Development of a unified approach for assessing sedimentation in Harbours

M P Dearnaley
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Summary

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The aim of this study is to identify a common approach to practical consideration of issues associated with sedimentation in harbours. This is achieved by distilling the best current practice based on HR experience and recent research output. The study is primarily aimed at improving the approach to undertaking assessments of harbour sedimentation where those involved are coming to a particular development without the benefit of significant site specific experience. The central theme of this study is that a unified approach to assessment of harbour sedimentation is appropriate irrespective of whether the investigations are entirely desk based or utilise state-of-the-art field investigation and modelling techniques.

The magnitude of the volume of sedimentation in a particular harbour is not related to the complexity of the sedimentation processes at the site. The financial cost of appropriate investigations leading to a reduction in dredging requirements, or optimising the dredging strategy, may be unacceptable in cases where the actual volume of sedimentation is small. It is, however, still important that for small developments the issue of sedimentation is considered. At most of the major european container ports a strategic approach to sedimentation studies is being adopted. The value of such an approach can be enormous when the cost of maintenance dredging and the benefits in being able to progress port development works quickly are considered.

The initial approach to the assessment will depend upon the availability of information at the site (including existing models and field measurements) and the particular problem that is being addressed.

The available information should be analysed in an assessment consisting of four stages:

i) Understanding the layout and operations of the existing/ proposed development
ii) Gaining an insight into the important sedimentation mechanisms at the site
iii) Quantifying where appropriate the magnitude of the sedimentation associated with the different mechanisms
iv) Making appropriate recommendations for further investigations if required.

Based on an initial assessment of the available information, usually at the time of tendering for a project, one of the following courses of action can be followed:

i) to recommend an initial site visit, including simple measurements and consultation, followed by a scoping exercise which will lead to defining the requirements for further studies.

ii) to recommend a site visit, including simple measurements and consultation, which will be a sufficient basis from which to undertake all the assessment required.

iii) to recommend detailed field measurements required as input to a desk based study which will provide the basis for undertaking all the assessment required.

iv) to recommend a modelling study for which all the required data exists and which will provide the basis for undertaking all the assessment required.

v) to recommend detailed field measurements required as input to a modelling study which will provide the basis for undertaking all the assessment required.

Assessment of the quantity of sedimentation requires putting into context the various different mechanisms that may be contributing to the sedimentation. If only one mechanism exists this may be come straight forward. In cases where a number of processes are important different approaches will be required. This will generally entail quantifying, to some degree, the hydrodynamic climate (waves and currents) at the site and using this in a probabilistic manner to estimate sedimentation rates associated with different processes.

Quantification of sedimentation will not normally lead to a single answer. In nearly all cases it is most appropriate to provide an answer in the form of a range or an upper limit. It is acceptable to quote ranges because this represents the uncertainty in the understanding of many of the processes involved.

Information presented in this report can be utilised as a series of check lists. Discussion of the different items is found within the main body of the report. It is unlikely that in any one case that it is practical or possible to obtain all the information described. However, by being aware of the importance and value of different types of data it should be possible to optimise data collation from different sources. The use of these lists will be particularly effective when arranging an overseas visit.

The assessment process can be broken down into three stages as shown in Figure 1: identification of the main sedimentation mechanisms, quantification of the sedimentation rate and finally optimisation of the harbour layout and operation.

It should be observed that there are often a number of sometimes conflicting issues which need to be resolved when optimising a harbour layout. The conflict between safe navigation, berth tenability, management of the sedimentation and minimum environmental impact sometimes lead to opposing engineering criteria. This study relates to harbour sedimentation but it is important that the potential interaction with these other parallel studies is considered.

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1 Introduction

1.1 Background

The rate of sedimentation is a key factor in determining the viability of a working harbour. Changes and additions to the relevant International legislation have led to the environmental impact of maintenance dredging and disposal of the material becoming important issues. Additionally, the requirement to consider the options for beneficial use of material arising from maintenance dredging has added to the pressure on the Harbour Engineer to optimise maintenance dredging practices and to develop an understanding of the sediment regime in the vicinity of his harbour.

There currently exist a range of techniques available to the Harbour Engineer and Designer for predicting sedimentation rates, considering dredging operations and the impact of these operations. These techniques vary from desk studies using limited field data to comprehensive computational or physical modelling studies based upon extensive field investigations. It is important from an economic point of view that the appropriate technology is applied to a particular problem at the right time.

In 1994 HR Wallingford were commissioned by the Department of the Environment Construction Directorate to undertake a study with the aim of providing a unified approach to assessment of harbour sedimentation.

1.2 Objectives

This study is primarily aimed at improving the approach to undertaking assessments of harbour sedimentation where those involved are coming to the particular development without the benefit of significant site specific experience.

Towards meeting this primary objective, this study will consider the value of classification systems for harbour types and harbour sedimentation mechanisms. It identifies the data required to undertake an assessment and defines the structure of the assessment process.

The study further considers computational modelling and field investigations as techniques to provide input to the assessment process. It makes the distinction between services that suitably qualified organisations can undertake and those presently requiring specialist organisations.

Note that for the purposes of this study the term harbour is taken to encompass all port, harbour and marina developments. Furthermore, consideration is given to the whole of the area of concern to the Harbour Engineer, namely the harbour and its approaches. However, the emphasis of this study is on issues of sedimentation in the berthing and turning areas.

1.3 'Sedimentation', 'Siltation' and timescales

In this study sedimentation refers to the accumulation of material in operational areas of the harbour. Siltation refers specifically to the accumulation of predominantly fine, muddy, material (median grain size less than 0.063mm). In this report, where appropriate, sand and mud transport processes are considered separately.

A further clarification is required with respect to the timescale of the sedimentation predictions considered in this study. This report refers to the timescales typically associated with the maintenance dredging operation. That is anything from a few days to a few years. This report specifically does not address the issue of predicting long term morphological change. The reader is referred to the recent scoping study on estuary morphology for a review of the present state-of-the-art with respect to approaches to predicting long term morphological change (Reference 1). Note that it is becoming necessary for the Harbour Engineer and Designer to be aware of the long term impacts of harbour development. This will become increasingly important as mitigation and amelioration measures drive the future options for placement of dredged material.

1.4 The assessment process

For the assessment of harbour sedimentation three types of input to the investigation must be considered:

i) desk based study
ii) modelling
iii) field investigation

These are shown schematically in Figure 1 interacting within the overall assessment process. These different elements must also be seen in the broader context of the various stages of a development project such as feasibility, preliminary design and detailed design. Issues associated with harbour layout and safe navigation are particularly important and should be considered in parallel to sedimentation aspects during the design of a harbour facility.

Continual assessment is the key to progressing the understanding, quantification and optimisation of harbour sedimentation. Figure 1 shows assessment at different stages of a study with available data, input from other studies and field data collection and predictive modelling all being used within the assessment process. There is a wide spectrum of technical levels at which the assessment process can be completed. In some cases it would be impossible to proceed without recourse to detailed field measurements, data analysis or computational modelling. In other cases there may be no economic justification for pursuing such approaches.

The most cost-effective approach to a study will nearly always be for an initial desk based assessment to be undertaken. Field investigations may be necessary prior to sediment transport modelling, alternatively pilot modelling may be required in order to identify the key processes which will require specialist field measurements against which to validate sediment transport modelling. The pilot modelling can also indicate where the measurements should be made. The initial phase of a study should identify the requirements for further work. Optimum application of modelling and field investigation is likely to involve an iterative process.

The general approach to assessment is the same whether it entails an analysis based on a short site visit and discussions with a potential harbour developer or makes full use of data resulting from studies costing several hundred thousand pounds. This report outlines this unified approach to assessment. It also provides guidance as to when and how decisions relating to the use of specialist field measurements or computational modelling are appropriate in the overall approach.

1.5 Structure of report

This report contains a further nine chapters. The approach to this study including a short commentary on the present approach to assessment of harbour sedimentation is outlined in Chapter 2. Chapter 3 of this report provides some general background to the issues relating to assessment of harbour sedimentation. In Chapter 4 the requirements for, and sources of, data for the assessment process are discussed. The decisions relating to the analysis of available data and the requirements for computational modelling and field data collection are outlined in Chapter 5. In Chapters 6, 7 and 8 respectively guidelines on the approach to desk study, predictive modelling and field measurements are provided. The conclusions arising from this study are provided in the final chapter.

2 Approach to the study

2.1 Experience of harbour sedimentation studies

This study has been undertaken in the Ports and Estuaries Group at HR Wallingford. During the course of this study the staff involved in this study have been responsible for more than fifty investigations into harbour sedimentation. Perhaps, more importantly, HR Wallingford has, over the past fifty years, been involved in more than a thousand investigations into harbour sedimentation throughout the world. Underpinning this practical experience is involvement in national and international research studies into all aspects of hydrodynamics, sediment transport and port operations. This experience provides the basis of this report. The aim is to identify a common approach to practical consideration of issues associated with sedimentation in harbours this is achieved by distilling the best current practice based on HR experience and recent research output.

In Sections 2.3 and 2.4 of this chapter a short review of common practice amongst Consulting Engineers asking for specialist advice or performing studies themselves is provided. The objective of this short review is to identify the particular areas where the adoption of the unified approach outlined in this report will improve current practice, without imparting undue economic constraints on the types of study presently being undertaken.

