.
4. Hammer corers – driven into sediment (similar to pile driving).

Each of the mechanisms requires a significant degree of down-force to drive the core tube into the seabed and thus must be based on a stable platform. The platform must also be able to maintain position to ensure that the motion of the vessel does not affect the sampling process.

In this instance the diver coring system is very simplistic and relies on the use of a hammer for core tube penetration. Further coring mechanisms are reviewed in the coring chapter (chapter five).

2.3.2. *In situ* testing

Even if coring could be undertaken with no sample disturbance, the likelihood is that the process of storing and transporting the core to the laboratory will cause changes to the sample such as compaction and loss of moisture. *In situ* testing eliminates most of the disturbance opportunities although it must be recognised that the insertion of a probe for testing *in situ* will also disrupt the sediment structure.

Marine cone penetration and shear vane testing are performed as standard investigation techniques within the marine geotechnical field. The cone penetrometer system consists of a cone and a sleeve both with load cells to measure resistance. (Fig. 2.9). As the cone is driven into the sediment, the cone cell measures the total force acting on the cone (Q_c) and the sleeve cell measures the total force acting on the sleeve (F_s). These two values can be used to determine the cone resistance and sleeve friction (q_c and f_s respectively) using the formulae:

$$q_c = \frac{Q_c}{A_c} \qquad f_s = \frac{F_s}{A_s}$$

Where Q_c = total force acting on cone
A_c = cone base area

F_s = total force acting on sleeve
A_s = sleeve surface area

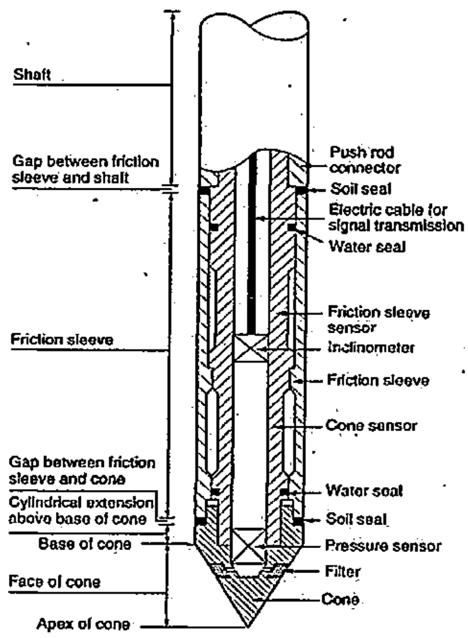
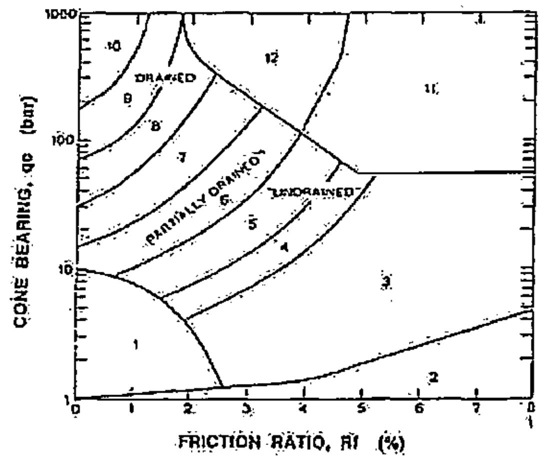


Figure 2.9: A cone penetrometer (Lunne et al., 1997b)

Geotechnical testing is not spatially continuous i.e. discrete locations are chosen and the data are interpolated across the survey area. Seabed landing systems have become common place in the offshore survey market (Table 2.11) and in many instances geotechnical investigation has become integrated, to maximise data acquisition and to compensate for the time required to lower a measuring platform to the seabed. As can be seen from Table 2.11 and Plates 2.14, 2.15, & 2.16, the offshore CPT landing frame is a large piece of equipment both in terms of dimension and weight. Deployment of such a unit would require the use of an A-frame or derrick and a large vessel for storage and transport.

Name	Height (m)	Length (m)	Width (m)	Weight in air (kgf)	Cone size (cm^2)	Penetration (m)	Water depth (m)	Load sensor (kN)	Reference
Fugro Deepwater Seascout	2.4		2.0	1016	1			10 kN	(Hawkins and Markus, 1998) (Fugro, 1995a)
Fugro Seasprite	7.35 5.0	3.0	3.0	8000		5 .0 3.0	1500		(Fugro, 1995b)
Neptune 3000 Miniature CPT	2.0	1.8	1.8	1500	2	15	3000		(Datem, 2001)
GTeC-1 Cone Penetrometer	6.3 / 4.3			3000 / 5000	2 / 5 / 10	5	2000		(Gardline Surveys, 2001)

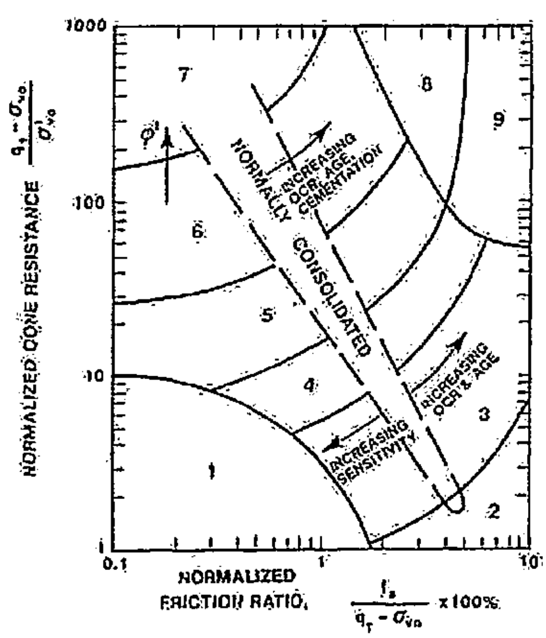
Table 2.11: Offshore CPT systems



ZONE	SOIL BEHAVIOUR TYPE
1	sensitive fine grained
2	organic material
3	clay
4	silty clay to clay
5	clayey silt to silty clay
6	sandy silt to clayey silt
7	silty sand to sandy silt
8	sand to silty sand
9	sand
10	gravelly sand to sand
11	very stiff fine grained (*)
12	sand to clayey sand (*)

(*) overconsolidated or cemented

Figure 2.10: Simplified soil behaviour type classification (Robertson, 1990)



1. SENSITIVE, FINE GRAINED
2. ORGANIC SOILS – PEATS
3. CLAYS – CLAY TO SILTY CLAY
4. SILT MIXTURES – CLAYEY SILT TO SILTY CLAY
5. SAND MIXTURES – SILTY SAND TO SANDY SILT
6. SANDS – CLEAN SAND TO SILTY SAND
7. GRAVELLY SAND TO SAND
8. VERY STIFF SAND TO CLAYEY* SAND
9. VERY STIFF, FINE GRAINED*

(*) HEAVILY OVERCONSOLIDATED OR CEMENTED

Figure 2.11: Soil behaviour type classification based on normalized CPT and CPTU data (Robertson, 1990)

Robertson (1990) goes on to point out further aspects, which will cause variations in classification, thus it may be concluded that the charts must be used in conjunction with supplementary site data:

> *"Factors such as changes in stress history, in situ stresses, sensitivity, stiffness, macrofabric, and void ratio will also influence the classification."*

It must also be noted that cone resistance data will also vary with increasing depth due to increasing overburden pressure, thus leading to misinterpretation of soil classification charts. This concern is obviously directly related to depth of penetration and thus shallow investigations are unlikely to be greatly affected.

The undrained shear strength (S_u) may be calculated from CPT data via an empirical solution:

$$S_u = \frac{q_c}{N_c} \qquad S_u = \frac{q_c - \sigma}{N_k}$$

where: q_c = measured cone resistance
N_c = cone factor
σ = overburden pressure
N_k = constant

The variability of cone factors are discussed in chapter four, but it is obvious from the above equation, that the shear strength determination is likely to be highly variable. Under normal circumstances direct *in situ* shear strength testing (shear vane) or laboratory analysis (triaxial testing) would be necessary to correlate the shear strength with the measured cone resistance.

Additional sensors may be added to CPT system to allow for the acquisition of a wide range of data. These include acoustic transducers (seismic cones), thermometers and thermal conductivity meters, electrical resistivity probes (resistivity cones) and pore pressure meters (piezocones) (Fugro a; Fugro b; Lunne et al., 1997b; Meunier et al., 2000; Newson and Fahey, 1998). Piezocone penetrometers allow dissipation tests to be undertaken and thus soil properties such as coefficient of consolidation and permeability may be determined (Fugro, 1996; Lunne et al., 1997b). The acquisition of pore pressure data also allows for the correction of the unequal area effect inherent to cone testing, which is particularly dominant in fine sediment (Lunne et al., 1997b; Robertson, 1990).

seafloor sediment instead of being reflected. Multiple returns, which represent the facies sequence of the seabed are received by hydrophones and a profile of the sub-stratum may be generated. Geophysical data are usually 'calibrated' using geotechnical core samples, thus allowing sediment type to be determined.

2.4.1. Seismic

Sub-bottom profiling is imperative when investigating an area for potential engineering works. The depth of sediment and distribution of stratigraphic sequences allows the geophysicist to understand some of the dynamic processes occurring in the area, including sediment flux and structure stability. The acquisition of this type of data in the nearshore zone is impeded by the access limitations of the surface vessel. Standard seismic survey would involve the use of a surface or sub-surface seismic source towed alongside a hydrophone streamer. In the nearshore zone a pinger may be used, in which case, no receiving streamer is required but penetration is limited.

Traditional surface seismic reflection techniques are difficult to apply in the nearshore zone not only because of streamer length but also because of the noise created when towing the cable. In deep water some of the towing noise is dispersed into the water column but in shallow water the entire water column may be noisy due to wave and current activity (Simpkin and Davis, 1993). The IKB-SEISTEC Profiling System was developed to overcome some of the noise problems associated with shallow water surveys and consists of a boomer and hydrophone mounted on a towed catamaran. The system can be operated in 1 m of water and has a potential system resolution of 0.25 m.

Fugro Australia have developed a seismic refraction system which allows sub-bottom facies velocities to be determined in real time (Fugro, 2001). An air gun source is towed along the seabed with a trailing streamer of 28 m in length containing 24 hydrophones. Air supplied from the surface allows the air gun to create the source noise, which penetrates as a strong signal with limited attenuation as a result of seabed proximity. First arrival signals are picked via a surface computer and are converted to depth intervals with associated sediment velocities. Correlations of velocity with shear strength have been made, allowing a section to be plotted illustrating variation of strength over the survey area. This system can, therefore, not only be used to ascertain sub-bottom structural data but also *in situ* geotechnical characteristics. Obviously the problem of restricted manoeuvrability and access would be a consideration when using such a system and alternatives might be sought. Ocean Bottom Cables (OBC) provide an alternative to surface towed hydrophone cables with the cables being fixed to the seabed leaving the gun boat to move freely on the surface. The cables can be placed in areas inaccessible by boat, for example underneath anchored vessels, thus increasing the survey area. Although the records will not show data totally obstructed, this approach would overcome turning problems thus reducing the 'no go zone'.

2.4.2. Resistivity

The majority of sub-bottom investigations undertaken both at sea and on land are based on the use of conventional seismic techniques. However more and more alternative techniques are emerging including ground probing radar (GPR) and electrical resistivity systems. Much of the development of resistivity based methods has evolved around the use of well logging and borehole investigations have become more numerous in the oil industry (Jackson et al., 1978). The range of applications in which electrical resistivity survey has been utilised is ever expanding and includes geothermal exploration, archaeological investigations and dam maintenance surveys (Jansen et al., 2002; Kearey and Brooks, 1991; Narayan and Dusseault, 1997; Roberts and Lewis, 1997). The success of such systems is therefore apparent and as Narayan and Dusseault, (1997) suggest, in certain conditions, they may be more useful than seismic systems:

> *"In some circumstances the direct current resistivity methods appear superior to seismic refraction methods, which have been restricted by the velocity inversion and to ground penetrating radar techniques where penetration depth is obstructed by the presence of highly conductive overburden."* (Narayan and Dusseault, 1997)

The investigation of sites with contaminated ground is an area in which resistivity techniques have been widely developed (Campanella and Weemees, 1990; Fenning and Williams, 1997; Narayan and Dusseault, 1997). Due to the risk of the release of methane gas non-invasive techniques are sought as an alternative to conventional investigation via trial pits and drillholes (Fenning and Williams, 1997). Although traditional resistivity techniques are used to map contaminated sites limitations do exist:

> *"Surface methods are commonly used to measure soil resistivity but require at least a 5-10% electrical contrast between contaminated and uncontaminated soil to successfully map a contaminant plume, assuming that there are no lithological variations."* (Campanella and Weemees, 1990)

Campanella and Weemees, (1990) describe a system based on a cone penetrometer, which has been developed to measure resistivity to a resolution of ±1% and distinguish changes in lithology (Fig. 2.12). The system has four narrowly spaced electrodes and operates at 1000 Hz.

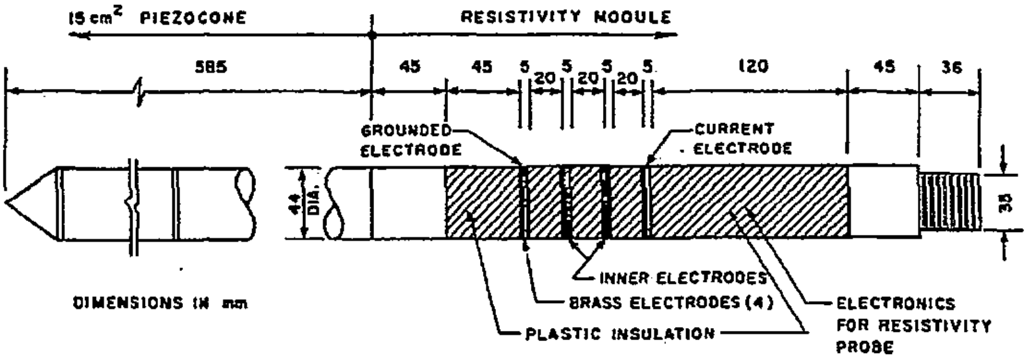


Figure 2.12: UBC resistivity cone (Campanella and Weemees, 1990)

The investigation of landslide sites is another area in which resistivity techniques have been adopted (McCann and Forster, 1990). The extent of the landslide and the slope of the slip plane can be determined, although inhomogeneities can lead to misinterpretation and investigations should be supported by ground truthing.

Resistivity surveying in the marine environment is hindered by the presence of the highly conductive seawater:

> *"With conductive seawater present only a small proportion of the current passes through the seabed, the magnitude of the current being inversely proportional to the ratio of the seabed and water resistivity. If seawater lies over unconsolidated sediments the ratio is less than 0.1; where granite and other basement rocks outcrop it is usually smaller than 10^{-4}. To achieve appreciable flow at depth, current electrodes have spacings of several times the thickness of the water layer."* (Jones, 1999)

Electrical resistivity surveys usually rely on electrolytic conduction to transfer electrical energy and thus the porosity of a sediment is the primary determinant of resistivity. Marine sediments often have high porosities due to their unconsolidated state and values can reach 80 – 100 % (Jones, 1999; Kermabon et al., 1969).

Penetrating probes such as the UBC resistivity cone (Campanella and Weemees, 1990) are well suited to the marine environment and reduce concerns about seawater conductivity. A free fall probe has been developed by Rosenberger et al., (1999) which is mounted on a 500 kgf weight stand and has been pressure tested to 4000 m (Fig. 2.13).

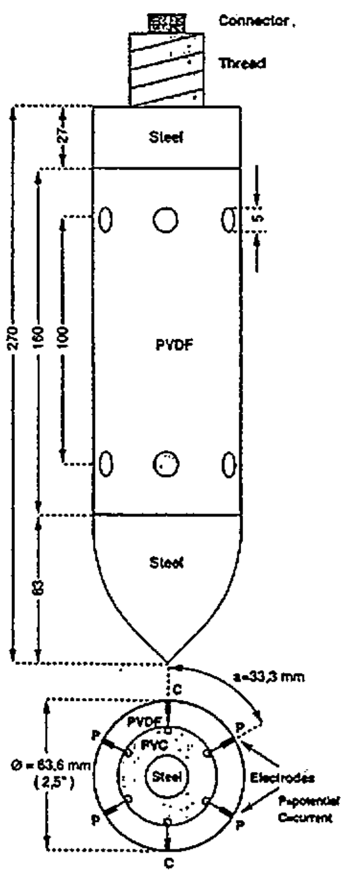


Figure 2.13: Free fall resistivity probe (Rosenberger et al., 1999)

The probe consists of two identical horizontal arrays which include two current and four potential electrodes. Measurements take place first via the lower array and subsequently through the second array and trials have confirmed that the system allows for the derivation of sediment physical properties (Rosenberger et al., 1999).

Whilst the acquisition of resistivity data is relatively simple the processing can be complicated and delineation of fine structures may not be as clear as for seismic methods (Kearey and Brooks, 1991; Narayan and Dusseault, 1997). Furthermore surveying in different directions can overcome the problem of sediment anisotropy and so no two final pseudosections are the same (Barker, 1997).

2.5. Positioning

In all marine surveys the positioning of equipment is a fundamental concern and the choice of system will determine the level of achievable accuracy. For engineering surveys the precision of the positioning systems is also important and surveys are carried out to the most appropriate level of precision and accuracy. Without reliable positioning the location of an object or feature is uncertain and the survey data is devalued.

2.5.1. Global Positioning System

The Global Positioning System (GPS), consists of at least 24 satellites (21 active and 3 spares) located within six different orbits, 22 200 km above the surface of the earth, inclined at 55° to the equator, with an orbital time of approximately 12 hours (Ingham et al., 1992; Smith, 1997). The three most common method of positioning surface vessels with GPS are stand alone GPS, Differential GPS (DGPS) and Wide area GPS (WADGPS). Stand alone GPS may provide position to an accuracy of approximately $\pm$ 10m although this may deteriorate to $\pm$ 100 m if satellite geometry is poor. DGPS works on the simple principle of calculating corrections for clock bias, atmospheric conditions and ephemeris data using a GPS receiver at a known location. These corrections when applied to a stand alone GPS receiver, can improve the accuracy of a position fix to 2-10m. However they may only be valid up to a range of 1500 – 2000 km between the receiver and the known location due to the requirement of observation of the same satellites. DGPS corrections are sent either by radio link or by satellite, with the former requiring a low frequency band to transmit the signals over the required distances (up to 800 km) offshore. Radio corrections are supplied inshore, for example around British waters, on the same wavelength as Classic FM and around the United States by the US Coast Guard.

The increasingly popular method of obtaining differential corrections offshore is via geostationary communication satellites such as INMARSAT thus allowing the transmission of corrections over the large distances. However, the above rule of thumb still applies with the separation between correction station and receiver being up to a maximum of 2000 km.

An additional differential correction system is WADGPS. As mentioned above, standard differential uses one reference station to calculate the necessary corrections, however, the fundamental principle of WADGPS is that the corrections from many reference stations are linked together at a control station, with local virtual stations collating and supplying locally relevant corrections. This means that the user receives data pertinent to his area but collected from many stations within that area, thus increasing the reliability and range of the corrections. However, there are associated problems with this type of system such as latency due to the lower rate of correction transmission thus leading to systematic errors where the receiver and reference station are using different sets of ephemerides. WADGPS corrections are usually sent via satellite and standard DGPS corrections are sent by radio link and can be generated from almost anywhere as long as the absolute position is known.

In the nearshore zone there are several intrinsic features which may degrade the quality of GPS data. As much of the work is undertaken in the vicinity of urban areas, multipath can become a large problem. In this instance the GPS signal is reflected off surfaces such as buildings which alters the travel time of the signal thus introducing positional error. Coastal areas may also be subject to loss of signal due to the surrounding hillsides and cliffs, which may mask the signals eliminating satellites from calculations.

corrections generated on board the ship (Relative Differential GPS – RDGPS), to give slightly higher accuracy.

2.5.2. Acoustic

Satellite positioning is a viable option above water only and the techniques used for underwater positioning are acoustic. However, there is an obvious need to interface these two systems for absolute positioning of underwater structures and for relative manoeuvring above water. Table 2.12 illustrates the need for external sensors to position underwater sensors:

Acoustic array	VRU	Gyro	DGPS
LBL	Possible	For deriving vessel offset directions	For absolute calibration
USBL	Essential	Most applications	For absolute calibration
SBL	Essential	Most applications	Possible

Where:
LBL = long baseline
USBL = ultra short baseline
SBL = short baseline
VRU = vertical reference unit

Table 2.12: Requirement for use of additional sensors for underwater acoustic positioning (Bromby, 1997)

As can be seen from Table 2.12, there are three principal methods of underwater positioning:

1. LBL systems (Fig. 2.16) use an array of transponders on the seafloor which are interrogated for relative baseline position by the vessel. These systems are used to position underwater objects such as drill templates and are also used for ROV tracking as they can cover a large area.

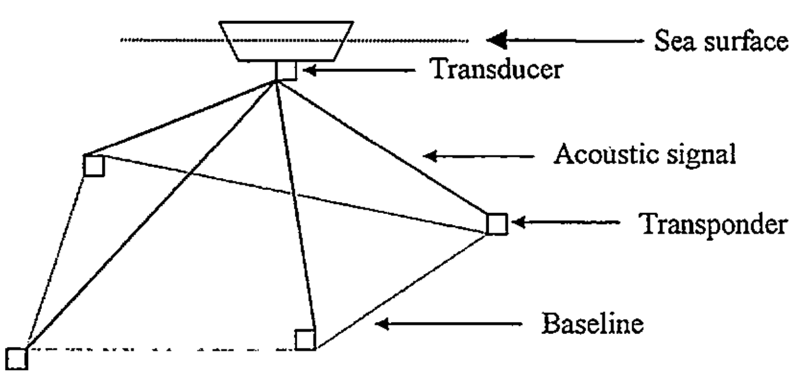


Figure 2.16: LBL acoustic array

2. Ultra short systems (Fig. 2.17) comprise of one large vessel mounted transducer which contains three or more individual transducer elements and a single seabed transponder. The transducers are positioned relative to the coordinate system of the vessel itself and the baselines are approximately 2 - 10 cm.

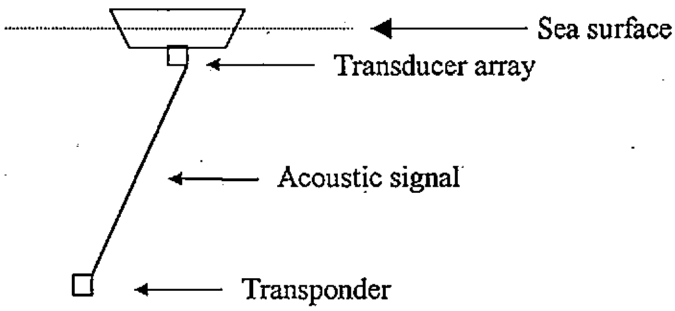


Figure 2.17: USBL acoustic array

3. Short baseline systems (Fig. 2.18) again use three or more transducers attached to the vessel, although the baselines are much longer, approximately 10 - 50m. Once again the transducer is positioned relative to the vessel and these systems tend to be used for dynamic positioning or for tracking.

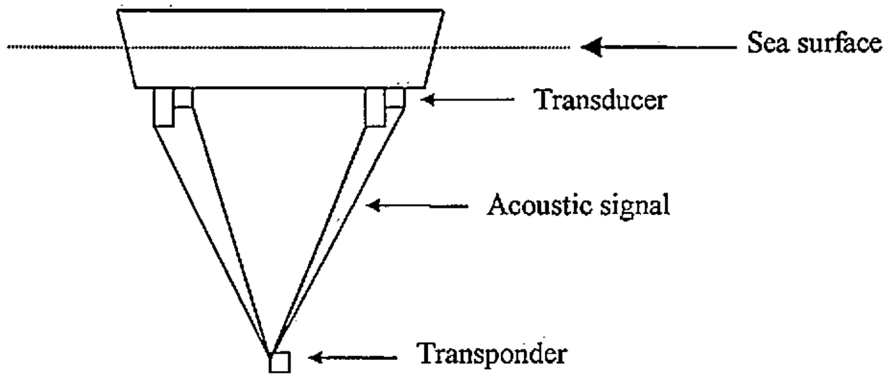


Figure 2.18: SBL acoustic array

As can be seen from the above overviews, the three systems have their own particular uses and can be further customised by using specific frequency transponders e.g. medium frequency of 18 - 36 kHz allows work in depths of 2000 - 3000m (Sonardyne, 1995). However, the range values obtained from the transponders are useless without referencing them in some way. For USBL and SBL the calibration is undertaken when the transducers are installed on the vessel using precise land survey techniques. In the case of LBL systems this is achieved in a relative form between the transponders themselves through baseline calibration or to the vessel for absolute positioning on the reference spheroid for the acquisition of geodetic coordinates using DGPS.

Positioning of ROVs is usually undertaken with the use of long baseline systems and seabed transponders. Once the survey site is defined the transponders can be lowered to the seafloor and are positioned using calibration procedures, providing absolute positions to the transponders through tie ins with surface positioning systems. The ROV is fitted with another transponder and can then be positioned relative to the seabed transponders. Table 2.13 gives a brief description of two ROV positioning systems:

System	Accuracy (m)	Depth rating (m)	Maximum range (m)	Reference
AquaMap ROV	< 1, 0.15 with controlled setup	1000 and 6000 standards	500, 1000, 4000	(Desert Star Systems, 2002)
Mini ROVNav	4	0-4000		(Sonardyne, 2002)
	2	0-2000		
	0.5	0-500		

Table 2.13: ROV positioning systems

The ability to provide accurate positioning capability to an ROV transforms it from a simple inspection tool to a fully functioning survey unit. An accuracy rating of better than 1 m within a defined survey site is extremely useful but does limit the survey to a predefined boundary. If the survey site is relatively small and is to be continuously surveyed by the ROV for some period then transponder deployment is appropriate. If however the ROV is to be used for a one off test then the process is time consuming and an alternative should be sought. These may include the use of a tethered surface buoy with GPS antenna (must remain above the ROV) or a USBL acoustic configuration.

2.6. Data management

Unification of equipment overcomes some of the problems associated with nearshore survey, however the issue of data management poses yet another problem. The diversity and complexity of site specific survey issues, arising when undertaking investigations in the nearshore zone, must be acknowledged if survey work is to be managed efficiently. Tidal regime, highly variable depth, traffic and restricted manoeuvrability are all issues that require particular consideration during the planning and execution phases.

In any organisation, data collection, storage and handling is a fundamental concern with the management techniques chosen determining the level of operating efficiency and product presentation. Clients expect data to be presented in a clear and concise manner, with all facets of information displayed in the most appropriate fashion thus allowing for optimum interpretation. The final product i.e. the map, plot or written report will be a 'summary' of the analysis undertaken by the contractor, a process that may have involved collating data from many sources. It is vital that the client is satisfied that not only has the survey fulfilled the wide ranging specifications, but that they are informed of as many aspects of the survey as possible.

Site investigation surveys involving hydrographic or geotechnical data acquisition often generate high volumes of data both from many locations and various equipment systems. These data will require handling through specialist software packages, with a range of output formats. The combination of the volume of data and the variety of software and formats, may hinder the analysis and presentation of data. Such a situation was acknowledged to be a problem at 'TSAC' in the Geophysical Science Section:

> *"The challenge facing the Geophysical Science Section at TASC was the need to integrate existing codes and data into a single easy to use tool. Data was stored in various locations (PC, CD-ROM, mainframe) and formats (ASCII, EPS, Sun raster). There were three basic requirements our systems needed to satisfy:*
> 1. *Ability to read and display data stored in various formats*
> 2. *Ability to integrate in-house and third party software*
> 3. *Easy to use"* (Drutman and Rauenzahn, 1994)

This description is typical of the situation in which many survey companies may find themselves. In order to attain a fluent operating system, many companies are choosing to integrate data sets and analyses through the implementation of structured data management solutions such as Geographical Information Systems (GIS). In an industry where the majority of primary data are spatially referenced, GIS offer the capability to merge datasets based on this fundamental property. However, the transition of GIS from their terrestrial roots to the marine environment has not been simple and many site specific issues must be addressed.

Increasingly sophisticated survey systems offer higher resolution mapping and data management and storage issues are becoming an intrinsic facet of survey planning and management.. The U.S. Naval Hydrographic Office (NAVOCEANO) have recently calculated that with their ships operating 24 hours a day, 7 days a week over a minimum of ten months a year, it is likely that they will face a 22 fold increase in the amount of bathymetric data collected (Depner et al., 2002). This would take their current volume of 125 gigabytes a year to over 2.75 terabytes a year. This forecast is even more dramatic for the more advanced survey systems:

> *"..rises to an overwhelming 2400 times the present data quantity (roughly 300 terabytes per year) if multibeam imagery and digital side scan sonar are included."* (Depner et al., 2002)

2.6.1. Geographical Information Systems

Due to the complexities of GIS, there are many definitions however according to Marble and Peuquet, (1983) a GIS has the following subsystems:

- *"A data input system that collects and pre-processes spatial data from various sources. This subsystem is largely responsible for the transformation of different types of spatial data.*
- *A data storage and retrieval subsystem that organises the spatial data in a manner that allows retrieval, updating and editing.*
- *A data manipulation and analysis subsystem that performs tasks on the data, aggregates and disaggregates, estimates parameters and constraints, and performs modeling functions.*
- *A reporting subsystem that displays all or part of the database in tabular, graphic, or map form."* (Marble and Peuquet, 1983)

GIS offer users diverse functionality enabling a fully interactive and integrated analysis environment. Utilities such as contouring, 3D mapping, inclusion of external plots and illustration by photographic representation are just some of the qualities described in papers from a range of disciplines (Bowley, 2001; Clodic et al., 2001; Fisher et al., 2001; Goldfinger et al., 1997; Green, 1995; Su, 2000). A further advantage of the digital mapping available in GIS is the ability to plot data across the artificial boundaries that would be present in paper maps (Select Committee on Science and Technology, 1983). The user is limited only by the availability of data and the scale to which they need to plot.

2.6.2. Marine GIS

Marine GIS differ from land based GIS due to the inherent difficulties associated with mapping a 4D environment in a 2D or possibly 3D computer program. Terrestrial systems have many specifically designed adaptations, but the same has not been undertaken for marine applications. For this reason, many off-the-shelf products, suitable for land use, are often not comprehensive enough for marine use (Lucas, 1996; Maslen et al., 1996). Li and Saxean, (1993) describe how most land based systems can analyse satellite remote sensing imagery whereas it is unlikely that you will find a system which can manage side scan sonar data. This lack of specialisation can lead to GIS being utilised solely as digital mapping packages, thus detracting from the opportunities it can offer (Thumerer et al., 2000). Furthermore, the specific problems faced in the marine world require development by those in the field with an appreciation of the diversity of data sources, manipulation techniques and display methods.

As a direct result of the multiplicity of type and manufacturer of marine data acquisition systems, numerous data formats exist:

> *"Data formats include raster (grids and images), two-dimensional vector points (vent/sample/marker/earthquake locations), lines (bathymetric contours, submarine/camera/equipment navigation tracks), areas (lava flow delineations), and three-dimensional vector data (water-column casts and tows)."*
>
> (Bobbitt et al., 1997)

In most cases, specialist software is required to interpret the data although the product can often be exported to other systems. Side scan sonar mosaics created in specialist packages can be exported as raster images to GIS but this removes the flexibility of the original system and makes the spatial analysis functions of GIS redundant. A method for standardising data formats is required before GIS will be able to handle many marine data (Mingins, 1996).

One of the basic concepts of GIS is the ability to map and analyse information based on spatial properties. In land based systems, co-registration sourced on streets, post codes, etc can be used to tie together datasets. Offshore there are very few fixed points and therefore registration is undertaken using positioning systems and the coordinates acquired (Li and Saxean, 1993). In the main, this is a simple but successful system but in certain circumstances the addition of an 'object' is useful. For example, when working in coastal regions delineation of the coastal boundary is useful for reference. However, use of a shoreline would be difficult due to variation as a result of tidal movement and sediment removal/deposition (Lucas, 1996). Fixed markers must be chosen carefully to ensure consistency and to reduce variability in the analysis process.

The United States National Oceanic and Atmospheric Administration (NOAA) Ocean Environment Research Division (OERD) describe scale issues faced:

> *"Data scale and accuracy ranged from a few meters (e.g. the location of a submersible sample at a hydrothermal vent orifice collected from 3000m below the sea surface) to remotely sensed earthquake locations accurate to within a few kilometers."* (Bobbitt et al., 1997)

This wide variation in scale poses a problem when analysing data, where it must be ensured that data from radically different scales is not used together without due care and attention. Much marine investigation work relies on the combination of data sets of varying scales. In remote sensing, satellite data may be used to identify gyres, which may be investigated further using *in situ* measurements (Lucas, 1996). GIS offer the opportunity to map data of different source scales on top of one another by altering the projection and scale but this process must be used with caution. Lucas, (1996) offers further warning with regard to calculating error when combing data from multiple scales.

Very little marine data is simply 2D and will usually include a third dimension of depth and possibly a fourth dimension of time (Mason et al., 1994; Robinson, 1991). The fundamental difficulty when assessing 4D data is that of display in two dimensions. The availability of 3D plotting within GIS is increasing, thus allowing for the combination of 3D data. Four dimensional data may be displayed through the use of video sequences although these may draw heavily on computer memory.

2.6.2.1. GIS in the survey industry

Given the ability of GIS to integrate and manipulate data, it would appear to possess qualities critical to the success of survey planning, execution and reportage. One of the most important stages in both marine and terrestrial surveys is planning as it provides the opportunity to set down the requirements of the survey and design the most appropriate method for achieving these aims. As a rule surveys are set up based on a simple grid, a structure that allows for the systematic control of data collection. However, the quality of these data capture strategies are difficult to quantify thus leaving an element of doubt as to whether or not the coverage is sufficient:

> *"As a result of the wide choice of assessment techniques available for use and their suitability for different stages of a project, the quality of a site investigation program can vary significantly and there is limited formal guidance available to help in optimising program design outside of qualitative experience based decisions."* (Parsons et al., 1998)

The move towards completely digital data acquisition and storage and thus the ability to query in spatial terms may however provide a solution. GIS ASSESS is a geostatistical tool which has been specifically developed to scrutinise the quality of site investigation plans (Parsons et al., 1998). The software has the ability to collate information on the type of investigation tool employed, its accuracy and precision, scope of use e.g. depth of penetration or coverage and will provide an indicator of the potential quality of a survey. As the system is continually updated, the software can alert the operator when data sufficient to meet a required criterion has been collected. Tools such as these enable the surveyor to ensure that surveys are planned to the optimum level and that the survey is both time and cost effective.

The fact that hydrographic surveys are inherently modular due to the multitude of equipment required to undertake even the most simple of surveys highlights the importance of integration. Once data has been collected and processed it will need to be integrated for site wide analysis. As discussed for many other types of investigation, this process can be lengthy so that the opportunity to utilise GIS to improve efficiency is apparent (Anderson, 1998; Beaubouef and Breckenridge, 2000; Bowley, 2001; Jeffries-Harris and Selwood, 1991; Li et al., 1998).

In 1994 work began on a shoreline erosion monitoring and management program in Malaysia, headed by the Coastal Engineering Division of the Department of Irrigation and Drainage (Li et al., 1998). Data ranging from bathymetry and storm surge data to the shear strength of the soil was required to design the required defence structures. The GIS allowed for numerical modelling to be carried out to ascertain the range of shoreline changes that might be faced.

The Crown Estates Commission (CEC), oversees the management and extraction of approximately 25 million tonnes of aggregate within an area of more than 200,000 km^2 (Jeffries-Harris and Selwood, 1991). Posford Duvivier was asked to undertake a study into the suitability of a GIS for solving the data storage and handling problems experienced by the CEC. ArcInfo proved to be a useful tool, although a number of problems particularly associated with the data entry process were encountered:

1. *"As usual identifying digital data sources and obtaining access to them proved difficult.*
2. *Digitising data: The time taken to do this was significantly greater than anticipated.*
3. *In creating a standard borehole system is it recognised that there will be a loss of detail from the data.*
4. *Chart scales varied from 1:200,000 to 1:75,000. In addition survey data is collected at scales of around 1:5000. Joining such data sets would be erroneous, so it is accepted that 'joints' will be present within the data coverage.*
5. *Quality control: applied to both text and graphics, as it is entered and when updating it."* (Jeffries-Harris and Selwood, 1991)

The problems described above along with others relating to the structure of data storage and the updating timescale may be seen as limitations of the GIS constructed. In comparison to the system being used prior to GIS implementation i.e. manual data handling, this integrated system may be regarded as a success. The CEC acknowledge that specialist systems may be required to complement the basic ArcInfo set up, nonetheless it is also acknowledged that the GIS created utilises all of the available functions and thus can be seen to be an *'ideal GIS'* (Jeffries-Harris and Selwood, 1991).

The coastal zone is an area of major interest for GIS development due to the complexity and dynamics of the environment. As illustrated by the CEC, surveying in coastal regions does not automatically mean a 'small' survey site or a minimal data source. Given that many economic and legal boundaries stem from the coast e.g. the exclusive economic zone (EEZ),

interactive contouring and plotting, a basic hydrographic charting requirement.. Many GIS packages have contouring facilities but require data to be input in a specific data format as opposed to a simple x, y, z ASCII file from which a grid could be created. This lack of flexibility means that contour maps may need to be imported as raster data from external software thus reducing the possible spatial analysis methods.

The application of GIS within the marine survey world is not restricted to research and industry, but also involves the military. 'HUGIN ChartLink' is a system that has been developed by the Royal Navy and facilitates the fusion of hydrographic, oceanographic and meteorological data (Bowley, 2001). One of the applications for this system is in the uncertain area of amphibious landings:

> *"A commander overseeing the amphibious assault will be able to drill down through the different levels of detail to reach the area proposed for the beach landing. A recent intelligence report may be highlighted which indicates that what was thought to be a shingle approach to a beach is actually mud."*
>
> (Bowley, 2001)

Bowley, (2001) goes on to discuss how other members of the landing team will be able to view the data simultaneously, allowing them to structure their approach to the landing mission based on the initial surveillance. This reference illustrates that GIS encourage not only the integration of digital data, but also of the survey team and the equipment that they command. This move towards fully integrated survey approach should make the hydrographic survey industry more efficient and thus more cost effective.

2.6.2.2. Engineering survey

Many marine survey projects involve both hydrographic/geophysical investigation and geotechnical studies. It is in the contractor's best interest to be able to plan both sides of the survey effectively and to be able to use both sets of data for post-processing analysis.

> *"A geographic information system (GIS) is a relatively recent addition to the growing number of software applications available to civil engineers. Although many engineers are familiar with the technology, they remain unaware of its analytical power and potential for wide and varied use."* (Hellawell et al., 2001)

As for all GIS, the first step towards achieving a successful system is to acquire digital data and to store it in an organised pre-determined manner within a relational database. Seismic micro-zonation studies of Kishinev, Republic of Moldova, undertaken by Zaicenco and Alkaz, (2000) were based on the development of a 3D database of geotechnical properties in ArcView. The importance of metadata is discussed with reference to *a posteriori* processing and the associated accuracy and precision propagation.

The development of the Channel Tunnel rail link between Cheriton and St Pancras involved approximately 1000 km of route options for the 108 km route (Oman, 1996). Finding the most suitable route involved Union Railways (UR) analysing vast quantities of data:

- *"2000 OS digital base maps used covering 900 km^2 and requiring 15 Gb storage*
- *20 000 environmental features identified*
- *10 000 properties referenced*
- *10 000 engineering features designed*
- *150 parliamentary plans produced"*

(Oman, 1996)

Once again, it can be seen that the scale of this investigation would have made it extremely cumbersome to analyse by traditional techniques, but once digitised, the data could be accessed and queried simply and quickly.

The financial commitment is a major consideration when establishing new computer systems and was a concern for WS Atkins GTG:

> *"The first stage in the introduction of the GIS was an investigation into its market potential. This involved the identification of projects and applications where the GIS would expand analytical capabilities, yield net savings, and generally add value to the existing services."* (Hellawell et al., 2001)

WS Atkins GTG found the GIS to be so useful in their projects that it was used as a standard tool within 6 months although it was also recognised that for some situations the system was unnecessarily complex in which case they reverted to independent specialist packages.

2.7. Summary

The techniques currently available for the acquisition of hydrographic, geophysical and geotechnical data are not only numerous but also highly variable. It has been shown that these systems operate successfully offshore but are not always easily transferred to the nearshore zone. Restricted manoeuvrability, limited access, tidal activity and variable depth are all issues specifically relevant to this zone and all require alterations to be made to current offshore investigation procedures.

Divers, ROVs and AUVs offer possibilities for overcoming some of the site specific survey problems with their innate ability to penetrate inaccessible regions. The qualities offered by divers must always be balanced with the inherent risk to human safety thus restricting survey time and depth. AUVs are rapidly becoming an acceptable method of acquiring high volumes of bathymetric survey data but design constraints limit the ease with which extra testing equipment may be added. The approach to nearshore survey offered by the ROV is that of a discrete integrated testing station. Off-the-shelf systems may be customised with a wide range of equipment dictated by the task in hand and the ROV may be accurately positioned using acoustic techniques.

Bathymetric survey has advanced from simple single beam echo sounding to multibeam swath surveys that allow for 100 % coverage in a reduced survey timescale. Nearshore bathymetric surveys are limited only by the access of the vessel and swath coverage does allow for some restricted areas to be surveyed. Sediment classification can be undertaken using side scan sonar and bottom classification systems such as RoxAnn and Quester Tangent and when combined with bathymetry data provides a complete seabed representation.

In situ testing is critical to geotechnical investigations and coring provides the means for further laboratory analyses. Although the cone penetration system is used extensively offshore the large down force required for penetration restricts inshore testing to open areas capable of holding a jack-up rig or other such suitable vessel. Sediment coring also falls into the same category of structural weight requirement, once again limiting the process to open waters.

Geophysical investigations are undertaken to provide information about the material and structures present beneath the seabed surface. The seismic reflection technique is the most widely utilised sub-bottom profiling mechanism and may be utilised in nearshore regions to acquire useful data over a wide area. Ocean bottom cables (OBC) may provide an alternative to surface towed hydrophone streamers where access is limited. An alternative sub-bottom profiling method is that of resistivity survey, an approach that will also provide continuous sub-seabed information. Due to the high conductivity of sea water resistivity techniques are not widely used either offshore or in the nearshore zone.

The functionality of GIS offers the marine survey environment a tool with which data integration, manipulation and presentation may become simpler than the techniques currently employed. If the GIS is to be used as a spatial analysis tool and not simply as a comprehensive method of data storage then issues including scale and data format need to be addressed. GIS is now becoming a recognised approach to data management in the offshore environment but nearshore systems are few and far between. The nearshore zone is an inherently dynamic environment and as such survey planning is fundamental for efficient execution. Although the survey area may not cover the same aerial extent as encountered in offshore surveys, there is an intrinsic requirement for high-resolution data. GIS may enable the user to cope not only with the associated high data volume, but also the requirement to display data at an appropriate scale.

The aim of this research is to assess the feasibility of acquiring geotechnical and hydrographic site investigation data with an ROV. ROVs have been shown to be capable of undertaking simple survey investigations and to be a possible solution to coastal congestion survey issues. There appear to be three techniques of site investigation, not as yet fully operational in the nearshore zone. These are cone penetration testing, sediment coring and localised high-resolution sub-bottom profiling. Although each of these techniques are fully operational

offshore, the development of improved nearshore techniques would be beneficial to surveyors and engineers alike. The feasibility of operating these systems from an ROV will be addressed in the following chapters with the intention that an integrated survey approach will further increase the value of the systems.

Chapter 3

Proposed ROV

3.1. Introduction

The techniques currently in use for offshore marine survey are not always transferable to the nearshore zone. Surveying in nearshore areas of restricted access or manoeuvrability requires manipulation of current offshore techniques and may demand the development of new methods. Localised or discrete site investigation is one such area of survey in which offshore techniques are not appropriate for use nearshore. Access of large surface vessels, temporary platforms or the deployment of large landing frames may be difficult to achieve, resulting in zones of uncertainty. To ensure continuity across the survey site, techniques must be developed to overcome these problems, of which the mechanism for deployment is the most pertinent. Remotely operated vehicles (ROVs) are currently utilised offshore for inspection and intervention but are currently under-developed for use nearshore. The possibility of adapting ROV technology for the operation of site investigation equipment in the nearshore zone will be examined in this chapter.

3.2. ROV adaptation

The move towards investigation in deeper water and harsher environments, in addition to the requirement for continuous survey has led to a rapid increase in the utilisation of remotely operated vehicles:

> *"In a little over 20 years the number of ROVs in commercial operation has grown from virtually zero to something in excess of 3000 operated by many companies worldwide. The majority are small inspection-class vehicles, but hundreds of military mine counter measures (MCM) vehicles have been produced, as well as about 50 experimental or prototype AUVs."* (Westward, 2000)

The user can choose to manipulate an off-the-shelf ROV to meet their needs through the addition of individual pieces of equipment or modules (consisting of several systems combined in one structural unit). These solutions to finding an ROV that fulfils specific requirements are relatively cost effective and provide the user with a satisfactory tool. However, this approach can lead to operational problems such as excess payload thus requiring modifications to the basic ROV. For example, adjustments to the buoyancy of the ROV would be necessary to

The Phantom measures 108 cm in length, 63 cm in width and 46 cm in height. The system weighs just 45 kgf and thus can be easily deployed either from a small vessel or a land platform. The limited payload capacity of 6 kgf and relatively weak thrusters, supplying a maximum of 19 kgf, are intrinsic to the intended purpose of the ROV as an inspection tool. Under these circumstances the primary task of the system is to provide video images, which requires the unit to be small and manoeuvrable. The Phantom ROV is presently fitted with a real time video camera, a high resolution Sonardyne LBL positioning system and flux-gate compass.

The payload and thruster capacity of the ROV must be borne in mind when supplementing the equipment range. The Phantom ROV has been designed so that it is neutrally buoyant when fitted with its basic equipment. If new systems are added the buoyancy must be adjusted to ensure that the ROV is still manoeuvrable and able to perform the tasks to its original specification. Buoyancy may be altered simply with the use of syntactic foam or air chambers, which with the addition and removal of air, allow for greater control of the ROV. These systems are frequently used by divers to lift loads from the seabed and may thus be adapted to an ROV.

In some instances, it may be necessary to increase the weight of the ROV, for example when using a system that requires the ROV to be stable on the seafloor. The use of anchorage systems or the flooding of air chambers with water to increase downforce may be necessary to achieve bottom stability. In certain circumstances the application of reverse thrust may be sufficient, however, the Phantom ROV has only a limited thrust capacity. In addition, the application of vertical thrust will inevitably lead to a level of surficial sediment disturbance.

The current study requires that a cone penetration system (CPT) (Chapter four), a sediment coring system (chapter five) and a sub-bottom resistivity profiler (chapter six) be operable from an ROV similar in size to the Phantom in order to retain the quality of manoeuvrability and access in nearshore regions. The ROV therefore needs to generate enough reaction force to maintain bottom contact during testing and must remain manoeuvrable when laden with equipment and when confronted with wave and tidal action.

To mount the testing equipment on to the Phantom ROV a frame would be required to provide connection locations, due to limited space on the crash frame. A frame was built from plastic tubing (25 mm internal diameter) into which the ROV would be secured during testing. Initial tests in the laboratory suggested that the Phantom was not capable of supporting this extra weight and that the bulk of the frame restricted movement. The Phantom ROV was designed to be neutrally buoyant and have a high degree of manoeuvrability. With the addition of a plastic frame the Phantom became inoperable and thus any other adaptations for equipment mounting and operation would not be feasible.

The adaptation of smaller ROVs to perform survey tasks normally undertaken by surface vessels or larger ROVs is illustrated by a survey undertaken into the biological consequences of anchor scarring associated with the installation of pipelines near Point Conception, California (Hardin et al., 1992). The survey team used a Phantom DS4 ROV measuring 173 cm in length, 91 cm in width and 71 cm in height. The ROV was fitted with a variety of survey equipment, the configuration of which can be seen in Figure 3.1.

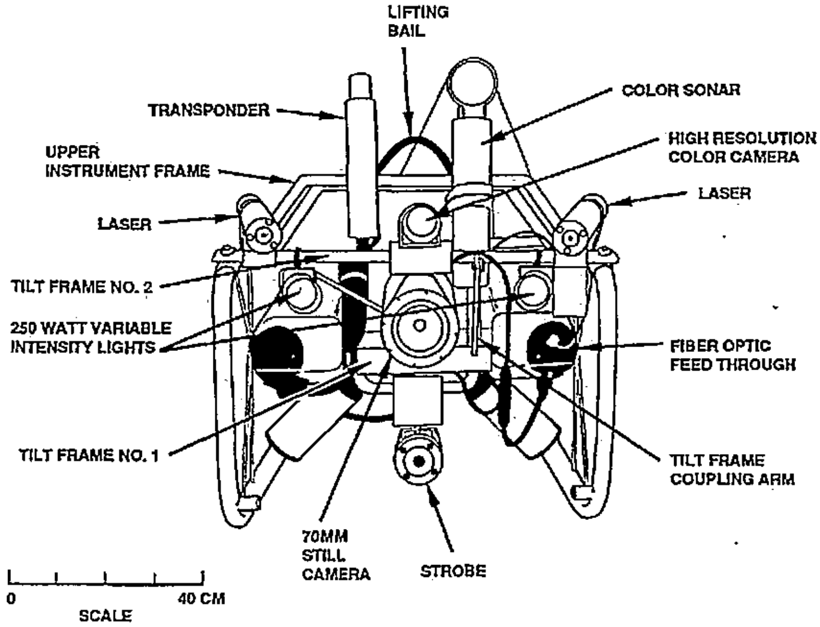


Figure 3.1: View of the Phantom DS4 as equipped for anchor scar surveys (Hardin et al., 1992)

To compensate for the addition of specialised equipment additional buoyancy was added in the form of syntactic foam. The survey team were pleased with the results acquired from the small ROV and felt that it was an acceptable alternative to the standard work-class systems:

> *"Small ROVs such as the Phantom DS4 are capable of successfully conducting scientific operations normally reserved for more powerful, and more expensive vehicles. This demonstrated ability by a relatively small ROV also means that smaller, less expensive surface support vessels can be utilised for complex operations such as ours, within the limits of expected sea conditions."*
>
> (Hardin et al., 1992)

Due to the stability requirements of penetration testing (sediment corer and the CPT system), the applicability of a lightweight flying ROV to the current research must be questioned, even if adjustments to buoyancy were made. Flying ROVs are inherently lightweight allowing for ease of movement and maximisation of thruster power for locomotion. Any desired increase in seabed stability leads to an associated increase in the weight of the unit, thus the need for more powerful thrusters and an increase in the physical size of the system. Larger systems such as this are known as 'work class' ROVs and necessitate specialist deployment mechanisms. To ensure that the size of the ROV remains constant, a possible method for overcoming stability is to use a seabed crawling ROV as opposed to a flying ROV. Most geotechnical investigations do not require measurements to be taken within the water column and thus there is no reason for the ROV to fly. By allowing the ROV to remain on the seabed, the weight of the unit can be increased without increasing the overall dimensions. For this reason a new type of ROV is proposed which retains the size and therefore manoeuvrability characteristics of the Phantom but is designed specifically with the testing equipment requirements in mind.

3.2.1. Proposed ROV design criteria

The utilisation of tracked ROVs is seen in the offshore sector where the suitability of traditional flying ROVs for post-lay burial operations has been questioned and an alternative approach has been chosen:

> *"Often the free-swimming ROVs available are far from ideal, with insufficient power available for water jetting because too much has to be used for the*

With regard to the proposed ROV there are two considerations when designing a crawling system:

1) The unit must exert minimum pressure on the seabed to ensure that the sediment is not disturbed.
2) The unit must be light enough to be deployed from a coastal survey vessel but have enough weight to remain stable during operation of equipment.

Unfortunately there is no ideal solution to these problems simultaneously and thus compromises must be made. For the purpose of this study, the equipment has been designed to illustrate the feasibility of using an ROV and thus the disadvantages are just as important as the advantages. Tracks such as those used on the Hydrovision Venom (Plate 3.3) would be the most appropriate as they allow for testing to be carried out in the centre of the ROV body as well as at each end.

3.2.2. Dimensions

The proposed ROV is based on the dimensions of the Phantom, thus maintaining the flexibility of access however the layout of the equipment has been suggested with the equipment constraints in mind. The system is a seabed crawling unit with power supplied from the surface via an umbilical. The ROV would be fitted with a colour video camera capable of relaying real-time pictures to the surface and a high-resolution positioning system as standard equipment. The unit should be capable of at least 1 knot survey speed thus allowing the unit to be a practical solution to survey requirements.

For equipment testing where penetration into the sediment is required, Newton's first law of motion, the law of inertia, must be considered in relation to the mass of the object:

> *"In the absence of outside forces, the momentum of a system remains constant."*
> (Barnes-Swarney, 1995)

Further Newton's third law of motion states:

> *"For every action there is an equal and opposite reaction."*
> (Barnes-Swarney, 1995)

As discussed in previous sections, the developed system needs to be of similar dimensions to the Phantom. Thus an ROV of 1.0 m length with 0.2 m wide tracks (and track separation of 0.2 m) is the base for the CPT study. Even with a weight of 250 kgf Figure 3.2 shows that an ROV of this size exerts a mere 6.1 kPa pressure.

The pressure exerted between the tracks is also an important consideration as this is the area of the seabed in which CPT testing is to be undertaken. This can be calculated using a strip loading equation (Randolph, 2001) derived from Figure 3.3:

$$\Delta\sigma z = \frac{q}{\pi}\left[\alpha + \sin\alpha\cos(\alpha + 2\delta)\right]$$

Where $\Delta\sigma z$ is the vertical increment stress change (Pa)
q = Pressure (Pa)

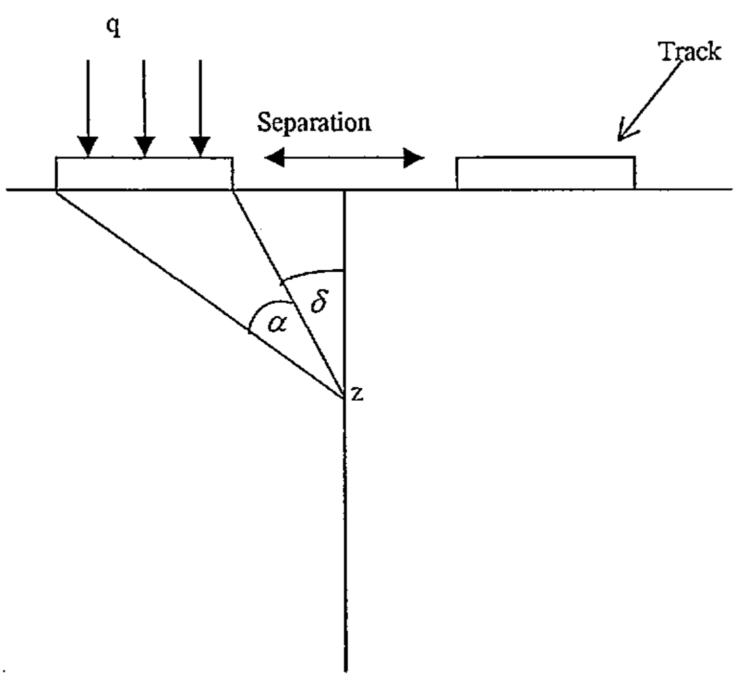


Figure 3.3: Strip loading diagram (Randolph, 2001)

Figure 3.4 shows the variation of the vertical stress increment with depth for an ROV with tracks of width 0.2 m and a separation of 0.2 m.

the unit lowered. The decision as to whether the ROV should be towed or stowed depends on the distance of the survey site from shore or the wave conditions which could cause damage to components on a towed unit. Other than for the sake of convenience there is no reason for the ROV to be on the deck of the ship whilst in transit to the survey site.

3.2.5. Positioning

The ability to acquire a variety of information pertaining to the subsea environment with the additional capability of absolute positioning makes the ROV a very useful tool. However the ability to remain 'on station' is a challenge for many light weight flying ROVs, a weakness which makes them unsuitable for some roles:

> *"Station keeping in the operation of underwater vehicles or robotic systems is the task of maintaining a particular position and orientation in the presence of various types of disturbances such as undersea currents. This is a critical capability for many scientific, commercial, and military applications of submersible vehicles including the inspection and repair of undersea structures, near-seabed data collection, and near-shore covert surveillance and reconnaissance missions."*
>
> (Negahdaripour, 2001)

Solutions to this problem such as visual object identification-based station keeping and dynamic positioning have been investigated and may in the future be a feature of all flying ROVs (Hsu et al., 2000; Negahdaripour, 2001).

In order to achieve penetration and stability during testing of cone penetration and sediment coring systems the proposed ROV utilises a bottom crawling system with its inherent weight advantages. In harsh environments such as the surf zone, the ability to maintain station is a challenge to the pilot, with tidal currents and wave breaking forces causing cavitation and subsequent movement. In an attempt to overcome some of these problems Dally et al., (1994) built the Surf Rover, a 5.2 m wide, 6.7 m long bottom crawling ROV with a dry weight of 1360 kgf. The utilisation of a tracked seabed system for the proposed ROV therefore assists the penetration force requirements and is also highly suited to investigations in the nearshore zone. The techniques employed for absolute and relative positioning of ROVs have been discussed in chapter two although the requirement for accurate positioning during the transition between submerged and exposed investigation demands either a combination of techniques or an adaptation of current systems. In the simplest case it may be possible to use an extended antenna, which remains above the water surface within the surf-zone so that the ROV can be continuously positioned via GPS. Alternatively a combination of an acoustic network and standard GPS techniques may be employed if water depth or wave height restrict the continuous use of the extended antenna.

3.2.6. Maintenance

All ROVs require maintenance and specialist personnel to maintain and operate them. Downtime is a major concern when working offshore due to the expense and delay to survey progress. For this reason a comprehensive set of parts should be kept on board the survey vessel to ensure rapid repair. For off-the-shelf systems this is a relatively easy criteria to meet whilst the utilisation of purpose built systems requires forethought and the manufacture of extra components. Although downtime is a consideration when choosing to operate an ROV, past records of ROV deployment have been impressive, for example:

> *"During a recent 150 day, 950 operating hour, deployment on an oilrig, a Max Rover experienced only one failure. Very early in the deployment a thruster module experienced an infantile failure of a digital component. A spare was quickly installed, and the ROV was back on line within a couple of hours."*
>
> (Nicholson and Lobecker, 2001)

3.3. Further ROV opportunities

With the increasing reliability and flexibility of ROV technology comes the necessity to perform a diversity of survey tasks as an alternative to standard surface or diver based survey techniques. As oil exploitation advances into deeper water the use of subsea cables and pipelines increases (Westward, 2000) and there comes an associated need for pipeline surveys.

> *"The proliferation of fibre optic cables and offshore pipelines laid almost spaghetti style throughout the world has emphasised cable tracking and inspection as one of the most important missions of the new generations of ROVs. It is important for these tasks to be accomplished from small and economical survey vessels."*
>
> (Nicholson and Lobecker, 2001)

The detection of buried objects, such as pipelines, can be achieved by systems like the RMD-1, which is capable of detecting large metal objects more than 5 feet away from the ROV mounted rig (Underwater Contractor International, 2002). ROV based systems specifically designed for pipe tracking, such as the TSS-340, have been in use for some time and are operable from small ROVs (Nicholson and Lobecker, 2001). ROV technology has also been adapted to allow for post-lay pipeline quality inspections to be undertaken. The use of Alternating Current Field Measurement (ACFM) techniques has become commonplace and allows for the detection of corrosion through coatings up to 10 mm thick (Raine, 1996).

Mass sediment extraction has also been conquered by ROV technology and the Aeolus system developed by Sonusub is able to excavate material with undrained shear strength of less than 20 kPa (Offshore Engineer, 2001).

3.4.Summary

As illustrated by Hardin et al., (1992), adaptation of off-the-shelf systems is a cost effective means of attaining ROV capability. For this reason there have been many developments in the field of ROV technology to facilitate equipment diversification of off-the-shelf ROVs. The Phantom XTL ROV was the basis for the current research but proved to be inappropriate for *in situ* testing due to its limited bottom stability capacity. As an alternative a bottom crawling ROV, maintaining the dimensions and therefore manoeuvrability of the Phantom is suggested. The proposed ROV measures 1 m in length and has two tracks each of 0.2 m width with a 0.2 m central separation. To achieve satisfactory penetration in cone penetration testing (chapter four) the system has a weight of 250 kgf, imposing a pressure of 6.1 kPa with a maximum centre line pressure of 1.7 kPa experienced at a depth of 0.5 m.

The dynamic forces experienced in the nearshore zone including wave and tidal action can cause the smaller flying ROVs to become difficult to manoeuvre. By utilising a bottom crawling mechanism the proposed ROV not only achieves successful penetration but also retains manoeuvrability and station in this dynamic zone.

The research has shown that ROVs are capable of overcoming some of the difficulties associated with surveying in the nearshore zone. The bottom crawling proposed ROV has also been shown to be capable of allowing the desired penetration of the *in situ* testing systems through the use of added weight. Deployment and retrieval of an ROV weighing 250 kgf may be difficult from small coastal vessels but the system can be deployed from the beach giving it added flexibility.

As an independent survey tool the ROV offers the surveyor the opportunity to decide exactly where testing is to be undertaken through the use of the on-board camera and acoustic positioning system. Once in position the ROV can be used as a platform for *in situ* testing with multiple pieces of equipment being mounted on the ROV frame and utilised at the same location. This integrated approach to nearshore site investigation is an efficient and robust alternative to techniques currently employed.

Chapter 4

Cone penetration testing

4.1. Introduction

The ability to acquire in situ sediment strength data removes the inherent disturbance effects imposed when sampling for subsequent laboratory based strength tests. Structural disturbance is not the only change likely to take place during sampling, storage and transport. The loss of moisture and drainage in the sample may also cause disruption to the sediment being investigated. In situ data is the only way in which all of the characteristics of the site may be represented in the results. The use of in situ testing systems offshore has been standard procedure for many years and although investigations in the coastal zone can adopt the same technique it has not been widely translated to use in the more congested nearshore zones. As discussed in chapter two, many inshore investigation platforms are large and thus potential survey areas are limited. A method for overcoming the need for large structures offshore has been the development of landing frames that may be deployed from surface vessels but again these systems depend on the utilisation of relatively large vessels due to their size and weight.

Cone penetration testing (CPT) is undertaken to ascertain in situ sediment shear strength for construction sites, geohazard evaluation and cross correlation with remote sensing data. Miniaturisation of the CPT frame has taken the weight from over 5 tonnes to only 1 tonne for mini-cone systems, however; these systems would still not be operable from a small coastal vessel. CPT systems developed for use from smaller craft include a hovercraft based system developed by Newson and Fahey, (1998) and an ROV mounted system developed by Fugro N. V. The requirement to undertake site investigation on soft tailings (S_u frequently less than 10 kPa), led to the design of a hovercraft measuring 3.8 x 2 m and weighing 220 kgf unladen, with a buoyancy of more than 400 kgf and a payload capacity of 300 kgf (Newson and Fahey, 1998). A 10 cm^2 resistivity piezocone (RCPTU) cone was used to acquire tip resistance data over 4 MPa. The mounting of a Seascout CPT system onto an ROV was undertaken by Fugro in a bid to overcome the problems of frame weight and manoeuvrability but the system has never been used due to a lack of confidence in the mini-cone data acquired (Fugro N. V.). In addition the base ROV, used by Fugro, was a work class system thus again restricting deployment from a small vessel and manoeuvrability in areas of congestion.

The inherent down force requirement limits the applicability of ROV operated CPT systems bringing the normal use back into the realm of large seabed landing systems. Although mini-cone systems have been developed most have been designed with the intention of enabling high sediment penetration. In the nearshore zone a fundamental depth of importance in seabed investigation is the top few metres. These top metres consist of the lowest shear strength sediments, which are of great interest in stability foundation investigations. The CPT based research undertaken has therefore focused on the feasibility of acquiring high-resolution CPT data from a small ROV (chapter three) in the top 2 metres of surficial sediment.

4.2. CPT systems

A brief explanation of CPT systems, including the method for calculating shear strength was provided in section 2.3.2. The following sections will focus primarily on the design and operating requirements of miniature systems. Mini-cones offer the user the possibility of discerning finer stratigraphic details. A general rule is that the minimum depth resolution that can be defined is equal to twice the cone diameter, thus 2 cm for a 1 cm^2 mini-cone is almost twice as good as 3.5 cm for a 10 cm^2 cone. Whilst mini-cones may allow for fine stratigraphic detail to be delineated they are subject to errors relating to scale effects due to the reduced difference between cone size and grain size. Many studies have been undertaken to quantify this variation and a summary of the results can be seen in Table 4.1.

Reference	Cone area (cm^2)	qc	fs	Friction ratio	Sediment type
(Rahardjo and Brandon, 2001)	4.2, 10, 15	5 – 10% lower			Sandy material (0.12 – 0.25 mm diameter), fine content 5 – 30%. Fines – negligible plasticity.
(Tumay et al., 1998)	2, 10	10 % higher	12% lower	23% lower	Overconsolidated, desiccated silty clay/clayey silt. ω_L – 52-76%, I_p – 26-40%
(Titi et al., 2000)	2, 15	11% higher	9% lower		0-9% sand, 15-68% silt, 29-85% clay. 32% < ω_L < 96% < I_p < 63%

qc = Cone resistance   fs = Sleeve friction

Table 4.1: Variation of miniature cone properties when compared with larger cones

The table shows that for fine materials, cone resistance (q_c) is 10-11% higher for the mini cones than for the larger cones and (sleeve friction) f_s is 9-12% lower. For coarser material, the q_c for the mini cone is 5-10% lower than for the larger cone. The 5-10% variation recorded by Rahardjo and Brandon, (2001), was concluded to be of little importance:

> *"This study shows there was no appreciable effect of the cone size and for practical purposes they yield the same results. The variations in the data of the tip resistance are likely due to the variation of densities of soil layers from one test hole to the other. It is also verified that the friction ratios show almost no differences. This conclusion is for silty sands with diameter less than 0.2 mm."*
>
> (Rahardjo and Brandon, 2001)

The effect of grain size on the resistance data was studied by Lee, (1990), who determined that for a range of cone diameters (B) 6.35 mm to 19.05 mm, ratio values of B/d50 in the range 28-85, did not show any affect of grain size (Gui and Bolton, 1998). The corresponding d50 grain sizes are 0.07 mm (fine sand) to 0.68 mm (coarse sand) (British Standards Institution, 1999). Fugro N. V. describe scale effects:

> *"MCT (Mini Cone Test) signatures may differ from CPT signature in ground with an effective particle size d50 exceeding about 2 mm. Individual particles rather than the soil mass may contribute to the measurements."*

This is an important concern when using miniature CPT systems in coarser grained material, where the relative size difference between the grain and the cone is reduced. A particle size of 2 mm represents the boundary between coarse sand and fine gravel (British Standards Institution, 1999). It is unlikely that a mini CPT would be used in sediment with a grain size larger than 2 mm due to the increased forces required for penetration which increase the chance of shaft buckling.

Penetration speed should be constant throughout cone penetration testing to ensure that drainage conditions remain constant; industry standard speed is 20 $mms^{-1} \pm 5 mms^{-1}$ (Lunne et al., 1997b). Data are usually collected at intervals between 1 and 5 cm with the International Reference Test Procedure (IRTP) recommending that the maximum separation be no more than 20 cm (Lunne et al., 1997b).

The drainage conditions, as determined by Finnie, (1993) may be given:

undrained: $\frac{vD}{c_v} > 10$ drained: $\frac{vD}{c_v} < 0.01$

where: v = speed of penetration
D = diameter of cone
c_v = coefficient of consolidation

It must be noted that high penetration rates lead to increasing resistance due to viscous effects and low rates lead to high resistance due to partial consolidation (House et al., 2001), thus the rate of penetration must be carefully considered. This resistance variation may be used to determine the coefficient of consolidation by undertaking tests during which the penetration rate is altered. Laboratory investigations with T-bar penetrometers, using this 'twitch' test method, have allowed determination of the coefficient of consolidation with an error band of ±20% (House et al., 2001).

As exploration and exploitation move into deeper waters the conditions for testing are dictated by the ambient conditions of high pore pressure and seabed material of low shear strength. For cone penetration testing the determination of the net bearing resistance (q_{cnet}), is dependent on vertical effective stress and ambient pore pressure. If the excess pore pressure acting on the back of the cone is estimated by:

$\Delta u_2 = B_q \, q_{cnet}$ then $q_{cnet} = \frac{qc - (\sigma'_v + \alpha \, u_o)}{1 - (1-\alpha)B_q}$

q_{cnet} = net bearing resistance
B_q = ratio between excess pore pressure and the net bearing pressure
qc = raw (measured) cone resistance
α = area ratio
σ'_v = vertical effective stress increase - relative to depth at which cone was zeroed
u_o = change in ambient pore pressure - relative to depth at which cone was zeroed
(Randolph et al., 1998)

The equation shows how the cone resistance is influenced by an "unequal area effect' whereby the projected area of the cone is not equal to the area of the back of the cone. In the equation this factor is represented by the area ratio, with typical values ranging from 0.55 to 0.95 (Randolph et al., 1998). Due to the complexity of the above equation, there is a large margin for error:

"In summary the various factors that contribute to uncertainty in estimating undrained shear strength from cone data include:

- *inaccuracy of raw cone resistance, q_c, in soft soils (± 5%)*
- *uncertainty in the effective overburden stress, σ'_v, (± 5%)*
- *variations in the effective area ratio, α, during cone penetration due to soil entering the groove at the back of the cone and due to the viscous nature of the seals (±10%)*
- *uncertainty in the factors B_q or β (±20%)*
- *uncertainty in the cone factor, N_c (±20%)"*

(Randolph et al., 1998)

The cumulative effect of these errors can lead to shear strength uncertainties of ± 35%, thus lowering the resolution of cone data. Although mini-cones offer the possibility of acquiring high-resolution stratigraphic data they are also influenced by the 'unequal area effect' thus reducing their overall resolution capabilities. An alternative technique for acquiring in situ resistance data, the T-bar penetrometer (Fig. 4.1), was designed at the University of Western Australia by Stewart and Randolph (1991). The symmetrical design of the T-bar means that forces act equally on both the top and bottom of the bar and thus the 'unequal area effect' of overburden and ambient pore pressures are not encountered (Fig. 4.2).

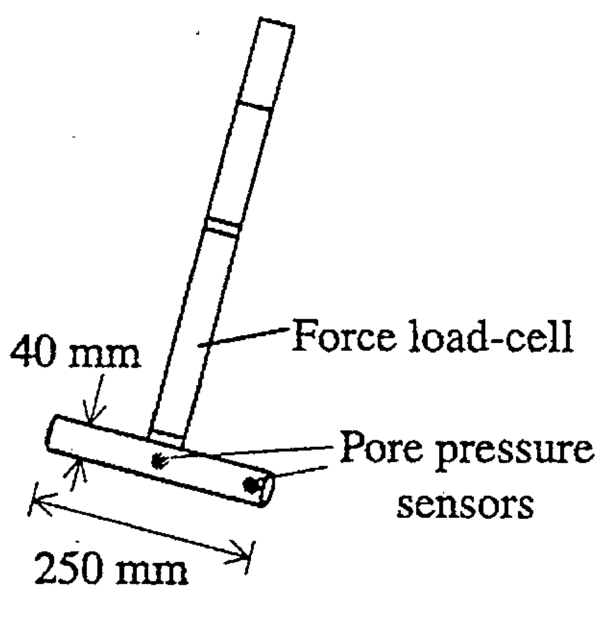


Figure 4.1: A T-bar penetrometer (Randolph et al., 1998)

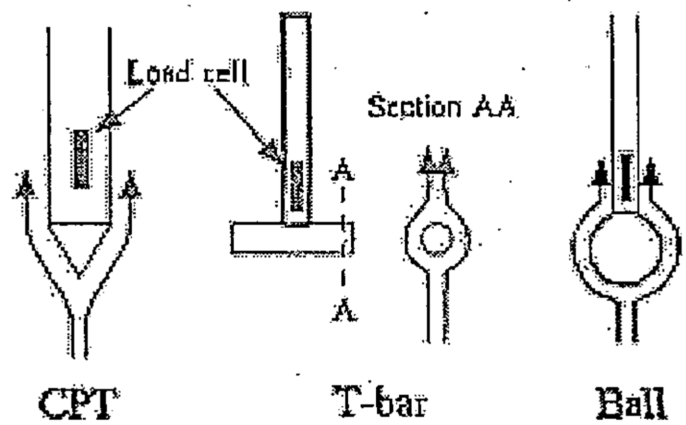


Figure 4.2: Penetration devices and deformation mechanisms (Watson et al., 1998)

Bearing resistance (q_b) may therefore be calculated:

$$q_b = \frac{Q_b}{\text{area bar}}$$

where: Q_b = total force on bar
area of bar = Length * diameter

As for the cone penetrometer, undrained shear strength may be attained via an exact plasticity solution:

> *"which assumes full closure of the soil behind the cylinder such that a gap does not occur"* (Stewart and Randolph, 1991)

$$S_u = \frac{q_b}{N_b}$$

where: q_b = measured bar resistance
N_b = bar factor

Due to the lack of pore pressure and overburden concerns, this simple calculation of undrained shear strength gives a much more reliable result than if the same equation was used for cone data.

References show cone factors to vary from 7 to 15 and even up to 30 (Randolph et al., 1998), from 5 to 12 (Chen, 2001) and from 15 to 19 for marine clays and 11 to 13 for soft clay (Lunne et al., 1976). The cone factor value is dependent on sensitivity, plasticity, lateral stress coefficient, micro and macro fabric and degree of overconsolidation (Randolph et al., 1998; Tumay et al., 1998). Tumay et al, (1998) also believe that the value depends on the cone penetrometer design and penetration speed. However, the theoretical T-bar factor only ranges from 9.4 to 11.9, with a value of 10.5 usually being adopted, giving a deviation of only ± 13% (Stewart and Randolph, 1991). Variation of the bar factor is dependent on the roughness / smoothness of the bar surface, with values increasing with increasing roughness.

Figure 4.3 shows the relationship between the cone factor and plasticity index and indicates a general trend of increasing cone factor with decreasing plasticity. This may account for the differences in tip resistance shown in Table 4.1, with the lower plasticity material requiring lower cone values than the higher plasticity material.

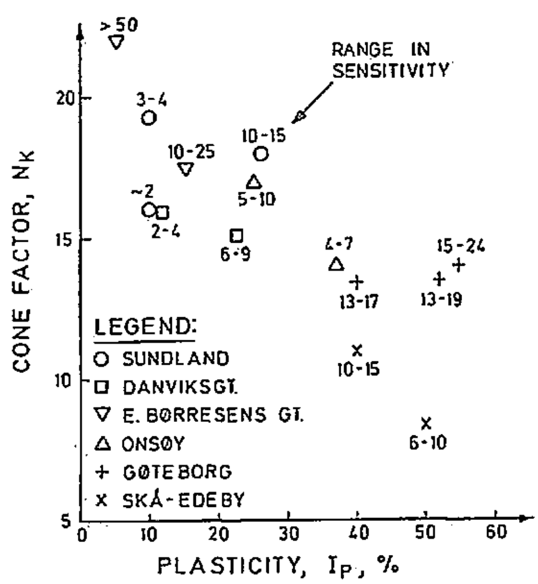


Figure 4.3: Comparison of obtained cone factor values (Lunne et al., 1976)

The T-bar may be described as a 'flow round' penetrometer due to symmetry of the system. Another flow round system, the ball penetrometer, has been shown to provide results similar to the T-bar in laboratory tests comparing data acquired from a mini-cone (1 cm^2), a T-bar (20 mm x 5 mm) and a ball penetrometer (12 mm diameter), with direct shear measurements (shear vane) and theoretical relationships (Watson et al., 1998). Ball factors calculated using plasticity solutions yielded values of 13 to 13.5 (~25% greater than N_{bar}), although testing on calcareous clays, calcareous silts and kaolin clays, has resulted in values identical to those used for the T-bar (Watson et al., 1998).

> *"The low factor, compared to theoretical estimates may be due to strength anisotropy, or differences between plane strain (T-bar) and axisymmetric (ball) shearing."* (Watson et al., 1998)

The shear strength data acquired from direct shear vane testing, showed shear strengths 10-20% higher than those acquired from the three penetration devices, which it is reported may be attributed to strength anisotropy and strain-softening effects (Watson et al., 1998). These tests were undertaken on calcareous silt and clay (obtained from two seabed sites in the North-west Australian shelf and the Timor Sea) and kaolin clay.

More recent studies, in calcareous silt and kaolin clay, (cone 1 cm^2, T-bar 24 x 6 mm and ball 10 mm) compared cone factors acquired through triaxial (Tx) and simple shear (SS) testing (Table 4.2). The samples were consolidated under a vertical pressure of 100 kPa, tested with the penetrometers and then isotropically consolidated in the triaxial and simple shear tests (Joer et al., 2001).

		Kaolin clay	Calcareous silt
From Tx results	N_c	12.2	13
	N_t	9.7	11.5
	N_b	9.7	11.5
From SS results	N_c	12.5	15.3
	N_t	10.3	13.5
	N_b	10.3	13.5

Table 4.2: Experimental determination of cone, T-bar and ball factors (Joer et al., 2001)

The data show good consistency between the triaxial and shear testing techniques giving values for N_c marginally higher than the value obtained for both N_t and N_b.

The T-bar may also be used to determine in situ remoulded strength by recording the bearing resistance during removal (Randolph et al., 1998). Tests undertaken with the flow round penetrometers indicate remoulded strength equal to approximately 70% of the undisturbed strength (Watson et al., 1998).

The 12-bit resolution achievable from a CPT unit is dependent on the load cell, the maximum required cone resistance and the size of the cone.

$$\text{Max } q_c \text{ (Pa)} = \frac{\text{Max load sensor capacity (N)}}{\text{Area of cone (m}^2\text{)}} \qquad \text{Resolution (Pa)} = \frac{\text{Max } q_c \text{ (Pa)}}{2^{12}}$$

A low load cell range with a small cone would, therefore, provide high-resolution measurements, but only to a limited maximum cone resistance. If a higher resistance is required then the resolution will suffer as is the case for cones used in deep water. T-bar penetrometers have inherently better resolution as the measured bar resistance is lower due to the absence of unequal area effect issues.

4.3. Cone penetration testing – research development

The development of a CPT system that could be operated from the proposed ROV (chapter three) was one of the aims of this research. At present CPT testing is restricted to open access areas due to the requirement for equipment stability during testing and the consequent size of the deployment vessel or platform. This chapter will describe, through the use of comparisons with past CPT research and development, a CPT system suitable for deployment from the proposed ROV, taking into account the restrictions and peculiarities of the nearshore zone. This investigative research was undertaken in conjunction with Professor Mark Randolph at the University of Western Australia, Perth (January – March 2002).

4.3.1. Environment

There are three main areas in which surface CPT data (that acquired in the top few metres of seabed sediment) may provide useful information:

- Areas of restricted access out of reach of the standard jack-up rig testing environment
- Areas with low shear strength
- For localised stability and pipeline investigations

The nearshore zone is the primary location for restricted access testing and as previously discussed the requirement in this zone is for a small and lightweight ROV that can be deployed from a small survey vessel. This criterion fits closely with the second area of interest: areas of low shear strength, as the ROV would also need to be of low weight to reduce site disturbance. In both instances, the deeper the penetration capabilities, the more useful the equipment. However, the penetration capabilities are linked directly to the weight of the unit (see equation below) and thus reducing one automatically results in a reduction of the other.

$$S_u = k\,z + S_{u0} \qquad Su = \frac{q_c}{N_c} \qquad q_c = \frac{Q_c}{\text{Cone area}}$$

$$\therefore \frac{Q_c}{(N_c * \text{Cone area})} = k\,z + S_{u0}$$

where: S_u = undrained shear strength | S_{u0} = undrained shear strength at the surface
k = shear strength constant | z = depth
qc = cone resistance | Nc = cone factor
Qc = total force acting on the cone

In this instance, if the shear strength of the sediment increases, then the total force acting on the cone, Q_c, (equivalent to the weight of the system) increases thus increasing the weight of the ROV. If therefore, the survey zone is either in a restricted area or of low shear strength, current techniques such as large landing systems could not be employed and thus *any* achievable penetration may provide useful data. However, for many applications such as engineering construction where foundations are being laid, information on the surficial sediment is not required as this material is often removed. In this scenario the ROV based system may, therefore, only provide information useful for research or local studies.

The third area of interest is pipeline cover, which must remain stable in order to protect the pipeline from exposure, thermal variations and upheaval buckle (Power et al., 1994). With the expansion of offshore oil and gas exploitation pipeline networks are rapidly increasing. The safety of these pipelines is of fundamental importance and surveys are carried out pre-lay, real-time whilst the pipe is laid and post-lay to ensure that no damage occurs. The financial implications of relaying or rerouting pipelines are obviously vast and thus a significant amount of time is put into site surveys. The instability of surficial material is discussed by Waterton and Price, (1994):

> *"Uncemented sea floor sediments in shallow waters are readily affected by the motion of the water above them and are, at best, in a metastable equilibrium. Under strong current loading, they can experience considerable mobility and large*

volumes can be moved by the action of currents. On a more localised basis, offshore structures commonly set up interaction processes that upset the equilibrium of surrounding sediments. The combined result of these processes is scour, with significant material being excavated and/or deposited variously around a structure."

For the above reasons it is crucial to ensure that the sediment covering the pipeline is stable and therefore in situ testing must be undertaken. Subsea pipelines, if buried, are generally buried to a depth of between 1 and 3 metres and thus only shallow testing is required. An ROV unit designed specifically for such a task would therefore be easier to deploy than a large scale deep penetration landing frame and would have the added advantage of mobility. In addition, as has been discussed above, the smaller cones allow for better resolution of fine stratigraphic features and have an associated reduced weight requirement thus reducing the likelihood of disturbing the sediment. If burial was not undertaken at the time of pipelay it is likely that the movement of local material would cause a degree of cover to occur. In these circumstances it is even more important to limit the force applied as the strength of this material is unknown and therefore, there is a heightened risk of damaging the underlying pipeline.

The investigation into pipeline burial material by Waterton and Price, (1994), brought to light an unusual bilinear q_c response (Fig. 4.4).

"In non-cohesive sediment, which comprised 92% of the pipeline route, a marked bilinear response was apparent, with a relatively smooth, linear section to a depth of 0.5 m followed by a section which was more erratic and had only an approximately linear response."

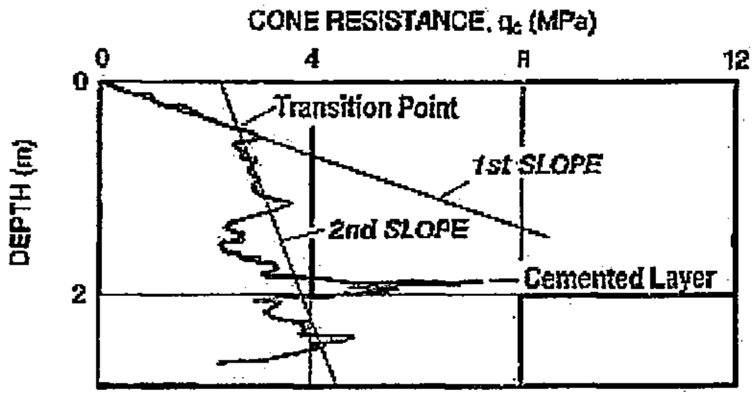


Figure 4.4 Cone resistance response for pipeline survey (Waterton and Price, 1994)

The conclusion that bioturbation may have been the cause of the unusual response was put forward and hence this case illustrates the uncertainty of profiling in the surface sediment. Further evidence of the uncertainty of near-surface testing was found by Rahardjo and Brandon, (2001) in a study comparing scale effects in small and large cones. They found that tip resistance values for both cones were very similar except in the top 1.5 m, thus indicating that testing in surface sediment is more complicated than at depth. For these reasons it would be prudent to compare the CPT data with shear strength data, preferably acquired in situ (shear vane method), or in the laboratory using a triaxial testing unit.

4.3.2. Dimensions

A number of steps are involved in the determination of the feasibility of operating a CPT from an investigation ROV. These include the determination of the required weight of the system, the size of the penetrometer and the expected shear strengths in which testing is to be undertaken. The impact of an ROV on the sediment at the survey site has been investigated in chapter three in relation to the design of the proposed ROV. It has been shown that an ROV measuring 1m in length with two tracks of 0.2 m width, separated by a gap of 0.2 m and weighing 250 kgf will exert 6.1 kPa pressure. A system developed by Christensen et al., (1998) (Fig. 4.5) offers an indication as to the potential penetration capabilities of the developed ROV. The unit measures 0.92 m in length, 0.46 m in width and 1.0 m in height. With a weight of 240 kgf, the system achieves penetration of approximately 45 cm, at a speed of 0.84 cm s^{-1} using a 3.2 cm^2 cone. The cone is driven into the sediment by a linear actuator with a 91 cm stoke and load capacity of 680 kgf. The program used to control the penetration also has the capacity to cease penetration when maximum resistance is encountered to ensure that the equipment is not broken.

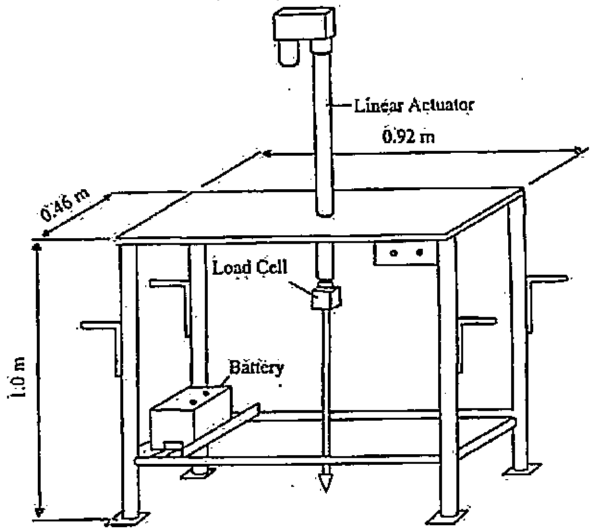


Figure 4.5: Portable cone Penetrometer (Christensen et al., 1998)

Flow round systems (T-bar and ball) were chosen for investigation in the current ROV study due to their inherent ability to acquire high-quality data in soft sediment such as that found in the nearshore zone. The size of the T-bar/ball to be used is very much dependent on the required resolution, weight of the vehicle and shear strength of the sediment. The exact dimensions of the system should be such that the ratio of area of the penetrometer to the area of the shaft is between 5 and 10. Tables 4.3 a & b gives some example values for T-bar systems

a)

			Ratio (with varying shaft diameters)									
T-bar Length (cm)	T-bar diameter (cm)	T-bar area (cm^2)	5	6	7	8	9	10	11	12	13	14
4	0.7	2.8	14	10	7	6	4	4	3	2	2	2
5	0.8	4.0	20	14	10	8	6	5	4	4	3	3
6	0.9	5.4	28	19	14	11	8	7	6	5	4	4
7	1.1	7.7	39	27	20	15	12	10	8	7	6	5
8	1.3	10.4	53	37	27	21	16	13	11	9	8	7
9	1.4	12.6	64	45	33	25	20	16	13	11	9	8
10	1.6	16.0	82	57	42	32	25	20	17	14	12	10

b)

Shaft diameter (cm)	Shaft area (cm^2)
0.5	0.20
0.6	0.28
0.7	0.38
0.8	0.50
0.9	0.64
0.10	0.79
0.11	0.95
0.12	1.13
0.13	1.33
0.14	1.54

Table 4.3: T-bar dimensions a) T-bar dimensions, b) Shaft dimensions

A high area ratio is important in the design criteria but it is also vital to bear in mind the strength of the shaft. Although a large T-bar will be able to withstand the high shear strengths that it may encounter the shaft must also be able to withstand the potential buckling forces. Stresses on the shaft may be lessened with the use of friction reducing systems, however it would be advisable to ensure that the shaft was strong enough to withstand the forces alone. It is also unlikely that the friction reducer would be very effective in the ROV based system due to the limited depth of penetration and associated length of shaft.

To determine the required ROV weight for different T-bar sizes, it is necessary to investigate the relationship between bearing resistance (q_b), the total force acting on the cone (Q_b) and the area of the proposed T-bar.

$$q_b = \frac{Q_b}{A_b} \quad \& \quad Q_b = \text{mass x gravity}$$

$$\therefore q_b = \frac{mg}{A_b}$$

The variation of required ROV weight for penetration of the T-bars described in Table 4.3 into sediment of varying shear strength can be seen in Figure 4.6. Based on a bar factor of 10.5 (Randolph et al., 1998) the bar resistance (q_b) would be a factor of 10.5 larger than the shear strength (S_u). A shear strength of 100 kPa (0.1 MPa) would therefore equate to sediment of bar resistance of approximately 1 MPa. The variation of weight with bar resistance is shown in Figure 4.7.

penetrometer sizes and the data show that a T-bar of dimensions 6 cm by 0.9 cm with a shaft of 0.8 cm (area ratio 11) is most appropriate to the study. It was felt that smaller penetrometers would be too weak to withstand the required maximum cone resistance and it was found that the larger penetrometers required too much weight to maintain stability (see later examples). From Figure 4.6 it can be seen that for a T-bar measuring 6 cm x 0.9 cm (area 5.4 cm^2), an ROV of weight approaching 175 kgf would be required to achieve penetration in sediment of S_u 300 kPa (q_b 3.15 MPa). The equivalent weight that is required for a T-bar measuring 7 cm by 1.1 cm is approximately 250 kgf. This weight is however a base weight i.e. it is sufficient only to achieve theoretical penetration into the sediment. It would be necessary to supplement this weight with a 'stability percentage' to ensure continuous ground contact. Values for both the 6 * 0.9 cm and 7 * 1.1 cm system can be seen in Table 4.4.

		6 * 0.9 (cm)					7 * 1.1 (cm)				
S_u (kPa)	q_b (MPa)	Weight (kgf)	+20%	+30%	+40%	+50%	Weight (kgf)	+20%	+30%	+40%	+50%
1	0.01	0.58	0.69	0.75	0.81	0.87	0.82	0.99	1.07	1.15	1.24
10	0.11	5.78	6.94	7.51	8.09	8.67	8.24	9.89	10.71	11.54	12.36
100	1.05	57.80	69.36	75.14	80.92	86.70	82.42	98.90	107.14	115.38	123.62
300	3.15	173.39	208.07	225.41	242.75	260.09	247.25	296.70	321.42	346.15	370.87
1000	10.50	577.98	693.58	751.38	809.17	866.97	824.16	988.99	1071.41	1153.82	1236.24

Table 4.4: Variation of weight with additional stability component

When looking at weights required for 3 MPa bar resistance, it can be seen that the 7 * 1.1 cm T-bar requires 100 kgf more than the 6 * 0.9 cm T-bar for a 50% stability weight. At a total weight of 370 kgf, this would make the system extremely difficult to operate from a small vessel. Figures 4.8 and 4.9, illustrate the required weight trend indicating that it is possible that the system only needs to have a weight of 100 kgf if bar resistance of 1 MPa or less are encountered.