2.2 Other parallel issues

It should be observed that very often there are a number of sometimes conflicting issues which need to be resolved when optimising a harbour layout. The conflict between safe navigation, berth tenability and minimising sedimentation in the harbour sometimes lead to opposing engineering criteria. For example, at a coastal port the entrance will be designed primarily for safe navigation and reduction of wave activity in the harbour. Depending upon the entrance configuration this may result in deposition of sand in a bar at the entrance to the harbour. At the time of design further optimisation of the harbour entrance to minimise sedimentation, which was probably of secondary importance, may not have been feasible. Nowadays techniques are available which optimise the harbour with respect to all three design criteria and this approach should be considered for all new harbour developments.

It can be seen therefore, that in many cases an assessment of harbour sedimentation forms only part of the design process. This study is concerned only with the issue of harbour sedimentation. However, the reader should bear in mind the other important design issues when considering the requirements for further study and data collection as part of optimising a harbour design. The reader is referred to References 2, 3, 4 and 5 for a review of other associated studies.

2.3 Issues concerning scale of the sedimentation problem

An unfortunate aspect of harbour sedimentation in its broadest sense is that the same complex mechanisms that lead to accumulation of millions of cubic metres of material in busy container ports can also occur at small marinas and wharves where intermittent removal of thousands of cubic metres of material is all that is required. The financial cost of investigations leading to a reduction in dredging requirements or optimising of the dredging strategy may be broadly similar in these two scenarios but the cost-effectiveness of the investigations very different.

Experience shows that, except in special circumstances (see Section 2.5), the level of study adopted is almost entirely related to the economic magnitude of the problem. This is unfortunate in that too often the view is that with a small development only a small sedimentation problem can occur, and that this is often not worth quantifying prior to construction. Present day practice has shown that this is not the case; accumulation of a thousand cubic metres of material at the mouth of a marina may be as important from an operational point of view, as blockage of the approach channel to one of the world's busiest container ports.

This study draws on experience from sites where detailed investigations have been undertaken and derives useful information which can be applied to any scale of harbour development. For example, investigations undertaken as part of this project have applied different computational modelling techniques to the marina basin at Conwy (see Section 5.4 of Reference 6). In themselves these studies would presently not have been cost-effective for the marina development. However, the hydrodynamic and sedimentation mechanisms that are important at the marina are noteworthy and the information gained from the investigations is enlightening with respect to other situations.

2.4 Iterative nature of detailed investigations

Notwithstanding the fact that the knowledge base on sedimentation mechanisms is continually expanding, detailed investigations into harbour sedimentation can take many years to complete. This is because there is an iterative aspect to the way in which the knowledge base at a particular site is enhanced. In ideal circumstances there will be a gradual application of computational prediction techniques and deployment of specialist field instrumentation. At most of the major european container ports such a strategic approach is being adopted. The value of such an approach can be enormous when the cost of maintenance dredging and the benefits in being able to progress port development works quickly are considered. However, most assessments of harbour sedimentation are undertaken for smaller or new developments. For such projects it is often the case that the Consultant and Harbour Engineer involved are coming fresh to the study. Whilst this report will provide some useful guidance to the development of strategic research into harbour sedimentation, it is primarily aimed at improving the approach to undertaking assessments of harbour sedimentation where those involved do not have the benefit of significant site specific experience.

Often, and particularly with overseas projects, the benefits of adopting the iterative approach outlined above cannot be fully attained. This can be because of the remoteness of the site or the timescales of a particular project. Generally, in a relatively short period the issues must be analysed, field measurements specified and undertaken and then followed up with a prescriptive application of computational modelling. All the required steps of the assessment are undertaken, but all too often there is insufficient time for full analysis and review. The field measurement programme and the computational modelling then become entities in themselves, somewhat isolated from the assessment process.

In recent years technology transfer has become an aspect of many overseas studies. Equipping local organisations with the required hardware and software for the field and computational studies has become part of the consultancy package and in some cases this often appears to be the most important element. Whilst the practice is in itself laudable, unfortunately, in all but the simplest locations, the sedimentation processes are complex, seasonal and episodic, and tools do not yet exist which can provide the basis for satisfactory investigation by non-specialists.

2.5 Special circumstances warranting more detailed investigation

The special circumstances mentioned in Section 2.3 are generally associated with relevant legislation. Consequently this includes cases where the material accumulating in the operational areas of a harbour is likely to be contaminated and therefore much more expensive to remove and dispose of in an environmentally acceptable manner. Another recent special circumstance might be where the harbour falls within or is likely to impact an area designated under the European Habitats Directive. In such cases detailed investigations into the impact of even relatively small scale dredging operations may be requested. In other cases there may be an overriding safety or economic issue associated with particular harbour operations which requires a greater level of investigation than might normally be warranted.

3 Harbour sedimentation - classification and mechanisms

3.1 Classification of harbour types

One possible way of classifying harbours is by their physical features. Harbours are generally built either in coastal locations, where their primary purpose is to provide protection from waves, or in tidal locations, where waves are generally less significant. These two broad groups of harbours can be further broken down as follows:

Coastal	- enclosed basins	Tidal	- estuarine
	- protected by breakwaters		- natural lagoon
			- locked

It should be emphasised that because harbours are so diverse no system of classification will be perfect. With the system proposed above there are harbours which could be considered to be both coastal and tidal. For example Great Yarmouth which is a riverside berth, but which historically has experienced significant wave action at its downstream berths. Consequently it is considered here that a more detailed classification of harbour types is inappropriate. Drawing a parallel with estuaries it is fairly well accepted that each UK estuary is unique and that a complex classification system is positively unhelpful (Reference 1). For this study, the broad classification above allows some generalisations to be made which are useful in considering and resolving sedimentation mechanisms.

For each of the classes of harbour identified above the principal features relevant to sedimentation are listed and some UK examples of each harbour type are given.

3.1.1 Coastal harbours

Enclosed basins

Enclosed basin harbours are constructed at coastal locations which are vulnerable to severe offshore wave activity. Waves will often approach from different directions and the harbour is characterised by almost complete breakwater protection and relatively narrow entrances. The harbours are very sheltered from waves so coarse sediment, which requires the additional effect of waves for transport, if present, is usually deposited close to the entrance. There is often the possibility of significant currents in the entrance if the tidal range is large. Inside the harbour the currents will generally be small. This feature often leads to constant deposition of fine material from suspension within the basin, limited either by settling velocity or supply of material. The flux of sediment into the harbour may be enhanced by residual circulations or eddies, hence the possibility of high accretion rates. If there is significant variation in salinity at the entrance location it is possible that vertical exchange may also be important.

Examples of this type of harbour in the UK include Dover, Portland, Llanelli, Littlehampton (West Haven) and Conwy marina. As an illustration Figure 2 shows Dover Harbour and the observed flow system within the Harbour at HW -1 hour. Several eddies can be seen. Currents entering the harbour can be as much as 2 knots (1m/s) whilst currents within the harbour are seldom more than 1 knot (0.5 m/s) (Reference 7). The principal incident waves are from east and south-south west directions which can produce wave heights of up to 3m within the Harbour (Reference 8). The dredging requirement for Dover Harbour has been estimated at about 250,000 m^3 per annum (Reference 9). Approximately half of this deposited sediment is sand and half mud. Sediment suspended by waves and currents outside the Harbour is brought into the Harbour on the flood tide and deposits due to the reduced wave and current action. This process is exacerbated by the eddies that occur in the Harbour flow system. These both increase the exchange of water into and out of the Harbour and create areas of slowly moving water where accretion can occur. Wave action within the Harbour itself is significant in terms of redistributing deposited material (Reference 10). The Harbour itself is likely to have an impact on the littoral drift along the coastline.

Protected by breakwaters
In some coastal locations otherwise untenable as a harbour, construction of a breakwater can provide adequate shelter from wave activity. The harbour area in the lee of the breakwater will be fairly sheltered from waves, probably with a rapid decrease in wave height when moving from open water to the shelter of the breakwaters. There is a high probability of tidal eddies adjacent to the breakwaters, leading to slack zones, for at least half of the tidal cycle. The breakwater structures are likely to have an impact on the littoral drift along the coastline.

Examples of this type of harbour in the UK include Newhaven, Kilkeel and Aberdeen. As an illustration Figure 3 shows the layout of Newhaven Harbour. Peak currents into the Harbour are approximately 0.8m/s (Reference 11). Flood tides entering the Harbour flow from the west around the breakwater in a circular motion travelling across the shallow area to the east of the channel, before travelling up the channel into the Harbour. Ebb currents maintain a similar, but reversed course. This same shallow area is exposed to strong wave action during storms in the English channel, although the Harbour is well sheltered from direct waves by the western breakwater and waves from the South East are smaller and less frequent. The main sedimentation mechanism is the suspension of sandy sediments in the shallow region to the east of the dredged channel which can be carried into the dredged channel by spring floods. There is a source of sediment from eastward longshore drift which is able to find its way past the Newhaven breakwater either bypassing it or being carried into the dredged channel. Annual maintenance requirements for the Harbour are about 225,000m^3. Approximately 150,000m^3 is removed in Spring and a further 75,000m^3 in the Autumn.

3.1.2 Tidal harbours

Estuarine
Estuarine harbours are situated on the banks of estuaries. They are typically moderately sheltered from offshore wave action because of their estuary location, but may be exposed to local waves from certain directions. They may experience large tidal currents. Estuarine harbours are dominated by the hydrodynamics of the estuary and consequently tidal range, freshwater flow and stratification will be important issues. In most UK estuary harbours the main sediment supply is from offshore. In estuaries with large tidal ranges there may be significant redistribution of sediment within the estuary.