As mentioned above, an alternative penetrometer is the ball penetrometer, which offers the same advantages of as the T-bar over the conventional cone. For the purposes of this investigation the ball penetrometer should have the same area and thus the same area ratio as the T-bar i.e. an area of 5.4 cm^2 equates to a ball diameter of 2.6 cm.

4.3.3. Mini-cone adaptation

In some instances it may be desirable to take measurements where shear strengths exceed 300 kPa when they occur in areas of restricted access. Table 4.4 has however illustrated that such an increase would lead to an ROV whose weight requirement would make it inoperable from a small survey vessel. An alternative solution would be to employ a mini-cone that could be fitted to the existing shaft to test in areas of high sediment shear strength. Table 4.5 a & b provide base weights and stability weights for a 1 cm^2 mini-cone with cone factors of 10.5 and 14 respectively.

a) $N_c = 10.5$

S_u (kPa)	q_c (MPa)	Weight (kgf)	+20%	+30%	+40%	+50%
1	0.01	0.11	0.13	0.14	0.15	0.16
10	0.11	1.07	1.28	1.39	1.50	1.61
100	1.05	10.70	12.84	13.91	14.98	16.06
300	3.15	32.11	38.53	41.74	44.95	48.17
1000	10.50	107.03	128.44	139.14	149.85	160.55

b) $N_c = 14$

S_u (kPa)	q_c (MPa)	Weight (kgf)	+20%	+30%	+40%	+50%
1	0.01	0.14	0.17	0.19	0.20	0.21
10	0.14	1.43	1.71	1.86	2.00	2.14
100	1.40	14.27	17.13	18.55	19.98	21.41
300	4.20	42.81	51.38	55.66	59.94	64.22
1000	14.00	142.71	171.25	185.52	199.80	214.07

Table 4.5: Variation of weight with additional stability component for mini-cone a) $N_c = 10.5$, b) $N_c = 14$

The tables illustrate the large variation of calculated q_c with the variation in cone factor, such that a bearing resistance of 4.2 MPa is equivalent to 400 kPa when N_c is 10.5 and S_u of 300 kPa

that obtainable with the T-bar. Table 4.6 illustrates the possible range in data acquired using a mini-cone using the possible 35% error margin described in section 4.2.

- 35 %	q_c (MPa)	+ 35 %	Range (MPa)
0.007	0.01	0.014	0.007
0.33	0.5	0.68	0.35
0.65	1	1.35	0.70
1.30	2	2.70	1.40
1.95	3	4.05	2.10
2.60	4	5.40	2.80
3.25	5	6.75	3.50
3.90	6	8.10	4.20
4.55	7	9.45	4.90
5.20	8	10.80	5.60
5.85	9	12.15	6.30
6.50	10	13.50	7.0
7.15	11	14.85	7.70
7.80	12	16.20	8.40
8.45	13	17.55	9.10
9.10	14	18.90	9.80
9.75	15	20.25	10.50
10.40	16	21.60	11.20
11.05	17	22.95	11.90

Table 4.6: Potential mini-cone error range

In sediment with a measured q_c of 3 MPa (S_u = 214 kPa, N_c = 14), the potential range of error in cone resistance is 2.10 MPa (S_u = 150 kPa) thus illustrating the disadvantages of the cone system. Although the potential error range at 17 MPa (S_u = 1214 kPa) is 11.9 MPa (S_u = 850 kPa), data acquisition in such sediment would not be possible with the proposed T-bar and thus the data collected with the cone system would still be useful. Such a large error could be reduced with accurate determination of in situ pore pressure. Given the limited water depth requirements, the pore pressure sensors would be more sensitive than those employed in deep water, thus improving the resolution. As the depth of penetration is limited the determination of overburden pressure may also be more reliable. The sediment sampled for laboratory testing would be investigated at a higher density than would be possible for a large sample, thus improving the accuracy of overburden pressure calculations.

As discussed in section 4.2 the miniature systems have, in laboratory and field testing, displayed qc results approximately 10% higher than standard size cone data. It may therefore be necessary to correct the acquired T-bar data for comparison purposes. When compared to the mini-cone though, the correction factor will not need to be as great, given that the area of the proposed T-bar is approximately 5 times greater than that of a mini-cone. The correction is thus reduced by a factor of 2 for a 10 cm^2 cone and a factor of 3 for a 15 cm^2 cone assuming a linear relationship.

4.3.4. Coarse material

The above calculations may be used to assess the potential bar resistance in cohesive material, however for non-cohesive material the relationship between bar resistance and shear strength is not so well known. Examples of two cone resistances encountered in non-cohesive material can be seen in Table 4.7, where it is shown that q_c can reach 25 MPa (S_u = 1786 kPa with N^c = 14) in the top 2 m of overconsolidated material and can reach 16 MPa (S_u = 1143 kPa with N^c = 14) in a medium dense sand.

Location	Sediment type	Ground water	q_c (MPa)
Dunkirk, France	3 m of very dense hydraulic sand fill overlying 30 m of medium to very dense sand (overconsolidated)	approx. 4 m below surface	Max of approx. 25 in top 2 m
Massey, Canada	3 m of sand fill over about 2 m of soft silt, 5 – 25 m is clean sand (Loose to medium dense sand)	2.5 – 3 m below ground surface	Max of 16 in top 2 m

Table 4.7: CPT behaviour in coarse grained material (Lunne et al., 1997b)

These data illustrate the variety of shear strengths to be faced when undertaking CPT surveys and the associated variation in required thrust capacity.

4.3.5. Sleeve friction

Although sleeve friction load cells are a standard in cone penetration testing they would be omitted from the proposed ROV based system. Whilst the friction sleeve offers useful information for the correction of cone data these data are not relevant to T-bar parameters. Friction sleeve load cells are also exceptionally vulnerable to damage and data acquired is often unreliable, adding maintenance and cost concerns to any project. In addition to these issues the limited required depth of penetration, and therefore the associated minor length of the push rod makes the use of a friction sleeve load cell difficult.

4.3.6. Load cells

Knowledge of the maximum required cone resistance and the area of the penetrometer allow a calculation of the load cell requirement. For a maximum of 3 MPa and an area of 5.4 cm^2, the ROV based system would require a load cell of 1.6 kN. It is important to use a load cell that corresponds as closely as possible to the required maximum cone resistance to ensure that the best resolution is obtained. The 12 bit resolution of the system is dictated by the maximum cone resistance (resolution = $q_b / 2^{12}$) and thus the best resolution will be achieved by systems that have been designed to closely fit the specific environment. Table 4.8 shows a range of systems with varying physical properties.

System	Penetrometer area (cm^2)	Max q_c/q_b (MPa)	Load cell (kN)	Tip resolution (kPa)	Reference
Fugro Seascout	1	100	10	24	(Fugro, 1995a)
Portable CPT	3.2	12.5	4	3.05	(Christensen et al., 1998)
Standard 15 cm^2 cone	15	10	15	2.44	(Randolph et al., 1998)
T-bar 25 *4 cm	100	2.5	25	0.61	(Randolph et al., 1998)
ROV 6 * 0.9 cm	5.4	3	1.6	0.73	Current study – calculated values

Table 4.8: CPT cone resolution

As can be seen, the ROV based system would allow 0.7 kPa resolution as compared to 24 kPa achievable by the Fugro Seascout and 3.05 kPa by the Portable CPT.

4.3.7. Penetration mechanism

Due to the limited penetration requirement and the dimensions of the proposed ROV, a linear actuator system is the proposed penetration mechanism. This method is simple and has been proved successful by Christensen et al., (1998) during land trials. To attain a penetration of 50 cm it would be necessary to have an actuator with a stroke of at least 60 cm, a height easily supported by the ROV. Due to weight restrictions the system would need to be powered from the surface via the umbilical.

4.3.7.1. Penetration rate

As discussed in section 4.2, the rate of penetration and coefficient of consolidation dictate whether the testing is drained or undrained. The conflict between penetration being too fast and thus causing viscous effects and too slow causing partial consolidation has also been discussed (House et al., 2001). Mini-cone penetration rates vary from 0.84 – 6 cm s^{-1} (Christensen et al., 1998; Power and Geise, 1995) illustrating the uncertainty that surrounds the conflicting relationships:

$$\text{Strain rate} = \frac{v}{D} \qquad \text{Drainage} = \frac{v\,D}{C_v}$$

D = diameter
v = speed
C_v = coefficient of consolidation

The question of penetration rate is most pertinent in silts as the actual drainage conditions are unknown unless a pore pressure meter is being utilised. It is generally assumed that in clays the penetration is undrained and that in sands it is drained. For the proposed T-bar system a rate of 2 cm s^{-1} is suggested as a compromise between the penetration issues described above and to coincide with industry standards.

4.3.8. ROV mounting

In order to operate a CPT system from the proposed ROV, a mounting and activation system would be required. The CPT module could be attached to the ROV crash frame or connected to an additional ROV equipment frame in which the ROV would sit. Placement of a simple video camera behind the mounting frame, with a real-time link to the surface, would allow for observation of the penetration procedure. The module itself could be placed either within the ROV tracks or at either end, depending on the final design of the ROV and the weight and centre of gravity specifications. To allow for the CPT head to be changed to a mini-cone or to a different size ball or T-bar configuration, the module should be easily accessible and possibly fully removable.

4.4. Summary

The research undertaken indicates that, in theory, it should be feasible to acquire in situ sediment shear strength data through the use of penetration devices. Investigations into the suitability of mini-cone systems have revealed fundamental limitations based primarily on the issue of resolution. To overcome this a flow round system is suggested as an alternative technique and would involve the utilisation of either a T-bar or ball penetrometer. Given a maximum in situ undrained shear strength of 300 kPa a T-bar measuring 6 cm in length by 0.9 cm in diameter and with a shaft diameter of 0.8 cm would be operable from an ROV weighing 260 kgf. Used in conjunction with a 1.6 kN load cell a tip resolution of 0.73 kPa could be achieved. By using a mini cone in place of the T-bar in situ sediment with shear strength of up to 1215 kPa could be tested when using a cone factor of 14. Although this system is affected by the unequal area effect, which leads to lower resolution, it does enable a 'small' ROV to acquire in situ data in sediments of high undrained shear strength. In areas of low sediment shear strength the weight of the ROV could be reduced, enabling it to gain access to the site and undertake in situ penetration testing.

As will be examined in the following chapter, sediment is easily disturbed during sampling, so in situ data is invaluable. The wide use of CPT systems offshore illustrates their importance and the ability to acquire these data in the nearshore zone could provide the surveyor or engineer with data currently unobtainable.

Chapter 5

Sediment coring

5.1. Introduction

A fundamental issue in geotechnical engineering is the ability to acquire bulk, disturbed and undisturbed samples for laboratory testing. Field samples are collected in order to ascertain index properties such as particle size analysis and to determine structural properties such as shear strength and consolidation characteristics. Index properties are dependent upon the particle characteristics and do not alter on removal from the site. Structural properties however are determined by the *in situ* conditions and are altered when a sample is removed. The level of this disturbance must be kept to a minimum if calculations undertaken in the laboratory are going to be taken as representative of the field conditions. Many current sampling techniques (section 2.3.1.) rely on the use of fixed platforms or large surface vessels for the deployment of coring systems. The cost associated with using these systems, in conjunction with their inability to gain access to restricted areas, limit nearshore investigation options. As with the cone penetration systems, a more versatile and cost effective alternative is sought for overcoming the peculiarities of surveying in the nearshore zone.

5.2. Sample disturbance

Although coring provides a mechanism for acquiring samples for laboratory testing, a fundamental principle, as illustrated by the behaviour of clay, must be borne in mind:

> *"During the sampling operations every clay passes from the solid into a partially lubricated state. Hence, information regarding the physical properties of clays in a solid state can only be obtained by means of field observations."*
>
> (Terzaghi, 1941)

Once it has been acknowledged that coring is by no means a perfect solution for ascertaining sediment shear strength and other structural parameters, steps must be taken to determine the extent of the alterations incurred. A great deal of research has been undertaken into disturbance impacts of various techniques for acquiring marine sediment cores (Bashar et al., 2000; Chandler et al., 1992; Clayton et al., 1998; Graham and Lau, 1988; Hight et al., 1992; Kallstenius, 1958; Lacasse et al., 1985; Lo Presti et al., 1999; Lunne et al., 1997a; Lunne et al., 1998; Schmertmann, 1953; Sheahan and DeGroot, 1997; Siddique et al., 2000; Skempton and

Sowa, 1963; Terzaghi, 1941). The range of factors which can cause a change in sediment structure have been defined by Hight et al., (1992) and are shown in Figure 5.1.

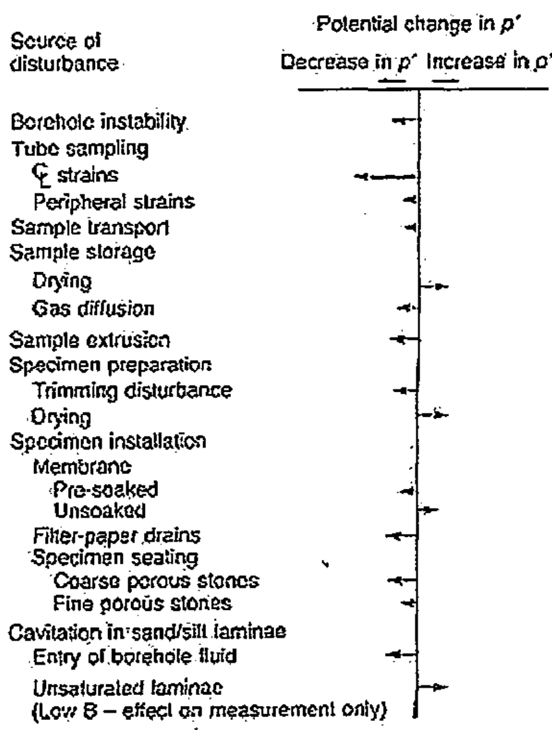


Figure 5.1: Factors influencing the mean effective stress in specimens of soft clay (Hight et al., 1992)

The size of the arrows indicates the proportional disturbance with the greatest source of disturbance resulting from centre line (CL) strains, which lead to a large decrease in mean effective stress. Bjerrum, (1973) recorded a drop of 3-4 % in the water content in the outer 5 mm of samples, resulting from increasing peripheral pore pressure during coring in clay samples (contractant) leading to migration of water to the centre of the sample and thus a reduction in centre line effective stress (Chandler et al., 1992). The figure also shows that specimen drying during both storage and preparation can lead to an increase in mean effective stress. Reductions in mean effective stress are also shown to occur during sample extrusion and trimming.

Graham and Lau, (1988) classify disturbance into two separate groups; mechanical disturbance (direct result of the physical sampling procedure) and process disturbance (resulting from extraction of the sample from the tube and the associated reduction of total stress to zero). Kallstenius, (1958) adds that disturbances may also result from changes in chemistry and temperature and that variations of imposed disturbance may not be consistent throughout the sample. Permeability and relative density are also listed as reasons for structural disturbance during coring (Kallstenius, 1958). Alteration of the sediment structure is most pertinent in brittle and sensitive clays, in which particular care must be taken during core acquisition (Kallstenius, 1958; Lacasse et al., 1985).

The interest focus of this study is the nearshore zone and hence the associated sampling difficulties specific to this area must be addressed. In terms of sampling, nearshore and coastal material is likely to have a very low shear strength and thus behaves very differently to higher shear strength consolidated deep sea material. The research undertaken by Sheahan and DeGroot, (1997) into specific nearshore and coastal sampling issues will be addressed later in the chapter.

5.3.Existing systems

Although there are many coring systems available to the offshore and nearshore survey industries many require the use of a large frame for stabilisation and deployment (section 2.3.1.). Independent systems have been developed for diver based coring, facilitating the acquisition of cores without the need for large surface vessels. Very simple tools such as the reverse corer (Fig. 5.2) have been designed specifically for use by divers (Anima, 1981). This corer can obtain cores 80 mm in diameter by 300 mm in length and is quick to operate in response to the depth/time limitations imposed on divers. The design criteria were based on a study into the movement of sediment by avalanche and the corer has been designed to sit in position whilst the sediment fills the barrel naturally. The cores can then be extracted from the seabed using a reverse plunger so maintaining the sediment matrix (Anima, 1981).

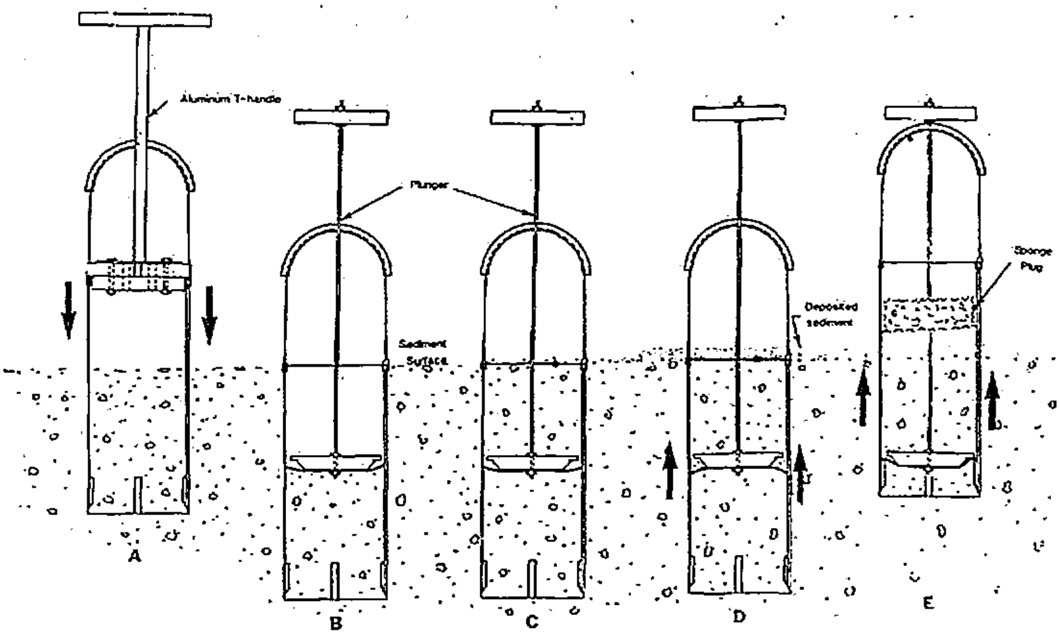


Figure 5.2: Diver operated reverse corer (Anima, 1981)

Where material is required immediately, the use of a diver based hammering mechanism has become common (Martin and Miller, 1982; Reddering, 1981; Sanders, 1968). This method simply involves the driving of core tubes into the sediment by application of down force through the use of a hammer on the top of the tube. The use of a guide plate and protection cap is common, preventing damage to the core tube and limiting the vibration experienced.

Mechanical systems utilising air provided by SCUBA tanks are another diver based alternative (Bonem and Pershouse, 1981; Jones et al., 1992). Figure 5.3 shows a corer based on a pneumatic drill operated by compressed air supplied from a scuba tank carried by the diver in tandem with his own air supply. Core tubes of diameter between 38.1 and 50.8 mm (1 ½ and 2 in) were used to collect sediment samples in water depths of up to 30 m when investigating the re-growth and development of reef material (Bonem and Pershouse, 1981).

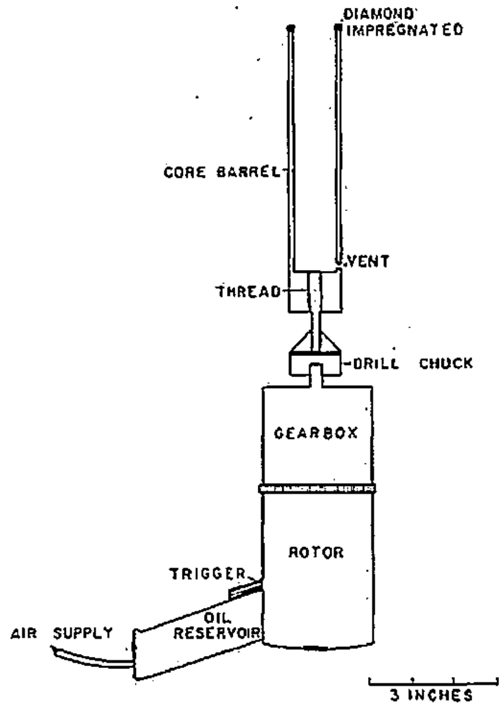


Figure 5.3: Diver operated inexpensive, portable corer (Bonem and Pershouse, 1981)

An alternative scuba based system, described by Jones et al., (1992), facilitates the acquisition of sediment cores up to 1 m in length. Once the PVC tube has been inserted into the bed sediment an air chisel is used to drive the core tube to full penetration. This system has been successfully applied in wet and dry beach sands, silts and peat. Samples can be acquired in as little as 45 seconds depending on the shear strength of the sediment.

In most of the examples cited above the sediment core is removed by simply pulling or digging the tube out (ends of the tubes are sealed with rubber bungs) thus potentially adding to the disturbance inflicted on the sediment matrix. Furthermore the inherent time / depth restriction of the diver based system limits their usage. ROV based systems may offer an alternative solution to the latter constraints and thus have been further investigated in this research.

To prevent an excess in ROV payload, tools can be lowered to the seafloor separately. Sprunk et al., (1992) describe a system in which a weighted sampling receptacle (Fig. 5.4) is lowered to the seabed on a tether. The ROV may then pick up sampling tubes using the manipulator arm and vertical thrusters and can obtain samples of 25 or 63 mm outside diameter (OD).

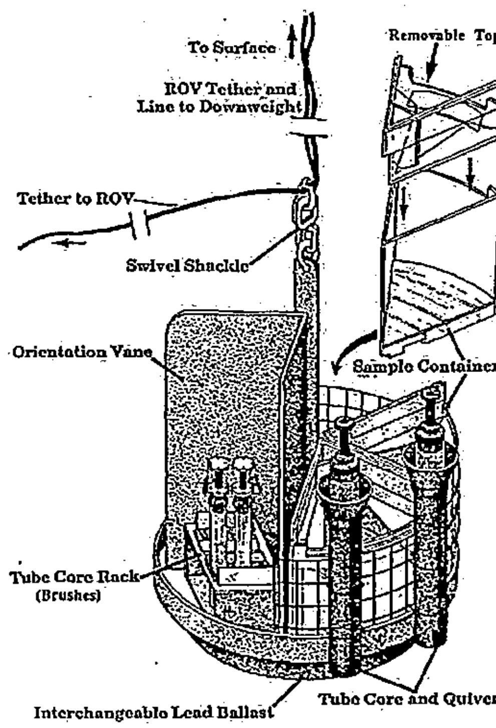


Figure 5.4: Sampling receptacle (Sprunk et al., 1992)

This system is successful in acquiring small core samples but the use of the manipulator arm limits the penetration capability. Furthermore the reliance on the vertical thrusters to provide down force may introduce site disturbance due to sediment drift or limited localised compaction. In this instance the ROV was mounted on a skid which raised the vertical thrusters 100 mm off the seabed to reduce this impact. A further limitation of this technique is the reliance on the power of the vertical thrusters to provide sufficient down force. Most small ROVs are designed for inspection purposes and consequently the power of their thrusters is limited.

Larger systems such as manned submersibles offer an excellent base for sediment coring due to their size and the increased power available. The Multiple-Barrel Coring System (MCS) developed for the Alvin manned submersible can acquire multiple rock cores of 33.5 mm diameter and 914 mm length (Plate 5.1) (Stakes et al., 1997). Initially the design revolved around the use of the manipulator arm for the full range of tube manoeuvring but this method was found to be unsatisfactory. To support the role of the manipulator arm a hydraulic motor was added for rotation purposes along with a system for drill advance. Coring was found to be

remotely operated and therefore surface driven gravity and hammer corers would be unsuitable. The mechanism was required to obtain and retrieve samples whist stationary on the seabed, to ensure that the disturbance is kept to the absolute minimum and that the sediment could be safely secured within a core tube. The system would then need to be able to hold the core safely whilst allowing the ROV to continue collecting data.

5.4.2. System design

The operating mechanism developed as part of the current research was a simple air driven piston corer. Air was supplied from the surface through a plastic hose via a compressor, operating at up to 800 kPa. A guide tube system was designed (Fig. 5.5) whereby the coring mechanism and sample tube were contained within a guide tube to reduce the risk of breakage of free parts.

The diagram shows the corer to have two air valves, connected to two air inlets on the corer, which are used to control tube penetration and removal. The first step in taking a core is to place the core barrel into the guide tube and secure with a bayonet fitting. The compressor is turned on and the reservoir is allowed to fill so that the gauge reads 800 kPa. Once the valve connected to the lower inlet is closed and vented to atmosphere, the upper air valve is opened so that pressurised air can be supplied to the upper chamber via the plastic hose (4 mm OD, 2.5 mm ID (Internal diameter)) and the upper air inlet. The ingress of air into the upper chamber drives the piston head and piston down, thus pushing the core tube into the sediment. During the coring process some air may leak around the seals in the piston head into the lower chamber but will be released to atmosphere via the lower inlet. Any water or sediment entering the guide tube through the non-return valve will disperse through the vents in the side of the guide tube.

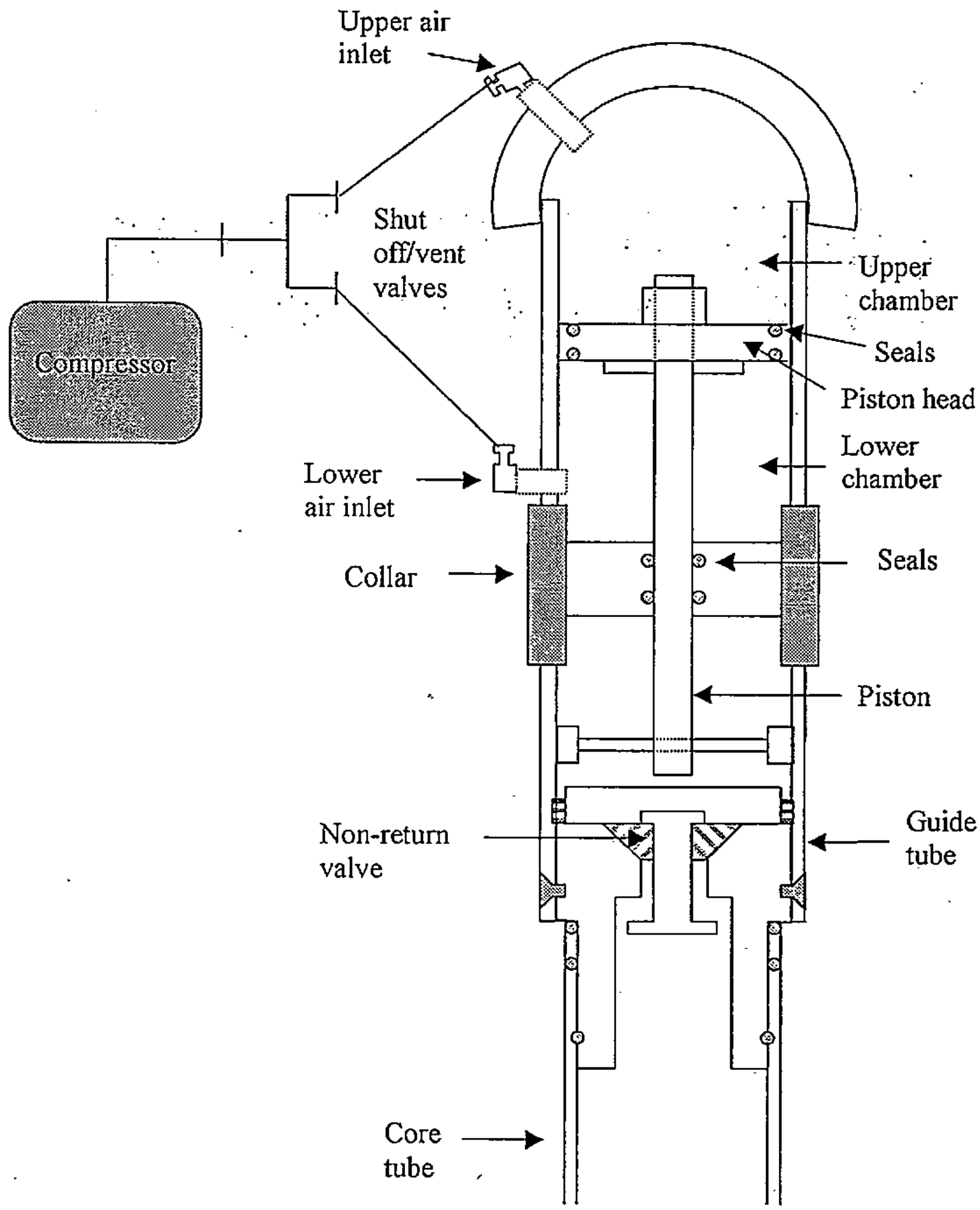


Figure 5.5: Coring mechanism (with piston rod) – Not to scale

Once the core tube has reached full extension the upper valve is switched off and vented to atmosphere and the lower valve is opened to allow pressurised air from the compressor to enter the lower chamber. The force of the pressurised air in the lower chamber drives the piston head and piston upwards, with air in the upper chamber being expelled through the upper inlet. During this process the non-return valve is forced downwards into the seating creating a suction seal that holds the sediment in the tube as the tube is removed from the ground. This mechanism has been used in other marine samplers and research by Onuf et al., (1996) included the use of a 'toilet flapper valve' (non-return valve) (Fig. 5.6) to achieve the same suction effect. Once the core tube has been fully retrieved the core catcher flips across the bottom of the guide tube and the lower valve can be closed and vented to atmosphere. The core can later be sealed and removed from the guide tube.

The disturbance of the retrieved sample is not only dependent upon the mechanism of coring but also on the dimensions of the coring tube. The level of disturbance decreases as internal diameter increases and wall thickness decreases (Kallstenius, 1958; Sheahan and DeGroot, 1997). For this reason, a plastic sample tube with an internal diameter of 75 mm and wall thickness of 4 mm was initially chosen. This tube size would also allow for British Standards oedometer tests (British Standards Institution, 1990b) to be undertaken increasing the versatility of the sample for laboratory testing. The length of sample retrievable is dependent on the power of the system and the strength of the material hence a barrel length of 600 mm was chosen and the end of the tube was filed to create a cutting edge.

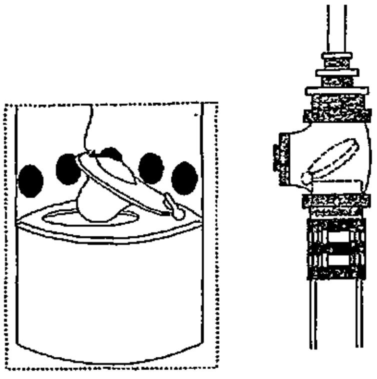


Figure 5.6: Suction corer using toilet flapper valve (Onuf et al., 1996)

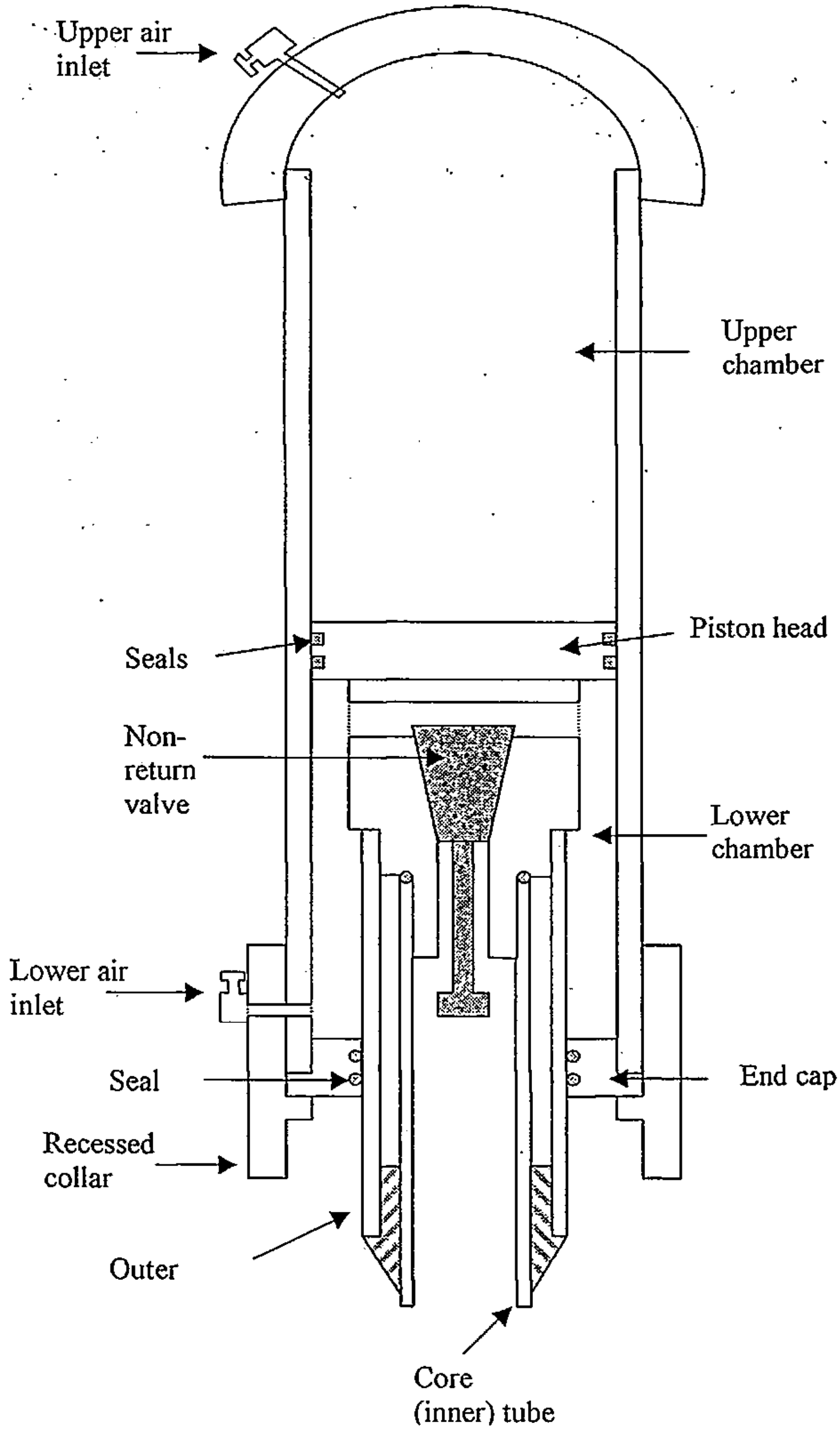


Figure 5.7: Coring mechanism (without piston rod) – Not to scale

As previously discussed, a requirement of the system was that the samples would be of a large enough size to enable as great a range of laboratory based geotechnical tests as possible to be undertaken. Reducing the size of the core tube to 40 mm in the previous adaptation removed the possibility of undertaking oedometer tests for consolidation but was still large enough for triaxial testing. Due to the location of sediment acquisition, i.e., the coastal zone, the sediments had low shear strength and high moisture contents. A sample for triaxial testing needs a sample diameter of 38 mm (British Standards Institution, 1990b). In consolidated samples this may be achieved by cutting away the outside material to reduce the sample size. In the case of samples that cannot stand independently this cannot be undertaken. For this reason the core tube size was reduced to 38 mm internal diameter with a wall thickness of 1 mm. Again the tube was marine grade stainless steel (316L) but was not finished with a high polish due to limited availability.

The basic mechanism for coring remained the same but the removal of the piston led to two changes. Once again it can be seen that the corer has two air valves, connected to two air inlets on the corer, used to control tube penetration and removal. The compressor is turned on and the reservoir is allowed to fill so that the gauge reads 8 bar (800 kPa). Once the valve connected to the lower inlet is closed and vented to atmosphere, the upper air valve is opened so that pressurised air can be supplied to the upper chamber via the upper air inlet. The application of air into the upper chamber drives the piston head down, pushing the core tube directly into the sediment. During the coring process some air will leak around the seals in the piston head into the lower chamber. This air will be released to atmosphere via the lower inlet along with any water or suspended sediment forced up through the non-return valve. Once the core tube has reached full extension the upper valve is switched off and vented to atmosphere and the lower valve is opened to allow pressurised air from the compressor to enter the lower chamber. The force of the pressurised air in the lower chamber drives the piston head upwards, with air in the upper chamber being expelled through the upper inlet. During this process the non-return valve is forced downwards into its seating thus creating a suction seal that holds the sediment in the tube as the tube is removed from the ground. Once the core tube has been fully retrieved the end of the tube can be sealed and the lower valve can be closed and vented to atmosphere.

5.4.3. Field work

As discussed in section 5.2., much research has been carried out to define the acceptable limits of disturbance. Geotechnical laboratory investigations rely on the structure of the material being as undisturbed as possible thus providing a reliable representation of the *in situ* conditions. A simple comparison study was devised to investigate the extent of sample disturbance resulting from the impact of the piston. To quantify the disturbance effects, the samples acquired in the field were used for laboratory triaxial testing and the data were assessed in conjunction with some *in situ* data and results from additional laboratory investigations.

Field tests were undertaken with the new coring system using the 38 mm (ID) tubes. As the new system did not have a frame, tests were carried out on the banks of the Plym estuary where soft sediments could be tested without the corer being fully submerged. Four sets of samples were collected from the survey site, each consisting of one piston core and one 'undisturbed' core, both collected as close to each other as possible. The absolute positions of the sites have not been taken into account and they have been labelled sites 1 to 4.

Two people held the corer; each holding the corer upright at the top and having one foot on a bar at the base of the tube to apply down force as required. Tests showed that no down force was required and that the corer easily penetrated the sediment to full extent and retrieved the full sample. When coring was completed an end cap was placed over the bottom end of the core tube and once removed from the guide tube another was placed on the top to ensure that minimum water loss was experienced. All cores were stored upright to prevent further disturbance. Samples of material from each site were collected to ascertain *in situ* moisture content, as some moisture is always lost during subsequent laboratory testing.

Field shear vane testing was also undertaken to allow for comparison with the shear strengths derived from the laboratory triaxial tests. This *in situ* measure of shear strength, when compared with the lab data, should given a simple indication of the total level of disturbance imposed as a result of sampling, storage and extrusion. Material was also collected to allow for further laboratory analyses including Atterberg testing to obtain further information about the behavioural characteristics of the sample.

5.4.3.1. Laboratory testing

The process of acquiring a sample for a triaxial test using the piston corer has 2 primary stages. The first is the acquisition of the sample and the second is the extrusion from the core tube. As discussed above the samples for triaxial testing need to be 38 mm diameter. This means that whatever the sampling method, the sample has to be either trimmed (a process not applicable for soft sediments), already be of the correct size, or sub-sampled. In the instance of the piston corer the sample was of the correct size so this factor was kept constant in the comparison study. A sample 170 mm in diameter and up to 320 mm in length could be acquired using a simple coring tube. Due to the size of the sample the centre section was essentially 'undisturbed'. In the laboratory this material was sub-sampled using the 38 mm tubing. This process was undertaken slowly and with maximum care to ensure that minimum disturbance occurred. This 'undisturbed' sample could then be extruded in the same way as the standard piston core sample. Using this technique two variables existed in the comparison; Firstly the method of sample acquisition and secondly the sediment sampled. The variation in sediment was kept to a minimum by coring at locations as close together as possible: this left the disturbance caused by the corer, as the main variable to be tested. Sample drying was kept to a minimum by only unsealing the cores as and when required.

5.4.3.2. Method

The piston cores were opened and extruded into a split plastic core tube to maintain shape. A section of the core was chosen, the depth of which corresponded to the depths of the field shear vane testing. Each triaxial sample was approximately 73 mm in length and 38 mm in diameter. The sample was then tested in the triaxial with a cell pressure of 100 kPa using a quick undrained technique. The sample was sheared at a rate of 1.5 mm per minute using a 0.723 N

Site	Depth (cm)	Field MC %	Salinity	w_P Plastic limit	w_L Liquid limit	I_P Plastic index	I_L Liquid index	> 425 (%)	< 425 (%)	Field vane C_u (kPa)	Type	G_S	Triaxial MC %	Triaxial C_u (kPa)
1	7	55.96	30.9	27.13	48.99	21.86	1.32	0	100	12	Piston	2.3800	49.83	15
1	7	55.93	30.9	26.89	50.20	23.31	1.25	3	97	11	U/D	2.3818	51.37	13
2	9	50.13	30.9	29.02	51.48	22.46	0.94	0	100	12	Piston	2.3300	50.85	14
2	9	58.52	30.9	27.85	47.97	20.12	1.52	16	84	9	U/D	2.3321	49.48	14
3	6	55.89	30.9	28.14	51.21	23.07	1.20	0	100	10	Piston	2.3300	50.97	15
3	6	53.24	30.9	26.22	46.40	20.18	1.34	40	60	11	U/D	2.3296	44.79	17
4	4	51.95	30.9	27.55	39.05	11.50	2.12	23	77	10	Piston	2.4700	60.95	10
4	4	43.28	30.9	27.70	40.59	12.89	1.21	18	82	11	U/D	2.4704	53.97	12

Piston = piston core
U/D = 'undisturbed' core
MC = Moisture content
C_u = Undrained shear strength
G_S = Specific gravity

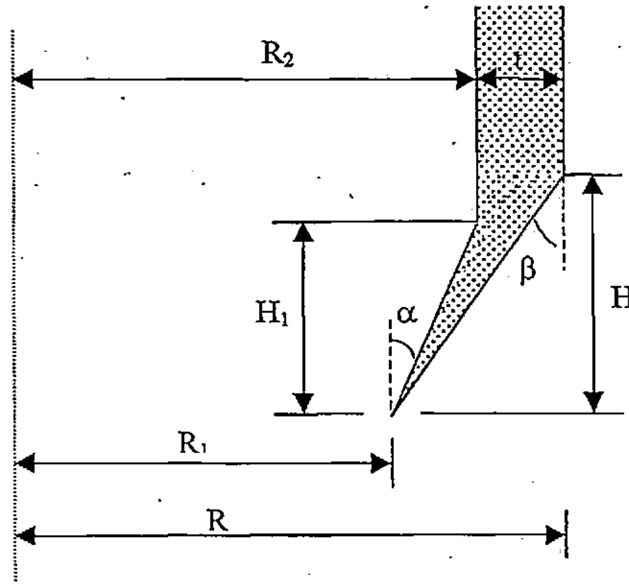
Table 5.1 : Triaxial testing laboratory data

The variation between the field moisture contents and the triaxial moisture contents may also be responsible for the discrepancies. With the exception of the site 2 piston core sample and both samples from site 4, the field moisture content is higher than the triaxial value. A higher moisture content would support a lower shear strength finding and thus the variation may be attributable to processes occurring subsequent to sampling. Such processes may include the loss of water form the sample due to leakage from the tube or from settlement during transportation.

The table shows a very simple particle size analysis (PSA) review where most of the sediment has a grain size of less than 425 microns, indicative of medium sands and finer. This division of sediment was needed to perform Atterberg tests requiring sediment of less than 425 microns. Atterberg tests allow distinctions to be made with regard to the behaviour of sediments with varying levels of water content (Appendix A). Most of the triaxial moisture contents fall very close to their liquid limits, which indicates that they are on the boundary between behaving like plastics and liquids. The triaxial moisture contents for site 4 are significantly higher than their liquid limits, which may explain the lower shear strength i.e., liquid behaviour. Site 3 shows considerable variation between the two sediment samples in terms of basic PSA with the undisturbed core having a higher percentage of coarser material (this is also supported by the lower plasticity index values).

5.5. Sample disturbance

Various parameters relating to the dimensions of a core tube may be defined as shown in Figure 5.12 and are supplemented by the dimension B which is equal to the outside diameter of the tube.



R = External core radius
R_1 = Internal core radius at inside cutting edge
R_2 = Internal core radius
H_1 = Height relating to inside-cutting edge angle
H_2 = Height relating to outside-cutting edge angle
t = Core barrel thickness

Figure 5.12: Dimensions of a tube sampler (Clayton et al., 1998)

Based on the tube dimensions some simple parameters can be defined:

$$\text{Aspect ratio} = \frac{B}{t}$$

$$\text{Area ratio of sampler (AR)} = \frac{R^2 - R_1^2}{R_1^2}$$

$$\text{Inside clearance ratio of sampler (ICR)} = \frac{R_2 - R_1}{R_1}$$

$$\text{Inside cutting-edge angle (ICA) } (= \alpha) = \tan^{-1} \frac{R_2 - R_1}{H_1}$$

$$\text{Outside cutting-edge angle (OCA) } (= \beta) = \tan^{-1} \frac{R - R_1}{H_2}$$

The sampling tube used in the research piston corer was a flat ended tube and its parameters may be compared with data acquired in a study by Clayton et al., (1998) (Table 5.2). The ICR value of a flat ended tube is obviously zero and thus is not included in the table.

Sampler	B (mm)	t (mm)	AR (%)	B/t
1	57.00	1.25	9.38	45.6
2	57.50	2.50	20.0	23.0
3	117.41	5.90	23.6	19.9
4	59.78	4.90	42.9	12.2
Study piston corer	40.00	1.00	10.8	40.0

Table 5.2: Core tube parameters (Clayton et al., 1998) and study based

From Figure 5.13 it can be seen that for the flat ended tubes the peak axial strain in compression decreases as the B/t ratio increases. With a B/t ratio of 40, as per the study piston corer, the peak axial strain compression is approximately 1.4 %, 1.5 % and 1.7 % at the centre-line, central 30 % and central 50 % of the sample respectively.

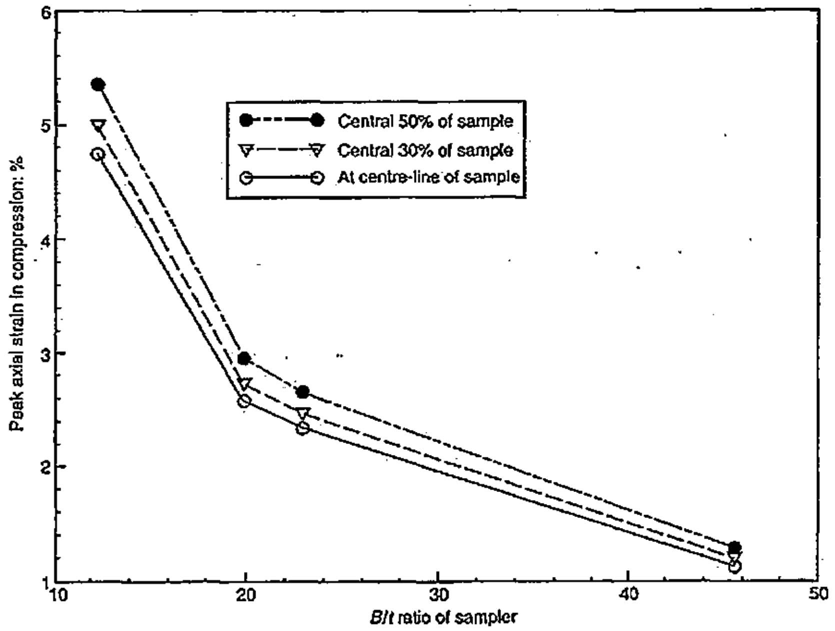


Figure 5.13: Variation of peak axial strain in compression with B/t ratio for various flat-ended samplers (Clayton et al., 1998)

The study showed that peak strains (sampling with no cutting shoe) are only observed in the compressive and not the extension phase (Fig. 5.14). The compressive strains are considerably higher than the extension strains and the strain in extension is constant for all strain paths due to the lack of inside clearance. In comparison with tubes having cutting shoes (Fig. 5.15) the compressive axial strain of the flat ended system is higher, approximately 2.5 % at vertical element location –0.5 (B/t 23.0), than that of a similar (B/t 20) system with a cutting shoe where axial strain is approximately 2.0 %. The extension axial strain in the flat ended system is constant at approximately –1.0 % but varies from approximately -0.3 % to -2 % in the system with cutting shoe (Clayton et al., 1998). The study showed that in systems with a cutting shoe and an aspect ratio of 40 (same as for the study) the axial strain is dramatically reduced to a maximum of 1 % in both the extension and compression phase.

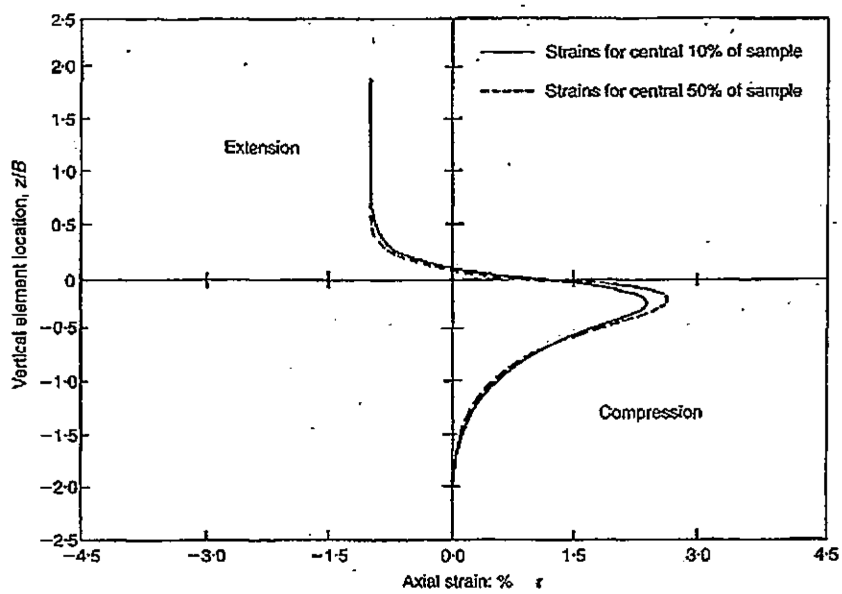


Figure 5.14: Coring extension & compression no cutting shoe (Clayton et al., 1998)

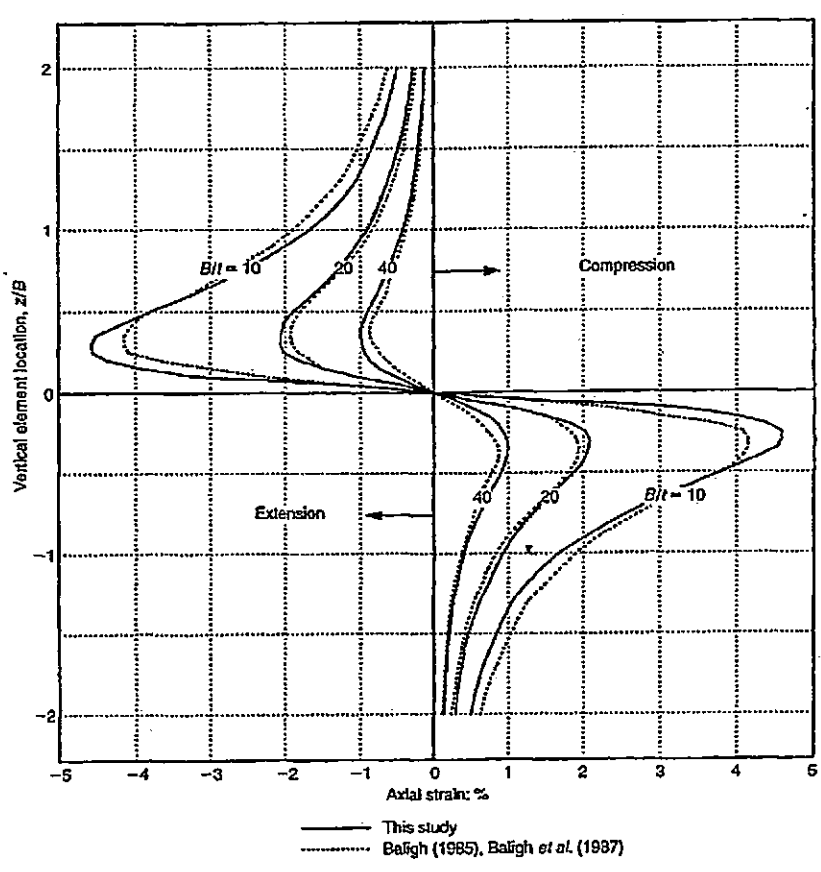


Figure 5.15: Coring extension and compression with cutting shoe (Clayton et al., 1998)
Note: 'This study' reference on chart refers to the Clayton et al., 1998 study

The study clearly shows that the dimensions of the core tube affect the disturbance of the sample obtained. The piston corer used in the study was a flat ended system and thus had fairly simple defining parameters. The lower the aspect ratio (B/t) the higher the amount of strain imposed on the sample (Clayton et al., 1998), and thus an improvement to the piston corer disturbance level would follow an increase in tube diameter. However an increase in tube diameter would require an increase in tube strength and thus it is likely that the tube thickness would also increase. The research by Clayton et al., (1998) found that:

> *"In practice the AR of tube samplers typically varies between about 10% (e.g. for a thin-walled piston sampler) to about 45% (for a thick walled composite piston sampler).... The fact that thick-walled composite samplers have been successfully used in sensitive clays (e.g. by the Swedish Geotechnical Institute) suggests that the AR (or the B/t ratio) is not the sole factor that must be specified for a successful sampler."*

The core tubes used in the current study had an area ratio of 10.8%, which indicates that minimal disturbance levels should be imposed when compared to thick walled samplers. As mentioned above there is a point at which the requirement for larger cores and sampling of higher shear strength material leads to the need for thicker walled tubing. There is therefore a play off between creating a system with a low area ratio for minimal disturbance and the requirement for penetration for sediment removal. As Clayton et al., (1998) have identified the successful operation of thick walled samplers leads to the proposal that the area ratio may not be the controlling factor in determining the level of sample disturbance.

The Clayton et al., (1998) research also showed that the addition of a cutting shoe alters the disturbance imposed on the sample. Although the tube used in this study was in effect a flat ended tube, i.e. no cutting shoe was added, the outside edge was filed slightly at the base to give a cutting edge. Using the outside cutting edge angle (OCA) formula the angle of this edge was 14°.

Conclusions drawn from studies undertaken by Siddique et al., (2000), include commentary on the impact of OCA:

> *"The quantitative values of degree of disturbance D_d of the tube samples increased significantly with increasing area ratio and increasing OCA of the sampler. It*

appeared that for good quality sampling in soft clays, a sampler should optimize the area ratio and OCA. From a practical point of view, the area ratio of a thin-walled tube sampler should not exceed 10 %, and OCA of the sampler should preferably be less than 5 %." (Siddique et al., 2000)

Based on these findings the OCA of the core tubes used in the current study should be reduced, however the impact of this angle variation should be investigated more thoroughly along with the impact of the addition of a cutting shoe. The findings do, however, verify the current dimensions of the tube with the statement that thin-walled samplers should have area ratios of no more than 10%.

Hight et al., (1992) investigated the impact of sampling on the sediment structure using triaxial compression tests and oedometer tests. The samplers compared were the Laval (200 mm diameter, 530 mm long), the Sherbrooke (blocks nominally 250 mm diameter, 400 mm height) and an ELE fixed piston corer (101.6 mm internal diameter, 2 mm wall thickness, no inside clearance, cutting edge taper 30°). The study concluded that the disturbance level of the piston corer was higher than that of either the Laval or Sherbrooke samplers. These findings again illustrate the bearing of overall tube size on the disturbance level incurred.

Lunne et al., (1998) undertook experiments to compare the disturbance between cores acquired with a Sherbrooke block sampler and the NGI 54 mm and Japanese 75 mm fixed piston corers. These observations were made based on the results of anisotropically consolidated undrained triaxial compression tests (CAUC) and Constant Rate of Strain (CRS) oedometer tests. A criterion for quantifying the level of disturbance experienced by a sediment was put forward by Lunne et al., (1997a) and was based on the parameter $\Delta e / e_0$ (equal to change in void ratio over the initial void ratio) (Lunne et al., 1998). Combining this parameter with the overconsolidation ratio Lunne et al., (1997a) proposed a method for quantifying the level of sediment disturbance (Table 5.3).

OCR	$\Delta e / e_0$			
	Very good to excellent	Good to fair	Poor	Very poor
1-2	< 0.04	0.04 – 0.07	0.07 – 0.14	> 0.14
2-4	< 0.03	0.03 – 0.05	0.05 – 0.10	> 0.10

OCR = Overconsolidation ratio

Table 5.3: Quantification of sample disturbance (Lunne et al., 1998)

It must be noted that these criteria are based on clays with specific characteristics:

> *"The sample disturbance criteria proposed above is mainly based on marine clays with a plasticity index in the range 10–55%, water content 30–90%, OCR = 1-4 and depths 0-30 m below ground level. For soils with properties outside this range the criteria in the above table should be used with caution."* (Lunne et al., 1998)

The main conclusion drawn from the study was that the disturbance caused by the block corer was the lowest followed by the 75 mm Japanese corer and the NGI 54 mm system. To correlate the findings of this report with that of the study corer would require changes to be made to the dimensions of the coring system in conjunction with extensive laboratory testing.

Following studies into the effect of sampling disturbance on a variety of sediment types and with the use of many coring systems Bashar et al., (2000) were able to propose a method of correcting unconsolidated undrained shear strength of coastal material. First the degree of disturbance (D_d) is calculated based on the plasticity index (I_P) and aspect ratio (B/t) (Fig. 5.16). Secondly a strength ratio (S_{ut}/S_{up}) value is derived based on the plasticity index and degree of disturbance (Fig. 5.17).

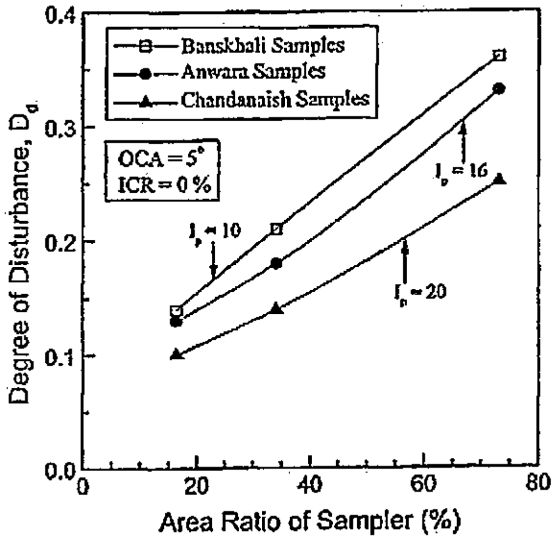


Figure 5.16: Variation of degree of disturbance with area ratio of sampler for samples of three coastal soils (Bashar et al., 2000)

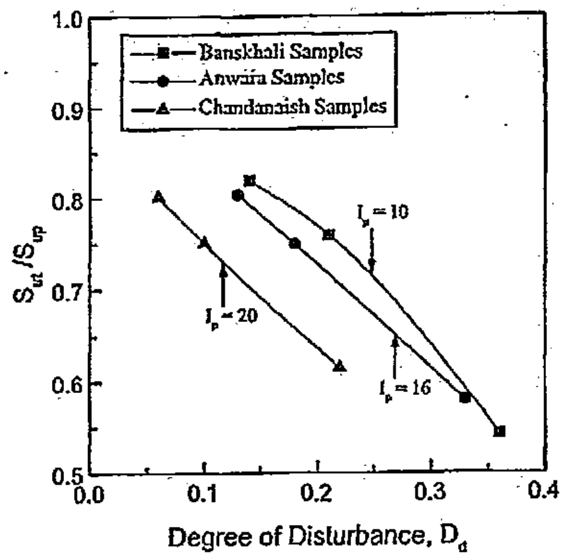


Figure 5.17: Disturbed strength ratio vs. degree of disturbance plot for samples of three coastal soils (Bashar et al., 2000)

If the data from the laboratory triaxial tests from the current study are taken (Table 5.1) corrected values can be calculated (Table 5.4) using graphic extrapolation techniques. Sites 1 to 3 have plasticity indices of approximately 20 and thus the I_P 20 data set was used. The I_P 10 data set was used for the site 4 data. These corrections are based on the disturbance caused by the sub-sampling technique (as used for 'undisturbed' samples) and not for the entire coring process. However as both processes involve the extraction of the sample from the same tube an element of this correction will also be true for the piston corers.

Site	Type	I_P	D_d	Strength ratio	Triaxial Cu (kPa)	Corrected Cu (kPa)
1	Piston	21.86	~ 0.07	~ 0.79	15	19
1	'Undisturbed'	23.31	~ 0.07	~ 0.79	13	16
2	Piston	22.46	~ 0.07	~ 0.79	14	18
2	'Undisturbed'	20.12	~ 0.07	~ 0.79	14	18
3	Piston	23.07	~ 0.07	~ 0.79	15	19
3	'Undisturbed'	20.18	~ 0.07	~ 0.79	17	22
4	Piston	11.50	~ 0.11	~ 0.85	10	12
4	'Undisturbed'	12.89	~ 0.11	~ 0.85	12	14

Table 5.4: Corrected undrained shear strengths

It must be noted that these relationships are based on sampler tubes with outside cutting edge taper angles (OCA) of 5 ° and ICR values of 0 %. The tubes used in the study had an outside cutting edge of 14° and thus these derived corrected values are not absolute but give a guide to the possible variation. The effect of sampling sediment is shown to lower the shear strength due

to the disturbance of the matrix. Based on this variation it is interesting to note that the field shear strength values acquired using the hand vane were lower than those acquired from triaxial testing (Table 5.1).

During research into sampling in nearshore locations, Sheahan and DeGroot, (1997) suggested that the core tubes be made of PVC due to the possibility of sampling sediment with corrosive pore fluid. Core barrel lining was suggested as an alternative for systems, which utilise metallic core tubes. This use of lining material was considered during the development of the piston corer but the introduction of a secondary layer leads to complications with regard to ensuring a smooth and consistent coring surface. If the internal layer is not properly secured then the material could be pushed towards the top of the tube during tube insertion causing a disturbance to the sample. The probable low shear strength (< 20 kPa) of the sediment being tested would also lead to problems retaining material when utilising a barrel liner. Further studies would need to be made to apply this technique to the present piston corer.

The suggestion that core tubes should not be too long was also put forward by Sheahan and DeGroot, (1997). To keep the imposed stresses as low as possible during storage, a maximum core length of 1 m is proposed. With regard to the preparation of samples for triaxial testing Sheahan and DeGroot, (1997) make an important statement relating to sample extrusion as used in the laboratory testing procedure:

> *"This method is not appropriate for any soil regardless of strength, since it imposes a second, more severe set of sampling stresses on the specimen than those applied during initial sampling."*

The testing undertaken by Hight et al., (1992) described above employed this technique and concluded that:

> *"Specimen preparation methods which involved penetration of a thin-walled tube caused disturbance additional to that produced by sampling, and which was evident as a further reduction in the initial effective stress and a further shrinking of the initial bounding surface."* (Hight et al., 1992)

In studies in which the absolute level of disturbance imposed by a corer is required or in which the sample acquired must be representative of the *in situ* sample, use of the extrusion subsampling technique is inappropriate. However this study was undertaken to ascertain the impact of the piston coring mechanism on the shear strength of the sample i.e. the absolute shear strength acquired was not as important as the variation between the two techniques. Since both systems required the samples to be extruded from the tubes the only variation between the techniques was the manual pushing in of a tube in the 'undisturbed' technique or the piston mechanism. Initial findings have shown that the variation in shear strength is negligible between the two techniques. The absolute impact of sample disturbance has not been assessed. As discussed by Sheahan and DeGroot, (1997) a more appropriate extrusion technique should be employed to reduce further disturbance. It must however be noted that the difficulties encountered with the ROV based piston corer are due to the size constraints. Larger core tubes were utilised in the initial trial but were found to be unsuitable for use on an ROV due to the requirement for a large stabilising down force. This problem is compounded by an increase in difficulty of trimming with a decrease in trimming area i.e., the closer the sample is to the size required the harder it is to trim. The use of a core liner or pre-split core tube is the only practical way to eliminate added disturbance. Using these approaches the sample (of exact size) may be accessed without any structural disturbance.

5.6. Summary

The piston corer has successfully acquired sediment samples in material with a shear strength of 17 kPa. The system requires minimum down force (less than 70 kgf required when using the original frame based piston corer) to achieve penetration and is capable of acquiring intact cores of up to 400 mm in length. Laboratory analysis has shown the system to cause little structural disturbance (variation in shear strength) when compared with relatively 'undisturbed' methods (up to 3 kPa). When the data are compared with *in situ* field vane testing results a variation of up to 6 kPa was observed. Disturbance levels could be further reduced if the extrusion process was replaced with the use of a pre-split tube. However due to the tight fit of the core tube to the outer tube any obstructions such as tape, with which the two halves might be joined, may prevent successful operation. This simple taping approach may also be difficult with stainless steel tubes due to their weight.

Further investigations should be undertaken with laboratory consolidated homogenous clay samples to determine the actual disturbance level. The use of a regulated material would remove possible variations recorded in the field work which may be the result of sediment inhomogeneity. Direct shear vane testing of the sample could then be undertaken and the data compared with triaxial analyses.

The current design of the sediment corer is not only highly efficient but is also very successful with no operational limitations. If however the system were to be used on a daily basis, one change and one operational procedure should be undertaken to ensure that current success continues.

- Make the core tube end cap removable to allow for cleaning which would;
    a. Remove the possibility of introducing sediment into the non-return valve seating thus reducing the possible loss of suction force.
    b. Ensure that the lower air chamber is kept clear of sediment to prevent blockages.
- Ensure that the core tubes are kept as clean as possible before and after coring because;
    a. Sediment on the outer tube may abrade the seals in the end cap and cause leaking thus reducing the air pressure applied for core retrieval.
    b. Sediment on the outside of the inner core tube may also abrade the seal to the outer tube thus making it difficult to insert and remove inner core tubes.

The coring system developed has been proven capable of collecting core samples of 38 mm diameter, 400 mm long in fine sediment of 17 kPa shear strength. The weight required to keep the system on the ground during testing is less than 70 kgf (weight in air) and the final unit is less than a metre in height. These parameters would make it suitable for deployment and operation by an ROV, with the recommendation that a heavier crawling system would provide extra ballast to ensure consistent ground contact. The system is simple to operate and provides a method with which to acquire sediment samples in areas of restricted access such as the nearshore zone. All components are readily available and ensure that the unit is cheap to build and operate. By utilising a hydraulic mechanism the sediment corer could be developed to operate in deeper waters. The move from pneumatics to hydraulics would be necessary to overcome the erratic flow of pressurised air at depth caused as a direct result of the increase in air hose length. This development has no bearing on the success of the current system but could be undertaken as a part of future research.

Chapter 6

Resistivity testing

data. The aim of the research is to investigate how such a system might be developed and the viability of the results acquired. As for the sediment coring system the equipment must be of an appropriate size to be operable from the proposed ROV described in chapter three.

6.2. Theory of technique

The principal of electrical resistivity surveying is to determine the resistivity of the underlying sediment in an area, in order to ascertain the type of material that is present and to allow the calculation of a profile i.e. depth of layers and their lateral variation. The resistivity of a material may be defined as:

> *"the resistance in ohms between the opposite faces of a unit cube of the material. For a conducting cylinder of resistance δR, length δL and cross-sectional area δA the resistivity ρ is given by":* $\rho = \frac{\delta R \, \delta A}{\delta L}$ (Kearey and Brooks, 1991)

Resistivity (ohm m) is measured by briefly introducing an alternating electrical current into the ground via two current electrodes and then recording the voltage (= current x resistance) of the signal using two potential electrodes (Barker, 1997; Jones, 1999; Kearey and Brooks, 1991). In a homogenous material current flows away from the source electrode creating hemispherical shells of constant voltage (Fig. 6.1).

> *"Consider a single electrode on the surface of a medium of uniform resistivity (ρ) (Fig. 6.1). The circuit is completed by a current sink at a large distance from the electrode. Current flows radially away from the electrode so that the current distribution is uniform over hemispherical shells centred on the source. At a distance r from the electrode* the shell has a surface area of $2\pi r^2$ so the current density i is given by: $i = \frac{I}{2\pi r^2}$" (Kearey and Brooks, 1991)

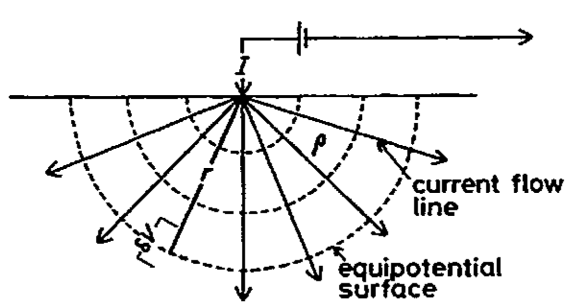


Figure 6.1: Resistivity current flow (Kearey and Brooks, 1991)

If a resistivity array is established which consists of four electrodes (two external current A, B and two internal potential M, N) (Fig. 6.2.) then the current sink is a finite distance from the

source. In this instance the potential at either internal electrode is equal to the sum of the potential contributions from the current source at A and the current sink B ($V_M = V_A + V_B$) (Kearey and Brooks, 1991). The depth (Z) to which the current in homogenous ground will flow is dependent upon the electrode separation (L):

> *"When L = Z about 30% of the current flows below Z and when L = 2Z about 50% of the current flows below Z."* (Kearey and Brooks, 1991)

The primary method of conduction in rocks and sediments is electrolytic whereby the current is passed on through ions in the pore water as opposed to via the grains themselves (Campanella and Weemees, 1990; Jones, 1999; Kearey and Brooks, 1991; Lauer-Leredde et al., 1998; Narayan and Dusseault, 1997). Porosity is therefore a factor in determining the resistivity of a sediment as are permeability, soil mineralogy, salinity, temperature (downhole survey) and water saturation (SteamTech Environmental Services).

There are five main methods through which electrical resistivity data can be acquired:

> *1. "Self potential (spontaneous polarization)*
> *Seabed electrodes and a high impedance voltmeter measure natural electrical potentials in the vicinity of mineralized zones.*
> *2. Induced polarization*
> *Anomalous conductivity is detected from the voltage decay following an interruption of current flow through an electrode or from the change in ground impedance with frequency.*
> *3. DC resistivity*
> *Resistivity is determined from the potential distribution when a direct current flows between two electrodes.*
> *4. Magnetotellurics*
> *Seabed resistivity is measured using natural, time-varying electrical and magnetic fields induced in the Earth by the flow of charge particles in the ionosphere and magnetosphere.*
> *5. Magnetometric resistivity*
> *Magnetic and electrical fields associated with a grounded electrical source are used to derive resistivity".* (Jones, 1999)

The most common technique is DC (direct current) resistivity surveying. A switched direct current (or low frequency AC) is utilised to prevent polarisation of the electrodes and to limit the influence of telluric or natural earth currents (Campanella and Weemees, 1990). The electrodes are set up in arrays of which there are two principal designs namely the Schlumberger array and the Wenner array (Fig. 6.2 a & b).

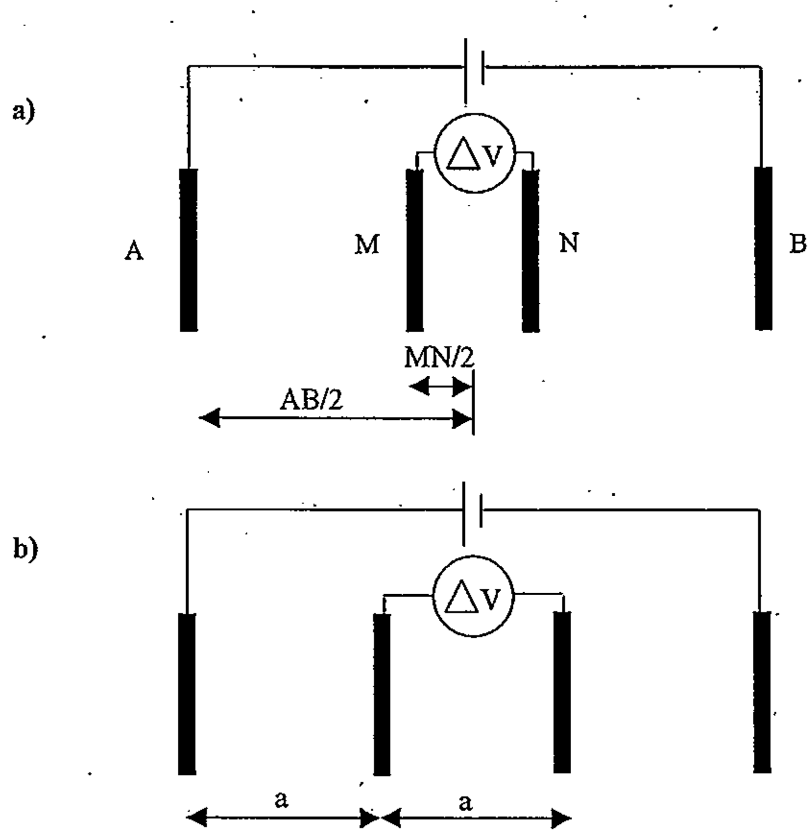


Figure 6.2: a) Schlumberger and b) Wenner resistivity arrays

There are two techniques used to determine the resistance of the underlying sediment; Vertical Electrical Sounding (VES) and Electrical Profiling (EP). The first technique, VES is used to determine the change in resistivity with depth i.e. vertical variation at a single position. An array is set up with the desired position as the midpoint of the array. A measurement is made of the resistivity and then the electrodes are moved outwards. The overall length of the array determines the depth of penetration of the electrical current; a longer array allows deeper penetration.

The Schlumberger array (Fig. 6.2 a) has two outer current electrodes which are connected to a power supply, and two inner potential electrodes which are connected to a voltmeter. When conducting a vertical electrode survey (to detect changes at depth), the spacing of the inner potential electrodes (r = MN/2) remains constant whilst the spacing between each outer and inner electrode (a = AB/2) is increased. After a predetermined distance, the inner electrodes spacing is increased, the outer electrodes are moved backwards to create an overlap and then are moved outwards again. The Wenner array (Fig. 6.2 b) also has two outer electrodes connected to a power supply and two inner potential electrodes connected to a voltmeter. However when conducting a VES survey both sets of electrodes are moved consecutively outwards by the same distance (a) so that the array is always symmetrical about the midpoint.

The second technique, EP is used to locate resistance anomalies i.e. variations in resistance due to changes in the underlying material. The array is set up at one end of the desired transect and is moved along with the spacing between electrodes remaining constant. This allows a profile to be produced of the resistance of the sediment and hence interpretations can be made of the type and distribution of the sediment present.

Resistivity will remain constant in homogenous ground irrespective of the movement of an array but will vary with inhomogeneities (Barker, 1997; Jones, 1999; Kearey and Brooks, 1991). This variation means that the value recorded is only valid for that location and array type and thus is termed an apparent resistivity (Erchul and Nacci, 1972; Jones, 1999; Kearey and Brooks, 1991). The electrical resistance of a sediment increases with depth due to reducing porosity (result of overburden pressure) and hence the apparent resistivity will slowly increase with depth. In the case of VES surveys, when the array has been extended such that current is flowing mainly in the lower layer, the apparent resistivity changes again because of the influence of this second layer. If this layer is of a higher electrical resistance then the apparent resistivity increases and as the array extends further the apparent resistivity approaches the resistance of the lower layer due to this being the primary region of current flow (Kearey and Brooks, 1991). This effect allows the depth determination of the layer.

This conversion from measured resistance to apparent resistivity is made using two simple geometric formulae, one for the Schlumberger array and another for the Wenner array. In both cases the apparent resistivity is given in ohm metres.

Schlumberger array (Fig. 6.2 a)

$$\rho_a = \pi \frac{a^2 - r^2}{2r} R$$

Wenner array (Fig 6.2 b)

$$\rho_a = \pi a R$$

where $a = AB/2$
$r = MN/2$
R = measured resistance (ohm)
ρ_a = apparent resistivity (ohm m)

A system that can overcome both the problems of moving electrodes (time and man power consuming) and detection of lateral discontinuities is the square array (Fig. 6.3).

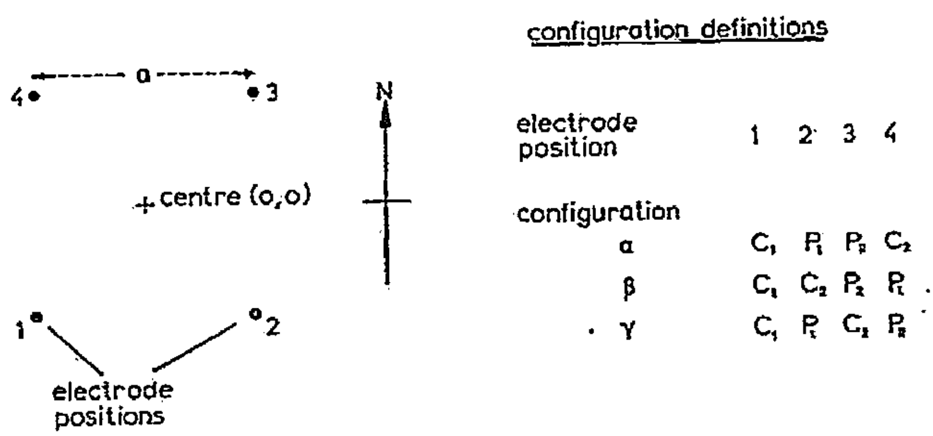


Figure 6.3: Square resistivity array configuration (Habberjam and Watkins, 1967)

Due to the arrangement, the resistivity of the alpha array is equal to the resistivity of the beta array plus the resistance of the gamma array. The resistivity values acquired from the alpha and beta arrays are weighted in an easterly and northerly direction and may be combined to give a mean resistivity to remove this bias (Habberjam and Watkins, 1967). In an isotropically resistive ground, the resistance measured by the alpha array should be equal to the beta array and vice versa ($\alpha = \beta + 0$). In comparison with linear arrays, the square arrays will give identical values to those obtained with the equivalent square array and similar values to those obtained using the Wenner array when undertaken in a homogenous isotropic medium (Habberjam and Watkins, 1967) (Fig. 6.4).

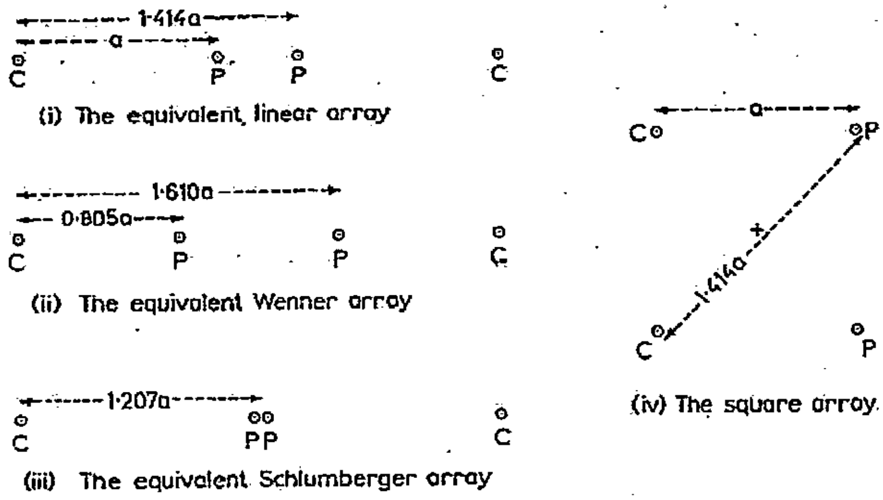


Figure 6.4: Square array and linear equivalents (Habberjam and Watkins, 1967)

Figure 6.4 illustrates the relationships between a square array and the equivalent linear, Wenner and Schlumberger arrays. In order to acquire the same resistance value, the square array of spacing a and 1.414a would need to be converted to a Wenner array with a current to potential electrode spacing of 0.805a, and a Schlumberger with a 1.207a spacing.

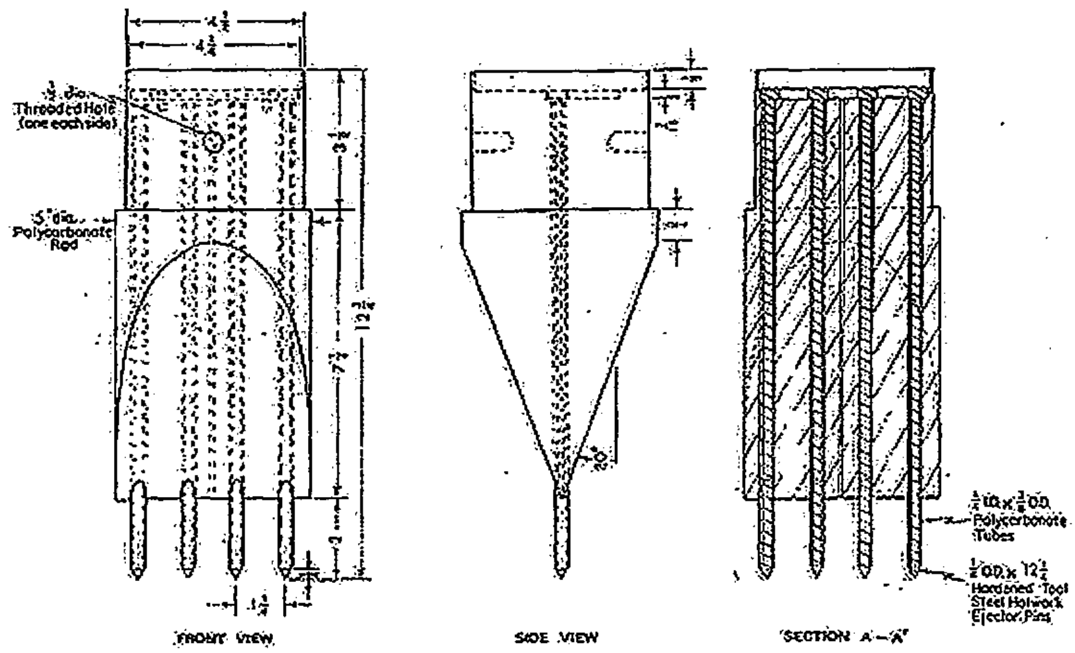
6.3. Resistivity profiling – research development

Seismic profiling systems have long been used to discern sub-bottom features and in conjunction with ground truthing offer a simple sediment classification system. Resistivity profiling offers an alternative approach particularly in areas where discrete testing is required. The aim of the current research was to design a sub-bottom profiling system that could be operated from the ROV proposed in chapter three. This chapter describes the design, manufacture and development of two resistivity testing rigs, the results obtained through testing and the suitability of resistivity testing in the nearshore zone.

6.3.1. Linear rig

In order to ascertain whether or not it is feasible to use ROV mounted resistivity systems for profiling in the nearshore environment the first step was to undertake laboratory testing of a

prototype model. Initial investigations were undertaken using a simple Wenner array based on a system designed for deepwater surveys described by Bennett et al., (1983) (Fig. 6.5).



Measurements in inches
Figure 6.5: Resistivity probe (Bennett et al., 1983)

The design criteria Bennett et al., (1983) dictated were stringent and covered all aspects of the possible mechanical and environmental factors:

1. *"The probe must be extremely durable to withstand being driven through semiconsolidated carbonate sediment and reef rock materials by a vibracore with an effective weight of approximately 360 kg and a high rate of vibration.*
2. *The probe must be shaped such that it will penetrate the substrate with a minimum amount of effort.*
3. *The electrode tips must be small in diameter to approximate a theoretical point source for the field generated, and must be located far enough ahead of the probe wedge to be out of the main zone of sediment disturbance.*
4. *The electrodes must be extremely rigid and tough enough so that they will not change geometry by bending or erosion while being driven into the sediment.*
5. *All materials other than the electrodes must have high volume resistivities.*
6. *Electrical connections to the electrodes must be waterproof and be able to withstand extreme amounts of vibration.*
7. *The probe must be easily mounted to the vibrocore pipe to minimize assembly and changeover time at sea, and to minimize cost".*

(Bennett et al., 1983)

The probes designed by Bennett et al., (1983) were 0.64 cm (¼ in) in diameter and were spaced 3.18 cm apart (1 ¼ in) from tip to tip. The probes were manufactured from hardened tool-steel hotwork ejector pins and were cemented over with a polycarbonate insulator. Each probe extended 5.08 cm (2 in) from the protective tapered probe head, which was 18.42 cm (7 ¼ in) long and 12.7 cm (5 in) in diameter. This tapered block was made from a polycarbonate plastic and was attached to a further block and the wiring connectors (Bennett et al., 1983). A smaller probe only 3.8 cm (1 ½ in) diameter with probes of 1.6 mm ($^1/_{10}$ in) diameter was also built for lab tests. This smaller unit proved to be extremely useful in discriminating smaller scale features. During tests in the northern Straits of Florida penetration of up to 11.3 m was achieved in water depths of up to 21 m and in sediments ranging from medium carbonate sands to cobble-sized reef debris (Bennett et al., 1983). Bennett et al., (1983) found the resistivity probe to be a useful tool:

> *"The study, combined with laboratory analyses, also indicates that the in situ techniques may prove to be a valuable method of obtaining in situ soil properties such as porosity and wet bulk density, provided accurate measurements of interstitial water salinity can be obtained during field operations."*
>
> (Bennett et al., 1983)

The simple design of the Bennett et al., (1983) resistivity probe gave a basic design for the linear resistivity system designed for this research. A rig consisting of four electrodes each 15.5 cm long, 4 mm diameter, set 2 cm apart and made from marine grade stainless steel (316L) was manufactured. Each probe tip was filed to a point, and the probes were covered in a tightly fitting plastic sleeve to ensure that signal dispersion was kept to a minimum. The other end of each probe was connected to a cable and these connections were isolated in a moulded plastic block to prevent interference. The rig was connected to an Abem SAS 300c terrameter (a high impedance, digital, commercially available resistivity system) to allow resistance measurements to be made. Plate 6.2 shows the linear rig.

named Mud 5 and Mud 6 for simple discrimination. The Mud samples were saturated *in situ* and water from the site was also collected to saturate the other 4 samples. This process ensured that differences between the results would be based solely on the sediment and not variations due to the salt content of the water. The samples were tested in plastic containers (25 cm deep and 25 cm diameter). These were filled with the material, up to a depth of 14 cm and were saturated with the collected water, leaving a water layer of approximately 8 cm above the sediment. Resistance measurements were undertaken one sample at a time. The rig was placed into the container at a depth of 4 cm from the water surface to first take a reading of the resistance of the pore fluid. The probe was then pushed into the sediment at 1 cm intervals to a maximum depth of 10 cm. At each interval the resistance was measured using the terrameter taking a 4 cycle average.

Apparent resistivity was calculated using the basic geometric Wenner calculation and the results can be seen in Figure 6.6 (raw resistance data in Appendix B). NOTE: In all apparent resistivity plots, the value at a depth of 11 cm is that of the instrument in the water above the sediment.

Figure 6.6 shows the Playpit, Lizard and Gravel to have very similar apparent resistivity trends with data ranging from approximately 100 ohm cm at 1 cm to approximately 250 ohm cm at 10 cm. The two Mud samples, have much lower apparent resistivities (approximately 50 ohm cm and do not show an increase with depth. The Beach sand shows an initial rise to 100 ohm cm in the first few cm then decreases to approximately 50 ohm cm at 10 cm depth. The water values for all samples should be the same given that the water used was collected from the same site and this can be seen on the figure.

An increase in resistivity represents a decrease in conductivity. This may be due to tighter particle packing and a consequent decrease in the highly conductive pore fluid. For the Playpit, Lizard and Gravel samples, this pattern might be expected with compaction leading to tighter packing at depth. The lower apparent resistivity of the Beach sand may indicate that there is less

particle packing and thus more pore fluid present. A decrease of resistivity with depth implies an increase in pore fluid, which is an unusual scenario. Constant apparent resistivity as seen in the Mud 5 and Mud 6 samples, indicates consistent particle packing, and the overall low resistivity indicates high pore fluid content.

The relationship between mean grain size (phi) and porosity (%) has been described by Richardson and Briggs, (1993) and is shown in Figure 6.7.

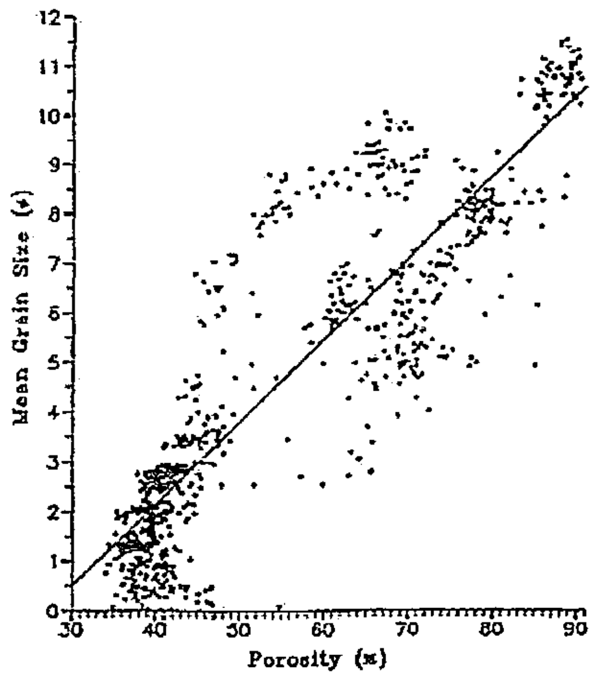


Figure 6.7: Relationship between porosity and mean grain size (Richardson and Briggs, 1993)

The trend shown by the chart indicating an increase of porosity with a decrease in mean grain size (high phi value is equivalent to a low size in mm) supports the data acquired in the laboratory tests. The platy particles in muds are electrically charged and usually form open structures, leaving large pore voids unless consolidated when the open structures may be compressed. The mud samples used in the experiment were not consolidated and have settled in a random way leading to a high porosity.

To eliminate the possibility that the sediment had settled in an unusual manner, each sample was vigorously stirred and allowed to resettle. The resistance measurements were repeated and the results can be seen in Figure 6.8. It can be seen that the plots are almost exactly the same, with the same grouping and trends. Figure 6.9 shows the difference between the original data and the data acquired after stirring. The variation is low with the largest change (50 ohm cm) in the Lizard sample. This variation may be ascribed to a simple settlement differences, however, the figure illustrates that on the whole the apparent resistivities measured are representative of the sample and its associated settling pattern.