Examples of this type of harbour in the UK include Felixstowe, Belfast, Tees and the Humber Ports. As an illustration Figure 4 shows the present day layout of Felixstowe in the mouth of the Stour and Orwell estuaries. Wave heights in the Harbour are typically less than 0.5m whilst offshore wave heights can attain heights of 3m or more. Peak currents on a spring tide are in the range 1.0m/s to 1.5m/s (Reference 12). The main mechanism for sedimentation in the Harbour is trapping of part of the sediment flux in the dredged areas. The main sediment supply is from offshore. The trapping of sediment in the harbour may have reduced the supply of sediment to the Stour and Orwell estuaries and there is some concern that inter-tidal erosion in the estuaries is associated with the port development. Currently maintenance dredging of about 2.5 million cubic metres per year is undertaken. The dredging is undertaken in four quarterly campaigns.

Natural lagoon

Natural Lagoons are characterised by a body of water with a narrow entrance to the sea. The narrow entrance protects the lagoon from wave action. There may also be flood and ebb generated sand banks present adjacent to the entrance. If the lagoon is large then locally generated waves may be significant within the lagoon. Unless the tidal range is very small, there are likely to be strong tidal currents in the entrance with smaller currents inside. Freshwater input to the lagoon may lead to stratification and/or gravitational circulation.

Examples of this type of harbour in the UK include Poole Harbour and Portsmouth Harbour. As an illustration Figure 5 shows the natural lagoon of Poole Harbour. The Harbour exhibits a double high tide resulting in a long period when the Harbour is full and a short period of low water. Tidal currents are the main cause of sediment movement in the Harbour. Peak speeds during a spring tide are over 1m/s at the Harbour entrance and 0.7-1.0m/s in the channels within the Harbour (Reference 13). Wave heights within the Harbour are typically less than 0.2m with storm values rarely exceeding 0.5m. The typical waves are not sufficiently large to transport sediment but can prevent sediment from adhering to the bed and thus allowing transport by currents. Storm waves are able to resuspend large quantities of fine sediment from the bed and redistribute the material to the areas of lowest waves action. Waves from the South West appear to prevent mud settling in the shallow area to the East of the Little Channel. The main exception to this is near the Ro-Ro terminals where some accretion occurs. The type of sediment within the Harbour varies. The central area around the Middle Channel is sandy with gravel and stones at the Harbour entrance. The inter-tidal areas on the North-eastern shoreline and the North coast of Brownsea Island are muddy. The bed of the North Channel is a mixture of mud and sand. There are two locations requiring maintenance dredging in the Harbour, both in the Middle Channel, and at these areas a total of about 25,000 m^3/yr of fine and coarse sand is deposited. The source of sand is from outside the Harbour, the flood-dominant tide bringing in the sand from sources along the coast. There is little or no mud siltation at present because the wave action is sufficient to prevent it.

Locked

In locations with high tidal ranges, impounded berths are quite common. Vessels enter via a lock system and the berths experience very low wave activity and very low currents. The locks may remain open around times of high water or may be operated as required. Sediment enters the impounded harbour either during periods when the lock gates are open or with pumped water required to maintain water level. Nearly all the sediment entering the harbour will settle out and can only be removed by dredging. Vessel operations within the harbour will lead to redistribution of fine sediment and typically the berths used least will tend to accumulate most material. The sediment input can be reduced by using settling basins (as is the case at Portbury) and by impounding during times of naturally low suspended sediment in adjacent waters (as is the case at Tilbury). Dredging of the settling basins is still required, but can be achieved with fixed plant, which is often more cost-effective and is less likely to interfere with harbour operations. Outside the lock entrance, there may be a requirement for a breakwater to provide protection from waves or strong tidal currents for vessels using the lock. Generally there is likely to be a high rate of siltation in these bellmouths. Locked harbours are usually in areas of large tidal range, so there is the likelihood of high concentrations of suspended material in the adjacent waters.

Examples of this type of harbour in the UK include Wallasey (Mersey estuary), Portbury (Severn) and Tilbury (Thames). As an illustration Figure 6 shows the layout of Birkenhead Docks in the Mersey Estuary. The impounded water is maintained at a level approximately 1m above the HW level of mean spring tides in the estuary and water lost through locking operations is made up by pumping water from the Mersey via Wallasey impounding station into the East end of Wallasey Dock. The water flows through the Dock and enters the operational Dock system via the East Float Passage. Some of the silt contained in that water settles out of suspension in Wallasey Dock, whilst the remainder passes through the dock and settles further up the dock in the relatively still waters of the East Float and beyond. Periodic dredging is necessary to remove this silt which amounts to about 50,000m^3/yr (Reference 14).

3.2 Factors influencing hydraulic regime of a harbour

The wave and current conditions at a harbour depend on a combination of the design and topography of the harbour and the location of the harbour. In this study the factors influencing the wave and current conditions are divided (somewhat artificially) into those environmental forcing influences, which are a feature of the location of the harbour, regardless of the design of the harbour, and those factors which depend on the details of the harbour itself.

3.2.1 Tidal currents

In UK coastal waters the dominant driving force for water movement is tidal action, caused by the gravitational pull of the moon and sun. There is a gradient of the water surface caused by the tidal action that in turn causes a current. It is the surface water slope that causes the motion and hence the tidal flow is nearly uniform through depth in the absence of density effects. This is the reason why two dimensional flow models in the horizontal are frequently and successfully used for harbour sedimentation studies in UK waters (see Chapter 8).

As the tidal wave passes from the deep ocean into shallower coastal waters, it increases in amplitude and undergoes distortions due to the frictional effect of the bed and interactions between the Coriolis force and the shape of the coasts and sea bed. These factors determine the variation in tidal range at a location and influence the variation in tidal currents. For example, the mid to upper part of many estuaries is `flood-dominated', that is the peak flood currents are faster than the peak ebb currents and the flood phase of the tide persists for a shorter duration than the ebb. This is caused by the frictional effect of the bed and the fact that the speed of propagation of the tidal wave is lower in shallower water. This current pattern will then be found in any harbour situated in that part of the estuary. Flood (or ebb) dominance in tidal flows can be particularly important when considering the movement of sand as the sand flux is very strongly dependent on the fastest flow velocities.

There is often tidal complexity in UK waters. Certain tidal constituents may have null points (called amphidromic points) resulting in tides of different shape, for example a double high water in the Solent and double low water nearby at Portland. Moreover estuaries have natural periods of oscillation that may be close to the periods of some tidal constituents either causing the tide to grow in amplitude (as in the Severn Estuary) or if it is a higher constituent then the tidal profile may change shape (as in the Forth estuary).

Tidal currents vary over a number of time scales. The most important of these is usually the tidal period, approximately 12.5 hours. Also of great significance is the spring-neap cycle, with a period of approximately 14 days, caused by changes in the relative alignment of the sun, moon and earth. Spring tides, with large range and consequently fast currents, are of greatest importance in moving sand. The cycle of ranges is also important in mud transport, with suspended concentrations generally high during spring tides and the possibility of consolidation of deposits during neap tides. Longer term variations in tidal ranges occur also, with largest annual tides usually occurring close to the equinoxes. The relationship between tidal range and suspended sediment concentration is non-linear and the largest tides can inundate areas of the estuary normally unaffected (Reference 15).

3.2.2 Density effects

Seawater density is dependent on the temperature, salinity and (to a lesser extent) suspended sediment concentration. In the sea there can be thermal stratification and estuaries are, by definition, areas of salinity variation. A large range of phenomena can result from density effects. In particular gravitational circulation in estuaries results from the salinity gradient between fresh at the head and salt at the mouth. A tendency is induced towards a residual flow seaward at the surface and landward at the bed. The residual flow is typically more than ten times as large as the freshwater inflow to the estuary. This flow field, like all of the flow induced by density variations, is three dimensional in form.

Other possible density driven flows include lateral circulations in estuaries caused by salt water flooding into lower salinity water and then sinking beneath it causing a convergence of surface water (as seen in the Conwy estuary, see Section 5.4 of Reference 6). Also there can be density driven exchanges between embayments or harbours and the waters outside if the salinity varies rapidly in the adjacent body of water. The flushing of a harbour or embayment may be dominated by this three dimensional phenomena (as in the Conwy Marina, see Reference 6).

It is important to note that a whole spectrum of density effects are likely to prevail in an estuary with the annual cycles of freshwater flow superimposed upon the spring-neap cycle. The strength of the density flow depends on the relative magnitudes of the volume of fresh water input over a tide and the tidal volume. Seasonally large river discharges may change the direction of residual (tide-averaged) currents and cause peaks of current speed on the ebb which tend to move sediment seaward. If a harbour is influenced by a significant river inflow then this may in some cases act as a mechanism for flushing of sediment. Conversely high river flows lead to increased fluvial sediment input, which in certain harbours may increase the supply of sediment available to cause siltation. In most UK harbours fluvial supplies are small but in monsoonal countries the effects can be the dominant cause of siltation. Increase in the fresh water input to an estuary system usually strengthens stratification and gravitational circulation effects, which may be important in some areas as the import of sediment from marine sources into the harbour can be enhanced. A prime example of this is the re-routing of freshwater flow into Charleston Harbour in the USA in 1942 which led to a sixty-fold increase in siltation rates in the harbour (Reference 16).

3.2.3 Wind induced flows

Wind driven currents are most important when tidal currents are small. They can be an important exchange mechanism in nearly enclosed harbours. The water near the surface moves in the direction of the wind, but the currents near the bed often move in the opposite direction, driven by pressure variations. This can increase the volume of water entering or leaving a harbour thus possibly bringing in a greater supply of sediment than in still conditions.