As described above, an increase of resistivity with depth may be due to a decrease in pore space as a result of compaction and improved packing. In each test, the rig was placed in the centre of the bucket; however due to the limited size of the bucket and tapering in with depth a boundary effect may be contributing to the measured resistance. The bucket was made of plastic and thus has infinite resistance. This would serve to increase the resistance measured with values being increasingly affected by the bottom of the bucket with depth along with increasing resistance due to the tapering bucket sides. Tests were undertaken whereby measurements were made as close to the side of the bucket as possible to increase any boundary effect. By comparing these values to those obtained when testing in the centre of the bucket, the effect of the boundary should be discernible. Figures 6.10 to 6.15 illustrate the results, with the dashed line representing data from the edge of the bucket. It can be see that the trends observed replicate those seen in the standard apparent resistivity plots (Figs. 6.6 & 6.8). In all cases the edge measurements are higher than the centre values, confirming that the bucket impinges on conductivity and thus increases resistance. For the three samples with high resistivity (Playpit, Lizard & Gravel), the increase due to the boundary is greatest. The increase experienced in the lower resistivity samples (Beach, Mud 5 & Mud 6) is far less. This may be because of the higher conductivity within the sample. For the higher resistivity samples, conductivity is already low and thus the addition of the infinitely resistive bucket would lead to a combined increase in resistivity. Furthermore, the resistivity at lower positions in the bucket (i.e. nearer to the bottom and tapering sides) is much increased in these samples. This would suggest that the

The graph shows that each pair of arrays does indeed have the same apparent resistivity value, however it also shows that the pairs do not coincide with each other. The large square arrays give significantly higher values (average 79.89 ohm cm) as compared to the linear arrays (average 56.47 ohm cm) and the small square arrays (average 49.47 ohm cm). Figure 6.4 shows the arrangement of an alpha or beta square array and its dimensions. The equivalent linear array has the same dimensions, as the square array, but is linear in shape. The equivalent Wenner array has different electrode spacing in order to bring the data in line with the square configuration. Equivalent linear and Wenner arrays for the two square arrays are given in Table 6.2.

	Square 1 a = 2 cm		Square 2 a = 6 cm	
	C - P	P - P	C - P	P – P
Equivalent linear array	2.00 cm	0.828 cm	6.00 cm	2.484 cm
Equivalent Wenner array	1.610 cm	1.610 cm	4.83 cm	4.83 cm

Table 6.2: Square array equivalent linear array dimensions

Given that the Wenner array being used has an electrode spacing of 3 cm which falls between both of the equivalent Wenner arrays it might be expected that the distribution of the three array types in Figure 6.18 would be more even. In a homogenous isotropic medium the apparent resistivity should be the same for all array types. The application of the geometric factor to the raw resistance values is undertaken to remove any disparity between array type and size. The variation between the three array groups must therefore be due to equipment defects. Although the electrodes utilised were manufactured from marine grade stainless steel, some rusting was observed. This would cause variations in resistance between the different arrays due to corrosion on individual probe tips. The effect of this variation was observed when using a multi-meter to measure the residual resistance between the probe tip and the associated pin leading from the rig. A small resistance was recorded for some probes and this may be the result of problems with probe to wire soldering or solely corrosion on the probe tips. It is unlikely that the disparity between array types observed was due to failure in the relay as this would be catastrophic. Further development of the equipment should involve the introduction of methods to reduce or calibrate this discrepancy. Alternative electrode designs such as removable or plated tips could be introduced along with a simple system to record the variations

The S1 small square data shows a larger variation than the S2 large square data a factor that may be related to the size of the arrays. The largest deviation in the S1 data is 0.16 ohm, which equates to an apparent resistivity of 3.43 ohm cm. In the S2 array the largest variation is 0.11 ohm, which equates to an apparent resistivity of 7.08 ohm cm. Corrections for this deviation have not been applied, as the intention of the study was to differentiate between sediment types and not to accurately map the stratification of the sediment samples.

As discussed in relation to the results from the linear rig, increases of apparent resistivity with depth may be attributed to improved packing and a consequent reduction in pore fluid along with the effect of the bucket. The Playpit sand (Fig. 6.19) has the highest resistivity of all the samples indicating a high level of packing. An average resistivity of approximately 200 ohm cm can be given for the six arrays.

The Lizard sand (Fig. 6.20) shows a far more consistent distribution with all three sets of arrays giving approximately horizontal readings. As described in relation to the linear rig, an increase is expected due to the improved packing with depth. For the Lizard sand, the levelling off shown at 3 cm may indicate the greatest packing efficiency. The apparent resistivity is approximately 100 ohm cm for all three arrays, taking into account variation seen in the water calibration. The Beach sand (Fig. 6.21) profile is very similar to that of the Lizard sand, with average values of approximately 100 ohm cm being measured. The Gravel sample (Fig. 6.22) again shows a similarity to the Lizard sand although the average resistivity from the three sets of arrays is approximately 90 ohm cm. In both the Beach sand and Gravel samples, there is a marked decrease in apparent resistivity at 9 and 10 cm. It is unlikely that these changes are due to anisotropy as there is not a marked difference within the array pairs and thus one can but assume that it is due to localised high porosity.

The two Mud samples are very similar and have significantly lower resistivities than the other test samples, with an average of 40 ohm cm for Mud 5 (Fig. 6.23) and 50 ohm cm for Mud 6 (Fig. 6.24). Mud 5 has the greatest agreement between arrays with a range of only approximately 20 ohm cm. The two Mud samples are also the most horizontal samples, indicating that the packing does not change or changes very little with depth in the sample leading to variations in porosity / permeability. A low resistivity is equivalent to a high conductivity. In areas of low resistivity the current will follow the path of least resistance therefore there is limited spread of current (Fig. 6.26 a). In these instances there will be less impact of the bucket sides i.e. no second layer with very high resistance. In areas of high resistivity (low conductivity) the current will again follow the path of least resistance and a divergence of current flow may be observed (Fig. 6.26 b).

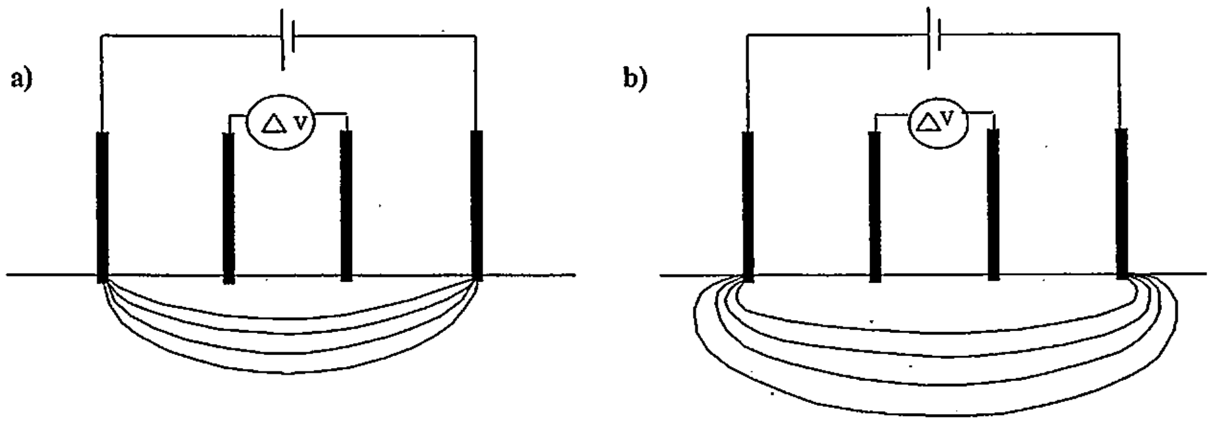


Figure 6.26: Current flow in sediment with a) low resistivity, b) high resistivity

Figures 6.27 to 6.32 show the apparent resistivity of the samples in groups of array type. Note the Playpit samples are plotted on a secondary (right-hand) axis in all graphs to allow for maximum scale expansion for the other five samples. In all of the figures a very clear distinction between the three groups is consistently seen. Firstly the Playpit sand, second the Lizard sand, Beach sand and Gravel and third the two Muds. Assuming no significant grain conduction this grouping implies an associated decrease in packing efficiency of the Playpit sand compared to the Muds and allows a clear distinction to be made between fine and coarse material.

The plots show a variation between the water value (seen at depth 11 cm on the plot) between the samples. All samples were saturated with the same fluid and thus the water values should be exactly the same within each array. It can be seen that the water value for the four coarse samples i.e., the Playpit, Lizard, Beach and Gravel are almost exactly the same at approximately 60 ohm cm. The Mud samples, however, have a water value of approximately 30 ohm cm. The variation observed may be due to the presence of a higher concentration of dissolved salts and minerals present within the Mud samples. Although the samples are saturated with the same fluid, the four coarse samples were clean samples i.e., they had been extensively washed and dissolved salts and minerals would have been removed. The two Mud samples were collected from the field and thus may contain substances not present or not in high concentration in the fluid itself. These dissolved substances may have been dispersed into the water within the buckets, thus altering the apparent resistivity. These findings are supported by previous observations by Jackson, (1975):

> *"A problem does exist in the assessment of the resistivity of the pore fluid. In surficial marine sediments it has been shown that the salinity of the pore waters varies little from that of the overlying seawater. Thus the resistivity of the pore fluid can be assumed to be equal to that of the seawater above. However, the effective resistivity of the pore fluid can be altered by ion-exchange phenomena in clay-rich sediments and also by a process called surface conduction, where water molecules are absorbed onto the surface of individual grains making them conductive."*

The two Wenner arrays (figs. 6.27 & 6.28) show very similar results, with an average Playpit value of approximately 220 ohm cm at 4 cm depth. The trend towards an increase of apparent resistivity with depth is apparent in contrast to the fairly stable apparent resistivities for the other four samples. An average value of approximately 120 ohm cm can be determined for the Lizard and Beach sands and the Gravel. An average of approximately 40 ohm cm can be seen for the two Mud samples.

The small square arrays plots (Figs. 6.29 & 6.30) are very similar to those of the Wenner arrays. The alpha array shows slightly more dispersion at small depths for the Lizard, Beach and Gravel samples than the beta array. A divergence of the Mud 6 sample from the Mud 5 sample can also be seen in the alpha array. These variations may be due to anisotropy in the sample and thus show the potential use of square arrays. The arrays show a more horizontal distribution for the Playpit sand than that observed in the Wenner arrays. Average values for the samples are Playpit 200 ohm cm, Lizard, Beach and Gravel 100 ohm cm and Mud 5 and Mud 6 40 ohm cm.

The large square array plots (Figs. 6.31 & 6.32) show a more exaggerated trend towards increased apparent resistivity with depth for all samples with the exception of Mud 5. This may suggest that the large square array is more sensitive to depth changes such as compaction or it may relate to the boundary effect. As this array is the largest it is also the nearest to the sides of the bucket. Although the boundary effects detected in the buckets were negligible it may still be a factor in sample testing. In the water test the medium is highly conductive and thus the boundary effect may not be obvious. However in a sample, which has a lower proportion of this medium present, the boundary effect may amplify the insulating effect of the sediment.

The average Playpit value is approximately 220 ohm at 4 cm, the Lizard, Beach and Gravel average is approximately 120 ohm cm and the Mud average is approximately 40 ohm cm. The Beach sample shows a much higher apparent resistivity from 5- 8 cm in the alpha array than in the beta array with a maximum of 150 ohm cm as compared to 130 ohm cm. The Mud 6 value also shows an increase in the alpha array compared to the beta array, reaching 60 ohm cm. These variations may be due to anisotropy in the samples.

The array plots show the three sample groups to have very similar average apparent resistivity values with variation of only 40 ohm cm. This variation may be attributed to the differences encountered in the water calibration check related to probe rusting or tip variation.

6.3.2.2. Particle size analysis

Particle size analysis was undertaken on the six samples for further analysis. Simple wet sieving techniques were utilised for the four coarser samples and the wet sieving with hydrometer analysis method (British Standards Institution, 1990a) was used for the two fine samples, Mud 5 and 6. The results are shown in Table 6.3, note the particle size data are given in mm and may be described using the British Standards classification BS 5930 (Fig. 6.33).

Sample	D16%	D50%	D84%	Mean	Median	Standard deviation		Skewness		Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Classification	G_S
Playpit sand	0.470	0.305	0.281	0.346	0.305	0.773	WS	-0.75	to coarse	0	0	100	0	Sand	2.662
Lizard sand	0.490	0.390	0.370	0.417	0.390	0.869	VWS	-0.67	to coarse	0	0	100	0	Sand	2.642
Beach sand	0.400	0.320	0.300	0.341	0.320	0.866	VWS	-0.60	to coarse	0	0	100	0	Sand	2.655
Gravel	3.400	2.700	2.450	2.794	2.700	0.849	VWS	-0.47	to coarse	0	0	25	75	Gravel	2.705
Mud 5	0.450	0.110	0.050	0.138	0.110	0.333	PS	-0.70	to coarse	10	41	45	4	Silty sand	2.570
Mud 6	0.310	0.031	0.020	0.059	0.031	0.254	PS	-0.92	to coarse	13	55	29	3	Sandy silt	2.629

PS = poorly sorted
WS = well sorted
VWS = very well sorted
Grain sizes in mm

Table 6.3: Laboratory advanced resistivity rig particle analysis data

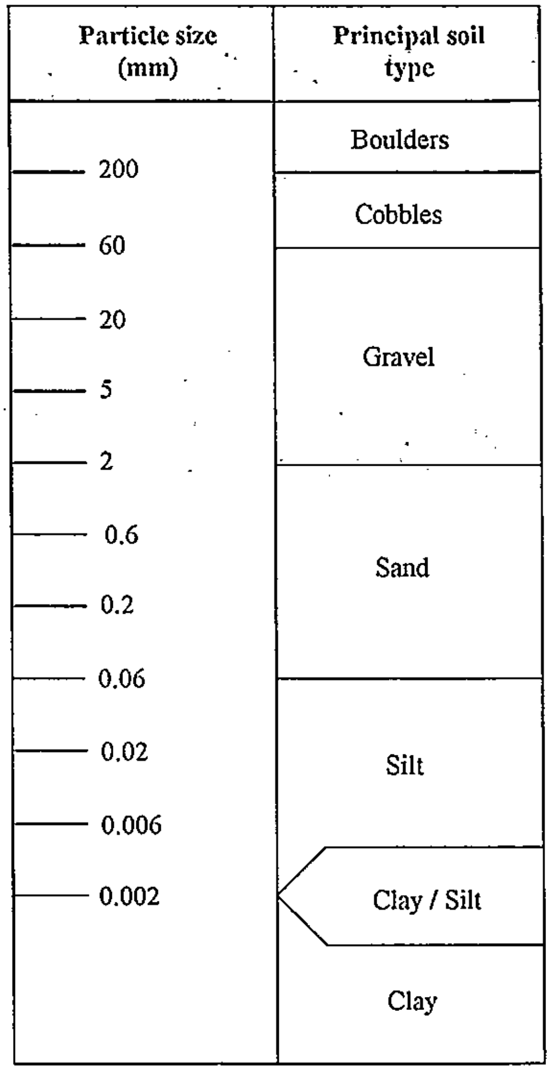


Figure 6.33; BS 5930 Identification and description of soils
(British Standards Institution, 1999)

The data show the Lizard and Beach sands and the Gravel to be very well sorted sediments i.e., there is very little variation in grain size, with the Playpit being well sorted and the two Muds being poorly sorted i.e., having a wide range of grain sizes. The sorting of the Lizard, Beach and Gravel samples may explain why they group together in the testing (Figs. 6.27 to 6.32) and why the Playpit and Muds also form separate groups. The mean grain size shows Mud 6 to be finer than Mud 5 which should mean that the apparent resistivity values would be lower than for Mud 5. However as previously discussed Mud 6 shows consistently higher values than Mud 5. Mud 6 has a standard deviation of 1.98, which gives a sorting classification of poorly sorted. At 2.0 this classification changes to very poorly sorted which may mean that the material is packing more effectively than that of Mud 6, leading to an increase in apparent resistivity.

The packing of the grains in the coarser sediment may also explain the grouping of the Playpit and other three sediments. Although the Playpit sand is finer than the Gravel and the Lizard sand it has a higher resistivity (lower conductivity). The Beach and Lizard sands are likely to contain angular fragments of shells etc along with the rounded grains of sand. This along with the limited sizes of grain present may lead to inefficient packing where large pore voids are left to fill with fluid. The same can be said for the Gravel as the particles are largely flat and angular with little variation in size thus leading to limited packing capabilities. The Playpit sand however is not as well sorted i.e., consists of a larger range of grain sizes and is unlikely to contain angular fragments. This combination may have created a very efficient particle packing system in which the pore voids are very small with little pore fluid resulting in the comparatively high apparent resistivity.

To avoid ambiguity, in acquired resistivity data, constraints may be imposed on the suitability of the rig in different sediments:

> *"the electrode separation is at least three times the expected grain size of the sediment."* (Bennett et al., 1983)

Given that the smallest electrode separation is 2 cm for the small square arrays (S1A, S1B), the largest grain size acceptable for measurement would be approximately 6.67 mm. The largest mean grain size encountered in the laboratory experiments was 2.79 mm for the Gravel sample (Table 6.3). The recommendations of Bennett et al., (1983) are therefore taken into account and electrode spacing should not influence results.

6.3.2.3. Boundary and object detection

If resistivity techniques are to be used as an alternative to standard seismic investigation techniques, they must be able to discern similar features. Issues such as the ease with which boundaries between sediment types can be detected and possibly the recognition of buried objects are therefore pertinent. Using five of the samples, four tests were undertaken to investigate the layer problem. The results from these tests can be seen in Figures 6.34 to 6.37

(raw resistance data in Appendix B).. In each case the sample making the top layer was added to the bucket containing the base sample. Enough sediment was added in each case to create a layer approximately 4 cm thick.

The Playpit on Gravel data (Fig. 6.34) show a fairly consistent response with depth, with values ranging between 100 and 150 ohm cm. When compared to Figure 6.22, showing only Gravel the difference can be seen to be negligible. As the Playpit sand has always shown the highest apparent resistivity, with values of approximately 150 ohm cm at 1 cm, it appears that the layer cannot be detected. It must be noted, however, that when adding the top sediment to each sample, a degree of disturbance was created. This caused some blending of the sediment that may have been sufficient to eradicate the intended sharp boundary. Thus it might have been expected that the introduction of the smaller Playpit grains to the Gravel would have decreased the pore spaces, thus decreasing conductivity. This change has not occurred and so the new packing structure must have remained similar to that in a 'Gravel only' sample.

The Playpit on Beach sand test (Fig. 6.35) shows some effect of the Playpit sand, with an increase in average resistivity from approximately 110 ohm cm to 125 ohm cm. The plot also shows a greater degree of consistency with depth, which may indicate a change in packing structure. No obvious boundary can be seen between the two layers.

The slightly more complicated Playpit sand on Mud 5 on Playpit sand (Fig. 6.36), shows some layering. The approximate average value from 1 cm to 7 cm is 110 ohm cm, whilst in the Playpit only experiment the corresponding value was approximately 210 ohm cm. The resistivity rises to a peak of approximately 180 ohm cm at 10 cm depth as compared to approximately 250 ohm cm in the pure sample. These data clearly show that the sample is not simply Playpit sand but the values do not fall low enough to allow the Mud 5 sample to be distinguished. It is likely that the Playpit sand filled some of the Mud 5 sample pore spaces thus increasing the resistivity.

The final layering experiment consisted of Beach sand on the Mud 5 sample (Fig. 6.37). The chart shows an apparent resistivity consistency throughout the test, with an average value of approximately 70 ohm cm. As previously discussed the Mud 5 sample has an average resistivity of approximately 40 ohm cm, and thus there is an increase of 40 ohm cm throughout the test. The simple Beach sand experiment showed an average resistivity of 100 ohm cm, thus the value from the layering experiment falls between the two sample test values. Again this may be due to an integration of particles during the addition of the Beach sand.

The layering tests show that although a definite layer cannot be detected, the resulting data clearly indicate a change in the resistivity when compared to each of the simple samples. In the field, this gradual layering effect may be encountered after two distinct layers have been recorded. In this instance ground truthing should allow for a distinction to be made with more certainty.

Object detection is another area of field survey that can provide useful information for geotechnical and hydrographic site investigations. A series of seven tests were undertaken to determine whether or not the advanced rig could detect manmade objects. As the objects could not be exactly positioned in sediment the tests were performed in the same water as for the other experiments. Four manmade objects were used; a 9 mm diameter steel bolt, a 1.5 mm diameter piece of wire, a 3 mm diameter piece of wire and a 2 mm diameter piece of plastic coated wire. The objects were placed in four different arrangements as shown in Figure 6.38 (in all cases the layout of the array is the same as that in Figure 6.16).

any ambiguities introduced to the readings as a result of induced polarisation or compaction were constant.

The apparent resistivities of the field data can be seen in Figures 6.48 to 6.51 (raw resistance data in Appendix B). The solid lines represent data collected from all points and the dotted lines represent data collected from the four corner points. The grid positions work from left to right beginning at point 0, 0 on Figure 6.47.

The data acquired at Dittisham (Fig. 6.48) show consistency not only within the grid but also between array types. Values range from approximately 0 – 50 ohm cm, with only the S2B array showing any obvious variation across this range. The upper Beach data (Fig. 6.49) were only collected from the lower depth and show the greatest variation of all four sites. Data range from approximately 70 – 200 ohm cm with the S2A array giving values of almost 300 ohm cm at grid point 5. This reading may be an anomaly due to the inconsistency of this reading when compared with the five other arrays, all of which indicate a value of approximately 125 ohm cm. The measurements at this site were taken high up the Beach when the tide was receding and thus the large variation may be due to the differential draining rates of the sediment causing anisotropy and the low moisture content. The lower Beach data (Fig. 6.50) show more consistency with an average apparent resistivity of approximately 50 ohm cm. These data have a larger range than those observed at Dittisham and values range between 0 and 100 ohm cm. Data acquired from the Harbour site (Fig. 6.51) show the least variation with a range of approximately 20 – 60 ohm cm. The average apparent resistivity is approximately 50 ohm cm, and the consistence across the site indicates a fairly homogenous medium.

At four corner locations (Fig. 6.52) samples of the sediment were taken using the 'undisturbed' sampling systems described in section 5.4.3.1. (note samples were not collected at the upper Beach site). Both particle size analysis and Atterberg testing was undertaken on the samples (Tables 6.5 & 6.6), each of which were divided into an upper and lower section to correspond with resistivity readings.

Location	Grid position	Depth (cm)	D16%	D50%	D84%	Mean	Median	Standard deviation		Skewness		Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Classification
Dittisham	1,1	0-5	4.100	0.064	0.001	0.074	0.064	0.019	EPS	-0.97	to coarse	0	35	36	29	Silty sand
Dittisham	1,1	6-10	4.500	0.310	0.009	0.236	0.310	0.045	EPS	-0.87	to fine	14	22	41	23	Gravel sand
Dittisham	9,1	0-6	0.520	0.047	0.001	0.033	0.047	0.051	EPS	-0.82	to fine	17	36	33	14	Sandy silt
Dittisham	9,1	7-12	2.500	0.080	0.002	0.077	0.080	0.029	EPS	-0.94	to fine	16	40	32	12	Sandy silt
Dittisham	1,9	0-5	4.300	0.115	0.062	0.317	0.115	0.120	VPS	-0.97	to coarse	18	32	29	21	Sandy silt
Dittisham	1,9	6-9	4.050	0.120	0.003	0.118	0.120	0.028	EPS	-0.94	to fine	0	28	31	41	Sandy gravel
Dittisham	9,9	0-5	1.150	0.052	0.001	0.046	0.052	0.036	EPS	-0.91	to fine	20	34	35	11	Silty sand
Dittisham	9,9	6-9	0.800	0.048	0.002	0.042	0.048	0.047	EPS	-0.88	to fine	16	31	36	17	Silty sand
Lower beach	1,1	0-6	3.200	0.240	0.070	0.381	0.240	0.148	VPS	-0.89	to coarse	0	11	80	10	Silty sand
Lower beach	1,1	7-13	1.700	0.185	0.088	0.306	0.185	0.228	VPS	-0.88	to coarse	0	9	86	5	Silty sand
Lower beach	9,1	0-6	2.200	0.195	0.086	0.337	0.195	0.198	VPS	-0.90	to coarse	0	15	72	13	Silty sand
Lower beach	9,1	7-13	2.000	0.210	0.074	0.318	0.210	0.192	VPS	-0.86	to coarse	0	16	70	14	Silty sand
Lower beach	1,9	0-9	1.050	0.140	0.082	0.233	0.140	0.279	PS	-0.88	to coarse	0	15	62	23	Gravel sand
Lower beach	1,9	10-17	0.380	0.140	0.090	0.172	0.140	0.487	PS	-0.66	to coarse	0	12	73	15	Gravel sand
Lower beach	9,9	0-6	1.450	0.150	0.070	0.251	0.150	0.220	VPS	-0.88	to coarse	0	9	73	18	Gravel sand
Lower beach	9,9	7-17	1.650	0.135	0.062	0.243	0.135	0.194	VPS	-0.91	to coarse	0	12	72	16	Gravel sand
Harbour	1,1	0-11	0.105	0.084	0.004	0.032	0.084	0.183	VPS	0.59	to fine	14	28	56	2	Silty sand
Harbour	1,1	11-18	0.078	0.032	0.001	0.015	0.032	0.124	VPS	-0.20	to fine	11	23	65	1	Silty sand
Harbour	9,1	0-6	0.115	0.092	0.005	0.037	0.092	0.198	VPS	0.58	to fine	17	37	44	2	Sandy silt
Harbour	9,1	7-16	0.115	0.090	0.001	0.026	0.090	0.112	VPS	0.56	to fine	15	28	56	2	Silty sand
Harbour	1,9	0-11	0.110	0.080	0.003	0.031	0.080	0.165	VPS	0.44	to fine	0	37	62	1	Silty sand
Harbour	1,9	12-20	0.110	0.084	0.008	0.043	0.084	0.270	PS	0.49	to fine	22	49	27	2	Sandy silt
Harbour	9,9	0-7	0.105	0.052	0.002	0.022	0.052	0.125	VPS	-0.03	to fine	0	35	64	1	Silty sand
Harbour	9,9	8-19	0.112	0.088	0.003	0.033	0.088	0.172	VPS	0.56	to fine	17	14	67	2	Clayey sand

EPS = extremely poorly sorted
VPS = very poorly sorted
PS = poorly sorted
Grain sizes in mm

Table 6.5 : Field site particle analysis data

Location	Grid position	Depth (cm)	Field Mois MC	Salinity	w_P Plas limit	w_L Liq limit	I_P Plas index	I_L Liq index	G_S	Field vane Cu (kPa)
Dittisham	1,1	0-5	88.69	30.1	32.22	52.44	20.22	2.79	2.4975	
Dittisham	1,1	6-10	48.32	30.1	26.31	46.75	20.44	1.08	2.3129	10.4
Dittisham	9,1	0-6	87.58	30.1	36.19	51.23	15.04	3.42	2.3191	
Dittisham	9,1	7-12	51.03	30.1	25.88	31.94	6.06	4.15	2.6441	14.0
Dittisham	1,9	0-5	89.53	30.1	27.08	50.62	23.54	2.65	2.3849	
Dittisham	1,9	6-9	48.28	30.1	24.42	43.27	18.85	1.27	2.5258	11.6
Dittisham	9,9	0-5	91.24	30.1	28.37	49.44	21.07	2.98	2.3531	
Dittisham	9,9	6-9	46.98	30.1	28.36	44.23	15.87	1.17	2.5696	11.1
Lower beach	1,1	0-6	35.14	31.5	27.88	34.79	6.91	1.05	2.6029	
Lower beach	1,1	7-13	32.81	31.5	-	-	-		2.5867	11.3
Lower beach	9,1	0-6	36.98	31.5	-	-	-		2.5999	
Lower beach	9,1	7-13	33.58	31.5	-	-	-		2.6381	7.3
Lower beach	1,9	0-9	36.66	31.5	-	-	-		2.5632	
Lower beach	1,9	10-17	33.87	31.5	-	-	-		2.5860	7.3
Lower beach	9,9	0-6	35.49	31.5	-	-	-		2.5246	
Lower beach	9,9	7-17	32.86	31.5	-	-	-		2.4351	10.9
Harbour	1,1	0-11	56.32	33.2	23.26	34.60	11.34	2.92	2.2485	
Harbour	1,1	11-18	44.26	33.2	22.65	33.52	10.87	1.99	2.5108	13.3
Harbour	9,1	0-6	52.69	33.2	27.53	33.22	5.69	4.42	2.3455	
Harbour	9,1	7-16	42.54	33.2	24.67	34.53	9.86	1.81	2.4892	16.9
Harbour	1,9	0-11	54.22	33.2	23.81	53.08	29.27	1.04	2.4473	
Harbour	1,9	12-20	43.38	33.2	24.92	35.51	10.59	1.74	2.6061	12.2
Harbour	9,9	0-7	53.29	33.2	26.64	36.48	9.84	2.71	2.4683	
Harbour	9,9	8-19	40.13	33.2	22.74	34.87	12.13	1.43	2.3542	13.3

Table 6.6 : Field site index data

size range has led to the creation of a high porosity material which gives high apparent resistivity values.

From these data some conclusions may be drawn as to the sediment characteristics of the upper Beach site. This region had the highest range of apparent resistivities (70 – 200 ohm cm) which suggests a coarse material. Visual inspection of the site showed the area to consist largely of sand with some larger features such as whole and fragments of shell. As mentioned above the readings were taken when the tide was receding leaving the material with little conductive pore fluid. This lack of pore fluid may explain why the readings are higher than those of the lower Beach and why there is more variation in the data.

Table 6.6 shows index data along with shear strength data acquired from the three sites. Dittisham has a highly variable field moisture content with the surface layer having a significantly higher value (average 89.26 %) than the lower layer (average 48.63 %). The liquid limit data from the top layer show all to be over their liquid limit whilst the lower layer is either close to or slightly above the limit. This would suggest that the material would have a low shear strength and indeed the values from the field vane range from 10.4 to 14.0 kPa. These data correspond well with the resistivity data, where the Dittisham site showed a low range of apparent resistivity values. The Harbour site has the next highest field moisture content with the top layer averaging 54.13 % and the lower layer averaging 42.58 %. The liquid limits for this site are fairly consistent at approximately 34 and all of the samples are above this limit. It would be expected that the plasticity index would be higher for the Harbour site than for the Dittisham site as the average mean grain size is lower i.e., Harbour sediments are finer. The average field vane strength for the Harbour site is 13.9 kPa, higher than for the Dittisham site. As the field moisture content values are closer to the liquid limit at the Harbour site than at Dittisham this trend would be expected. As moisture contents decrease towards the liquid limit the material becomes more plastic until at the liquid limit the material undergoes the transition from liquid to plastic behaviour. A plastic material will have a higher shear strength than a liquid material. The lower moisture contents of the Harbour site also support the slightly higher apparent resistivity values. The Lower Beach site exhibits the lowest field moisture contents which supports its high apparent resistivity values. Due to the coarseness of the material Atterberg tests could not be undertaken. However this in itself implies a low undrained shear strength as there are fewer charged particles for granular bonding.

6.3.3. ROV mounting

The limitations imposed on the resistivity system are size, weight and the requirement for bottom stability. A simple mounting system could be developed using a linear actuator in which the resistivity rig could be lowered to the seabed and penetrate using a stepped motion. In this way regular intervals of depth could be achieved which would allow detailed mapping. The rig could be mounted in front of a camera to allow 'real-time' monitoring of the system and to ensure that the rig is only deployed in areas of suitable sediment i.e., areas of appropriate grain size.

Improvements to the rig such as increases in size spacing and length of the probe could be undertaken to make the system more flexible. It must be noted however, that the array spacing must be kept constant; long probes may diverge or converge with increasing sediment consolidation and overburden. The force required to drive the rig into the seabed will increase with depth and thus the actuator must be powerful enough. Increasing power is likely to lead to a larger unit so the disadvantages might outweigh the benefits. The fundamental issue is that of sediment disturbance. As discussed in chapter three the pressure exerted by the proposed ROV will increase with added mass. If the ROV becomes too heavy it will not be able to sit on the lower shear strength sediments without disturbing them.

To improve the speed of system operation, each array should be linked directly to a terrameter to prevent delays whilst switching between the arrays. Automation of data recoding and probe penetration will improve the efficiency of the system and negate doubts relating to variation in the readings between arrays with time.

6.4. Summary

The data acquired from the laboratory and field tests suggest that the advanced resistivity rig offers a simple method for acquiring *in situ* sub-bottom data. The system is obviously limited in depth penetration due to the small spacing of the arrays but it has been proven to provide a method for distinguishing between coarse and fine sediments. The addition of ground truthing data in the form of particle size analysis and index testing has been shown to support the data acquired.

Three categories of sediment classification have emerged. Fine sand (Playpit sand mean grain size 0.35 mm) having an apparent resistivity of approximately 200 ohm cm; coarser material (Lizard and Beach sands and Gravel, mean grain size 0.74 mm) mean 100 ohm cm; and silts and clays (Mud 5 and 6, mean grain size 0.09 mm) mean 45 ohm cm. Variations due to dissolved salts, and electrode tip differences were not applied, as they could not be reliably calculated. Rough estimates of 'dissolved salt impact', based on the differences seen when comparing the water tests for each sample (Figs. 6.19 – 6.24) show the two mud samples to have values of approximately 30 ohm cm whilst the other four samples have values ranging from 50 – 100 ohm cm. A correction could be applied to bring the Mud sample values in line with the other four samples' water reading, however the variation would not be great enough to change the three group pattern. The deviation of the large square array water data from the small square and Wenner arrays water data (Fig. 6.18) could also be corrected, but it is uncertain which array is providing the correct information. If the large square array data were reduced then the dispersion of points observed in Figures 6.19– 6.24 would be reduced.

The validity of the data in this study can be confirmed by comparison with data from other studies of marine sediment resistivity, a range of which are given by (Jones, 1999):

> *"Resistivities of marine sediments normally fall in range 0.1-1.0 ohm m, with clay rich accumulations being some of the most conductive."* (Jones, 1999)

Telford et al., (1990) provide a list of resistivity values for various rocks and sediments. Clay is listed as 1 – 100 ohm m and unconsolidated wet clay at 20 ohm cm. The mean value of 45 ohm cm or 0.45 ohm m found in lab testing is well below the Telford et al., (1990) clay value but is more consistent with their wet clay value. The samples used in this research were fully saturated, therefore, the resistivity values would be expected to be significantly lower than those obtained with either 'dry' or 'slightly wet' samples. Telford et al., (1990) provide values for the resistivity of seawater as 0.2 ohm m; saline water 3% as 0.15 ohm m; and saline water 20% as 0.05 ohm m. These values are slightly lower than the range observed in Figure 7.18 of approximately 50 – 80 ohm cm or 0.5 – 0.8 ohm m but are of the correct order of magnitude.

Lauer-Leredde et al., (1998) describe models produced prior to the testing of their FICUS probe (section 2.4.2.) in which marine sediments had values of apparent resistivity ranging from 0.5 – 5.0 ohm m. Subsequent lab tests undertaken in a tank measuring 1m by 0.5 m by 0.5 m with material saturated in a NaCl solution of 3.3% resulted in apparent resistivity values: silica (90%) ~ 0.55 ohm m, silicon carbide ~ 0.8 ohm m and a clayey-sand ~ 0.5 ohm m. Measurements undertaken by Lei and Nobes, (1994) of the resistivity of underconsolidated sediments in the Cascadia Basin (west coast of Vancouver Island) show three layer sedimentation with values decreasing from 1.1 ohm m at the seabed to 0.4 ohm m at 1 km depth.

In all of the above studies the values given are of similar magnitude to those obtained in this study, indicating that the system does provide reliable sediment classification data. This study has, however, indicated that further investigations are needed to discriminate between different types of coarse material (i.e. the similarity of the Beach and Lizard sands and the Gravel) including ground truthing and subsequent lab analysis.

The two-layer effect seen in the majority of the laboratory investigations (illustrated by a relatively gentle initial slope followed by a steeper slope) indicate that the bucket in which the tests were undertaken is affecting the data. Although the water calibration plot (Fig. 6.18) shows negligible boundary effect this masking could be due to the highly conductive nature of the water medium in comparison to the infinitely resistive bucket. As would be expected no boundary effects are seen in the field data (Figs. 6.48 – 6.51) thus confirming the above hypothesis.

Tests undertaken to detect whether a change in sediment or the presence of an object would be apparent in the data were not conclusive. Variations in the value of the apparent resistivity compared to the raw sample were observed although the boundary change was not apparent. This may be due to mixing of the sediments or the similarity of the samples. The investigations undertaken to ascertain the ability of resistivity readings to detect objects were inconsistent making it difficult to draw conclusions. The data do show a variation from the normal water test suggesting the presence of an object but the exact size or shape of this object is unclear. Further tests could be carried out in regulated sediments (constant grain size and porosity) to determine whether or not the variation observed can be interpreted in a useful manner.

Three equipment limitations may need to be addressed during further development. First the problem of variable tip corrosion should be corrected with the introduction of either removable tips or use of calibration procedures. Secondly the current rig is held within a nylon block which may lead to problems due to water absorption and subsequent deformation of the array shape and size. The array geometry must be kept constant to ensure data are correct and thus the use of an alternative material may be appropriate. Thirdly the plastic insulation tubes although tight in fit may allow water to seep upwards along the probe. This could cause a variation in data recorded and could be overcome by the use of bonded insulation.

Chapter 7

The Dart Estuary, a case study

7.1. Introduction

The application of data management techniques, in particular GIS, to marine data has proved highly successful in both research and industry sectors (chapter two). GIS are used as archive, integration and visualisation systems with the spatial analysis functionality further enhancing their potential use. To assess the feasibility of establishing a GIS for the nearshore environment a timed exercise using an off-the-shelf GIS package (ArcInfo 8) was undertaken. If GIS are to be useful to surveyors, engineers and local bodies (e.g. harbour authorities) they must demonstrate an ease of construction. During a specified two month period the aim was to establish the ease with which a range of data could be introduced to the ArcInfo 8 GIS and the usefulness of these data.

The development of equipment operable from an ROV was based on the current lack of nearshore site investigation techniques. The difficulties associated with surveying in the nearshore zone not only include equipment shortfalls but also include the handling of a range of data intrinsic to the location. The Dart estuary was chosen as the case study location due to its range and complexity of nearshore survey issues. This chapter will describe the geology, geomorphology and human activity as detailed in past research and through new surveys and observations. The development of the Dart GIS will be described with analyses of the methods employed. The advantages and disadvantages encountered during the timed exercise will also be discussed.

7.2. The Dart estuary

The Dart estuary is situated in the South West of England in the South Hams district of Devon (Fig. 7.1). The principal town of the estuary, Dartmouth, lies approximately 1 mile north of the mouth on the west bank, with the town of Kingswear on the facing east bank.

The diversity of information relevant to nearshore surveys ranging from tidal movements and seabed sediment classification to vessel movement and local environmental factors can be viewed as separate entities. If however the integration of equipment on a remote platform and the subsequent integrated analysis can provide useful additional information then it can be surmised that this same approach would be useful for the entire survey process. This synergistic approach to nearshore site investigations requires an understanding of the multiplicity of processes occurring in the region of interest and thus an appreciation of their interleaving.

The research into the area involved a desk study of the geology of the estuary and the surrounding area, along with the hydrographic features and an investigation into the contemporary oceanographic and geomorphological processes. Studies of the geology and geomorphology have been supplemented with the new survey data to provide an up-to-date analysis of the distribution of materials and the processes acting in the estuary.

7.2.1. Geology

7.2.1.1. Stratigraphy

Devonian lithology predominates in the River Dart estuary as can be seen in Figure 7.2 with like lithology spanning the dividing estuary. The sequences become younger moving inshore with Lower Devonian rocks (Dartmouth Slates, Meadfoot Group and Staddon Grits) at the mouth of the estuary overlain by Middle Devonian Slates and Shales. Igneous tuff formations located approximately 6 ½ kilometres from the estuary mouth fall within this Middle Devonian sequence. Further upstream at Flat Owers, the lithology of the east bank is Upper Devonian Limestone, a lithological unit stretching from Berry Head inshore. Dolerite is found at the coast within the Dartmouth Slates and further inshore within the Meadfoot Group and Tuffs.

7.2.1.2. Structural geology

The Variscan Orogeny was primarily felt in Great Britain during the late Carboniferous (Durrance, 1971; Owen, 1976), with the Cornubian Batholith representing a significant part of this activity in the region (BIRPS and ECORS, 1986). This tectonic activity also caused intense folding of Devonian strata and it is generally accepted that the orogenic activity caused an East-West deformation in the Devonian material of Devon (Chapman et al., 1984; Dearman, 1971; Edmonds et al., 1985; Hobson, 1976; Owen, 1976).

In the Dartmouth region, this activity is reflected in the Dartmouth Antiform (Fig. 7.3) within which according to Hobson, (1976), there are three major elements:

> *" a large F1 anticline: a major late formed Antiform: and a large fault zone along the northern boundary of the Dartmouth Beds. "*

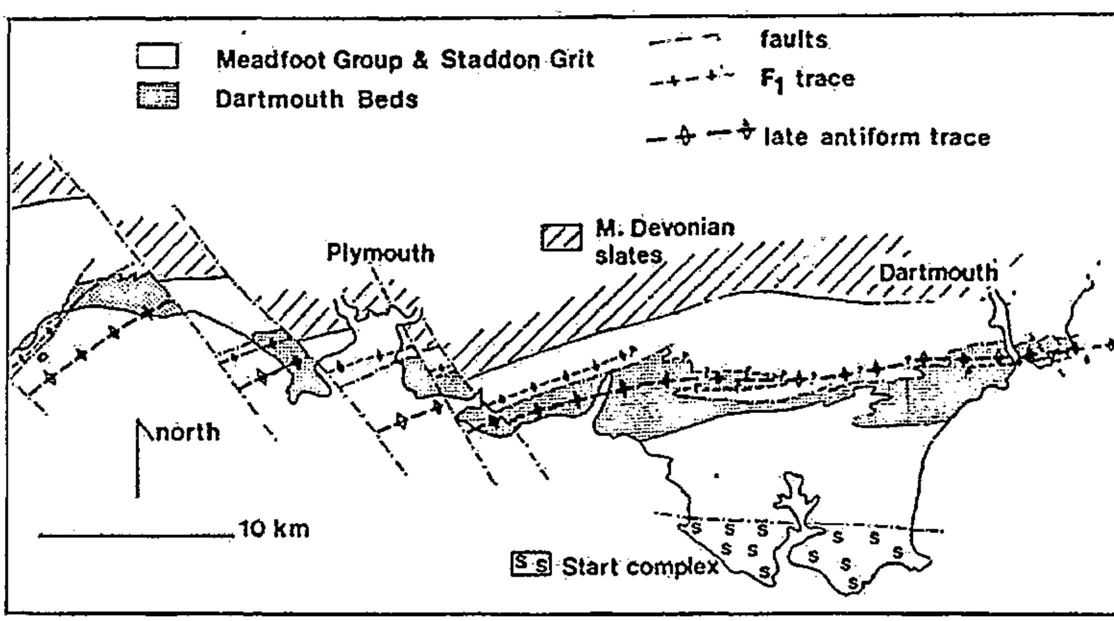


Figure 7.3: Tectonic map of the Dartmouth Antiform (Hobson, 1976)

The Alpine Orogeny, which raised the British Isles above sea level, caused the formations of the south-west up to the mid-Oligocene to be folded and a number of mainly dextral wrench faults to be created (Durrance, 1971; Edmonds et al., 1985; Owen, 1976).

7.2.2. Geomorphological development

Geomorphological processes acting on the bedrock geology since the Tertiary period, along with tectonic activity, have determined the 'base shape' of the present day landscape of Dartmouth. The geomorphological development of this terrain is dictated partly by this framework, but also partly by recent environmental input.

7.2.2.1. The relict Tertiary landscape

The present day morphology of any region is determined by phases of deposition and denudation over many millennia and under varied environmental conditions. The base 'platform' of this development is determined by the geological history of the area and is termed the relict landscape. This landscape forms the base for all subsequent sedimentary and geological changes and as such often determines the mechanisms and extent of future morphological development.

Goudie (1990) describes the history of the investigations into the relict landscape of the British Isles in detail. He depicts four stages of progression of the relict landscape theories.

1. Planation surfaces created by wave action (Plant, 1866; Ramsay, 1846; Ward, 1870).
2. Formed from long term sub-aerial denudation, and termed peneplains (Davis, 1895).
3. Development of time period peneplains through geological history (Brown, 1960; Wooldridge and Linton, 1939).
4. Tropical planation whereby chemical decomposition and surface wash lead to the production of etchplains (Battiau-Queney, 1984; Büdel, 1982; Isaac, 1983; Smith and McAlister, 1987; Summerfield and Goudie, 1980; Walsh et al., 1987).

It is not yet certain which of these theories is correct and all need to be considered. All that is known for certain is that the landscape of the south of England is dominated by a plateau / plateaus stretching some distance inland from the coast. After formation, the surface was subjected to the flow of water and drainage systems soon developed incising their way into the rock to form river valleys. These initial 'v' shaped incisions, dictated the later depositional events, with landslides occurring regularly, and with subsequent Quaternary events further deepening and infilling the channels.

It has been discussed by Green, (1949) that during the Pliocene:

> *"The streams from Dartmoor probably ran eastward at first and that the Dart originally passed along the present Teign estuary."*

Green, (1949) goes on to say that there is also valley evidence of a course of the Dart to Brixham (Fig. 7.4).

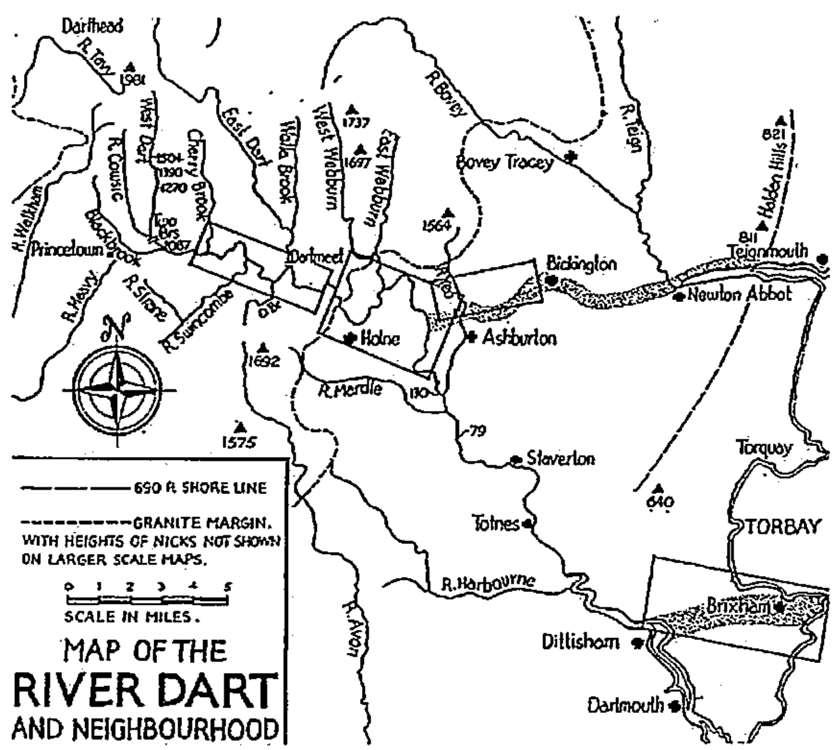


Figure 7.4: Map showing past courses of the River Dart (Green, 1949)

7.2.2.2. Quaternary

The Quaternary brought lower global temperatures and much of the landscape of Great Britain was covered in ice sheets. The south-west of England escaped direct ice cover with glacial ice sheets only once reaching as far south as North Devon (Durrance, 1971). The peripheries of the various ice sheets were however areas of permafrost and seasonal active layer development. This resulted in meltwaters transporting material down slopes and the accumulation of large quantities of periglacial debris known as 'head'. In addition, a marine platform had been

below. It is likely the silt was transported to the present location from the east by aeolian processes where it was mixed with local material via frost, pluvial or biological action (Harrod et al., 1973).

7.2.3. Sea level variation

In the past the Dart region has experienced both eustatic and isostatic sea level variations. The mechanism for both was the waxing and waning of Quaternary ice sheets; glacio-eustasy and glacio-isostasy. The geomorphological development of coastal features is strongly influenced by local variations in mean sea level (a combination of eustatic and isostatic changes) with the creation of features such as raised beaches and drowned river valleys in the locality of the Dart.

Raised beach deposits can be seen at Dartmouth, and are thought to have been created during two inter-glacial periods when the sea level was higher than it is today (Durrance, 1971; Orme, 1960). It has been recorded by Orme, (1960) that subsequent cryogenic activity has been seen to have remoulded deposits and incorporated them into the head. Beach material can however, be distinguished from the head as the particles have been rounded by the marine processes that deposited them (Mottershead, 1971). Three strandlines (beach cut notches), which are often associated with beach deposits have also been identified in the area by Orme, (1960), at ~20 m, ~7 m and ~4 m above Ordnance Datum (mean sea level) with some beach deposits surviving *in situ* on the lower strandlines.

Many river valleys in the area, including the Dart and the Exe were formed when the sea level dropped as a result of the periods of glacial ice build-up during the Quaternary. River beds were deeply eroded by the movement of water and their mouths migrated with the coastline. As the Pleistocene ice sheets retreated, sea level in the south-west rose and the estuaries of the area were drowned. The mouths and river beds were buried under sediment, resulting in rias and drowned river valleys (Durrance, 1969; Durrance, 1974; Orme, 1960).

Codrington, (1898) studied some of the submerged rock-valleys in Devon and Table 7.1 illustrates his findings at Dartmouth.

Location	Water depth (m)	Depth of sediment (m)	Depth to rockhead (m)	Slope on south side	Slope on North side
Maypool	8	26	34	1 in 3 1/3	1 in 3
Longwood Creek	- 3	23	20	1 in 1 3/4	1 in 3
Waterhead Creek	-1	29	28	1 in 2 1/3	1 in 2 ½
Kingswear Jetty	6	16	22		

Note: all measurements refer to low water

Table 7.1: Submerged rock-valley data from Dartmouth (Codrington, 1898)

(Codrington, 1898) also found that:

> *"The depth of the rock bottom at Maypool is not reached until nearly as far out as the 37 m line about 2 miles outside the mouth of the Dart."*

Durrance, (1969) explains that the Dart has a rockhead channel lying at a depth of 38 m at Maypool and 9.5 m at Totnes, which gives a gradient of approximately 1 in 350. He goes on to say that with these measurements, the rockhead at the present mouth would be expected to be at a depth of approximately 52 m.

A report by Kelland, (1975) of a geophysical survey undertaken in the area demonstrates the presence of a buried cliff in the vicinity of the Dart (Fig. 7.5).

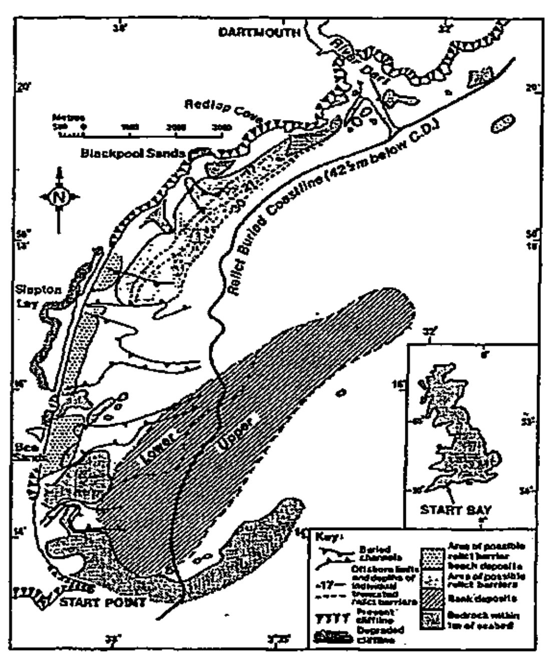


Figure 7.5: Map showing distribution of major geological features in Start Bay (Kelland, 1975)

Kelland, (1975) also discusses the presence of buried channels at the mouth of the estuary:

> *"A number of buried channels dissect the bedrock surface between the 42m contour and the present shoreline and are probably former extensions of modern river valleys. Channel widths vary between 100m and 450m and the deepest lies below the approaches to the River Dart at a depth of more than 40m."*

The above information would be difficult to correlate and confirm without undertaking a full geophysical survey not only of Start Bay but also of the Dart estuary with the acquisition and subsequent dating of rock cores. The data sources do however suggest that the south-west was subject to large and rapid sea level fluctuations which had a major impact on the landscape.

Future local rises in mean sea level either due to eustatic or isostatic factors are likely to bring about morphological changes similar to those described above. As the sea moves further inland, low lying towns such as Dartmouth and Kingswear will be flooded, and the Dart estuary will become deeper and wider. This will result in the tides advancing further inland along with a probable increase in range (Bird, 1993). Fluvial sediment will not be transported to the coast but will be deposited closer to the source, thus adding to water level and increasing the likelihood of flooding (Bird, 1993; Leatherman, 2001).

7.2.4. Contemporary River Dart Estuary

The history of the River Dart spans many years and includes many important dates in history, such as the sailing of Richard I, on crusade, in a Dartmouth built ship and discovery voyages in the reign of Elizabeth I, which set sail from Dartmouth (Hughes, 1950). Charles I used Dartmouth as a naval base during the civil war until it was captured in 1646. The naval importance of Dartmouth then declined during the 18th century due the increasing size of the vessels (Hughes, 1950). In 1941 Dartmouth became a convoy staging port to protect ships during daylight hours from the second world war air attacks. The Royal Naval college became the United States Advanced Amphibious Base, some of whose troops were involved in the D-Day landings. The influx of marine vessels continued and in 1944, an invasion fleet of 485 ships was gathered together in the port (Griffiths, 1995).

The commercial port of Dartmouth has not been particularly active since the second world war despite the fact that the deep water harbour is accessible at any state of the tide although it is a designated standby NATO port (South Hams District Council, 1996b). The South Hams Local Plan for the period 1989 to 2001 (South Hams District Council, 1996b) stated that the council recognised the potential of the locality and a feasibility study undertaken in the 1980s showed that:

> *"Noss on the east bank of the Dart, would be a good location to provide a new deep water commercial quay".*

It is understood by the author that these plans were dismissed due to local objections although it is believed that new plans may be put forward in the near future (Humphreys, 2001).

The estuary has two permanent ferries: the upper ferry, which is chain driven, and the lower Dart ferry. These vessels cross the river approximately every 10 minutes (approx. 0700-2245) and thus create a semi-permanent obstacle. An additional 30 or so pleasure craft operate in the lower estuary and have trips leaving throughout the day, some on a half hourly basis from 0900-1700. In addition to this there are approximately 1500 private, 30 charter, 11 commercial and 20 fishing vessels registered with the Dart Harbour Authority (Dart Harbour Authority, 2002). Commercial fishing and fish farming is also actively operating from the estuary.

Due to the natural beauty of the area many protection orders are in place: National; Area of Outstanding Natural Beauty (AONB), Historic Coast, Sites of Special Scientific Interest, Nature Reserves, Scheduled Ancient Monuments, Listed Buildings, Local; Coastal Preservation Area (CPA), Areas of Great Landscape Value (AGLV), Nature Conservation Zones, Conservation Areas, Tree Preservation Orders (TPO's) and Regionally Important Geological / Geomorphological Sites (RIGS) (South Hams District Council, 1996a). These protection orders limit the growth of the populations of the towns as well as that of industry. Access to the area is poor, and it is unlikely that new roads or rails connections will be created due to the restrictions of the orders.

7.2.4.1. Channel form

The morphology of the Dart estuary has been determined by past morphological processes as described above, and is constantly being altered by present events such as the weather, marine forces and land use and development. Non-sequential aerial photographs illustrate the high percentage of arable land around the estuary, with a large proportion of the banks being given over to forest or moor land at the higher entrance (Plates 7.2 & 7.3).

After entering the estuary the sides remain high, having become rolling hills. Table 7.2 in conjunction with Figure 7.6, illustrates the slope of the hills determined from east – west measurements to the water line.

West bank Location	Grid coords	Height (m)	Distance (m)	Slope	Slope	Distance (m)	Height (m)	Grid coords	East bank Location
Beacon Parks	287150 E 50625 N	167	875	1:5	1:7	1050	147	289400 E 51325 N	East of Kingswear
Balcombe Pits Copse	287125 E 53100 N	118	375	1:3	1:8	1300	170	289475 E 53175 N	Furland Trig point
E of Fire Hill Beacon	286950 E 53800 N	162	675	1:4	1:8	800	106	288525 E 54275 N	SE of Oakham Hill
Dittisham Court	286300 E 55275 N	53	475	1:9	1:6	625	103	287650 E 54875 N	S of Lower Greenway

Table 7.2: Slopes of surrounding hillsides within the Dart estuary
Source of raw data (Ordnance Survey, 1995)

The estuary itself can be classified as a 'ria', that is it has been created as a result of successive sea level rises and falls, has a wide mouth and is open to the influence of the sea (i.e. is tidal). Several systems are in place for the classification of estuaries including the simple morphological slope analysis investigated in Table 7.2, along with circulation and tidal systems.

The tidal system is based on the tidal range experienced within the estuary and this plays an important role in the estuarine processes (Pethick, 1996). The tidal range within the lower estuary (Dartmouth to Greenway Quay) is 4.3m at springs at 1.8m at neaps, where mean high water springs (MHWS) is 4.9m and mean high water neaps (MHWN) is 3.8m (United Kingdom Hydrographic Office (UKHO), 1988). The direction and speed of tidal activity within and around the estuary is presented in Table 7.3.

Time	Direction in Dart	Speed in Dart (knots)	Speed at castle	Speed at mouth	Direction in channel	Speed in channel (knots)
-6	Ebb	0.5-0.9	1.0-1.9	0.1-0.4	SW	0.5-0.9
-5	Flood	1.0-1.9	1.0-1.9	0.5-0.9	SW	"
-4	Flood	"	"	"	SW	"
-3	Flood	"	"	1.0-1.9	SW	"
-2	Flood	"	"	0.5-0.9	NE	"
-1	Flood	"	"	"	NE	"
0 (HW)	Flood	0.5-0.9	"	"	NE	"
1	Ebb	0.1-0.4	0.1-0.4	0.1-0.4	NE	"
2	Ebb	0.5-0.9	1.0-1.9	0.5-0.9	NE	"
3	Ebb	1.0-1.9	"	"	NE	"
4	Ebb	"	"	"	SW (MIX)	1.0-1.9
5	Ebb	"	"	"	SW	"
6	Ebb	"	"	1.0-1.9	SW	"

Table 7.3: Tide direction and speed in the Dart estuary (Fennessy, 1997)

The morphology of the Dart is also expressed by the bathymetry (seabed morphology) and some of the estuarine processes may be inferred from the surficial seabed sediment. A description of the formations is given below and some of the features (such as mud banks) can be identified on the aerial photographs (Plates 7.2 & 7.3).

The southern harbour limit of the Dart estuary is defined as a transect between Combe Point and Inner Froward Point. The 10 metre contour runs close to this line with the 15 and 20 metre contour lines approximately 370 m and approximately 740 m beyond respectively. Within the harbour limits in the area known as 'The Range', the depth of water is approximately 7 to 8 metres although shallows of 5 metres and troughs of 9 metres are also found. Bed type here includes sand, shells, stones, gravel and rock exposures (United Kingdom Hydrographic Office (UKHO), 1988).

A channel with a prime depth of 10 metres begins within 'The Range' and remains until the town of Dartmouth. Within the channel are two depressions, the first at 'One Gun Point' is approximately 300 m long with a maximum depth of 25 m and a steep drop off on the west bank and the second begins at 'Warfleet Cove' and stretches approximately 750 m, with a maximum depth of 19.8 m. This second depression forms a trough of fairly consistent 19 m depth with shallow slopes. The seabed in this region consists primarily of mud (United Kingdom Hydrographic Office (UKHO), 1988).

The estuary then shallows off with a mid-channel depth range between 6.6 and 9.1 m up to the entrance to 'Old Mill Creek' although a deeper channel of 10 – 13.8 m is situated on the East bank of the estuary between Sandquay and the entrance to the creek. Mud flats start to appear along both sides of the estuary in this area and bottom type in the main channel includes mud, fine sand, sand, broken shells, and rock exposures (United Kingdom Hydrographic Office (UKHO), 1988).

The area surrounding 'Lower Noss Point' shallows to a maximum depth of 4.8 m although a narrow channel of approximately 6m depth can be followed. The seabed here consists of mud, stones, fine sand and shells (United Kingdom Hydrographic Office (UKHO), 1988). At 'Higher Noss Point' a 10 m channel is once again present and within this channel at the 'Anchor Stone', a 200 m long depression with a maximum depth of 21 m is located, with very steep east bank slopes 1:0.8 (26 m drop over approximately 20m). Here the seabed consists of mud, broken shells and gravel (United Kingdom Hydrographic Office (UKHO), 1988).

At the end of this channel is 'Flat Owers', a site where drying heights of approximately 0.2 to 2m occupy a large section of the waterway, with the main channel having recorded depths of approximately 0.3 to 1.7 m. This area consists of extensive mud flats, along with broken shells and gravel (United Kingdom Hydrographic Office (UKHO), 1988).

The presence of large mud banks within the estuary indicates that the tidal regime is highly active. The asymmetry of the tidal wave increases as it advances into shallow water, thus increasing the differences between the flood and ebb velocities and causing more sediment to be carried into the estuary than is removed (Pethick, 1996). The fine sediment is suspended by the currents and deposited in the upper estuary (Dyer, 1979) either as flocs or as single particles. Once deposited the particles consolidate due to overburden pressure, thus creating a mudflat that

is difficult to erode. Deposition of this fine grained sediment is the mechanism for the creation of the estuarine shape (Pethick, 1996) as can be seen in plates 7.2 & 7.3, whereby the shape of the Dart is strongly dictated by the numerous mud flats.

7.2.4.2. Meteorology

The maintenance and development of the Dart estuary has been described in terms of tidal and marine processes but the weather also plays a role. The inherent proximity to the sea is a large factor in the climate of the Dart estuary with the sea acting to reduce the range of temperature. The weather experienced in and around the Dart estuary has been described in general terms by the meteorological office in their Climatological Memorandum for the South-west peninsula of Great Britain (Meteorological Office, 1990):

"♦ *Coastal and low lying areas have annual mean temperatures of 11 °C*
- ♦ *The sea reaches its coldest temperature in late February or early March, so that on average February is the coldest month.*
- ♦ *July and August are the warmest months with a mean max temperature around 19 °C to 21 °C.*
- ♦ *Dartmouth average monthly rainfall over period 1941 –1970 = 1000 – 1200 mm.*
- ♦ *November, December and January are the wettest months and April and June are the driest.*
- ♦ *The influence of the sea produces a more even distribution of thunderstorms throughout the year than in areas inland, and there are on average 5 to 12 days a year with thunder.*
- ♦ *Average hours of fog (predominantly sea) between 1971 and 1980 in Plymouth are 101.7 hours of fog (< 1000 m visibility) and 28.0 hours of thick fog (< 200 m visibility).*
- ♦ *South-west of England is particularly exposed to the predominant south- parts westerly winds and the average number of days of gale are higher than in other of England."*

The mouth of the estuary is subject to south westerly through to easterly winds and entrance to the estuary may be difficult in south westerly to south easterly winds (D'Oliveira et al., 2000). However, the presence of the Prawle Point – Start Point headland shelters the area from the full force of the Atlantic wind and wave forces thus leaving it open to more locally generated and dampened Atlantic action. A high cliff line and an unusual bend in the river caused by the prominent position of Kingswear mean that the estuary itself is very sheltered.

At the time of formation, subaerial processes dominated over marine action (due to the inherent lower sea levels) allowing the deposits to reach sea level. These areas have since been subjected to higher marine attack due to the raised sea level and thus have created the coastline profile seen today (Bird, 2000; Pethick, 1996) (Fig. 7.8 and Plate 7.1).

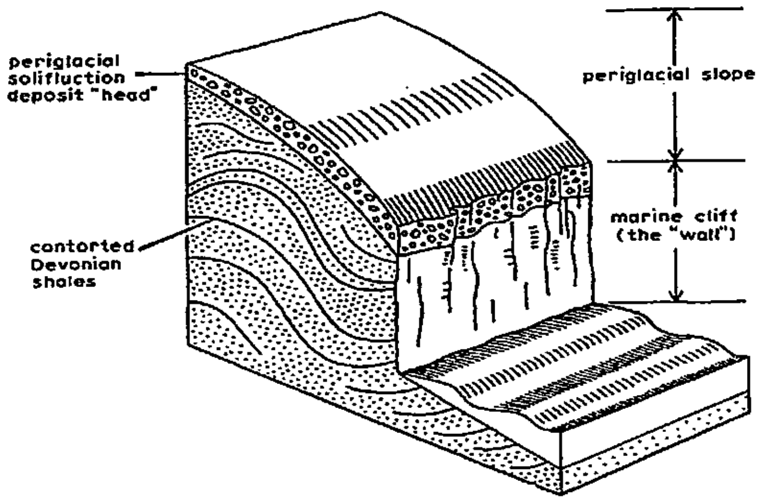


Figure 7.8: Present slope-over-wall cliffs (Pethick, 1996)

The current erosion of these slopes is described by (Bird, 2000):

> *"On soft formations, such as unconsolidated glacial or periglacial drift deposits, cliffs and steep coastal slopes recede by recurrent slumping, particularly after wet weather or the thawing of a snow cover."*

This description is confirmed by the presence of isolated rock outcrops near to the coast where the weaker periglacial deposits have been eroded, but the more resistant Dartmouth slate and Dolerite bedrock remains. These outcrops and other deposits at the cliff base are covered and uncovered with the tide indicating the importance of tidal action in this area. Furthermore as described in section 7.2.4.2. the study location is 'hidden' from large prevailing winds and waves and thus erosion of the basal cliffs may be reduced as compared to more exposed sites such as Bolt Head to the West.

7.2.4.4. Nearshore

Nearshore bedrock formations such as the presence of buried coastlines have been described in section 7.2.3, as being the result of fluctuations in sea level. At present these are submerged and the surface morphology illustrates a pattern of stepped depth increases with progression offshore. The current 1:6250 chart of the area indicates that in places these changes may be quite quick (1:5) and in others more gentle (1:85, 1:88). The 10 m contour lies close to the southern harbour limits. At its closest the 15 m contour is approximately 160 m (1: 32) from the 10 m contour and at its furthest extent, it is about 425 m (1:85) away (United Kingdom Hydrographic Office (UKHO), 1988). The 20 m contour ranges from approximately 25 m (1:5) to 438 m (1:88) seaward of the 15 m contour line (United Kingdom Hydrographic Office (UKHO), 1988).

The aspect of the Dart means that many of the waves reaching the area are short waves, i.e. they have been produced either within the English Channel or in the short distance between the Prawle Point – Start Point headland. These waves have little energy and move slowly, thus causing little erosion. However, long waves (those generated within the Atlantic), are fast and powerful, and do reach the coastline in some locations. These waves produce surf conditions and cause marine erosion (Pethick, 1996).

7.2.4.5. Boat surveys

During the course of the research, data has been acquired for two purposes: firstly to provide background information on the field site and secondly to acquire the relevant field information with the new systems developed, thereby testing these systems. Background information was acquired via boat surveys and the system development test sites were chosen based on simple land reconnaissance taking access issues into consideration.

The initial survey was undertaken from 8th to 12th May 2000 in conjunction with the students enrolled on the Post Graduate Diploma in Hydrographic Survey (2000) and their course leader Gwyn Jones, specifically to acquire background data for the current research. The extent of the survey site was defined such it would allow investigation into a range of coastal features and encompasses an area bounded by 'Flat Owers' (55500 N) at the Northern extent and 'The Range' (49500N) at the Southern limit. The area is approximately 6 km in length and varies from approximately 200 m to 750 m in width.

A suite of hydrographic and geophysical equipment was utilised comprising of:

- Geoacoustics Side scan sonar
- Multibeam Sonar – Reson Seabat 8101
- Boomer sub-bottom profiler – Model CAT 200 with Applied Acoustics Boomer Plate
- Pinger sub-bottom profile – ORE Pinger

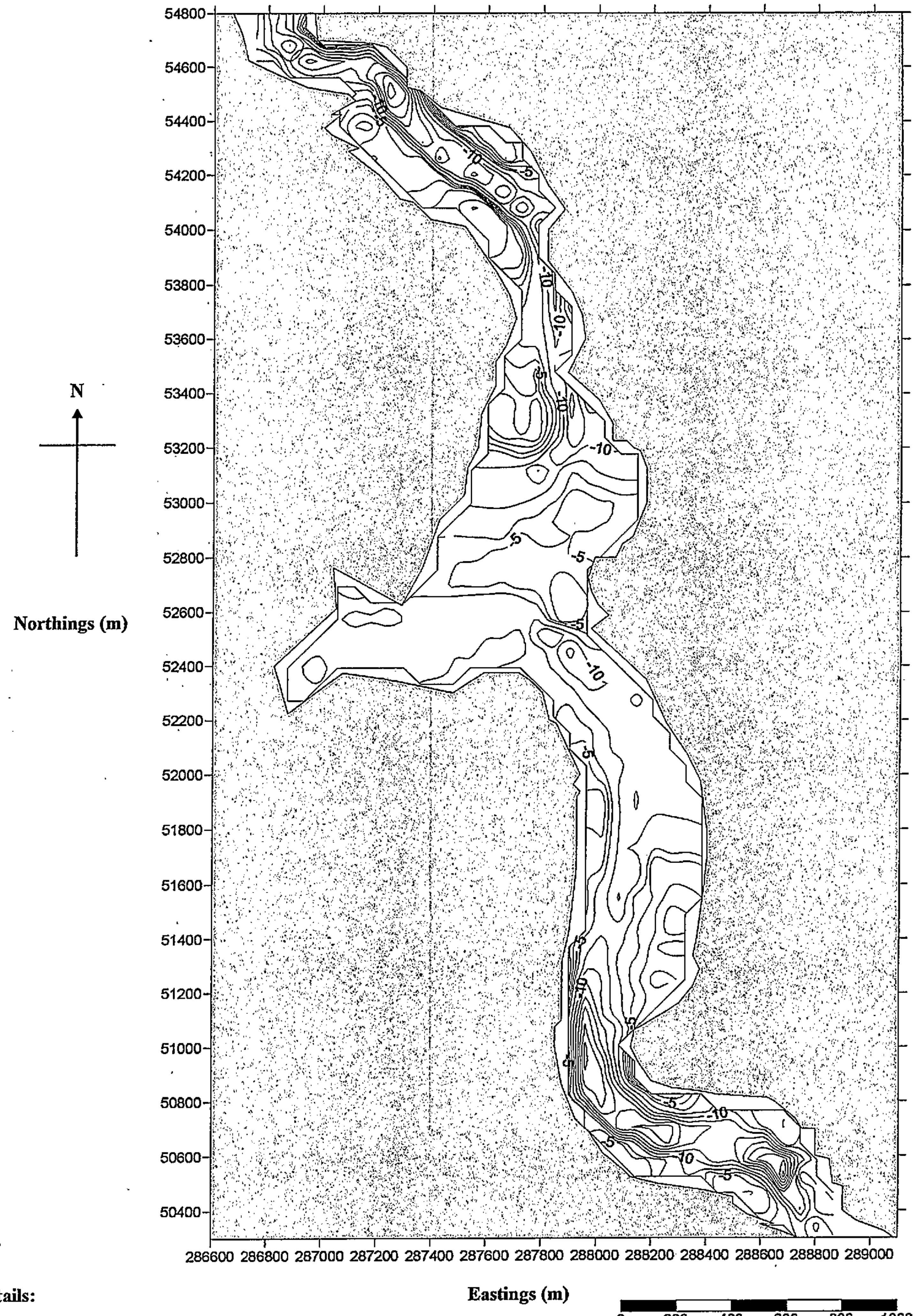
Two boats were used for the survey, a Royal Naval College Picket boat (skipper Paul Rampling) and Lynx, one of the harbour master's launches. The Picket boat was set up as a hydrographic vessel with the side scan and the multibeam, and the launch was used as a geophysical survey vessel towing both the pinger and boomer. The Fugro SeaSTAR Spot DGPS system was utilised on the Picket boat for positioning services whilst a stand alone Trimble 4000 SSE GPS unit was utilised on the geophysical vessel.

Although the data were acquired primarily for this research it was also used by the Diploma Group to create an overview report of the area. For this reason processing guidelines were established specific to the current research thus allowing the group to perform the raw processing whilst ensuring that the data were suitable for further use.

Multibeam data were reduced to chart datum using tidal data from the Dart Harbour Authority and were cleaned and gridded (at 2.0 m intervals) within the TerraVista 2 and Sounding Grid programs within the Reson software (Hydrographic Diploma Group, 2000). The ASCII files of processed data were input into the Golden Software package for Surfer 8 as part of this study to create four sets of multibeam maps including contour, wire-frame and surface plots. A plot of the whole extent of the survey site has been produced along with three overlapping sections (sites 1, 2, 3) (Figs. 7.9 to 7.20).

The contour maps (Figs. 7.9 – 7.12) show good agreement with the Admiralty chart of the area (United Kingdom Hydrographic Office (UKHO), 1988) although the irregular shape of the contour lines suggests a weakness in the data or contouring method. The wire-frame models (Figs. 7.13 – 7.16) show the main channels in the estuary and illustrate the shallows around 'Old Mill Creek' (~287500 E, 52500 N). The plots also give a visual indication of the steepness of the estuary banks particularly near Kingswear (~288200 E, 51000 N) and towards the mouth and towards the Anchor Stone (~288200 E, 54500 N). All of the contour plots show some signs of irregularity with the contours at the banks of the estuary being represented as very angular. These features are a function of the contouring method and the method used to delineate the shape of the estuary. Some irregular features are also the result of gaps in the data record with interpolation occurring across these regions.

The surface plots (Figs. 7.17 – 7.20) provide a simple illustration of the large variation in depth throughout the estuary. Figure 7.17 illustrates that the majority of the estuary has a water depth of less than 10 m with areas by the main towns of Dartmouth and Kingswear (50400 N to 51600 N) and the region of the Anchor stone having deeper channels of down to 24 metres. The extent of the bank slopes can be seen in Figure 7.18 along with the sudden reduction in water depth at 51600 N, just north of Kingswear. The middle section of the estuary (as illustrated in Fig. 7.19) has a range of depths of 2 m to 15 m with a visible central channel. Once again the steep banks can be seen in the top section of the estuary (Fig. 7.20) where depths range from 2 m to 22 m. The central channel has a depth of approximately 12 m to 18 m and is flanked by regions predominantly less than 6 m on each bank.



Plot Details:

50300 - 54800 N
286600 - 289100 E

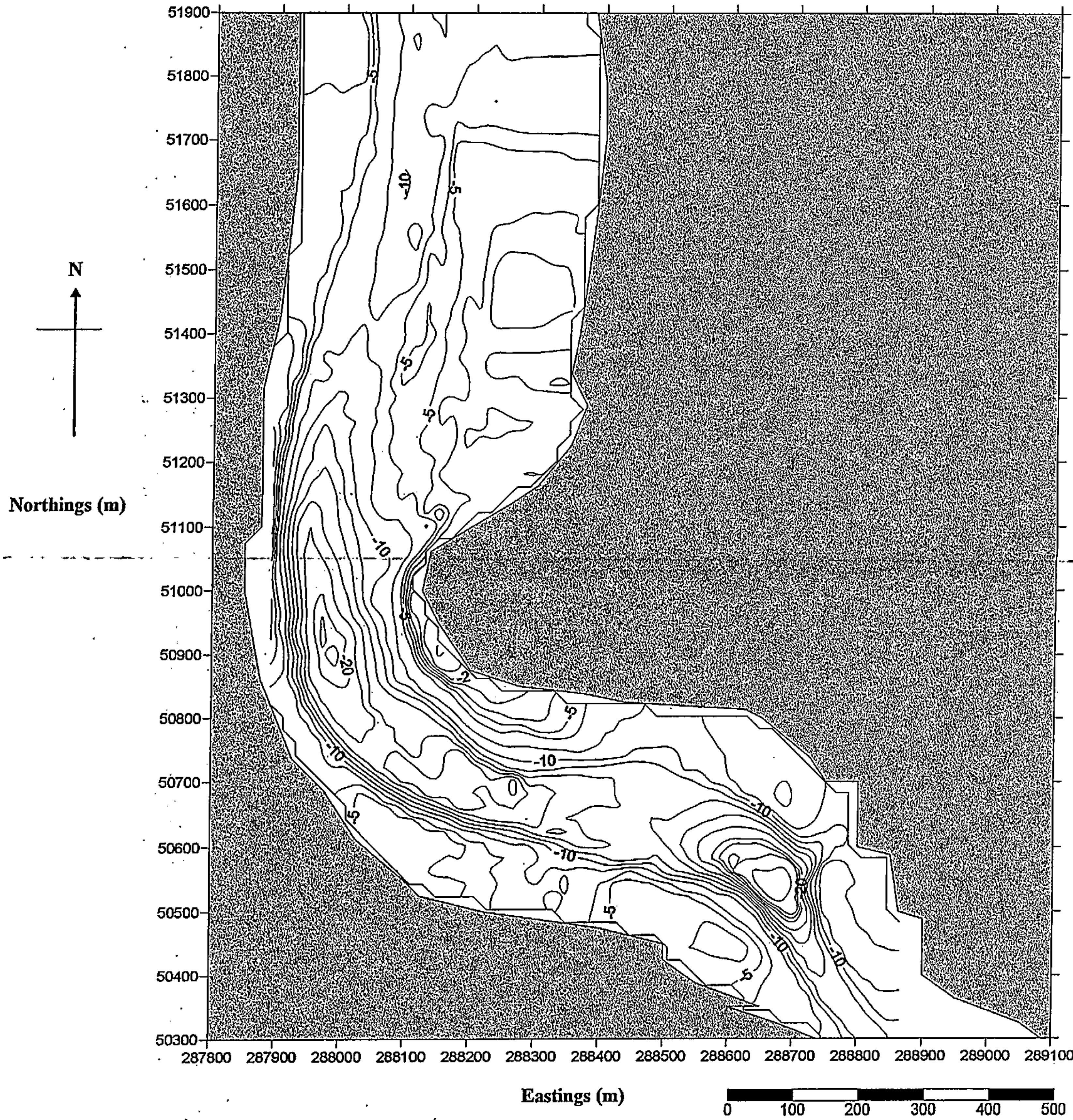
Grid Intervals: 200m

OSGB National Grid 1936.

Scale 1:15,000

Dart Estuary, UK, Contour Plot

Figure 7 9 Dart estuary contour plot



Scale 1:6500

Plot Details:

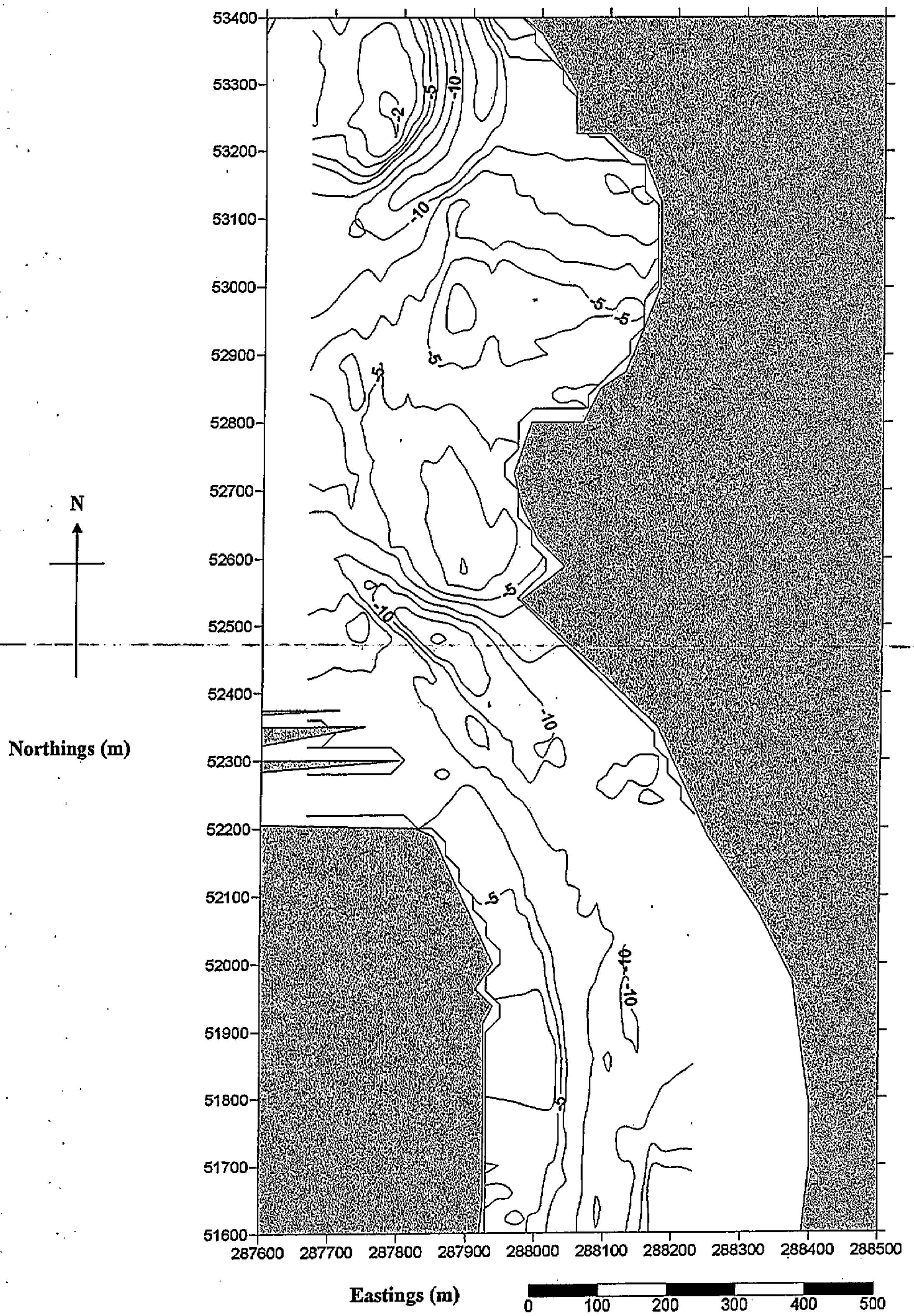
50300 - 51900 N
287800 - 289100 E

Grid Intervals: 100m

OSGB National Grid 1936.

Site 1 Dart Estuary, UK, Contour Plot

Figure 7 10· Site 1 Dart estuary contour plot



Scale 1:6500

Plot Details:

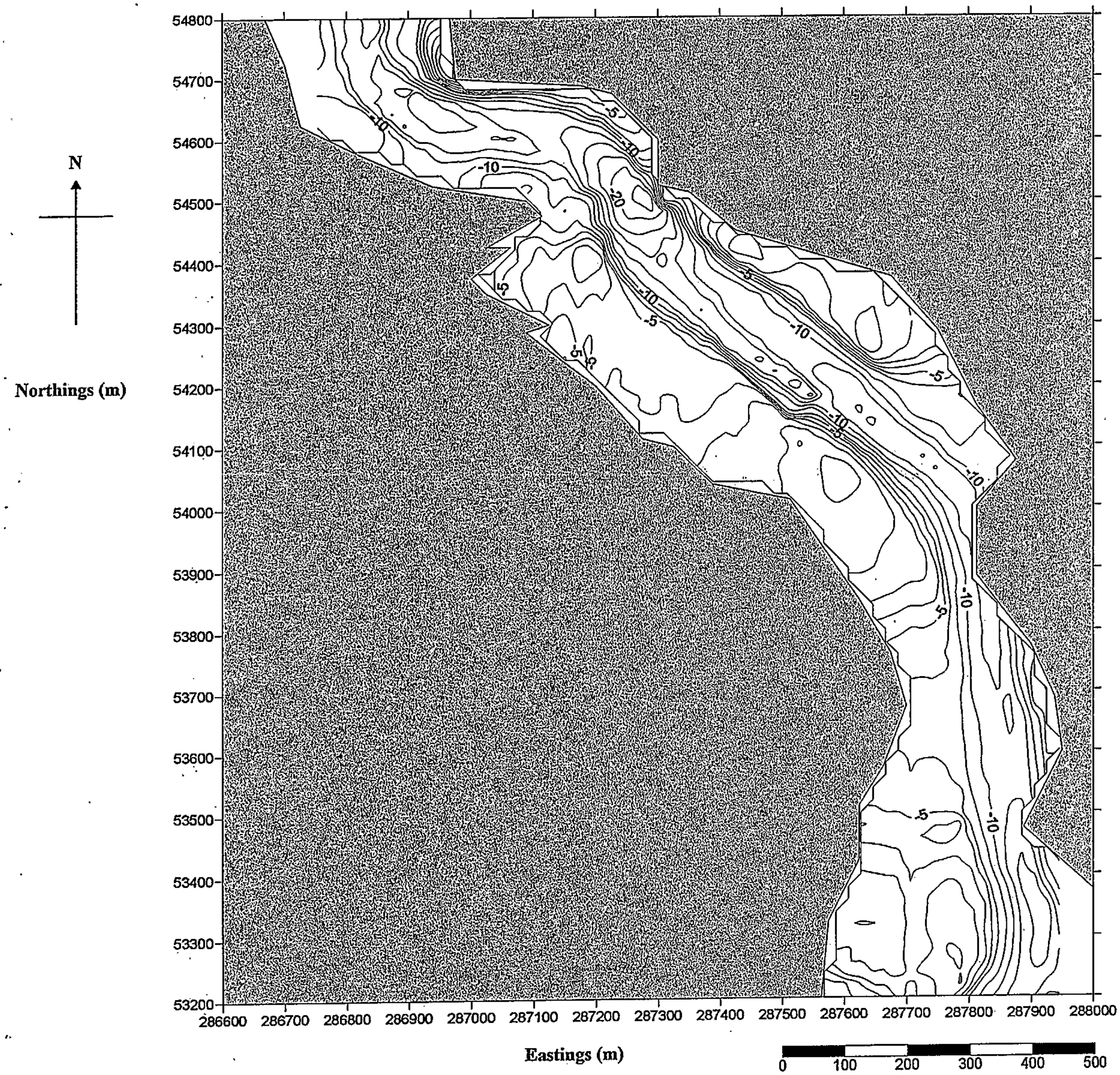
51600 - 53400 N
287600 - 288500 E

Grid Intervals: 100m

OSGB National Grid 1936.

Site 2 Dart Estuary, UK, Contour Plot

Figure 7 11 Site 2 Dart estuary contour plot



Scale 1:6500

Plot Details:

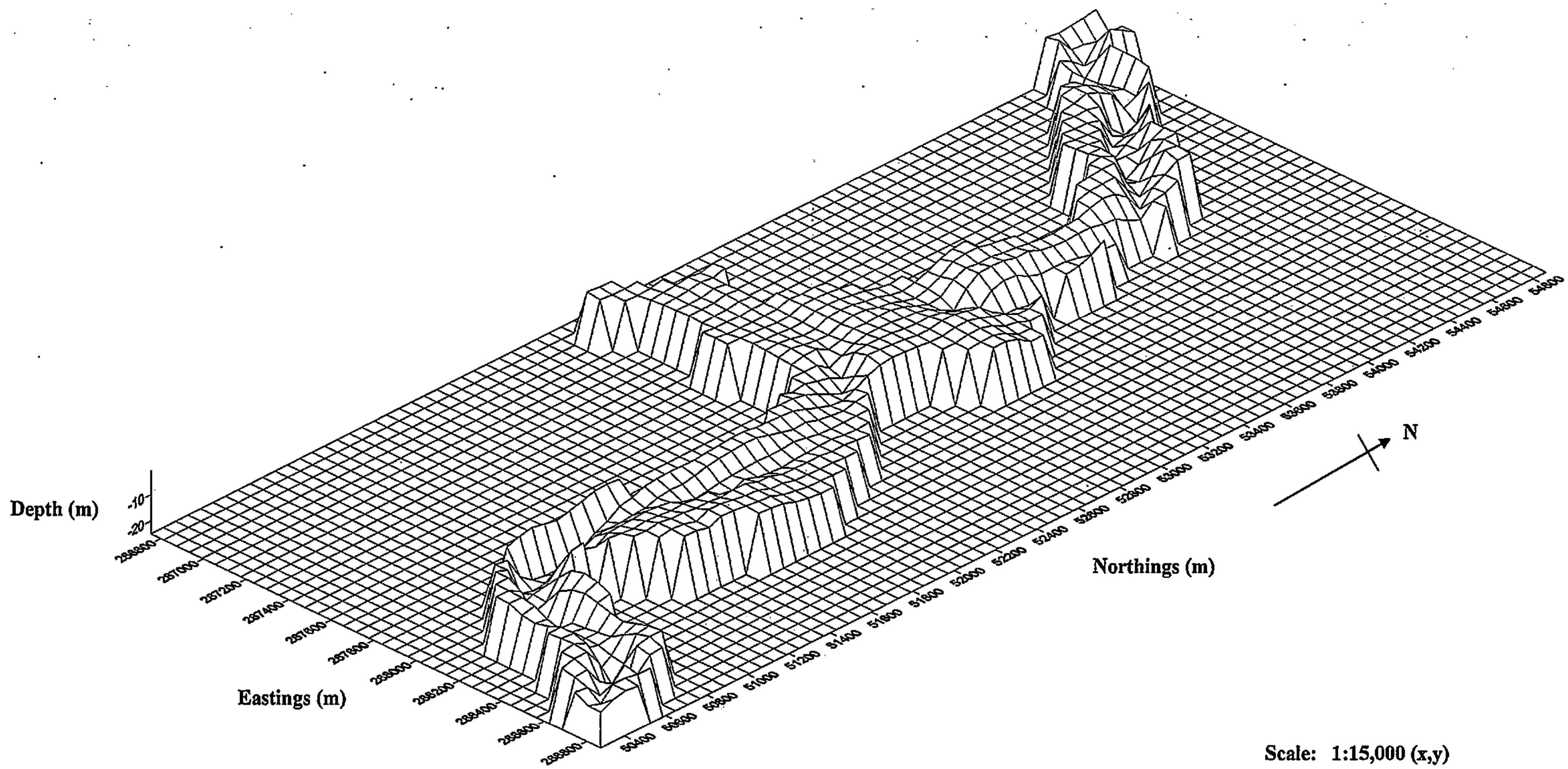
53200 - 54800 N
286600 - 288000 E

Grid Intervals: 100m

OSGB National Grid 1936.