3.2.4 Wave induced currents

When a wave breaks, the momentum of the wave is transferred to the water body to create a current, initially and locally in the direction of wave travel. The average effect of breaking waves on a beach can create quite substantial currents, by two main mechanisms. The first occurs when the waves impinge on the beach at an angle (ie not perpendicular to the beach). In this case, a component of the stress arising from the breaking wave acts along the beach, tending to create a current. The component of stress acting towards the beach leads to wave set-up, an increase in the mean water level at the beach, and this is part of the second mechanism. Variations in topography or shelter from breakwaters or headlands can cause wave set-up to be smaller at some parts of the beach than others. This leads to a mean pressure gradient (variation in water level) which can cause longshore currents and rip current systems.

Close to the shore, within the breaker zone, breaking waves can be the dominant influence on currents, which may act in some cases in the opposite direction to the tidal currents. When considering coastal harbours the influence of the harbour on wave induced currents may be the most significant impact.

The turbulence caused by breaking waves and by swash, leads to high concentrations of suspended beach material (and/or high bed load transport rates) which are responsible for movement of often large quantities of sediment along beaches. This is discussed further in Section 3.7.1.

3.3 Effect of harbour layout on current conditions

The fact that many harbours have historically been designed for wave shelter means that they often contain large areas of slow currents, which together with the calm wave conditions often provides ideal conditions for sedimentation. In this section, the effects of harbour layout on the current conditions are discussed.

A common feature of harbours is the existence of circulations, or eddies, in the flow pattern which are a result of the inertia of a flowing liquid. When presented with a sudden change in the boundaries constraining the flow, such as a harbour wall perpendicular to the flow direction, the flow will tend to continue in the same direction for some distance, entraining some of the static water behind the harbour wall. This volume of entrained water must be replaced from another part of the flow to maintain a reasonably flat water surface and this leads to the characteristic eddy structure, see for example, Figure 2. The central part of eddies generally have quite low current speeds and so are zones of possible sedimentation. Also, the flow structure is such that currents close to the bed tend to move towards the centre of the eddy, which can concentrate sediment in that area (the `tea-leaf in a cup' effect).

For nearly enclosed harbours with a single entrance, the net volume of water passing through the entrance during half a tidal cycle (ie low water to high water or vice versa) is equal to at least the tidal volume of the harbour (roughly equal to the tidal range multiplied by the enclosed plan area). Considering this together with the width and depth of the entrance gives a minimum value of the currents through the entrance. These can often be higher however due to eddying effects, whereby water can flow into the harbour at one side of the entrance simultaneously with outflow at the other side because of the speed of the adjacent currents. This increases the volume of water passing through the harbour on each tidal cycle which can in some cases increase sedimentation rates. An example of this is Conwy Marina (References 6 and 17). Salinity changes in the marina lag behind those in the estuary and as a result there are marked differences in density experienced at the marina entrance which cause vertical exchange and gravitational circulation.

The flow patterns in enclosed harbours with more than one entrance, such as Dover, can be very complex, and include features such as eddies and residual currents. Figure 2 shows observed currents in Dover Harbour at HW -1 hour on a spring tide. Various eddies are present together with jets of water entering and exiting the harbour.

Most harbours have deep channels, either natural or created and maintained by dredging. In areas of deeper water the frictional resistance to flow is less and currents can be consequently larger. The layout of the deep channel with respect to the prevailing current is important as regards sedimentation. A channel aligned with the local tidal current may benefit from a scouring effect due to reduced friction. A channel aligned perpendicular to the current will act as a sediment trap, as velocities are reduced in the channel because of the increase in depth in comparison to the sea bed on either side.

3.4 Waves

Surface waves are produced by wind blowing over the surface of the sea. The magnitude of these waves is dependent on the wind-speed, duration and the distance (known as the fetch length) over which the wind can affect the wave motion. Waves offshore of the UK coast are normally described as either wind-sea or swell. The former refers to waves generated by wind across fetches local to the coast, for example in the English Channel. Swell is waves generated distantly which then propagate towards the coast, for example those waves arriving on the south Cornish Coast which are generated in the Atlantic Ocean. Swell in general has energy at longer periods than wind-generated waves. There is considerable interaction between wind-waves and swell with energy exchange occurring between different frequencies. A discussion of the characteristics of waves offshore of the UK is presented in Reference 18.

In deep water offshore of the coast the dominating influence on the character of waves is the wind. As waves approach the shore and travel into shallower water they are increasingly affected by changes in bathymetry. The near shore effects on wave propagation include refraction, shoaling and diffraction due to depth variation, refraction by currents and energy dissipation through friction and breaking. A more detailed discussion of the physical processes of wave transformation is given in Reference 19.

Wave action within an estuary generally reduces landward. This is due to the meandering of the tidal channels, the tendency of waves to refract towards the shoreline and also the loss of energy due to friction as the wave travels through increasingly shallower water. A corollary to this is that waves generated by wind action within the estuary can be more significant to sediment transport than those propagating into the estuary from offshore.

3.5 Effect of harbour design on wave conditions

Harbour design can have a considerable effect on the nature of waves inside the harbour. A breakwater will shelter the harbour from incident waves, reducing wave heights inside the harbour, but waves may still enter the harbour as a result of refraction (due to changes in bathymetry) and/or diffraction about the breakwater. The alignment and design of breakwaters governs the extent of this refraction and diffraction and thus has a significant effect on the wave action within the harbour. Harbours tend to be associated with naturally deep or dredged channels which can also have an effect on wave-action; either through refraction, or through partial reflection of the incident wave which occurs due to the rapid change in bathymetry. The effect of harbour design on the wave environment of the harbour means that it also has a great effect on the sediment transport system within the harbour. There are various methods that are employed in harbours to absorb wave energy, such as spending beaches and partially reflecting structures and these will all have an effect on sedimentation.

3.6 Classification of sediment type

Marine sediments are generally classified in two ways: as cohesive or non-cohesive and by grain size. Cohesive sediments are composed mainly of silt and clay and so contain a large proportion of very small particles. These particles have a large surface area such that the effect of the surface physico-chemical forces becomes as important as the effect of gravitational forces. Flocculation occurs when the net physico-chemical inter particle forces become attractive and particles come into contact with each other. Cohesion is determined by the balance of the short-range attractive forces of the clay and the repulsive forces generated by the cloud of cations around the particles, which depend upon the mineral composition and the types of cations present in the suspending fluid. Collisions of particles are the result of Brownian motion of suspended particles, internal shear of the water and differential settling velocities of the particles or flocs. However, the size of flocs formed by collisions is limited by the maximum rate of internal shear that the flocs can withstand. Non-cohesive sediments are coarser in nature and their behaviour is dominated by gravitational forces. In nature the distribution of sediment is rarely homogeneous and mixtures of muds and sands are often encountered. Non-cohesive sediments can be stabilised by the presence of cohesive material.

Sediment samples will generally involve a range of grain sizes and often contain sediments of different types. A variety of schemes exist for describing such mixtures, in terms of percentage of the grains under a particular size or the grain diameter which is larger than a certain percentage of the grains (d_{50}, d_{90} etc). Mixtures of sediment types can be classified according to the modified Folk scheme. For example a sediment which is predominantly sand, but including up to 50% mud is described as muddy sand. This scheme is described in full in the Manual of Marine Sands (Reference 20). The composition of a sediment is usually derived by analysing samples of bed and suspended material using sieving or in the case of smaller particles, laser measurement.

For the purposes of the description of sediment transport, sediment will hence be referred to as either mud (cohesive) or sand (non-cohesive). As noted in Section 1.2 in this report the term siltation refers to the accumulation of mud whereas the term sedimentation refers to the accumulation of any material.

3.7 Sediment transport mechanisms

3.7.1 Sand transport - Bed and suspended load

Sediment transport occurs as a result of the shear stress imposed on the bed by the flow of water above it, or by the action of waves, or a combination of both. Sand transport occurs in two ways. The first is described as `bedload'. Those grains which are too large to be completely entrained by the current (or waves) into the upper water column, but yet small enough to be moved by the current at the bed move along the bed by a series of small jumps (saltation), or by rolling. The second is described as `suspended load' and consists of smaller particles being entrained into the upper water column where they move in suspension according to the currents they experience, until the current speed decreases and the particles descend through the water column as a result of gravitational force. The speed at which the particles fall depends primarily on grain size and tends to be larger for sand than mud by orders of magnitude. Sand particles may then deposit on the bed until re-entrained by the current once more. In a tidal environment the net movement of sand over a tide is the resultant of sand movements in different directions on the flood and ebb.

A common mechanism of sedimentation in harbours is the mobilisation of sediment by waves outside the harbour, this sediment being carried into the harbour by currents and then deposited in areas sheltered from wave-action.

3.7.2 Sand transport - Littoral drift

The action of breaking waves on beaches can cause the movement of large amounts of sediment along the beach, the material being typically sand or gravel. As described in Section 3.3.4, breaking waves usually cause longshore currents, which increase in strength with the angle between the breaker and the shoreline. In addition, the high energy turbulent flows which result from a breaking wave are responsible for mobilising large quantities of sediment which is then carried by the longshore current. Observations indicate that the highest suspended sand concentrations occur at the point of breaking and in the swash zone at the top of the beach. The combination of this with the cross-beach profile of the longshore current results in the peak sediment transport rate most commonly occurring in the offshore half of the area between the breaker zone and the shore. Rip currents carry sediment offshore, as can the flow and wave conditions at headlands.