Site 3, Dart Estuary, UK, Contour Plot

Figure 7 12 Site 3 Dart estuary contour plot



Scale: 1:15,000 (x,y)
1:1500 (z)

Plot Details:

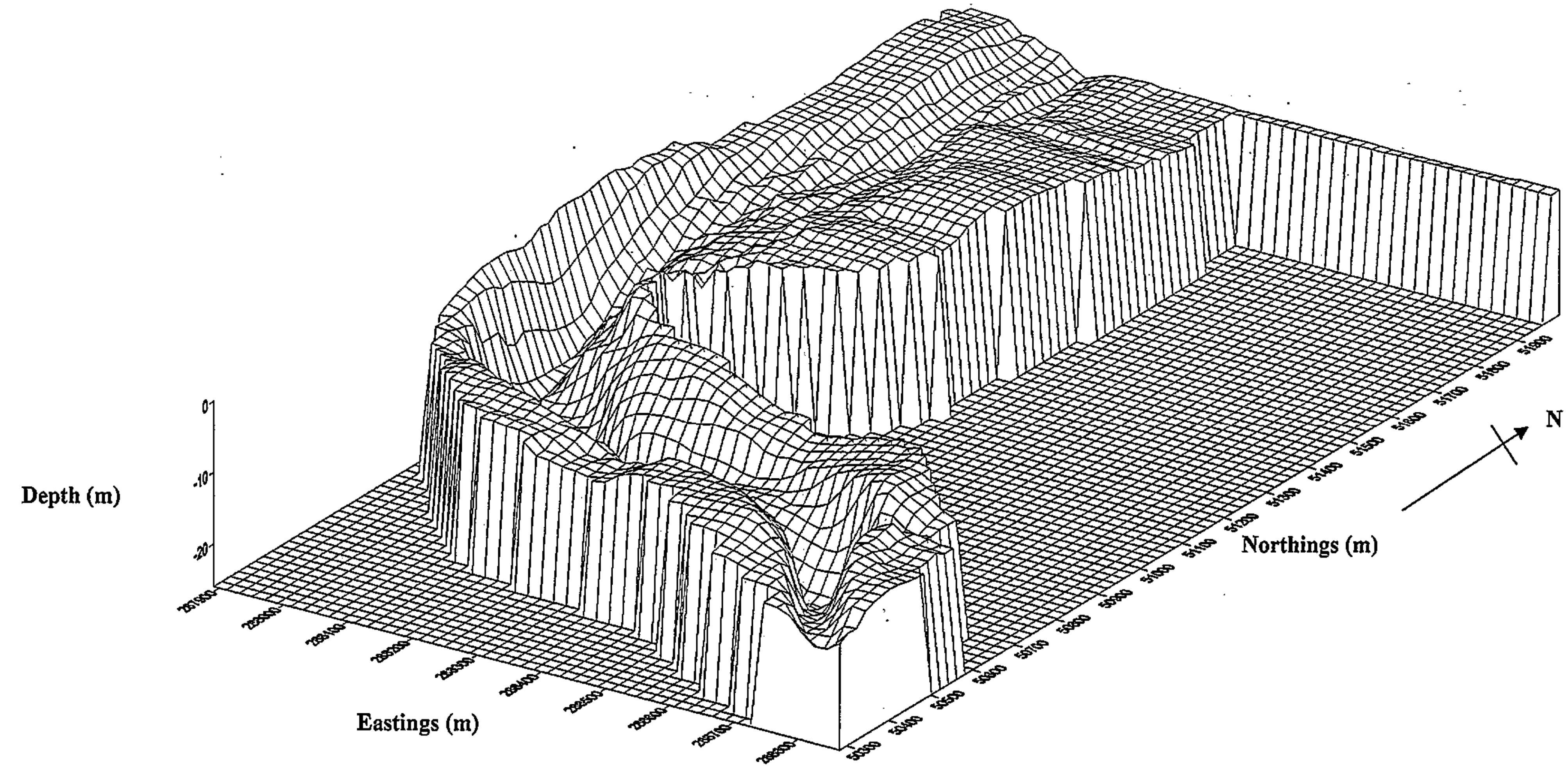
50400 - 54800 N
286800 - 288800 E

Grid Intervals: 200 m

OSGB National Grid 1936

Dart Estuary, UK, Wire-frame Plot

Figure 7 13 Dart estuary wire-frame plot



Scale: 1:10,000 (x,y)
1:1000 (z)

Plot Details:

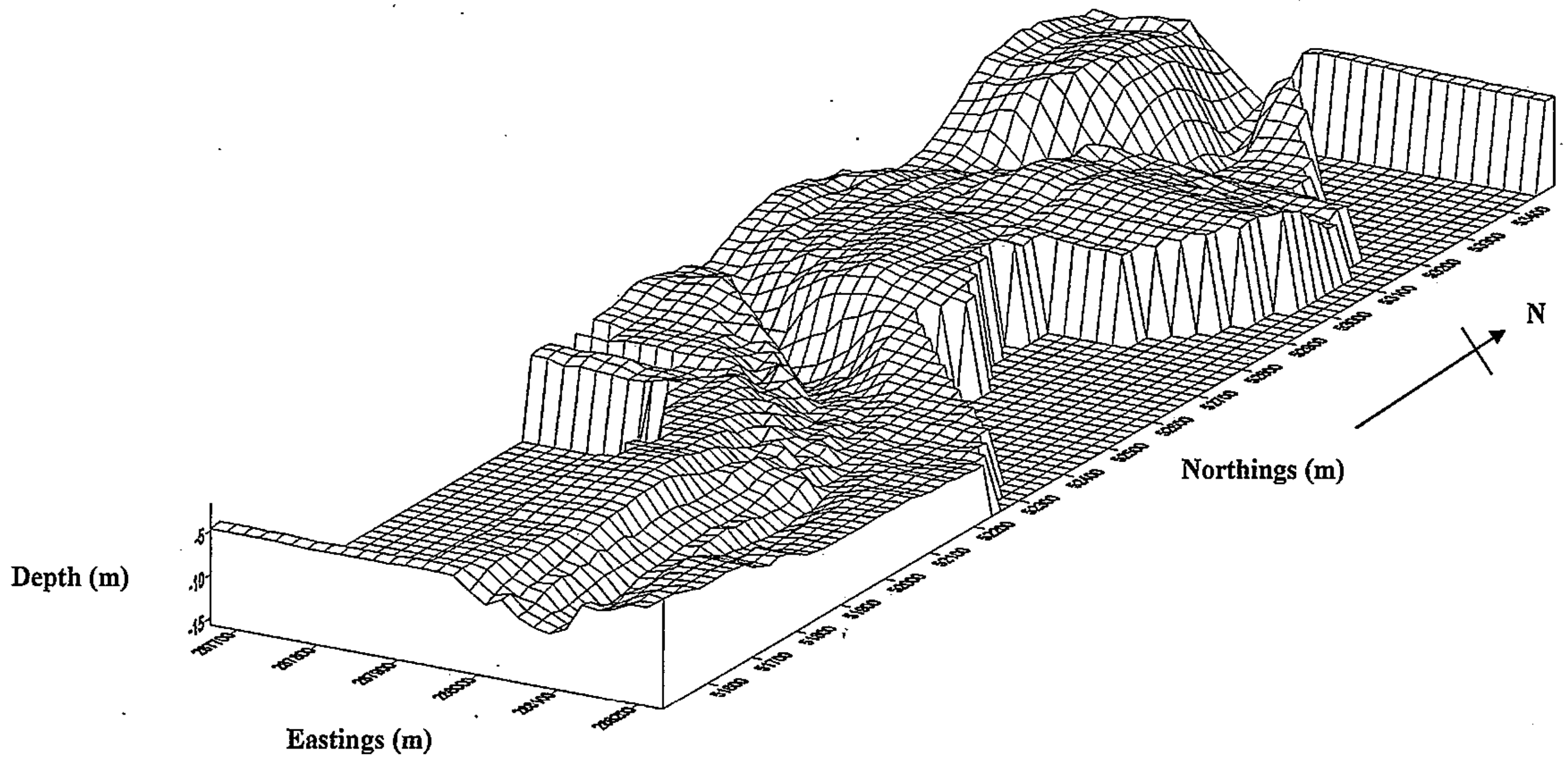
50300 - 51900 N
287900 - 288800 E

Grid Intervals: 100 m

OSGB National Grid 1936

Site 1 Dart Estuary, UK, Wire-frame Plot

Figure 7.14 Site 1 Dart estuary wire-frame plot



Scale: 1:10,000 (x,y)
1:1000 (z)

Plot Details:

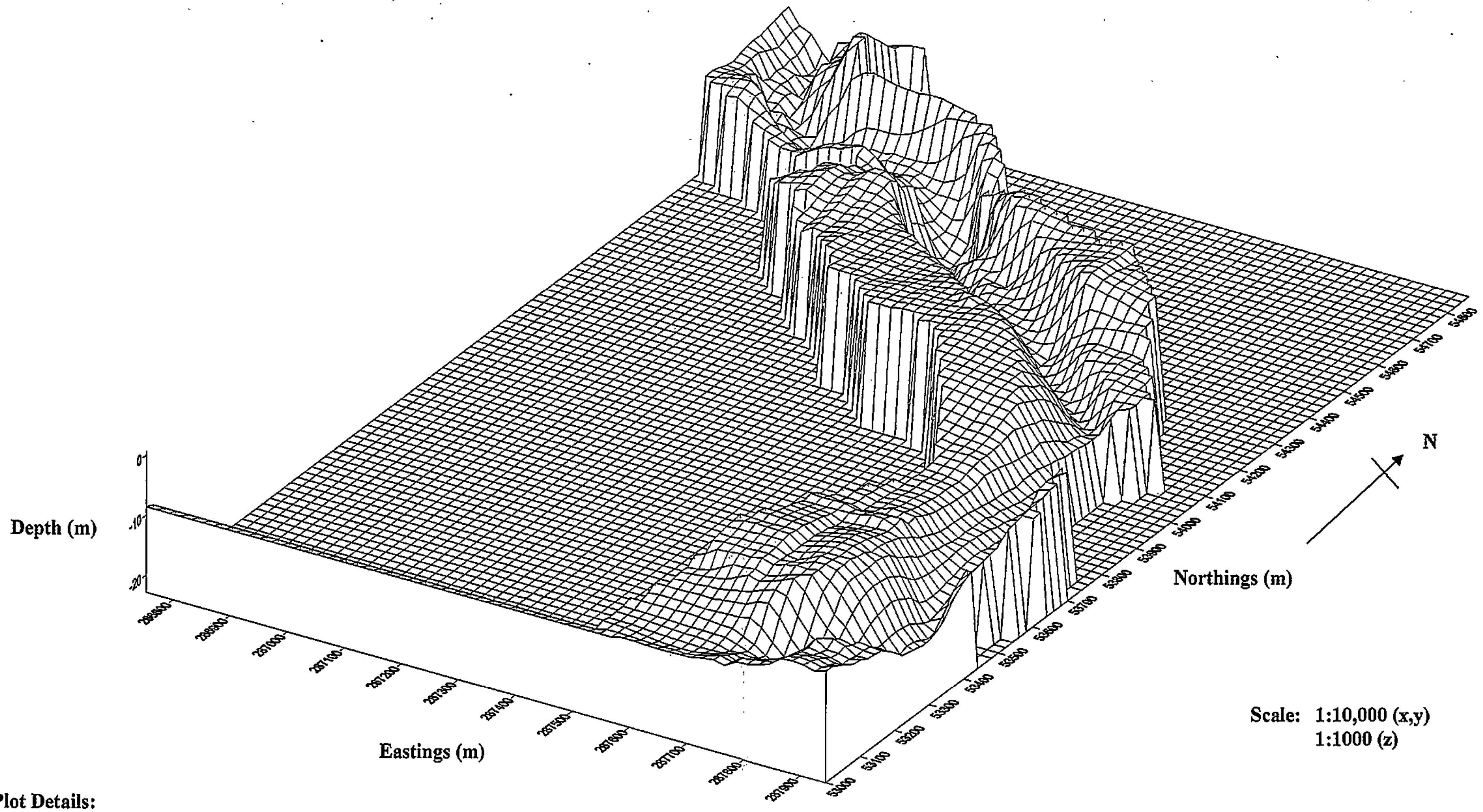
51600 - 53400 N
287700 - 288200 E

Grid Intervals: 100 m

OSGB National Grid 1936

Site 2 Dart Estuary, UK, Wire-frame Plot

Figure 7.15 Site 2 Dart estuary wire-frame plot



Scale: 1:10,000 (x,y)
1:1000 (z)

Plot Details:

53000 - 54800 N
286800 - 287900 E

Grid Intervals: 100 m

OSGB National Grid 1936

Site 3 Dart Estuary, UK, Wire-frame Plot

Figure 7.16 Site 3 Dart estuary wire-frame plot

The side scan sonar was not processed by the Hydrographic Diploma Group, (2000) due to problems with position stamping. The images show evidence of anchor scarring and the presence of the navigation mark weights along with variations in the bed forms but due to the lack of positional data no reliable information can be gleaned from these records.

The sub-bottom boomer data acquired during the survey was analysed by Philpott, (2000) and were found to show evidence of the buried channels described by Codrington, (1898) and Durrance, (1974).

> *"The presence of a buried channel of the Dart extending to a depth of –24 +1.9 m at Maypool is evident from the results of the seismic survey. The greatest depth recorded of the buried channel (-28.6 m) compares reasonably well with the borehole investigations (-33.5 m) recorded at Maypool by (Codrington, 1898)."* (Philpott, 2000)

7.2.4.6. Land surveys

A study undertaken by Paine, (2001) into landslide susceptibility in the area gives some indication of the current state of the terrestrial environment. Aerial photographs and LIDAR (airborne Light Detection and Ranging) data were utilised in conjunction with bedrock geology data to determine landslide data including Landslide Area Factors and Landslide Susceptibility Indices based on the methodology used by Cross, (1998). An example of the range of instability features located at Dartmouth is shown in Table 7.4.

No.	Grid ref.	Type
1	865 481	Crumbling cliffs
2	868 484	Zone of falling rocks
3	869 484	Crumbling cliffs
4	870 485	Zone of falling rocks
5	871 485	Zone of falling rocks
6	873 485	Old apparently stable scree/stabilised landslide scars
7	875 485	Stabilised landslide scars
8	878 485	Zone of falling rocks/rock slide
9	881 487	Crumbling cliffs
10	881 488	Crumbling cliffs/old apparently stable scree
11	881 489	Crumbling cliffs
12	884 492	Zone of falling rocks
13	884 494	Old apparently stable scree/stabilised landslide scars
14	886 498	Zone of falling rocks

Table 7.4: Zones of instability at Dartmouth – grid refs in OSGB National grid (Paine, 2001)

The table shows areas of instability in 14 zones with a range of different structural conditions including past landslides and present rock crumbling. This research illustrates the dynamic environment of the Dartmouth estuary that is constantly reshaping.

7.3. Dartmouth Marine Engineering Survey GIS

Pipeline landings, sewage outfalls, land reclamation, coastal engineering construction and hydrographic charting are just some of the examples of the requirements for nearshore surveys. The techniques employed for acquiring survey data in the nearshore zone are hindered by many difficulties inherent to the location such as water depth, tidal activity, vessel movement and obstructions, e.g. pontoons, mooring buoys. Finding solutions to these problems should be undertaken as part of the pre-survey planning stage to avoid costly delays later. By creating a GIS version of the standard pre-survey desk study before survey work begins, users would be able to ensure that all site conditions and restrictions have been investigated. The research undertaken as part of this study into the role of the ROV within integrated geotechnical and hydrographic site investigation has led to the development of such a nearshore survey GIS. In the same way that the equipment has been integrated to operate from an ROV, it makes sense to try to integrate the survey data acquired. It is apparent that GIS offer a solution to a great many storage and analysis problems, not least of which is diverse subject integration. Providing that the contractor is controlling both the hydrographic and geotechnical data acquisition, it would seem favourable to combine the data to encourage cross-discipline analysis. However, these systems would need to be modified in order to satisfy the demands of a nearshore / inter-tidal survey. The GIS developed for this research is a case study of the Dart estuary, (Devon, UK) presented in a form which should assist the engineer, surveyor or harbour authority to manage nearshore activities. ArcInfo 8.0 (ESRI) was chosen as the GIS software, so that an investigation could also be made into the ability of 'off-the-shelf' GIS to manage nearshore marine data.

7.3.1. Construction of the GIS

The GIS was constructed during a two month time period in order to assess the ease with which data could be incorporated into this type of data management system. The aim of this research was not only to assess the functionality of GIS but more importantly to determine the skills and software packages required and data format / volume issues associated with the process. The usefulness of GIS can only be appreciated or investigated once an operational system has been established. The functionality of GIS is already known and the applicability of the analysis capabilities to the marine environment have been discussed in chapter two. The key to the use of GIS in the nearshore zone is therefore the ease with which a user could construct a system from scratch using only an off-the-shelf GIS package.

ArcInfo 8 consists of three main components: ArcMap, ArcCatalog and ArcToolbox. ArcMap is the front end part of the system where data can be added to a base map in the form of layers. In this part of the GIS the display characteristics of the layers can be altered and spatial analyses can be performed. ArcCatalog is the system used for controlling a GIS project and is similar to the Windows Explorer format. All files and datasets connected to the GIS are controlled through this program, the GIS formats of the data are displayed here and the coverages of data can be viewed here. The ArcToolbox program is used to perform data manipulation, enabling data to be input to the GIS or output to other software.

The construction of the GIS starts with the creation of a new GIS project in ArcCatalog. Within this project workspaces can be created into which raw data are added, this system is similar to the use of folders in Windows Explorer. Once the raw data are in each of the relevant workspaces, ArcToolbox can be used to create GIS format data. For example, if data in an ASCII file (.txt) were to be added to the GIS as a point coverage, the following steps would be taken. First the file would be changed to a 'generate' file by changing the txt extension to a. gen extension. The ArcToolbox 'generate to coverage wizard' would then be used to create a point coverage from the gen file. The co-ordinate system for the coverage can then be set and the data can be viewed in ArcCatalog. The coverage file will appear in the specified workspace marked by a coverage icon. If however the workspace is viewed in Windows Explorer, this coverage file will not be shown as a single file but as a number of individual components. For this reason it is imperative that all work is carried out with the use of the ArcCatalog thus limiting the potential of deleting crucial files. Once the coverage has been created, ArcMap can be launched and the coverage can be viewed in conjunction with other data.

7.3.1.1. Background data

Base map data were taken from the Edina Digimap website (EDINA, 2002), where Ordnance Survey (OS) data is available in a digital format for a variety of their products. Due to the scale of the survey area, the most appropriate OS data was provided by the Land-Line Plus series of 1:2500 data (tiles sx 8654-8656, 8750--8756, 8849-8853, 8950). Using the U.K. National grid as the base co-ordinate system allowed for the correlation of land data with marine data, which can be acquired with reference to any co-ordinate system. The Land-Line Plus data set provides detailed mapping for the region, with full delineation of jetties and routes for the local ferries. The Land-Line Plus data sets were downloaded from the Digimap website as zip files and were extracted directly into the appropriate workspace using the 'Map Manager' extraction program to covert the map files to coverages.

The level of congestion in the Dart estuary is high due to numerous pleasure and commercial craft and the addition of over 100 navigation markers located within the 7 km stretch between the Range and Flat Owers (United Kingdom Hydrographic Office (UKHO), 1988). A large percentage of these markers are linked anchorage buoys and were input to the GIS to illustrate the congestion and survey line planning problems the estuary poses. The locations of the navigation marks were determined through the digitisation of Admiralty Chart No. 2253 (1:6250) (United Kingdom Hydrographic Office (UKHO), 1988). At this scale 1 mm on the chart represents 6.25 m on the ground and thus there may be errors of up to $\pm$ 6.25 m in the navigation mark positions as a result of the digitisation process. Once the position data were digitised they were converted from geodetic co-ordinates to UK Ordnance Survey 1936

National Grid co-ordinates using conversion software. These data were then formatted such that the file consisted of a point identification number (point ID), an x co-ordinate and a y co-ordinate. These data had to be stored as comma delimited files to adhere to ArcInfo formatting. This ASCII text file was then converted to a generate (.gen) file and was imported to the GIS using the 'generate to coverage wizard' in ArcToolBox. Once the co-ordinate system has been defined in ArcCatalog, the data could be opened in ArcMap in conjunction with the Land-Line Plus data. Tidal diamonds were also imported as point coverages to give an indication as to the distribution of tidal data within the estuary. A simple illustration of the use of GIS in the nearshore environment is given in Figure 7.21 where navigation marks (blue) are supplemented by tidal stream diamonds (purple).

Figure 7.21 shows the high concentration of navigation marks in and around Dartmouth and Kingswear localities. ArcInfo allows further information about a point to be obtained through the use of attribute tables. In this instance tidal diamond data as displayed on the Admiralty chart were input to the GIS to be displayed in a point attribute table (PAT). Once the diamond point coverage had been generated a second table was created using ArcToolbox. This new table was given an identifier of the same name and potential value as in the original coverage table i.e. diamond ID. The table was then designed to have columns that would contain the tidal information for each of the diamonds including rate and direction at each period 6 hours before and 6 after hours high water. Once the table had been created, the corresponding data were imported, again from a comma delimited ASCII file with diamond ID, and data for each of the specified categories. This table was then merged with the original coverage table via the use of the common diamond ID feature to give one point attribute table. Interrogation of one of the diamonds in ArcMap brings up the appropriate point attribute table (PAT) containing the pertinent information. This PAT can be seen in Figure 7.21 the data from which may be used to perform spatial analyses. The same process of inputting background data could be undertaken for the navigation marks thus allowing the user to determine the type of navigation mark.

7.3.1.2. Hydrographic data.

The multibeam data collected in 2000 by the University of Plymouth Postgraduate Diploma Hydrographic Survey group (2000), from Flat Owers to the mouth of the estuary provides high density x, y, z data (section 7.2.4.5.). These data were imported to the GIS through a similar process to that undertaken for the tidal diamonds. First a point coverage was generated using an ID value and x and y co-ordinates. Using the same identifier and the depth (z) values a new table was created and data input. The two tables were then joined so that each point when queried had a depth attribute value. This process was undertaken for five datasets; the standard reduced depth data and the depths experienced at mean high water springs & neaps (MHWS, MHWN) and mean low water springs & neaps (MLWS, MLWN) calculated from data supplied in the Admiralty chart (United Kingdom Hydrographic Office (UKHO), 1988). The display parameters in ArcMap were then defined such that the points were displayed in depth categories. Depth intervals and colours were defined and an example of the data can be seen in Figure 7.22.

The legend shows two metre depth intervals and the data are plotted in conjunction with navigation marks. The depth data range from 2 to 12 metres and the map gives a simple indication as to the variation of depth within the estuary. Figure 7.22 also shows the Land-Line Plus data and it can be seen that the multibeam bathymetry coverage stops at the edge of the pontoons. Although multibeam systems operate on a swathe mechanism which allows for data to be acquired some distance either side of the survey vessel, it is still not always possible to obtain 100% coverage of the survey area. In Dartmouth, the pontoons are heavily filled with private craft, which extend beyond the limits of the pontoon edge and survey vessels must maintain a separation from this offset to reduce the risk of damage to the moored vessels. The restricted access of the survey vessel is clearly displayed and the navigation marks give an indication as to the reason for this narrow band of survey data.

opportunities for the user to specify parameters. For example, smoothing is chosen on a level of one to ten with no explanation of the method used. This lack of user control is adequate when the desired output is a simple contour map however if the map were to be used for survey purposes a little more control would be essential. This shortcoming is essentially a reflection of the fact that off-the-shelf GIS are not designed to be used for hydrographic surveys. The user may choose to use conventional data analysis and mapping products to create maps and models and import these to the GIS at a later stage. However unless these data can subsequently be imported as vector data they will appear simply as images within the GIS and the user will not be able to use them for spatial analysis.

A limitation pertinent to the utilisation of GIS in the nearshore environment became apparent when using the GIS to display the field sites. As was shown in Figures 7.25 and 7.26 the issue of scale is important when surveying at very high resolution. The survey sites consisted of a grid of 9 data points but in Figure 7.26 the two Beach sites are displayed only as single points. Using the zoom control the user can alter the scale to show more detail, but as the site detail increases the site location map backdrop disappears (Figs. 7.28 and 7.29).

Although the absolute positions of the survey sites and data points can be ascertained with the use of the pointer and the position display in the bottom right of the screen, the sense of location has been lost. Although a scale of 1:150 would be unusual in standard hydrographic surveys detailed engineering investigations may on occasion necessitate such detail. This shortfall could be overcome when using paper maps by increasing the size of the paper thus including the surrounding area. However a computer screen can only display a limited area of information thus compounding the problem.

The final difficulty faced when inputting the field testing data was that of multi-dimensional input. At each testing site data were acquired from a range of sediment depths thus adding a third dimension to the data. When data are input they are given an identification unique number and this controls the PAT information. When a user selects a point in ArcMap the appropriate PAT is displayed. If only one depth value at the position is represented then this is an excellent means of viewing data. However a method for viewing multiple data points at one location was not found during the course of the timed study. The only known option is to create different layers for each depth thus allowing for the top layer to be removed and the bottom layer to be exposed. As only a limited number of data points were available this process was not undertaken.

7.3.3. Further opportunities

The GIS described above was constructed in a two month period using ArcInfo 8, an off-the-shelf GIS package. The majority of the time was dedicated to the input of the x, y, z multibeam data as the method required to input the data was not initially apparent. In addition a large proportion of the time was spent in determining the correct data input format and finding programs to achieve this. For example the requirement for the data to be comma delimited could only be achieved through the use of a text formatting program (TextPad) in which text files could be stored as comma delimited as opposed to the more common tab delimited format. This option may be available in other more common packages but was not present on the versions of software utilised by the author.

The GIS illustrates the ease with which data can be stored and manipulated and the advantages of data integration. More advanced spatial queries were not undertaken due to lack of time and this is an illustration of the time required to establish a GIS. To avoid GIS being used simply as a data storage tool it is apparent that a significant period of time must be dedicated to establishing the system. For this reason GIS cannot be used as a quick solution to data management issues. An example of the potential spatial analysis functionality of the Dart GIS can be given with reference to the *in situ* and lab data. For example, queries could be undertaken to show all areas with *in situ* shear strength less than 10 kPa and which are located within water depths of more than 10 m. To facilitate this type of spatial analysis a relatively high number of data points should be input to the GIS, otherwise a simple manual analysis may be more appropriate.

The addition of meteorological data, landslide data, vessel movements, and environmental data including fishing grounds and protected areas, would all increase the viability of the Dart GIS as a survey tool.

7.4. Summary

As a result of the presence of a diversity of geomorphological, hydrographic and geological features the Dart estuary is an interesting area for coastal site investigations. The presence of numerous mud flats in the region interspersed with coarser grained beach areas gives the opportunity for a wealth of investigations to be undertaken. Multibeam studies of the area have shown results consistent with the Admiralty chart data from the region and illustrate the complex bathymetry of the estuary. The steep slopes of the estuary banks combined with the tidal regime in the area combine to create testing conditions for traditional surface vessel surveys. In addition to these concerns, the estuary is a busy shipping area with many man made obstructions cluttering the way for vessel passage. Coastal and nearshore site investigations cannot rely solely on the use of surface vessels for survey. There is an inherent need to transcend the boundary between terrestrial and marine environments if the full picture is to be obtained. For these reasons the Dart estuary provides an interesting area in which to undertake a study specifically addressing issues of survey and site integration.

In the set time period a GIS was established which contained a base map, navigation and tidal stream data, depth data as derived from the multibeam surveys and information relating to *in situ* surveys described in chapter six. The GIS successfully illustrated the use of GIS as a solution to data storage, management and display and with further development could be used for spatial analyses. The difficulties encountered with regard to the input of data relate not only to marine data (x, y, z input) but also to the formats required (comma delimited ASCII). For these reasons it is the author's belief that when setting up a GIS using an off-the-shelf GIS, certain additional software packages should be made available. These include co-ordinate conversion programs and programs able to convert data to comma delimited format. Although the input of x, y, z data was initially time consuming the process is relatively straightforward and so further data could be added quickly and easily. Issues relating to the three-dimensional nature of marine data were not overcome in the set time period and would need to be further investigated.

This research has shown that GIS do offer solutions to many marine data storage and manipulation issues. The primary conclusion drawn from the timed exercise was the requirement for comprehensive training in the appropriate GIS package. Once the user has performed a task once it is easy to repeat but finding the right method in the first place can be time consuming and might lead to the conclusion that GIS cannot be used for the more basic nearshore surveys.

Chapter 8

Discussion and summary

8.1. Discussion

The implementation of new survey techniques or data management strategies into a specific environment requires a comprehensive understanding of the equipment requirements and the site specific restrictions. The aim of this research was to investigate the feasibility of acquiring geotechnical and hydrographic survey data from an ROV and within the constraints imposed by the nearshore zone.

8.1.1. Marine survey techniques

A vast range of investigation techniques are employed in the offshore survey environment to acquire data pertaining to the surface bathymetry and morphology and the sub-seabed sediment characteristics. Survey in the nearshore or coastal zone however presents problems not met in deeper open waters and translation of the current survey techniques is not always straightforward. Restricted access, manoeuvrability, traffic movement and the physical impact of waves and tidal activity define the nearshore environment addressed in this study and are the obstacles to survey. Although a comprehensive range of survey and testing techniques may be operated in nearshore surveys, some are less adaptable than others. Cone penetration testing and sediment coring are fundamental to geotechnical site investigation and at present the devices are cumbersome and require large stationary surface vessels for deployment. Sub-bottom profiling using seismic methods may be adapted to meet the restrictions of manoeuvrability but information cannot easily be collected within restricted access areas.

An alternative to surface based survey techniques is the utilisation of ROVs which offer the manoeuvrability to penetrate previously inaccessible regions. Unlike large surface vessels the ROV may survey beneath fixed or floating obstructions and may be fitted with a range of equipment at any one time. As a safer alternative to divers, and a more adaptable alternative to AUVs, ROV based survey is currently an undervalued solution to many nearshore survey issues. The possibility of creating an integrated ROV survey system should therefore be considered with particular reference to cone penetration testing, sediment coring and sub-bottom profiling.

If an integrated equipment approach to nearshore surveys is considered a solution then a similar approach to data management may also be a possibility. GIS are rapidly becoming the most accepted form of data integration when dealing with a wide range of data controlled by a spatial element. GIS pertaining to terrestrial data have, for a long time, dominated the market with the inherent difficulties associated with marine data impeding development of equivalent marine systems. The adaptation of off-the-shelf systems, by researchers and industry alike, to cope with marine data concerns including data volume and three or four dimensionality has promoted GIS usage. Although many marine data cannot yet be analysed in GIS there is an acceptance that the use of specialist packages remains necessary and probably desirable so as not to reduce current analysis accuracy and reliability. The move towards totally digital data acquisition and processing will inevitability lead to a growth in systems such as GIS. Even if not used as an analysis tool GIS offer the user an excellent facility for data storage, integration and archive.

8.1.2. Proposed ROV

Given the manoeuvrability restrictions inherent to the nearshore zone the ROV would need to be small enough to gain access to restricted spaces but large enough to carry and operate equipment independently. The Phantom XTL is a small and highly manoeuvrable ROV that is most often used as an investigation tool with limited scope for equipment operation due to the low payload capacity. The Phantom has a video camera and positioning system, which allows the user on the surface to pinpoint its location and to view in 'real-time' the activities on the seabed or within the water column. These very basic properties offer the user a great deal of potential when developing an equipment platform. The ability to accurately pinpoint the equipment is invaluable with many current systems relying on layback calculations from a surface vessel. Not only can the equipment be positioned when *in situ* but it can also be deliberately placed at a specific test site. Large surface deployed landing frames are lowered to position at the approximate location but cannot adjust position when on the seabed. The added benefit of monitoring the equipment activity allows the surface operator to ensure that all systems are running smoothly, aiding quality control. Furthermore the 'real-time' link to the surface offers the operator the opportunity to hand-pick test locations with the ROV acting as a reconnaissance tool.

The development of the Phantom as a base for geotechnical and hydrographic investigations in the nearshore zone was limited by one fundamental property: weight. The Phantom is designed to be neutrally buoyant thus allowing for flexibility in movement. Geotechnical investigations require a stable platform for testing and so require significant down force. With a low weight and limited thruster capabilities the Phantom was not powerful enough to carry or operate the equipment being developed. Furthermore the limited thrust capacity limits manoeuvrability in the potentially tidally active and wave dominated nearshore zone. For these reasons a proposed ROV is described; one which would meet the requirements of stability whilst retaining the manoeuvrability and size of the Phantom.

A simple bottom crawling tracked ROV is proposed as a solution; a system that may be deployed from the shore or from a surface vessel and can survey the seafloor whilst remaining stable enough to perform *in situ* testing. A system measuring 1m in length by 0.6 m in width with two 0.2 m wide tracks is suggested as the base, a size which corresponds well with the Phantom. The ROV needs to be heavy enough to withstand marine forces and maintain position but must cause limited sediment consolidation. Loading calculations showed an ROV with a weight of 250 kgf and the above dimensions to exert a pressure of 6.1 kPa. The pressure exerted between the tracks is also important when considering the possibility of mounting equipment within the safety of the crash frame. Strip loading calculations showed the 250 kgf ROV to exert a maximum centre line pressure of 1.7 kPa at a depth of 0.5 m.

Equipment deployment and retrieval is a key issue when surveying nearshore due to the limited lifting capacity of small survey vessels. The proposed ROV benefits from the use of tracks, making it deployable from the beach with the addition of free weights an option once the vehicle is at the waterline. By mounting several pieces of equipment onto the ROV, an integrated survey tool is created that offers the opportunity to acquire multifarious data at one location. This is not only a time and cost saving arrangement but also ensures that a diversity of data can be used together to increase understanding of the location.

8.1.3. Cone penetration testing

The ability to acquire *in situ* strength data is invaluable in the geotechnical industry. Removal of sediment through coring for subsequent laboratory testing imposes disturbance and alters the sediment matrix and strength characteristics. Cone penetration testing (CPT) is commonplace in terrestrial and offshore marine surveys and can be undertaken in the nearshore zone with the use of jack-up rigs or landing frames. The access of large vessels to sites in the nearshore zone can however restrict testing locations to open channels, limiting the range of data acquired. In order to extend the range of CPT testing the possibility of using an ROV mounted system was researched.

Flow round systems, as developed by Stewart and Randolph (1991), offer the possibility of acquiring high-resolution *in situ* strength data in material of low undrained shear strength. The study focussed on the T-bar system and an ROV with a weight of 260 kgf and assessed the possibility of acquiring strength data. It was found that a T-bar system measuring 6 cm in length and 0.9 cm in diameter with a shaft diameter of 0.8 cm would require a base weight of 175 kgf for penetration that increases to 260 kgf with a 50 % stability component. If a 1.6 kN load cell were used a resolution of 0.73 kPa could be achievable when testing in sediment up to 300 kPa undrained shear strength.

Measurements in sediment of higher shear strength could be undertaken using a 1 cm^2 mini cone. With a 260 kgf ROV the mini cone could acquire strength data in sediments with undrained shear strengths of up to 1215 kPa. Although this adaptation allows the system to be used in a wide range of sediments the potential error range for a test undertaken in material with an undrained shear strength of 1215 kPa is 850 kPa ($\pm$ 425 kPa).

8.1.4. Sediment coring

The problems associated with *in situ* testing such as the ability to acquire data to a high enough resolution, given the local conditions, can lead to the requirement for additional laboratory based investigations. Even without the requirement for comparison with *in situ* data, laboratory analyses allow for comprehensive ground truthing of data acquired remotely including side scan sonar and sub-bottom profiler data. Sediment samples may either be collected in an obviously disturbed state through techniques such as grab sampling or through more contained methods including piston and vibro coring. Index properties of sediments are those, which do not rely on the maintenance of the sediment matrix but are intrinsic to the particles. These form the basis of many laboratory investigations from particle size analysis to organic matter content. The sediment shear strength is an example of a structural property and is altered by sediment disturbance during sampling and subsequent handling and testing. If sediment coring is to be undertaken for lab testing, it is important not only that the mechanism acquires sufficient sediment but that it is designed to impose the minimum disturbance possible. A sediment corer was designed which would allow samples to be collected from the proposed ROV in areas previously inaccessible using current sampling techniques.

The final sediment corer utilised a pneumatic mechanism to drive a core tube into the sediment and also to enable retrieval of the tube. By using the core tube as the piston, the system was designed to be 0.9 m in height allowing acquisition of samples up to 0.6 m in length. Marine grade stainless steel (316L) core tubes of 38 mm internal diameter were utilised to ensure that samples could be used for triaxial testing. A wall thickness of only 1 mm limited sample disturbance caused by friction forces at the sides of the tube. Minimal down force was required to maintain ground contact and the system successfully acquired samples in sediment with an undrained shear strength of 17 kPa. Comparison with *in situ* shear strength testing and with an 'undisturbed' coring system showed the pneumatic mechanism to inflict negligible disturbance, with some variation in measured shear strength being attributable to changes in moisture content.

To ascertain an absolute value for the level of sediment disturbance caused by the pneumatic coring mechanism, further investigations should be undertaken with laboratory consolidated homogenous clay. The use of a regulated material would remove possible variations recorded in the field work which may be the result of sediment inhomogeneity. Direct shear vane testing of the sample could then be undertaken and the data compared with triaxial analyses.

8.1.5. Resistivity system

Traditional techniques for acquiring sub-bottom sediment information rely on acoustic systems that use either the reflection or refraction responses of the different acoustic interfaces to provide a profile. By miniaturising the transducer this technique can be operated by either a diver or an ROV to ascertain sub-bottom information in the top few metres. An investigation was undertaken to establish the feasibility of utilising resistivity techniques for acquiring sub-bottom information as an alternative to acoustic methods to allow for high-resolution data acquisition to support *in situ* CPT data and laboratory analyses of material from the sediment corer.

An eight array rig was developed which consisted of two linear Wenner arrays and six square arrays from two square probe arrangements. Laboratory testing showed the rig to be capable of distinguishing between coarse material (Gravel), a range of sand sizes (Playpit, Beach and Lizard) and two finer 'muds' (Silty sand and Sandy silt). Three groups were discernable, the Playit sand had the highest apparent resistivity (~ 200 ohm cm), the Beach sand, Lizard sand and Gravel all had similar values (~ 100 ohm cm) and the two mud samples formed the final group (~ 45 ohm cm). The close correlation of the distribution of data with index testing of particle size and sorting during the laboratory testing allowed for predictions to be made with regard to field data. Sediment samples were not acquired at the Upper Beach site but the resistivity data were used to predict the conditions. Comparisons with published data of apparent resistivities for a range of materials indicate the absolute values acquired during testing to be reliable. Variations observed during laboratory testing as a result of dissolved salts or minerals do not detract from this correlation.

Further development of the resistivity rig could include increasing depth of penetration by increasing the size of the array spacing or lengthening the probes. Variations in apparent resistivity resulting from tip corrosion or circuit errors should be corrected with a calibration system. This system could be a physical testing device or could be integrated into a digital circuit with the resistance of each array being zeroed before commencement of survey. Removable probe tips might also be considered as a solution to tip corrosion.

8.1.6. Dart estuary – A case study

A timed exercise was undertaken to ascertain the feasibility of using GIS (ArcInfo 8) as a data management and analysis tool for data acquired in the nearshore zone. The Dart estuary was chosen as the field site due to the diversity of features specific to the nearshore zone. Simple point data including navigation marks and tidal diamonds were input to the GIS and when combined with a 1:10,000 Land-Line Plus (EDINA, 2002) map provided a useful tool for visual assessment of congestion in the estuary and paths of restricted access. Multibeam sounding data acquired during boat surveys in conjunction with the Hydrographic Diploma Group (2000) University of Plymouth, were input to the GIS and could be viewed in point form as a method of quality assessment. Data acquired during testing at four sites in the Dart estuary (chapter six) were also input and hyperlinks were used as a simple display tool.

By imposing a time constraint on the development of the GIS a more realistic conclusion can be drawn with regard to the suitability of GIS for use in the nearshore zone. The GIS was found to lack functionality when importing data with lengthy alternatives required. When using the GIS to assess the data acquired at the four testing sites, the scale issue became apparent. As the testing grids were only 1 m^2 the coastal features and reference points were lost on high zoom.

When using the system for localised high-resolution surveys this could be a problem, limiting the visual assessment capabilities of the system.

This research has shown that GIS are an excellent solution for many data management and analysis functions but require adaptations when handling marine data. Establishing a GIS project from scratch is labour intensive and time consuming but once the data have been imported the flexibility of the system can prove invaluable.

8.2. Further work

There are many other investigation techniques that could be adapted to operate from an ROV and which would supplement the data acquired and add to the integrity of the results. For example *in situ* shear strength data can also be acquired with the use of a shear vane. By acquiring strength data with this system in addition to the CPT, a better understanding of the sediment conditions could be acquired as well as adding quality control to the procedure. There are however many simple shear vane systems and it would be relatively straightforward to waterproof the mechanism and add the unit to the ROV. Several other possibilities are described below.

8.2.1. Grab sampling

In areas where the sediment shear strength is high, the material has a large mean grain size or is non-cohesive and is unsuitable for coring a grab sampler may facilitate simple material collection. These samples may be used to acquire intrinsic sediment characteristics such as particle size and Atterberg limits where structural maintenance is not required. A simple grab mechanism operated by a manipulator arm or with the use of hydraulics or pneumatics could be developed and added to the ROV. The requirement for down force would be significantly lower

This type of system would only be able to provide information based on the survey lines followed by the ROV but would again supplement the information being gathered. Using a digital recorder the data could be logged almost continuously and providing the resolution of the pressure transducers and positioning system were high enough a profile of the site could be created. By measuring the angle of slope of the seabed supplementary information could be acquired, possibly leading to an improvement in seabed representation obtained through stand alone depth sounding.

8.3. Summary

The purpose of this research has been to investigate the role of the ROV within integrated geotechnical and hydrographic site investigation. This has been undertaken by determining the current nearshore site investigation equipment limitations and suggesting alternative equipment through extensive research and development. An additional investigation into the viability of GIS as a data management strategy has also been undertaken.

The seven main conclusions resulting from this research are:

1. Marine survey techniques have not been fully adapted for investigations in the nearshore zone.
2. Geographical Information Systems (GIS) provide a means of data management and manipulation and facilitate analyses but may require support from specialist packages when handling marine survey data.
3. Bottom crawling remotely operated vehicles (ROV) are excellent platforms from which *in situ* testing can be undertaken.
4. *In situ* undrained shear strength (sediments up to 300 k|Pa) could be measured through the use of a T-bar penetrometer mounted on a 260 kgf ROV.

5. The pneumatic piston coring mechanism facilitated acquisition of 400 mm long, 38 mm diameter sediment cores in material with undrained sear strengths of 17 kPa, and may be operated from an ROV weighing less than 70 kgf.
6. The resistivity rig facilitates sediment classification and allows differentiation between gravel, coarse to fine sand, and 'mud'.
7. The Dart Estuary is a typical nearshore environment and can be used to illustrate the particular difficulties of establishing a GIS in the inter-tidal zone.

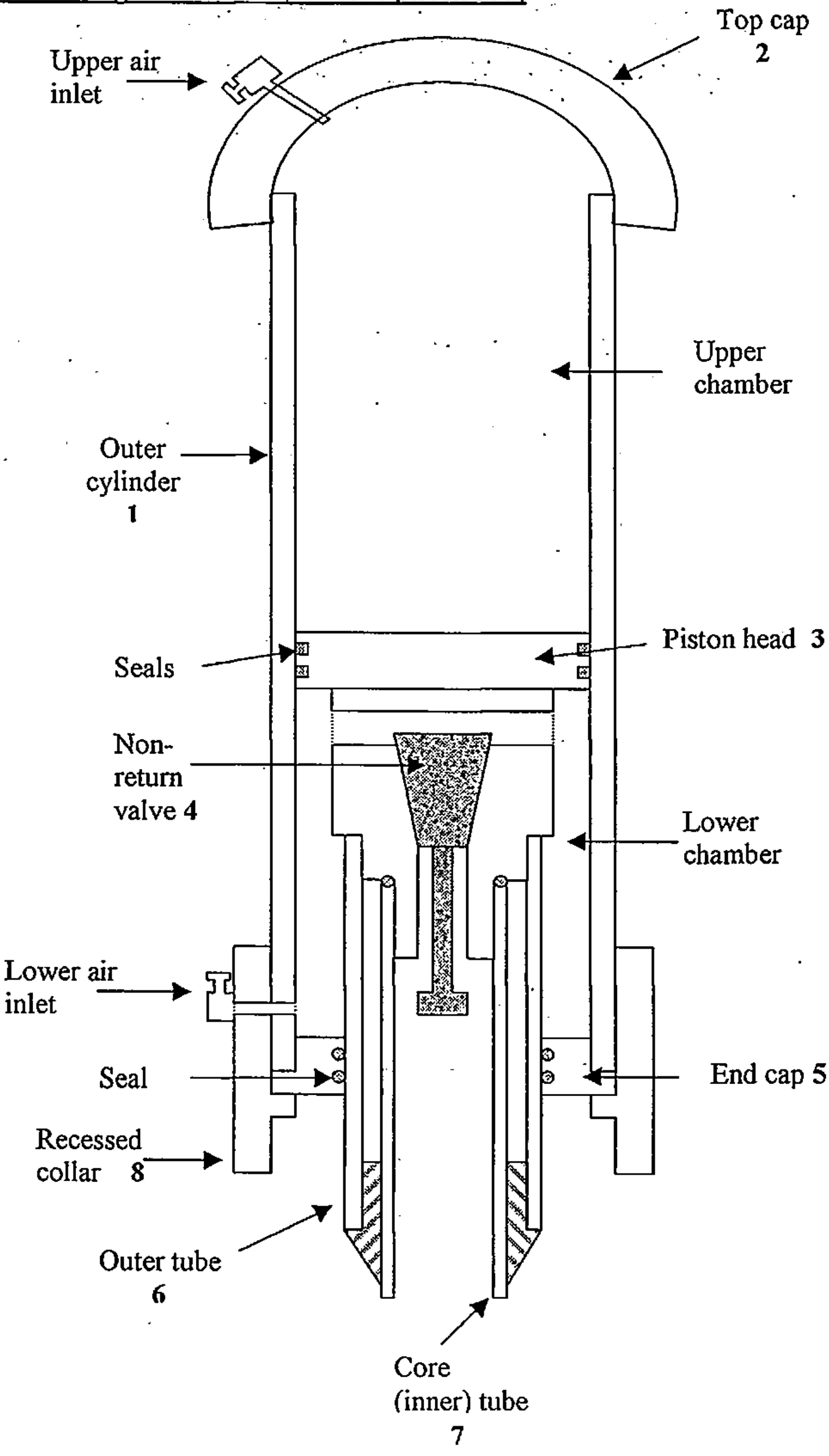
It is, therefore the author's opinion that remotely operated vehicles could potentially play a vital role in nearshore geotechnical and hydrographic investigations. The integration of equipment on a single testing platform can be further extended to include the integration of complex nearshore data in a geographical information system. The nearshore zone is a highly dynamic and challenging survey environment and warrants development of techniques specific to requirements.