A large structure such as a coastal harbour which extends seaward past the breaker zone will act as a block to littoral drift, usually leading to accretion of beach material at the up drift side of the harbour and erosion at the down drift side. A smaller harbour which does not block littoral drift, is likely to intercept some of the longshore transport at the harbour entrance or approach channel. The fact that waves can propagate into the harbour entrance, so generally do not break in the entrance area, and the presence of a deeper entrance channel which means less wave stirring at the bed, result in the accumulation of sand in the entrance of the harbour. This sand may then move into the harbour or offshore, or perhaps both, in response to the current pattern at the entrance. The problems caused by the interception or blocking of littoral drift can be ameliorated by sand bypassing, whereby sand is moved artificially from the up drift side of the harbour to the down drift side. This can be effected by a dredger or by land-based plant.

3.7.3 Mud transport processes

Cohesive sediment can be considered to exist in four states - mobile suspended sediment, a near bed stationary suspension of high concentration with a small cohesion referred to as `fluid mud', a partially consolidated bed and as a settled bed.

The transport of mud consists of the entrainment of mud from the bed, when the current-imposed (and/or wave-imposed) shear stress is sufficiently strong to break bonds between flocs, and the suspension of the break-away flocs into the water column. These flocs, now in suspension, may in time collide with other flocs in suspension and coalesce. When current speeds decline, the weight of the flocs will cause them to drop at a rate depending on their size and density. The flocs may then deposit on the bed and consolidate until re-suspended by a current of sufficient magnitude. The transport of mud differs from sand in the absence of bedload, slower settling velocities, and a lower threshold of current-induced shear stress before which deposition can occur. However, as mud consolidates the shear stress needed to suspend it increases.

As a rule, increased levels of suspended sediment concentration lead to increased deposition during slack water. However, where suspended sediment levels are very high (such as 5 kg/m^3) a layer of very thick, liquid-like mud can be produced at slack water, known as fluid mud. The fluid-mud acts like a liquid in that it will flow downhill or in the direction of the water surface slope. It can also be produced in situations where a muddy bed experiences sufficient wave action to break the bonds between flocs on the bed but not to entrain them into the water column (fluidisation). This feature can be important where dredging has been carried out in muddy environments (Reference 21). Fluid mud forming in the vicinity can flow right into the dredged area. A good example of this is at Kumamoto Harbour in Japan (Reference 22). A similar effect can occur where the banks of a muddy channel slump into the middle of the channel producing a thick layer of mud that responds like fluid mud (for example the Avon Estuary).

The most typical mechanism for siltation in harbours is similar to that of sand - mud carried into the harbour in suspension is deposited in areas where currents are low and/or wave-action is much reduced. Such siltation can be enhanced by eddies in the harbour and the `tea-leaf' effect described in Section 3.3 which has a trapping effect on sediment.

Mud deposited on the bed will consolidate under its own weight. This process consists of the expulsion of the pore water and the compression of the floc matrix to form a structure of higher dry density and lower permeability. Generally the consolidation process results in a density profile that increases with depth below the surface and with time.

The density structure of muddy beds varies considerably between sites and at any particular site. The sand content of the muddy bed is an important factor with dry density generally increasing with the proportion of sand present. In a navigation channel experiencing continual siltation the dry density could increase from 200kg/m^3 near the surface to 500kg/m^3 at a depth of 1m. An inter-tidal mudflat, however, is likely to have a near surface dry density of 500kg/m^3 and a dry density of approximately 1,000kg/m^3 at a depth of 1m. Some inter-tidal mudflats attain relatively high densities within a few cm of the surface. The transitory soft deposits that form during a single slack water may initially have a dry density of only 100kg/m^3.

4 Information for an assessment of harbour sedimentation

4.1 Information requirements and sources

4.1.1 Type of information available

A variety of sources of information should be considered as part of an assessment of harbour sedimentation. The importance of different sources will depend upon the complexity of the sedimentation mechanisms likely to occur at a particular site. Ideally it will be possible to visit the site and undertake some simple measurements as part of an initial assessment however, in some cases, particularly those associated with small overseas developments, this will not be possible. The following section outlines the type of information that should be sought during the initial stages of the assessment process prior to defining the requirements for further data collection or modelling.

The initial approach to the assessment will depend upon the availability of data (including existing models and field measurements) and upon the question that is being asked by the Port Operator or Consulting Engineer. An important aspect is to what extent the assessment of harbour sedimentation is able to interact with other potentially parallel studies associated with safe navigation, berth tenability, environmental impact and the design of structures (see also Section 2.2).

4.1.2 Information on the harbour facility

The following general information will be useful for the initial study of sedimentation at the harbour:

- Drawings showing the layout of the harbour
- Aerial photographs of the site
- Bathymetric surveys of the site
- Information on harbour operations (lock operation, turning areas, ferry traffic)
- Information on past and present dredging requirements
- Information on dredging volumes
- Information on material dredged
- Information on disposal site(s)
- Information on episodic sedimentation rates
- Information on seasonal variations in conditions
- Information on river discharges in the vicinity of the harbour
- Information on local coastal processes (erosion of cliffs, intertidals, marshes, mangroves)
- Information from other nearby harbours
- Information on navigation issues at the port (currents, waves and wind)
- Information on the types of vessels using the harbour
- Anecdotal information from other users of the local waters (normally fishermen)

This information is likely to be readily available and can most satisfactorily be obtained through a site visit and appropriate consultations. Note that not all the information will be available in all cases.

These different data sources are discussed in Section 4.2.2

4.1.3 Information on the local hydrodynamic regime

Information initially available concerning the layout and operations at the site will inevitably provide some detail of the hydrodynamic conditions at the site. However, it will be necessary to consider the following as part of the assessment.

- Tidal range at the harbour
- Tidal volume of harbour (if enclosed)
- Tidal currents (direction and speed) in and adjacent to the harbour
- Flow patterns throughout the tide in and adjacent to the harbour (eddies etc)
- Wave climate (height, period and % occurrence) in and adjacent to the harbour
- Density variations in the harbour and adjacent waters (importance of stratification)
- Importance of wind induced flows in the harbour area

Useful sources for such information include:

- Admiralty Charts
- Admiralty Tide tables
- Admiralty Pilot
- Data from local Harbour Authority
- Data from local Pilots
- Previous studies and measurements
- Data from local research organisations (typically Universities)
- Observational data from the Meteorological Office
- Data from Meteorological Office wave model
- Data from local airports (wind speeds)
- Aerial photographs
- Remotely sensed images (Satellite, CASI data)

During an initial site visit some simple measurements can generally be made but mounting an extensive field survey should ideally be undertaken on a separate occasion after consideration of the requirements for the survey (see Chapter 7).

These different data sources are discussed in Section 4.2.3

Note that collation of available information may identify that field data may already exist and predictive modelling studies may have been undertaken previously at the site. Consideration should be given to fully utilising data available from such sources should they exist.

4.1.4 Information on the local sediment regime

Information concerning the layout and operations at an existing harbour will provide some information about the sediment regime at the site. However, the following should also be considered:

- Identification of material causing sedimentation
- Natural suspended sediment concentrations at the site
- Natural variability of suspended sediment concentrations at the site
- Potential sources of suspended sediment adjacent to the harbour
- Magnitude and direction of littoral movements adjacent to and within the harbour
- Importance of river flow on sediment supply
- Importance of wave action on sediment supply
- Importance of fluid mud as a sediment transport process
- Importance of vessel operations as a mechanism for re-distributing sediment
- potential for slumping of sea bed.

Useful sources for such information include:

- Admiralty Charts
- Ordnance Survey maps (for low and high water positions)
- Admiralty Pilot (information on anchorage areas and requirements for dredging)
- Data from local Harbour Authority (dredging and type of material)
- Data from MAFF public record of offshore licensed disposal sites
- Information from Dredging Contractors concerning materials dredged
- Data from local Pilots (seasonal changes in navigability etc)
- Previous studies and measurements
- Data from local research organisations (typically Universities)
- Aerial photographs
- Remotely sensed images (Satellite, CASI data)
- Information from geological surveys
- Information from geotechnical surveys for existing and proposed structures

These different data sources are discussed in Section 4.2.4.

During an initial site visit some simple measurements can generally be made including sampling of bed material to examine potential sources of sedimentation. However, as with hydrodynamic data mounting an extensive field survey should ideally be undertaken on a separate occasion after consideration of the requirements for the survey.

Note that water sampling as part of an initial site visit can be informative, but it should be borne in mind that there may be considerable natural variability in the suspended sediment concentrations at the site. It is as important to try to assess this variability as it is to make measurements of the conditions pertaining on a particular occasion.

4.2 Discussion of the available data

This section aims to outline the use to which the various data described in Sections 4.1.2 to 4.1.4 can be put. This section obviously can not be exhaustive and should be considered more as a cautionary checklist. The analysis and assessment of the available information consists of four stages:

i) Understanding the layout and operations of the existing/proposed development
ii) Gaining an insight into the important sedimentation mechanisms at the site

iii) Quantifying where appropriate the magnitude of the sedimentation associated with the different mechanisms
iv) Making appropriate recommendations for further investigations if required.

4.2.1 Assessing information on the harbour facility

The following sections briefly discuss some of the issues associated with assessing the data described in Section 4.1.2.

<u>Drawings/Charts showing the layout of the harbour</u>
From the drawings and discussion with the Client or Consulting Engineer it should be possible to understand the layout of the existing and/or proposed development.

It may also be appropriate to use a series of drawings to gain insight into the historical development of the harbour.

<u>Aerial photographs of the port</u>
These may provide further clarification of the existing layout. Ideally the state of tide and information on other environmental data is available for the time of the photograph.

<u>Bathymetric surveys of the harbour</u>
These are important if they exist. A series of bathymetric surveys may enable identification of areas of accretion and erosion. It is however, important to note that harbour operations and dredging practice may have changed over the duration of a number of surveys. It should also be noted that the bathymetric surveys will almost certainly not cover all of the area of interest. For example, inter-tidal banks are rarely surveyed by a harbour authority. Note also that the bathymetric surveys, particularly those shown on Admiralty Charts are for purposes of safe navigation and may tend to emphasise areas where soundings indicate shallow depths.

<u>Information on harbour operations</u>
Clarification of operational procedures associated with the development is important. This includes confirmation of the manner in which vessels manoeuvre, whether there are any particular practices associated with ferry traffic (which tends to move time and not to tide) and how lock gates are operated (for example are they left open at high water) and where does make-up water comes from and at what stages of the tide does pumping occur.

<u>Information on past and present dredging requirements</u>
Dredging practice will be dominated by the requirements for harbour operations. Consequently dredging records need to be interpreted with care. This is particularly so in harbours where dredging is undertaken infrequently. The dredging may be associated with economic factors in such cases. However, discussion of past and present dredging practice is one of the most useful parts of the analysis of sedimentation at an existing harbour. At a new site it may be appropriate to discuss dredging practice at a nearby harbour.

<u>Information on dredging volumes</u>
In addition to discussions with the harbour operator information on dredging volumes may be available from other sources such as national data bases. In the United Kingdom the Ministry of Agriculture Fisheries and Food hold a public register of the volumes of material placed at the offshore disposal sites which they licence (Reference 23).

It is important when considering dredging volumes to be aware of the different means that exist whereby volumes of material can be calculated. These include hopper tonnes and in-situ volumes. Ideally, for purposes of sedimentation assessment, an estimate of the in-situ dry density of the material dredged and in the hopper should be used to estimate the mass of solids removed by dredging.

Information on material dredged
In addition to the comment above relating to dry density, it is always useful to know what type of material is dredged and whether there are any significant variations in material properties throughout the area of interest. For example in a marina basin there may be a sand bar at the entrance with silt and muddy material in the basin. In a large basin there may be a significant variation in bulk density of the silty material.

Information on disposal site(s)
In order to develop an understanding of the dredging operation at a particular harbour and to identify whether aspects of the dredging practice are associated with the sedimentation in the harbour it is important to be aware of the manner in which material dredged from the harbour, and elsewhere in the vicinity, is disposed. In the UK this information can be obtained readily from MAFF (Reference 23). Elsewhere it can be very difficult to find sources for this data.

Information on episodic sedimentation rates
The port operators will know whether they suffer severe episodic sedimentation following particular environmental conditions. The operator will not know, unless they undertake regular surveys, if they suffer from ongoing sedimentation associated with a particular set of environmental circumstances. Consequently, just because the port operator is not aware of an episodic sedimentation process does not imply that it is not important or that it does not occur.

Information on seasonal variations in conditions
In the UK there are only limited seasonal variations in environmental conditions. In tropical or more polar countries these variations can be extreme. It is important that an understanding of how severe these variations are is established through discussion with local operators. For example, fishermen using an estuary for shelter may acknowledge that for parts of a monsoon season they cannot safely navigate the entrance to the estuary because of changes to a sand bar and wave conditions at the mouth. In other locations it may be recognised that when the local rivers are in full spate the whole area is inundated and normal vessel operations are impossible.

Information on river discharges in the vicinity of the harbour
In areas where there can be very variable freshwater flow it is important to have an estimate of the magnitude of the potential flow and an insight into how much material might be carried by the river in spate. In many countries data bases are being established for this type of information. This type of information is therefore often available if the source can be identified.

With respect to river flows it is also important to identify whether there is likely to be significant seasonal stratification in the area of interest. Should this exist then a number of additional possibilities exist for sedimentation mechanisms in the harbour associated with density induced currents.

Information on local coastal processes

Information, anecdotal or otherwise, on the environment adjacent to the harbour location is always important. Whilst this information may not in itself help to identify sedimentation mechanisms at the harbour it will help to place the sedimentation at the harbour in the context of the natural variability of the site. For most ports some environmental concerns over the port operations will exist. An understanding of the local environment will enable the impact of the port operation to be placed in its proper context.

Features to consider include: coastline change, cliffs, salt marshes, inter-tidal mud flats, mangrove areas, sand banks and bars and positions of low water channels.

Information from other nearby harbours

For new developments information from other nearby harbours can often be an initial source of local data. However, the information should be treated with caution since local conditions can vary quite significantly.

Information on navigation issues at the port

An assessment of sedimentation at a harbour is often undertaken in parallel to other aspects of the design and operation of the harbour. Consequently information associated with navigation in the harbour can be useful. For example, if it is acknowledged that there is presently some difficulty with operations then any solutions proposed to alleviate sedimentation should ideally try to incorporate improvements in navigability as well.

In some cases the environmental issues associated with navigation may be the same as those associated with the sedimentation. For example the formation of strong eddies in the approaches to a berth because of the particular layout of the harbour.

Information on the types of vessels using the harbour

If the type or number of vessel operating in the harbour changes then there may be consequential impacts on sedimentation. Vessels transiting an approach channel will tend to resuspend soft material from the channel. If the underkeel clearance of vessels transiting the channel increases this may lead to a reduction in the natural scouring of a particular area.

Locking operations are associated with shipping traffic. Less vessels require fewer lock operations and less make-up water, consequently sedimentation should reduce in an impounded area. Changes in berth occupancy can affect dredging requirements and may therefore reflect in simple analyses of dredging records and bathymetric surveys.

Anecdotal information from other users of the local waters

A variety of local people will hold valuable information associated with the particular area of interest. It is important that anecdotal information received can be filtered and judged appropriately. It is always sensible that the Client is made aware of individuals with whom it is proposed to hold discussions or who have contributed information.

4.2.2 *Assessing information on the local hydrodynamic regime*

The following sections briefly discuss some of the issues associated with assessing sources of hydrodynamic data.

Tidal range at the harbour

This information can normally be obtained from Admiralty Charts or Pilots. For sedimentation assessments it is not necessary to obtain tidal harmonics. However, should further investigations be required this data can be useful.

Tidal volume of enclosed harbour

A simple assessment of the tidal exchange mechanism can be made by calculating the tidal volume of an enclosed harbour. Note that the volume calculated will need to be appraised with respect to residence times and the possibility of horizontal and vertical circulation at the harbour entrance enhancing the exchange.

This approach enables estimates to be made of the tidal currents at the harbour entrance and an initial estimate of the amount of silt that might enter and accumulate in the harbour when appropriate assumptions are made concerning settling rates.

Tidal currents (direction and speed) in and adjacent to the harbour

Admiralty Charts and Pilots may indicate the magnitude of such currents for existing harbours. The harbour staff may also have a view of the strength of such currents, particularly if they cause concern to navigation. However, it is most sensible to undertake measurements of the currents using an appropriate instrument if such data does not exist.

Note that in some cases the Admiralty data is very old. If there have been significant developments (such as dredging of approach channels or natural migration of sand banks) then the data may be unreliable.

Flow patterns throughout the tide in and adjacent to the harbour

Insight into flow patterns in the area of interest can come from an analysis of various measurements but this is not normally achieved during the assessment stage. The concern here is to identify whether there are any features of the harbour layout which result in generation of areas of slack water or areas of recirculation. If such areas are deemed to exist limited measurements may identify the presence of such flow patterns during stages of the tide. Harbour staff may be aware of such features and Tidal Atlases may exist for purposes of Pilotage.

For new developments the presence of such features can normally only be hypothesised by recourse to predictive modelling techniques (see Chapter 8).

Wave climate (height, period and % occurrence) in and adjacent to the harbour

Wave height distributions within a harbour can normally only be determined using predictive modelling (see Chapter 8). However, studies may already be in existence of the wave heights within the harbour or anecdotal information may exist.

More importantly, wave conditions in the approaches to a harbour, particularly at the bar at the mouth of an estuary, will be required when assessing the mobility of sediment at the bar.

Assessment of the impact of a coastal harbour on coastline evolution will require wave climate data. Wave data can be obtained from the UK Meterological Office either from model output or from records of Voluntary Ship Observations.

Salinity variations in the harbour and adjacent waters
Under some circumstances salinity variations either through depth or through tide can be a significant factor in controlling the sedimentation in a harbour. Significant through tide salinity variations may exist in estuaries with large tidal ranges, for example the Conwy Estuary. Vertical stratification may occur in estuaries with smaller tidal ranges and a significant freshwater flow. In coastal zones high freshwater discharges from an estuary may influence local stratification in the water column for periods of the year.

Measurements of salinity can be made during the assessment stage particularly if the variations are through tide. With episodic or seasonal variations it is harder to organise a site visit to coincide with the phenomena and a dedicated set of measurements may be required. Knowledge of the tidal range and the freshwater discharge can provide a basis for considering the importance of density effects on the sedimentation process.

In some cases salinity effects may become important because of a modification to the harbour layout. For example diversion of freshwater flow into an impounded dock so as to reduce the requirements for make-up water.

Importance of wave induced flows in the harbour area
In some coastal areas with small tidal ranges, for example the Mediterranean, the only significant currents are those generated by wave action on the coastline or associated with meteorological conditions. It is important to be able to quantify such currents. Typically a predictive model will be required for this. The magnitude of these currents will reduce in deeper water and the bypassing of sediment around structures associated with harbour development can be entirely dependent upon such forces.