Appendix A

Coring mechanism (without piston rod) component list

Atterberg limits

Figure 5.7: Coring mechanism (without piston rod)



Sediment corer – Component Details

1. Cylinder

   ABS (Acrylonitrice Butadiene Styrene) 102mm ID
   114mm OD
   750mm Length

2. Top Cap

   Standard ABS end cap for 4 inch tube 114mm ID
   140mm OD
   63mm Recess Depth

   Fitted with a self-sealing push fit air connection for 10mm OD nylon pneumatic tube.

3. Piston Head

   Fabricated locally from acrylic and fitted with "Walker Lionsele P" sealing rings. Boss, turned out of nylon, acts as a securing stub for inner and outer core tubes and holds the nylon + steel non return valve. The piston head and nylon boss are screwed together using A4 stainless steel machine screws.

4. Non Return Valve

   Manufactured of nylon + A4 (316L) stainless steel. Allows displaced water from the inner core tube to flow into the lower chamber during the core inserting process. Acts as a suction retaining device to prevent the core sample being lost during core retrieval and also prevents pressurised air in the lower chamber from blowing the core sample out during retrieval. Note: Airline to the lower chamber must be open to atmosphere during insertion.

5. End Cap

   Manufactured of ABS and bonded into the cylinder using ABS solvent cement. Fitted with 'O' ring seals.

6. Outer Tube

   Made of 316L grade stainless steel 51mm OD
   49mm ID
   706mm long

   Secured to nylon boss with stainless steel machine screws. The bottom open end is fitted with a nylon guide for central alignment of the inner tube and to prevent sediment from clogging the gap between inner and outer tubes.

7. Inner Tube

Made of 316L grade stainless steel — 41mm OD, 38mm ID, 770mm long

Fitted to the inner boss using a bayonet type connection, which engages on two SS, pins on the inner boss. A 'O' ring seal on the inner boss provides a downward force to keep the bayonet engaged. Another 'O' ring seal on the inner boss provides sealing. The outer end of the tube is chamfered to allow the core tube to cut into the sediment.

8. Recessed Collar

This collar is fitted to retain an extension guide.

Atterberg limits

The liquid limit represents the water content at which the material starts to behave as a plastic as opposed to a liquid. The plastic limits represents the point at which the plastic behaviour changes to brittle behaviour. The plasticity index shows the water content range over which the material behaves like a plastic and the liquid limit allows a comparison with the soil in its natural water content (Smith and Smith, 1998).

Liquid limit (ω_L) = ω at 20 mm penetration (cone test)

Plastic limit (ω_P) = ω when a 3 mm roll of the material falls apart

Plasticity index (I_P) = $\omega_L - \omega_P$

Liquidity index (I_L) = $\dfrac{\omega_f - \omega_P}{I_P}$

where ω_f = field moisture content

Appendix B

Linear rig laboratory testing

Advanced rig laboratory testing

Advanced rig resistance data - laboratory testing (multiple sediment layers)

Advanced rig resistance data - laboratory testing (object detection)

Advanced rig resistance data - field testing

Linear rig resistance data - laboratory testing

Resistance

Depth (cm)	Playpit sand	Lizard sand	Beach sand	Gravel	Mud 5	Mud 6
1	5.13	6.49	3.92	6.00	2.47	2.80
2	8.71	7.93	5.69	7.53	2.17	2.93
3	9.32	8.77	5.77	8.74	2.09	2.70
4	10.21	11.16	5.09	9.04	2.08	2.99
5	10.28	11.30	4.81	10.90	2.12	2.62
6	10.87	11.14	3.69	11.12	2.18	2.58
7	11.20	13.11	3.83	11.74	2.14	2.37
8	11.38	12.25	2.90	12.07	1.89	2.66
9	12.68	12.76	2.60	13.73	2.40	2.52
10	14.95	14.13	2.33	15.14	2.67	2.81
Water	2.63	2.90	2.55	3.29	1.83	2.15

Boundary resistance

Depth (cm)	Playpit sand	Lizard sand	Beach sand	Gravel	Mud 5	Mud 6
1	5.48	8.78	6.19	6.51	2.80	3.45
2	11.51	10.74	7.07	9.01	3.59	2.83
3	12.53	12.19	7.92	10.36	3.66	3.56
4	13.08	14.05	8.35	11.12	3.56	3.86
5	14.71	14.70	7.10	12.61	3.64	2.99
6	16.33	16.30	6.30	14.26	3.63	3.15
7	18.20	18.50	5.90	15.88	3.65	5.00
8	20.40	21.00	5.80	17.54	4.67	5.50
9	22.80	23.30	5.50	23.10	4.80	5.86
10	25.00	24.10	4.80	27.10	5.10	5.85
Water	3.70	3.39	3.52	3.71	2.16	2.62

Resistance after stirring

Depth (cm)	Playpit sand	Lizard sand	Beach sand	Gravel	Mud 5	Mud 6
1	6.28	4.32	4.66	5.47	2.08	2.14
2	7.37	7.29	4.51	8.52	2.19	2.91
3	8.62	8.44	5.53	7.94	2.19	2.47
4	9.22	8.96	4.57	8.71	1.88	2.67
5	9.36	9.76	5.70	9.27	3.00	2.86
6	10.77	10.64	4.41	9.65	3.14	2.89
7	10.26	10.33	4.16	9.54	2.38	3.41
8	11.08	13.53	2.25	10.92	2.59	2.95
9	12.37	12.71	3.20	12.19	2.75	3.76
10	14.92	13.39	3.40	14.47	4.71	3.93
Water	3.47	3.17	2.81	3.41	3.54	1.34

Advanced rig resistance data - laboratory testing

Playpit sand

Depth (cm)	W1	W2	S1A	S1B	S1G	S2A	S2B	S2G
1	7.53	8.08	6.89	7.17	-0.30	2.21	1.87	0.29
2	9.68	10.51	8.31	8.81	-0.36	2.63	2.31	0.19
3	10.85	11.77	8.86	9.31	-0.39	3.02	2.55	0.19
4	11.67	12.49	9.10	9.60	-0.26	3.34	2.88	0.19
5	12.20	13.03	9.36	9.48	-0.24	3.69	3.31	0.13
6	12.61	13.73	9.52	9.67	-0.36	4.00	3.64	0.34
7	13.00	14.33	10.05	9.74	-0.39	4.37	3.95	0.46
8	13.51	14.95	10.48	9.71	0.57	4.77	4.20	0.54
9	14.33	15.82	10.71	9.99	0.56	5.27	4.88	0.33
10	15.14	16.71	11.18	10.58	0.60	5.81	5.23	0.53
Water	3.71	3.75	1.89	1.91	0.06	1.90	1.93	0.49

Lizard sand

Depth (cm)	W1	W2	S1A	S1B	S1G	S2A	S2B	S2G
1	4.76	4.91	4.35	4.37	-0.31	1.31	1.26	0.18
2	5.67	5.69	5.03	5.32	-0.27	1.47	1.54	0.14
3	5.98	6.35	4.94	4.97	-0.37	1.65	1.72	0.11
4	6.01	6.38	4.60	4.69	-0.40	1.73	1.84	0.16
5	5.98	6.38	4.43	4.64	-0.43	1.80	1.73	0.08
6	5.90	6.31	4.35	4.52	-0.45	1.81	1.84	0.20
7	5.83	6.26	4.31	4.44	-0.41	1.86	1.86	0.06
8	5.77	6.31	4.31	4.27	-0.25	1.98	1.98	0.13
9	5.77	6.30	4.23	4.34	-0.87	2.08	1.95	0.06
10	6.05	6.44	4.19	4.69	-0.34	2.25	2.20	0.08
Water	3.07	3.08	1.76	1.77	-0.40	1.32	1.38	0.09

Beach sand

Depth (cm)	W1	W2	S1A	S1B	S1G	S2A	S2B	S2G
1	4.26	4.27	4.03	3.77	-0.30	1.26	1.29	0.13
2	5.17	5.40	4.54	4.30	-0.89	1.40	1.39	0.14
3	5.50	6.08	4.56	4.65	-0.57	1.57	1.50	0.08
4	5.83	6.40	4.53	4.71	-1.00	1.76	1.62	0.15
5	5.90	6.45	4.53	4.49	-0.84	1.95	1.69	0.28
6	5.97	6.34	4.62	4.39	-0.71	2.13	1.72	0.33
7	6.16	6.46	4.43	4.47	-1.19	2.23	1.89	0.28
8	6.17	6.60	4.44	4.61	-0.86	2.27	1.99	0.24
9	4.35	4.33	3.14	3.18	-0.14	1.40	1.48	0.12
10	4.45	4.52	3.23	3.19	-0.13	1.47	1.57	0.10
Water	2.75	2.73	1.63	1.67	-0.44	1.24	1.22	0.14

Gravel

Depth (cm)	W1	W2	S1A	S1B	S1G	S2A	S2B	S2G
1	4.09	4.44	3.29	3.86	-1.13	1.19	1.13	0.18
2	4.78	5.18	3.80	4.20	-0.88	1.25	1.32	0.11
3	5.15	5.54	3.86	4.34	-0.73	1.43	1.44	0.06
4	5.38	5.72	3.96	4.04	-0.64	1.56	1.60	0.17
5	5.48	5.93	3.68	4.14	-0.90	1.63	1.64	0.14
6	5.74	5.96	3.88	4.32	-0.69	1.74	1.80	0.05
7	5.81	6.16	4.06	4.39	-0.56	1.86	1.84	0.13
8	6.01	6.57	4.17	4.59	-0.25	2.00	1.91	0.21
9	3.97	4.34	2.64	2.72	-0.20	1.27	1.45	0.15
10	4.60	4.87	2.86	2.88	0.44	1.57	1.54	0.23
Water	3.01	2.99	1.45	1.49	-0.43	1.19	1.23	0.12

Mud 5

Depth (cm)	W1	W2	S1A	S1B	S1G	S2A	S2B	S2G
1	1.36	1.69	1.23	1.11	-0.38	0.49	0.61	0.17
2	1.69	1.92	1.47	1.41	0.10	0.51	0.60	0.20
3	1.86	2.09	1.53	1.20	-0.26	0.54	0.62	0.19
4	1.85	2.23	1.57	1.70	-0.22	0.59	0.66	0.21
5	1.98	2.38	1.69	1.86	-0.28	0.62	0.66	0.22
6	2.16	2.47	1.76	1.97	-0.18	0.68	0.69	0.51
7	2.21	2.62	1.83	1.96	-0.18	0.70	0.70	0.22
8	2.25	2.74	1.90	2.05	-0.27	0.73	0.76	0.49
9	1.49	1.87	1.83	1.39	-0.23	0.50	0.58	0.27
10	1.63	1.95	1.12	1.53	-0.33	0.55	0.64	0.31
Water	1.23	1.21	0.64	0.65	0.00	0.52	0.52	0.07

Mud 6

Depth (cm)	W1	W2	S1A	S1B	S1G	S2A	S2B	S2G
1	1.81	2.04	1.55	1.49	-0.61	0.68	0.43	0.02
2	2.26	2.36	1.84	1.74	-0.50	0.51	0.67	0.08
3	2.57	2.73	2.13	1.70	-0.64	0.71	0.78	0.04
4	2.67	2.92	2.29	1.80	-0.82	0.80	0.55	0.05
5	2.88	2.98	2.36	1.60	0.07	0.84	0.80	0.07
6	2.86	3.08	2.43	1.86	0.01	0.90	0.50	0.07
7	3.01	3.16	2.47	1.77	0.27	0.98	0.58	0.06
8	3.49	3.23	2.60	1.77	0.11	1.03	0.72	0.33
9	3.13	3.35	2.65	1.85	0.20	1.11	0.77	0.08
10	3.25	3.51	2.80	1.68	0.35	1.20	0.77	0.11
Water	1.55	1.60	1.02	1.05	-0.10	0.61	0.59	0.33

Advanced rig resistance data - laboratory testing (multiple sediment layers)

Playpit sand on gravel

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	5.42	5.87	4.79	4.96	1.84	1.81
2	6.16	6.46	5.25	5.56	1.92	1.85
3	6.11	6.43	5.00	5.46	2.00	1.90
4	6.29	6.73	4.57	5.44	2.04	2.07
5	6.27	6.66	4.58	4.97	2.20	2.09
6	6.43	6.87	4.78	4.50	2.25	2.24
7	6.94	7.06	5.04	4.50	2.36	2.23
8	6.98	7.29	5.14	4.67	2.40	2.39
Water	4.25	4.25	2.25	2.25	2.05	2.05

Playpit on Beach sand

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	5.70	6.13	5.38	5.46	1.76	1.63
2	6.32	6.71	5.42	5.63	1.87	1.76
3	6.59	6.95	5.15	5.44	2.03	1.92
4	6.59	6.82	5.02	5.31	2.15	2.02
5	6.54	6.87	4.78	5.05	2.24	2.14
6	6.48	6.77	4.67	5.09	2.27	2.18
7	6.55	6.78	4.78	5.36	2.35	2.21
8	6.61	7.13	4.87	5.37	2.43	2.32
9	6.63	7.33	5.08	5.36	2.52	2.39
10	6.95	7.40	5.22	5.51	2.65	2.49
Water	3.84	3.75	2.13	2.17	1.83	1.82

Playpit sand on Mud 5 on Playpit sand

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	4.47	4.61	3.95	4.21	1.62	1.64
2	4.88	5.09	4.03	4.25	1.75	1.72
3	5.17	5.43	3.90	3.66	1.93	1.82
4	5.38	5.61	3.40	3.62	2.03	1.98
5	5.71	5.92	3.67	3.76	2.11	2.07
6	5.99	6.12	4.25	4.03	2.15	2.14
7	6.39	6.78	5.14	4.61	2.16	2.15
8	7.10	7.59	6.23	5.43	2.26	2.28
9	8.22	8.96	7.24	6.78	2.50	2.59
10	9.09	10.37	7.92	7.82	2.81	2.91
Water	3.88	3.86	2.22	2.05	1.84	1.81

Beach sand on Mud 5

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.34	3.33	3.24	3.35	0.90	0.91
2	3.87	4.04	3.55	3.62	0.98	0.99
3	4.16	4.40	3.52	3.61	1.09	1.08
4	4.19	4.35	3.41	3.49	1.13	1.07
5	4.14	4.23	3.33	3.31	1.18	1.18
6	3.93	4.06	3.15	3.23	1.21	1.20
7	3.98	3.92	2.90	3.04	1.26	1.18
8	3.91	3.86	2.86	2.81	1.28	1.29
9	3.88	3.86	2.78	2.67	1.32	1.30
10	3.79	3.95	2.69	2.61	1.42	1.38
Water	2.18	1.98	1.25	1.09	0.94	0.84

Advanced rig resistance data - laboratory testing (object detection)

9mm test 1

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.01	3.07	2.33	2.21	1.24	1.12
2	2.91	3.05	2.34	2.06	1.10	1.14
3	2.25	3.19	2.43	2.54	-0.72	-0.59

9mm test 2

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.12	3.00	2.31	2.20	1.23	1.34
2	3.08	2.98	2.32	2.34	1.13	1.40
3	3.18	3.10	2.11	2.67	1.03	1.21
4	3.27	3.22	1.51	3.35	1.01	1.31
5	3.08	3.00	2.36	2.60	1.05	1.30
6	3.03	3.00	2.31	2.27	1.12	1.21

9mm test 3

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.05	3.01	2.33	2.16	1.32	1.06
2	3.02	3.13	2.40	2.23	1.28	1.09
3	3.12	3.18	2.96	1.85	1.26	0.96
4	3.12	3.16	2.96	1.96	1.24	1.02
5	2.99	3.00	2.40	2.35	1.24	1.09
6	3.00	3.03	2.31	2.35	1.26	1.21

9mm test 4

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.00	3.08	2.31	2.19	1.25	1.32
2	2.86	3.07	2.34	2.10	1.07	1.10
3	2.66	3.22	2.34	2.29	0.72	0.78
4	2.44	3.54	1.79	2.18	0.21	0.39
5	2.60	3.58	1.93	2.17	0.58	0.75
6	2.81	3.50	2.14	2.24	0.80	1.06

1.5 mm

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.05	3.03	2.29	2.29	1.31	1.35
2	2.95	2.95	2.26	2.22	1.24	1.31
3	2.94	2.95	2.27	2.25	1.21	1.23
4	2.93	2.97	2.26	2.26	1.20	1.21
5	2.94	2.94	2.26	2.28	1.20	1.21

3 mm

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.03	2.99	2.28	2.22	1.30	1.16
2	2.99	2.95	2.28	2.10	1.24	1.30
3	1.90	2.96	2.29	2.24	-0.32	-0.17

2 mm

Depth (cm)	W1	W2	S1A	S1B	S2A	S2B
1	3.04	3.12	2.27	2.27	1.31	1.25
2	2.98	2.95	2.26	2.12	1.24	1.22

Advanced rig resistance data - field testing

Dittisham

Depth (cm)	10	10	10	10	10	10	10	10	10	5	5	5	5
Grid position	0.1, 0.1	0.1, 0.5	0.1, 0.9	0.5, 0.1	0.5, 0.5	0.5, 0.9	0.9, 0.1	0.9, 0.5	0.9, 0.9	0.1, 0.1	0.1, 0.9	0.9, 0.1	0.9, 0.9
W1	1.30	3.30	3.10	2.10	2.20	2.60	1.90	1.80	2.70	1.30	2.51	1.30	1.60
W2	3.40	3.30	3.48	3.30	3.58	3.57	3.20	3.30	3.50	3.30	3.22	2.70	2.89
S1A	5.00	1.80	2.44	2.30	3.80	2.00	2.30	2.90	1.80	3.10	2.35	2.50	2.14
S1B	1.62	1.70	2.28	2.37	2.40	2.58	1.65	1.40	3.00	1.87	3.10	0.80	2.07
S1G	2.60	-0.40	-0.70	-0.20	0.70	-1.00	-0.80	0.00	-1.40	0.70	-1.50	0.01	-1.00
S2A	0.90	1.00	1.00	0.90	0.80	1.10	0.70	0.90	1.00	0.90	1.10	0.80	0.80
S2B	0.50	0.10	0.20	1.21	1.21	0.67	0.40	0.50	0.10	0.70	0.20	0.30	1.00
S2G	0.30	2.10	0.12	0.13	-0.12	0.33	-0.13	0.22	0.06	0.08	0.23	0.11	0.03

Upper Beach

Depth (cm)	3	3	3	3	3	3	3	3	3
Grid position	0.1, 0.1	0.1, 0.5	0.1, 0.9	0.5, 0.1	0.5, 0.5	0.5, 0.9	0.9, 0.1	0.9, 0.5	0.9, 0.9
W1	7.48	5.99	6.25	10.13	7.78	6.94	7.64	6.37	8.17
W2	8.90	6.92	7.60	10.36	7.69	10.87	8.28	6.64	7.97
S1A	6.26	5.35	4.86	4.68	6.34	4.01	4.77	5.22	3.57
S1B	4.65	4.06	4.14	7.77	4.58	3.21	5.28	3.06	6.49
S1G	2.02	0.06	0.14	-3.59	0.83	-0.55	-1.20	1.47	-3.55
S2A	2.50	2.04	2.51	3.41	4.46	2.02	2.75	2.31	2.78
S2B	2.47	1.97	1.86	2.63	1.47	2.18	2.27	1.50	2.18
S2G	0.68	-0.19	-0.24	0.44	0.60	-0.09	-0.12	0.19	0.22

Lower Beach

Depth (cm)	9	9	9	9	9	9	9	9	9	5	5	5	5
Grid position	0.1, 0.1	0.1, 0.5	0.1, 0.9	0.5, 0.1	0.5, 0.5	0.5, 0.9	0.9, 0.1	0.9, 0.5	0.9, 0.9	0.1, 0.1	0.1, 0.9	0.9, 0.1	0.9, 0.9
W1	5.87	3.25	3.18	2.93	2.76	2.48	3.08	2.89	4.40	4.29	2.12	2.81	2.45
W2	4.41	5.14	4.00	4.33	5.02	2.68	5.48	4.40	4.45	4.38	3.68	4.22	3.12
S1A	4.92	2.11	2.71	1.46	2.39	2.83	2.84	2.56	2.59	3.27	2.27	3.82	2.80
S1B	1.36	1.41	1.04	2.53	1.49	5.86	1.06	0.60	1.65	3.99	1.90	0.92	1.79
S1G	3.60	-0.55	0.28	-0.83	0.11	-2.42	1.06	0.29	-0.65	-0.53	-0.15	1.52	-0.08
S2A	1.90	0.42	1.22	0.91	0.98	0.91	1.03	1.06	0.83	1.27	0.96	1.41	1.18
S2B	1.42	0.39	0.48	1.01	0.58	1.04	0.39	0.09	0.69	0.52	0.96	0.54	1.71
S2G	0.88	0.10	0.66	-0.13	-0.13	-0.12	0.20	0.18	-0.41	0.19	0.41	0.28	0.12

Harbour

Depth (cm)	10	10	10	10	10	10	10	10	10	5	5	5	5
Grid position	0.1, 0.1	0.1, 0.5	0.1, 0.9	0.5, 0.1	0.5, 0.5	0.5, 0.9	0.9, 0.1	0.9, 0.5	0.9, 0.9	0.1, 0.1	0.1, 0.9	0.9, 0.1	0.9, 0.9
W1	2.87	3.00	2.71	2.65	2.71	2.75	2.76	2.54	2.49	2.41	2.46	2.69	2.34
W2	3.44	2.99	3.18	3.50	3.13	2.72	3.41	1.98	1.99	3.13	2.88	3.19	1.81
S1A	1.98	1.96	2.39	2.82	2.31	2.47	1.82	1.46	2.44	2.07	2.13	1.89	2.53
S1B	2.13	2.21	1.56	1.83	2.17	2.52	2.94	5.16	1.99	1.98	2.14	2.48	1.88
S1G	-0.87	-0.60	-0.06	0.15	-0.08	-0.43	-1.32	-4.16	0.08	-0.47	-0.22	-0.96	0.29
S2A	0.88	0.84	0.84	0.93	0.82	0.79	0.81	0.84	0.72	0.84	0.82	0.82	0.72
S2B	0.58	0.34	0.53	0.51	0.59	0.56	0.74	0.53	0.54	0.40	0.60	0.76	0.54
S2G	-0.06	0.01	0.02	-0.04	-0.12	-0.09	-0.11	-0.07	-0.03	-0.02	0.00	-0.12	-0.09

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Publications

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GIS applications for nearshore investigations

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Abstract

Surveys undertaken for engineering, environmental or observational purposes may yield vast quantities of hydrographic, geophysical and geotechnical data, creating logistical problems for storage and subsequent analysis. The key to understanding and interpreting these data lies in a synergistic approach i.e. the combination of the parts provides a better picture than the sum of the individual components.

GIS offer a mechanism for resolving storage, integration, interpretation, standardisation and presentation issues within the marine survey. Existing systems are intended primarily for use in the offshore industry where data are high in volume but resolution is low (tens of metres). In the nearshore zone, a resolution of centimetres is likely to be required and so the issue of scale and representation becomes fundamental.

The development of a simple GIS which incorporates not only the primary survey data, but also information such as tidal regime and shipping activity has been undertaken at the University of Plymouth. The research illustrated that integration need not stop at the data acquisition stage but may be usefully extended into post-processing.

Although GIS cannot replace the specialist contouring, digital terrain mapping and geophysical packages required to analyse much of the data obtained, they do offer the possibility of making a positive difference in the management and cost effectiveness of survey and engineering operations.

Introduction

One of the most important stages in both marine and terrestrial surveys is planning as it provides the opportunity to set down the requirements of the survey and design the most appropriate method for achieving these aims. As a rule surveys are set up based on a simple grid, a structure that allows for the systematic control of data collection. However, the quality of these data capture strategies are difficult to quantify thus leaving an element of doubt as to whether or not the coverage is sufficient:

> *"As a result of the wide choice of assessment techniques available for use and their suitability for different stages of a project, the quality of a site investigation program can vary significantly and there is limited formal guidance available to help in optimising program design outside of qualitative experience based decisions."* (Parsons et al., 1998)

The move towards completely digital data acquisition and storage and thus the ability to query in spatial terms may provide a solution. In any organisation data collection, storage and handling is a fundamental concern, with the chosen management techniques determining the level of operating efficiency and product presentation. In the survey world clients expect data to be presented in a clear and concise manner with all facets of information displayed in the most appropriate fashion, thus allowing for optimum interpretation. The final product, i.e. the map, plot or written report will be a 'summary' of the analysis undertaken, a process that may have involved collating data from many sources. It is vital that the client is satisfied that not only has the survey fulfilled the wide ranging specifications, but that they are informed of as many aspects of the survey as possible.

Site investigation surveys involving hydrographic or geotechnical data acquisition often generate high volumes of data both from many different locations and various equipment systems. These data will require handling through specialist software packages, with a range of output formats. The combination of the volume of data and the variety of software and formats may hinder the analysis and presentation of data.

In order to attain a fluent operating system, many companies are choosing to integrate data sets and analyses through the implementation of structured data management solutions such as Geographical Information Systems (GIS). In an industry where the majority of primary data are spatially referenced, GIS offer the capability to merge datasets based on this fundamental property. However, the transition of GIS from their terrestrial roots to the marine environment has not been simple and many site specific issues must be addressed.

Marine GIS differ from land based GIS due to the inherent difficulties associated with mapping a 4D environment in a 2D or possibly 3D computer program. Terrestrial systems have many specifically designed adaptations, but the same has not been undertaken for marine applications. For this reason, many 'off-the-shelf' products, suitable for land use, are often not comprehensive enough for marine use (Lucas, 1996; Maslen et al., 1996). Li & Saxean (1993) describe how most land based systems can analyse satellite remote sensing imagery, whereas it is unlikely that you will find a system which can manage side scan sonar data. This lack of specialisation can lead to GIS being utilised simply as digital mapping packages, thus detracting from the opportunities it can offer (Thumerer et al., 2000). Furthermore, the specific problems faced in the marine world require development by those in the field with an appreciation of the diversity of data sources, manipulation techniques and display methods.

GIS issues

Unless the survey being undertaken is restricted to a very small area, it is likely that marine surveys will collect a large volume of data. The specified resolution will obviously dictate this volume and whilst nearshore surveys may require a much higher resolution of data than surveys undertaken offshore this is often balanced by restricted spatial extent.

The high technical level of equipment utilised for marine surveys including, multibeam swathe sounders, seismic sources and streamers, ROVs (remotely operated vehicles) and manned submersibles put a high price on any survey. As a direct result of this multiplicity of type and manufacturer of marine data acquisition systems, numerous data formats exist:

> *"Data formats include raster (grids and images), two-dimensional vector points (vent / sample / marker / earthquake locations), lines (bathymetric contours, submarine / camera / equipment navigation tracks), areas (lava flow delineations), and three-dimensional vector data (water-column casts and tows)."* (Bobbitt et al., 1997)

In most cases, specialist software is required to interpret the data although the product can often be exported to other systems. Side scan sonar mosaics created in specialist packages can be exported as raster images to GIS, but this process removes the flexibility of the original system and makes the spatial analysis functions of the GIS redundant. A method for standardising data formats is required before GIS will be able to handle many marine data (Mingins, 1996).

Very little marine data is simply 2D (x, y) and will usually include a third dimension of depth and possibly a fourth dimension of time (Mason et al., 1994; Robinson, 1991). The fundamental difficulty when assessing 4D data is that of display in two dimensions. The availability of 3D plotting within GIS is increasing, thus allowing for the combination of 3D data. Four dimensional data may be displayed through the use of video sequences although these may draw heavily on computer memory.

Marine survey position data may be collected in many different formats, the two most widely used being the world wide World Geodetic System (WGS) 84 latitude, longitude and Universal Transverse Mercator (UTM) grid. The format in which the data are collected needs to be selected depending upon the extent and location of the survey. Investigations undertaken in the nearshore zone, which coincide with land investigations, would be most appropriately collected in local grid coordinates. However, UKHO Admiralty chart data is given as latitude and longitude, thus posing problems for data transformations and the associated introduced errors.

The United States National Oceanic and Atmospheric Administration (NOAA) Ocean environment Research Division (OERD) describe scale issues faced:

> *"Data scale and accuracy ranged from a few meters (e.g. the location of a submersible sample at a hydrothermal vent orifice collected from 3000m below the sea surface) to remotely sensed earthquake locations accurate to within a few kilometers."* (Bobbitt et al., 1997)

This wide variation in scale poses a problem when analysing data, where it must be ensured that data from radically different scales are not used together without due care and attention. Much marine investigation work relies on the combination of data sets of varying scales. In remote sensing, satellite data may be used to identify gyres, which may be investigated further *using in situ* measurements (Lucas, 1996). GIS offer the opportunity to map data of different source scales on top of one another by altering the projection scale. As will be discussed below with reference to ethics and law, this process must be used with caution (Lucas, 1996).

One of the basic concepts of GIS is the ability to map and analyse information based on spatial properties. In land based systems, coregistration sourced on streets, post codes etc can be used to tie datasets together. Offshore there are very few fixed points and therefore registration is undertaken using positioning systems and the coordinates acquired (Li & Saxean, 1993). In the main, this is a simple but successful system but in certain circumstances the addition of an 'object' is useful. For example, when working in coastal regions delineation of the coastal boundary is useful for reference. However, use of a shoreline would be difficult due to variation as a result of tidal movement and sediment removal/deposition (Lucas, 1996). Fixed markers must be chosen carefully to ensure consistency and to reduce variability in the analysis process.

Due to the increasing volume of data held by companies and the manipulation undertaken, the issue of data ownership is becoming a common concern. Furthermore, the quality and update period of metadata can be cause for trepidation when integrating public domain or 'bought' data into private GIS. For example, a map displayed at a scale of 1:10,000 may be used to select sites for survey investigation. If, however, the map is in fact of 1:50,000 scale and has been 'blown-up' then the nature and extent of features will have been generalised and the survey in the field is unlikely to correspond to that planned in the office. It is therefore, crucial that metadata is made available and accessible to avoid costly litigation (Scott, 1994).

Proving liability for mistakes arising from the use of digital data is a complicated issue. The provider of the information must be responsible for ensuring that the data is kept updated and that the metadata is freely available. Charging for use of public domain datasets may aid in the process of ensuring that the data are used solely by those aware of the implications of use. It must then be decided if the user has a licence for the data, i.e. the onus remains on the supplier to update, or whether the ownership changes hands on purchase. In such instances the user would from the time of purchase become responsible for updating as for UK Hydrographic Office (UKHO) Admiralty

Charts and Ordnance Survey (OS) digital data. Copyright can also become an area of confusion; for example who holds the copyright for a map produced with data from the Ordnance Survey along with data from the Hydrographic Office, integrated with data held by the company itself?

The law and ethics relating to GIS will no doubt change in the foreseeable future as the technology expands and is utilised by more diverse commercial and private sectors. In addition consideration must be given to the development of digital technology for presentation. If GIS become more commonplace will the output format change from hardcopy to digital reports? It is unlikely that hardcopy responses will be eliminated due to the ease with which they convey data. Digital data may be useful for expanding simple issues discussed in a report, but they require access to specific software. The advent of systems such as ArcIMS (Environmental Systems Research Institute Inc, 2002), with which companies may display selected facets of data through an internet backdrop, may go some way towards advancing the long term use of GIS throughout industry.

Examples of applications of GIS

Marine GIS are relatively few and far between, but there is an increasing trend for employing this mechanism of integrated digital data management. Customisation of off-the-shelf products is a solution for many, but the range of requirements often 'forces' the development of in-house software. GIS ASSESS is a geostatistical tool which has been specifically developed to scrutinise the quality of site investigation plans (Parsons et al., 1998). The software has the ability to collate together information on the type of investigation tool employed, its accuracy and precision, scope of use e.g. depth of penetration or coverage and will provide an indicator as to the potential quality of a survey. As the system is continually updated, the software can alert the operator when data sufficient to meet the required criteria have been collected. Tools such as these enable the surveyor to ensure that surveys are planned to the optimum level and that the survey is both time and cost effective. As an integral part of the data acquisition and processing software, this system illustrates the scope for GIS within the survey industry.

Marine survey typically involves intensive data collection followed by processing in specialist packages. This processing takes place either on board ship, e.g. at the completion of a section of acquisition, or back at the land base once the survey has been concluded. In some instances, data may be relayed back to the shore processing station during or at the end of a phase of survey and whilst the vessel is still on site (Anon, 1997). The advantage of processing data as quickly as possible is that it allows for quality control to be undertaken when the contractor is still in a position to fill in or re-survey poor quality sections.

Real-time quality control (QC) is the ultimate qualitative and quantitative survey tool nevertheless the practicality of undertaking real-time QC on the volume of data acquired is a difficult issue. Most GPS systems have real-time QC allowing for degradation of position data to be recorded, and this type of real-time analysis may become feasible for other survey data with the implementation of GIS.

A system called Real-Time Geographical Information System (RT-GIS), has been developed at the US Naval Research Laboratory which:

> *"will provide a means for hydrographic sensor data to be ingested, stored and organised in a spatial database so it is available for immediate analysis, display and output both locally and remotely."* (Beaubouef & Breckenridge, 2000)

As Beaubouef & Breckenridge (2000) point out there is room for confusion as to the meaning of real-time. Due to the diversity of data coming into the GIS, an element of processing is required, e.g. positional correction, before QC can be performed. In the absolute sense of the word, this makes real-time QC virtually impossible. However, given the size and cost of marine surveys, it would be far better to be able to stop a survey mid-line to re-calibrate equipment or alter set-ups than to complete a section only to find the data were not of a high enough quality.

The fact that hydrographic surveys are inherently modular due to the multitude of equipment required to undertake even the most simple of surveys highlights the importance of integration. Once data has been collected and processed it will need to be integrated for site-wide analysis. As discussed for many other types of investigation, this process can be lengthy so that the opportunity to utilise GIS to improve efficiency is apparent (Anderson, 1998; Beaubouef & Breckenridge, 2000; Bowley, 2001; Jeffries-Harris & Selwood, 1991; Li et al., 1998).

In 1994 work began on a shoreline erosion monitoring and management program in Malaysia, headed by the Coastal Engineering Division of the Department of Irrigation and Drainage (Li et al., 1998). Data ranging from bathymetry and storm surge data to the shear strength of the soil was required to design the required defence structures. The GIS allowed for numerical modelling to be carried out to ascertain the range of shoreline changes that might be faced. West Dorset District Council undertook similar research in 1995 in conjunction with the Dorset Coast Forum (Badman et al., 2000). Once again, the emphasis was on digitising data and creating an integrated approach to shoreline management.

The Crown Estates Commission (CEC), oversees the management and extraction of approximately 25 millions tonnes of aggregate within an area of more than 200,000 km^2 (Jeffries-Harris & Selwood, 1991). Posford Duvivier was asked to undertake a study into the suitability of a GIS to solving the data storage and handling problems experienced by the CEC. ARCINFO proved to be a useful tool, although a number of problems particularly associated with the data entry process were encountered:

1. *"As usual, identifying digital data sources and obtaining access to them proved difficult.*
2. *Digitising data: the time taken to do this was significantly greater than anticipated.*
3. *In creating a standard borehole system is it recognised that there will be a loss of detail from the data.*
4. *Chart scales varied from 1:200,000 to 1:75,000. In addition, survey data is collected at scales of around 1:5000. Joining such data sets would be erroneous, so it is accepted that 'joints' will be present within the data coverage.*
5. *Quality control: applied to both text and graphics, as it is entered and when updating it."* (Jeffries-Harris & Selwood, 1991)

The problems described above along with others relating to the structure of data storage and the updating timescale may be seen as limitations of the GIS constructed. In comparison to the system being used prior to GIS implementation, i.e. manual data handling, this integrated system may be regarded as a success. The CEC acknowledge that specialist systems may be required to complement the basic ARCINFO set up, nonetheless it is also acknowledged that the GIS created utilises all of the available functions and thus can be seen to be an *'ideal GIS'* (Jeffries-Harris & Selwood, 1991).

The coastal zone is an area of major interest for GIS development due to the complexity and dynamics of the environment. As illustrated by the CEC, surveying in coastal regions does not automatically mean a 'small' survey site or a minimal data source. Given that many economic and legal boundaries stem from the coast, e.g. the exclusive economic zone (EEZ), comprehensive

management policies are critical. Integrated Coastal Zone Management (ICZM) is a phrase now used to describe the long term integrated planning strategies directly related to the coastal zone (Thumerer et al., 2000).

MIKE INFO Coast has been developed by the Danish Hydraulic Institute in response to the specific requirements of the coastal environment (Anderson, 1998). The system has been built as an extension to ArcView 3.0 and thus has full GIS functionality.

> *"A situation of typical use would be a coast, where bathymetric line surveys are performed regularly to record the depths. After each survey, the recordings will be imported into MIKE INFO Coast and processed. This processing involves organising the survey lines into so-called profiles. These profiles can then be compared from survey to survey, and differences (i.e. changes in the bathymetry) can then be calculated."* (Anderson, 1998)

One of the primary features of MIKE INFO Coast is the ability to acquire hydrographic data in a simple ASCII-format. The import of x, y, z data into a GIS enables interactive contouring and plotting, a basic hydrographic charting requirement. Many GIS packages have contouring facilities but require data to be input in a specific data format as opposed to as a simple x, y, z ASCII file from which a grid could be created. This lack of flexibility means that contour maps may need to be imported as raster data from external software thus reducing the possible spatial analysis methods.

The application of GIS within the marine survey world is not restricted to research and industry, but also involves the military. 'HUGIN ChartLink' is a system that has been developed by the Royal Navy and facilitates the fusion of hydrographic, oceanographic and meteorological data (Bowley, 2001). One of the applications for this system is in the uncertain area of amphibious landings:

> *"A commander overseeing the amphibious assault will be able to drill down through the different levels of detail to reach the area proposed for the beach landing. A recent intelligence report may be highlighted which indicates that what was thought to be a shingle approach to a beach is actually mud."* (Bowley, 2001)

Bowley (2001) goes on to discuss how other members of the landing team will be able to view the data simultaneously, allowing them to structure their approach to the landing mission based on the initial surveillance. This reference illustrates that GIS encourage not only the integration of digital data, but also of the survey team and the equipment that they command.

Many marine survey projects involve both hydrographic/geophysical investigation and geotechnical studies. It is in the contractors best interest to be able to plan both sides of the survey effectively and to be able to use both sets of data for post-processing analysis.

> *"A geographic information system (GIS) is a relatively recent addition to the growing number of software applications available to civil engineers. Although many engineers are familiar with the technology, they remain unaware of its analytical power and potential for wide and varied use."* (Hellawell et al., 2001)

As for all GIS, the first step towards achieving a successful system is to acquire digital data and to store it in an organised pre-determined manner within a relational database. Seismic micro-zonation studies of Kishinev, Republic of Moldova, undertaken by (Zaicenco & Alkaz, 2000) were based on the development of a 3D database of geotechnical properties in ArcView. The importance of metadata is discussed with reference to *a posteriori* processing and the associated accuracy and precision propagation.

The financial commitment is a major consideration when establishing new computer systems and was a concern for WS Atkins GTG:

> *"The first stage in the introduction of the GIS was an investigation into its market potential. This involved the identification of projects and applications where the GIS would expand analytical capabilities, yield net savings, and generally add value to the existing services."* (Hellawell et al., 2001)

WS Atkins GTG found the GIS to be so useful in their projects that it was used as a standard tool within 6 months although it was also recognised that for some situations the system was unnecessarily complex in which case they reverted to independent specialist packages.

Dart Estuary GIS Research

Pipeline landings, sewage outfalls, land reclamation, coastal engineering construction and hydrographic charting are just some of the examples of the requirements for nearshore surveys. The techniques employed for acquiring survey data in the nearshore zone are hindered by many difficulties inherent to the location such as water depth, tidal activity, vessel movement and obstructions, e.g. pontoons, mooring buoys. Finding solutions to these problems should be undertaken as part of the pre-survey planning stage to avoid costly delays later. By creating a GIS version of the standard pre-survey desk study before survey work begins, users would be able to ensure that all site conditions and restrictions have been investigated. Research undertaken at the University of Plymouth into the role of the ROV within integrated geotechnical and hydrographic site investigation led to the development of such a nearshore survey GIS. In the same way that the equipment has been integrated to operate from an ROV, it makes sense to try to integrate the survey data acquired. It is apparent that GIS offer a solution to a great many storage and analysis problems, not least of which is diverse subject integration. Providing that the contractor is controlling both the hydrographic and geotechnical data acquisition, it would seem favourable to combine the data to encourage cross-discipline analysis. However, these systems would need to be modified in order to satisfy the demands of a nearshore / inter-tidal survey. The GIS developed for this research is a case study of the Dart estuary, (Devon, UK) presented in a form which should assist the engineer, surveyor or harbour authority to manage nearshore activities. ArcInfo 8.0 was chosen as the GIS software, so that an investigation could also be made into the ability of 'off-the-shelf' GIS to manage nearshore marine data.

Base map data were taken from the Edina Digimap website (Edina, 2002), where Ordnance Survey (OS) data is available in a digital format for a variety of their products. Due to the scale of the survey area, the most appropriate OS data was provided by the Land-Line Plus series of 1:10,000 data (tiles sx 8654-8656, 8750-8754, 8755-8756, 8849-8853, 8950). Using the U.K. National grid as the base coordinate system allowed for the correlation of land data with marine data, which can be acquired with reference to any coordinate system. The Land-Line Plus data set provides detailed mapping for the region, with full delineation of jetties and routings for the local ferries. The estuary has two permanent ferries: the upper ferry, which is chain driven, and the lower Dart ferry. These vessels cross the river approximately every 10 minutes (approx. 0700-2245) and thus create a semi-permanent obstacle. An additional 30 or so pleasure craft operate in the lower estuary and have trips leaving throughout the day, some on a half hourly basis from 0900-1700. In addition to this there are approximately 1500 private, 30 charter, 11 commercial and 20 fishing vessels registered with the Dart Harbour Authority (Dart Harbour Authority, 2002).

A set of multibeam data collected in 2000 by the University of Plymouth Postgraduate Diploma Hydrographic Survey group Hydrographic Diploma Group (2000), from Flat Owers to the mouth of the estuary provides high density x, y, z data. Using the contouring facilities contained within the

1988). A large percentage of these markers are linked anchorage buoys and were input to the GIS to illustrate the congestion and survey line planning problems the estuary poses. Each marker can be queried to acquire the navigation data supplied by the UKHO Admiralty chart No. 2253 (United Kingdom Hydrographic Office, 1988).

The merging of land based data such as the Land-Line Plus map sections, with marine data such as the navigation marks pose a potential issue with relation to ethics and law. As previously discussed the responsibility for the updating of OS and UKHO data once purchased falls to the user. One of the may analysis functions offered by GIS is the ability to pick out like features; for example, the coastline as depicted on adjacent Meridian 1:50,000 (Edina, 2002) scale digital map sections, may be selected and merged. In this way a simple coastline spanning several map tiles may be displayed. However any alterations to the data caused as a direct result of the merging process would be the responsibility of the user and not of the primary source provider. Thus such processes must be undertaken with the greatest of care, and associated metadata should be comprehensive.

Further data including the results of local survey work undertaken as part of the ROV project research will be incorporated into the GIS at a later stage. These data will include side scan sonar images along with the results of geotechnical and geophysical field testing. The geotechnical and geophysical data are centered on very small sites, approximately 1 m^2 (consisting of 16 grid points) and thus pose the problem of scale. If the survey grid is displayed, the background coast outline is lost and therefore, the site has no visual locator. The use of hyperlinks to display grid diagrams when the area of the survey is selected will be used to overcome this problem, thus allowing the user to view the arrangement of a survey site, in relation to the known area. The issue of scale relates in a much broader sense to the use of GIS in relation to the display of data. For example, a map displayed at scale of 1:10,000 may be used to place the sites for survey investigation. If, however, the map is in fact of 1:50,000 scale and has been 'blown-up' then features will have been generalised and the survey in the field may not correspond to that planned in the office.

Conclusions

The functionality of GIS offers the marine survey environment a tool with which data integration, manipulation and presentation may become simpler than the techniques currently employed. If the GIS is to be used as a spatial analysis tool and not simply as a comprehensive method of data storage then issues including scale and data format need to be addressed. As the number of companies adopting GIS increases the legalities of digital data usage are likely to change. The importance of metadata must not be underestimated when dealing with the legalities of digital data and the user must take on the responsibility for changes made to copyright protected data.

GIS is now becoming a recognised approach to data management in the offshore environment but nearshore systems are few and far between. The nearshore zone is an inherently dynamic environment and as such survey planning is fundamental for efficient execution. Although the survey area may not cover the same aerial extent as encountered in offshore surveys, there is an intrinsic requirement for high-resolution data. GIS may enable the user to cope not only with the associated high data volume, but also the requirement to display data at an appropriate scale.

The integration of data facilitated by GIS is an invaluable asset to surveys in both the nearshore and offshore marine environments. As these systems become more common place, the analysis and data handling techniques are likely to improve, thus expanding the accessibility of data to users from different levels of the survey process.

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