Knowledge of the wave climate at a site is important in order to be able to predict the wave induced flows. Wave data can be obtained from the UK Meterological Office either from model output or from records of Voluntary Ship Observations.

Importance of wind induced flows in the harbour area
In some areas wind may be the most important driving force for currents. Again predictive models and an understanding of the wind climate at the site is important in order to predict the hydrodynamic forces at the site. Wind data can be obtained from the UK Meterological Office or the actual site itself.

Meterological induced flows in the harbour area
In tropical areas of the world seasonal oceanic currents may be the predominant driving mechanisms for regional sediment transport. Seasonal flows are generally well documented in Admiralty Pilots.

In some locations storm action may be associated with typical movements of weather systems. The moving weather system may in itself be responsible for generating significant along shore flows. Such occasions may generate movements of water many times larger than those generated by the associated storm waves. Site specific investigations (measurements or modelling) are required to identify such phenomena.

Previous studies at the site
Valuable information for the area of interest may already exist. A harbour authority or other local organisation should know of the existence of particularly relevant information. However, often such valuable sources of information are overlooked. Tracking them down can be a matter of identifying likely organisations which might have undertaken work. If work has been undertaken it is nowadays unlikely that the data or results will be provided without some type of enumeration.

Aerial photographs and remote sensing
Aerial photographs and images produced from remotely sensed data can provide useful insight into physical phenomena occurring in the area of interest. Many images appear to show plumes of sediment in near shore water. Careful analysis of such images may help to identify sources of sediment.

4.2.3 Assessing information on the local sediment regime

The information described in Sections 4.2.2 and 4.2.3 provides the basic input data to an analysis of the importance of the different sedimentation mechanisms described in Chapter 5. However some additional data is required which pertains to the potential sources and types of sediment at the site. A discussion of possible data sources is given in the following sections.

Samples of bed material at the site
Some information may be available with respect to material type from dredging operations, however it is always worthwhile to undertake a bed sampling exercise as part of the initial stage to identify potential sources of material that might cause sedimentation in the harbour development. If the sampling is being undertaken by an experienced sedimentation specialist detailed particle size analysis of the samples may not be necessary. However, if the sampling is being undertaken by others it is usually best to prescribe full particle size and bulk density analysis of all of the samples obtained. If a specialist is involved then the specification for the area to be sampled can be established on site. If the sampling has to be specified then it is necessary to include coverage over a large area particularly when the sediment types are variable. It is always sensible to sample in the shallowest water in the vicinity of the site so as to be able to consider the importance of wave mobilisation of bed material.

The Admiralty Pilot often comments broadly on sediment types, especially in anchorage areas. Admiralty Charts also generally provide an indication of bed material type.

Mobile bed features such as sand waves are also noteworthy, their presence, particularly if large, may have been detected on regular bathymetric surveys for safe navigation.

Samples of suspended sediment at the site
Obtaining very near bed (0.5m or less) samples of suspended sediment usually requires specialist equipment and should not normally be considered as part of the initial site visit. Analysis of bed samples and an understanding of the hydrodynamic climate at the site can be used initially to assess the likelihood of bed material being mobilised at the site.

The aim of water sampling at a site is to gain an initial insight of the likely range of suspended sediment naturally in the water column at the site. It must of course be noted that there is likely to be a very high variability in such concentrations associated with the sources of material, tidal range, wind and wave direction and freshwater inputs. A single set of measurements should not therefore be taken as anything more than an indication of the range of suspended sediment at a site.

As part of an initial assessment it is therefore not considered necessary to undertake extensive water sampling unless this can be achieved over a large scale either temporally or spatially. For example at a coastal location suspended sediment concentrations may be higher inshore than offshore because of wave activity. Samples along sections perpendicular to the coast can therefore be valuable to obtain during an initial site visit.

In other locations it may be possible for someone to collect a series of simple water samples at a given state of the tide over a period of a few months to provide some insight into the natural variability at the site. It is sensible for repeat measurements to be made on spring, mean and neap tides and if possible following storm activity or periods of high freshwater flow (if appropriate).

Further information about suspended sediment sampling strategies is provided in Sections 7.3 and 7.4.

<u>Littoral drift at the site</u>
In some locations the main sedimentation mechanism will be associated with the natural movement of sediments along the coastline driven by wave action. In situations where this is likely to be important then samples of beach material and the cross-shore profile of the beach are necessary. Identification of the build up of material against structures is also useful. In some areas local authorities may have established monitoring programmes to investigate the variability of beach shape. If available this data should be utilised.

Quantification of littoral drift requires knowledge of the near shore wave climate and application of an appropriate sediment transport formula (Reference 24).

<u>River borne sediment</u>
Whilst it may be possible to find records of peak discharges in a river system it is not normal to find associated records or relationships from which to establish the sediment load of the river during the periods of flood.

However, some approximations can be made. For example it can be assumed that the flow is completely saturated with non-cohesive sediment. Application of an appropriate sediment transport relationship will then enable estimation of the sediment load. Transport of cohesive material is more difficult to assess but a hypothetical vertical profile of suspended sediment concentration can be assumed to estimate cohesive sediment load.

In developing areas the rates of upstream erosion can be used to estimate the annual flux of sediment into the river system.

Presence of fluid mud
The generation of fluid mud either from deposition from high concentrations of suspended sediment or by fluidisation of the sea bed by wave action may be an important mechanism at some sites (see References 21 and 22).

During the assessment stage it is unlikely that direct evidence of fluid mud will be found. However, important evidence includes the inability to maintain steep sided channels in cohesive material, rapid infill of dredged areas with mud following storms or floods and the presence of very low density muddy sediments at rather uniform gradients in shallow water on the sea bed in areas where large waves can occur.

4.3 Summary
The information presented in this chapter should be considered as a checklist. It is unlikely in any one particular case that it is practical or possible to obtain all the information described. However, by being aware of the importance and value of different types of data it should be possible to optimise the efficiency with which data can be obtained from different sources. The use of these lists can be particularly effective when arranging an overseas visit.

5 Undertaking an assessment of harbour sedimentation

5.1 Stages in an assessment
Within this report the assessment process is recognised as a basis for understanding harbour sedimentation. The assessment process does not just occur at the onset of an investigation, it is revisited as more information becomes available from field investigations (described in Chapter 7) and predictive modelling (described in Chapter 8). The assessment process is also revisited as the different aspects of a project are investigated. Figure 1 shows this process schematically.

In this chapter the aim is to outline some of the key steps in the assessment process. The assessment process is broken down as shown in Figure 1 with the three stages being identification of main sedimentation mechanisms (Section 5.3), quantification of the sedimentation rate (Section 5.4) and finally optimisation of the harbour layout and operation (Section 5.5). Depending upon the particular circumstances there may also be a requirement for an initial scoping phase (see Section 5.2)

At the onset of an investigation the level of study required is often prescribed by the Client/Consulting Engineer. Whilst this should not be adhered to rigidly it must be acknowledged that in order for a Consultant to undertake the work they will have to be broadly in agreement with the Client's approach. This is not to say that a Consultant should blindly accept the requirement for detailed studies particularly recommendations as to modelling methodology or field investigations. Similarly the Client may need to be informed that a desk based assessment will be insufficient to meet his requirements.

The central theme of this study is that a unified approach to assessment of harbour sedimentation is appropriate irrespective of whether the investigations are entirely desk based or utilise state-of-the-art field investigation and modelling techniques.

5.2 Scoping - The initial stage of assessment

The initial stage of the assessment process is a review of available data and recommendations as to the way in which the study should proceed. For many UK sites this part of the assessment is actually undertaken when a Consultant puts a proposal to the Client. For overseas sites there may be almost no useful information readily available and the first part of the studies recommended must include an initial assessment of available data.

Various data sources have been described in Chapter 4. At the onset of a study, possibly following an initial enquiry but prior to making a site visit, it is appropriate to consider what data may already exist for the site. This information can be used as the basis for an initial pass through the three stages of assessment identified in Figure 1.

Based on this initial information the needs of further data gathering can be considered. The aim being here to identify the requirements for a site visit. The questions which need to be addressed are, for example: Is sufficient information already available that a small targeted set of field measurements could provide the final input to identify the main mechanism of sedimentation? Is a more general visit required to simply view the site, make some measurements and hold discussions with key individuals? Alternatively perhaps sufficient information is available with which to identify the mechanisms and the main requirement is predictive modelling to quantify and investigate the impacts of different schemes for optimising the layout?

Every prospective investigation into harbour sedimentation that the Consultant encounters will require an evaluation of what is already known. The experienced Consultant will be able to optimise the approach based initially on relatively small amounts of information. This will allow identification of key issues for a particular site that must be resolved in order to proceed with the assessment. Ideally when such issues are encountered, a number of alternatives are obtained for resolving them to a level where sufficient information is available to proceed with the engineering studies. For example, at most sites it will be impractical to make measurements of wave conditions in the field for long enough to derive a wave climate for purposes of investigating littoral drift or wave induced currents. If such data is required then recourse to predicted wave climates should be considered.

Based on an initial assessment of data, usually at the time of producing a proposal for the assessment studies, the Consultant must decide on one of the following courses of action:

i) to recommend an initial site visit, including simple measurements and consultation, followed by a scoping exercise which will lead to defining the requirements for further studies.
ii) to recommend a site visit, including simple measurements and consultation, which will be a sufficient basis from which to undertake all the assessment required.

iii) to recommend detailed field measurements required as input to a desk based study which will provide the basis for undertaking all the assessment required.
iv) to recommend a modelling study for which all the required data exists and which will provide the basis for undertaking all the assessment required.
v) to recommend detailed field measurements required as input to a modelling study which will provide the basis for undertaking all the assessment required.

Practical experience is generally the basis for determining which recommendation is made. This is particularly important when considering options which do not include modelling on which to base quantification and optimisation. The requirements for undertaking detailed field measurements (see Chapter 7) are usually obvious; if nothing is known about a particular phenomena and it can be practically measured it may be appropriate to recommend measurements. The requirements for undertaking predictive modelling (see Chapter 8) depend largely upon the site location and the details of the harbour layout under consideration. The discussions in the following sections will aid confirmation of the appropriate recommendation.

5.3 Assessment of important sedimentation mechanisms

Table 1 summarises the main mechanisms that need to be considered in terms of the mobilising force, the mobilisation mechanism, the advection mechanism and the mechanisms leading to deposition. The reader is referred to References 20 and 25 for methods to quantify the importance of the different mechanisms. The algorithms presented in these manuals can be used as the basis of desk assessments. Various models described in Chapter 8 can be used to represent the processes described.

5.3.1 Mobilising forces

The following forces are recognised as being able to mobilise sediment:

- wave action alone
- the combined effects of waves and currents
- currents alone
- wind
- operational activities (including vessel movement and dredging)
- bank stability
- ecological processes

A general review of the harbour layout and hydrodynamic regime in and adjacent to the harbour will enable the importance of these forces to be identified. The reader is referred to References 20 and 25 for further detail.

5.3.2 Mobilising mechanisms

The following mechanisms generally account for mobilisation of bed material by the forces listed in Section 5.3.1:

- wave breaking
- wave stirring
- fluidisation of a muddy bed by wave action
- creation of a fluid mud layer by rapid deposition
- erosion of bed by currents
- pick up of material by wind

- fluvial discharge of sediment
- re-suspension by dredging activity
- re-suspension by vessel movements
- slumping of sea bed (dredged channels and inter-tidal mud flats)
- bioturbation

A general review of the harbour layout and the sediment types in and adjacent to the harbour will enable the importance of these different mobilising mechanisms to be gauged.

5.3.3 Advection mechanisms

The following mechanisms account for the movement of material from the point of mobilisation to the harbour:

- wave-driven flow
- littoral drift
- wind driven flow
- meteorological induced flow
- tidal currents
- near bed flow
- density currents
- mixing/dispersion of material in suspension
- localised secondary flows
- fluvial flow
- vessel induced currents
- movement of fluid mud

Consideration of the layout of the harbour and the local hydrodynamics will enable the most important of these advection mechanisms to be identified.

5.3.4 Mechanisms resulting in sedimentation

The following mechanisms can account for the deposition of material within the harbour:

- reduction of wave breaking
- reduction of wave-driven flow
- interception of littoral drift
- reduction of wave stirring
- reduction of tidal flows
- interception of fluid mud
- interception of bed load
- deposition from suspension
- interception of wind-load
- interception of material from slumping
- ecological stabilisation of sediments

By considering the material likely to be entering the harbour (sand, mud or fluid mud) and the different mechanisms through which the material is advected into the harbour it is possible to establish the importance of the mechanisms whereby material will deposit in the harbour.

5.3.5 *Requirements for field investigations and predictive modelling*

If required further field investigations (see Chapter 6) or computational modelling (see Chapter 7) can be used provide quantification of the importance of these different mechanisms. Note that in cases where the presence of the harbour development may significantly affect the advection patterns then predictive hydrodynamic (waves and currents) modelling will be required.

5.4 Assessment of quantities of sedimentation

5.4.1 *Number of important mechanisms*

Assessment of the quantity of sedimentation requires putting into context the various different mechanisms that may be contributing to the sedimentation. For example, if the only mechanism for sedimentation is associated with the input of impounding water to a locked dock system, quantification can be undertaken if the volumes of impounded water and the levels of suspended sediment in that water can be established with some degree of accuracy. Such quantification lends itself to establishing the impounding requirements and field measurement of the natural variability of the suspended solids content at the intake location at the times when impounding can be undertaken. This assessment is, in theory, relatively straight forward although in practice fraught with difficulties associated with the field measurements (see Section 7.4).

In cases where a number of processes are important which all relate to the hydrodynamic regime (waves and currents) and where the hydrodynamic regime will be significantly modified by construction of a new harbour development then the study is likely to revolve around computational modelling of the impact of the development on the hydrodynamics (see Sections 8.3 to 8.6). This will be combined with quantification of the sedimentation associated with the different combinations of wave and flow conditions. Probabilistic analysis of the results can then lead to quantification of sedimentation. Note that when undertaking such probabilistic approaches it also worthwhile considering the sedimentation that can occur during a single event, such as the annual storm, as well as over a longer period represented by average annual or seasonal conditions.

5.4.2 *Appropriate level of quantification*

Quantification of sedimentation will not normally lead to a single answer. In nearly all cases it is most appropriate to provide an answer in the form of a range or an upper limit (for example, up to 0.5m a year). It is acceptable to quote ranges because this represents the uncertainty in the understanding of many of the processes involved. For example, in the relatively simple situation where sedimentation is associated entirely with silt entering an enclosed harbour basin with the rise and fall of the tide and where it has been established that there is no additional exchange of water associated with vertical or horizontal flow structures at the harbour entrance, uncertainties exist in the natural variability of the silt supply in suspension and the rate at which the silt that enters the harbour settles. If the variability in supply were quantifiable a worst case could be assumed where all the sediment entering the harbour deposits. Alternatively based on some criteria associated with settling velocity and residence times a reduced rate of deposition could be predicted. The most significant assumptions in this case are those associated with sediment supply and settling velocity (see also Section 7.4). In the absence of long term records of suspended sediment concentration and associated settling velocity or sediment flux measurements it will be impossible to sedimentation with a high degree of accuracy.

5.4.3 Data available for verification

An important point to consider is that where a harbour development already exists data may be available against which to verify or calibrate the predictions of sedimentation rate. In these cases a good basis for prediction for developments at the harbour or for the effects of optimisation exists (see also Section 8.7.5). However, it should be noted that it will be important to consider whether the proposed development or optimisation influences other presently less important sedimentation mechanisms.

5.4.4 Use of qualitative comment

It is presently not possible to derive formulae for quantification of some of the mechanisms considered in Section 5.2. Generally this does not lead to difficulties because these mechanisms are not normally the most important. However, in some cases the effects of vessel resuspension, slumping of slopes and bioturbation may be significant. In most cases sensible qualitative comment is a satisfactory approach to discussion of the mechanism. For example, the mass of sedimentation in a relatively shallow marina basin may be dominated by the exchange processes described previously. The pattern of distribution of the sediment throughout the marina may however be dominated by the movements of vessels within the marina. Similarly in the berths of a dock which are not frequently used there may be greater accumulations of sediment than at berths with regular movements. The importance of ecological factors on sedimentation rates is an area of ongoing research which is yet to be distilled into a form for inclusion in practical engineering solutions in generic terms. However, site specific information may demonstrate factors which require particular consideration.

5.5 Assessment of optimum harbour layout and operation

5.5.1 Level of accuracy

Accurate quantification of the sedimentation rate requires very good data against which to verify predictions of present day sedimentation and then acceptance that if the same mechanisms will be important when a development is undertaken then this verification will hold. If not detailed field measurements will be needed to achieve the same level of understanding and verification. However, in most engineering cases it is not necessary to have this level of accuracy. In a small marina for example, the fact that annually 20,000m^3/year of material in total accumulates may be less important than the fact that five times a year there might be a 1m bar formed in the entrance to the marina that will constrain operations. Similarly in a large container port some variability in sedimentation rates should be expected by the operator. Quantification of this variability by quoting a range of likely sedimentation may be more useful than providing a single figure. For example quoting 1 to 3 million cubic metres of sedimentation may be more realistic than stating a single rate of 2 million cubic metres per year.

In many cases the fact that absolute quantification of the sedimentation rate is neither possible nor appropriate is not a significant problem. Often the important question being asked is one associated with optimisation of the harbour layout and, in this case, a comparison of relative sedimentation rates, providing that the important sedimentation rates are incorporated, is more appropriate. It should be noted that from an operational point of view the requirement is not necessarily one of reducing the absolute rate of sedimentation but more generally the requirement to manage the dredging operation.

Depending upon the complexity of a scheme, and to a certain extent the value of the works, it is likely that it will be necessary to utilise predictive modelling for the optimisation process (see Chapter 8). In Chapter 6 a discussion of the limitations of providing advice on harbour optimisation based on desk study only (ie without either detailed field measurements or predictive modelling) is provided.

5.5.2 Options for reduction of sedimentation or management of the dredging requirements

There are a number of different strategies which can be applied to reduce the rates of sediment build up in dredged areas or to improve the management of the dredging operation (Reference 26). These include:

- location of development
- training walls/deflection works
- alignment of dredged area with natural flow directions
- alignment of dredged channels perpendicular to bed slopes
- consideration of underkeel allowance
- phasing of locking/impounding operations
- construction of sediment traps
- sand bypassing
- location of disposal grounds
- change in dredging strategy
- upgrading of harbour owned dredging plant
- beneficial use of some of the dredged material

Many of the options are appropriate for application to more than one of the sedimentation mechanisms outlined. In the following sections each of the different options above is outlined. Note that this study focuses on harbour sedimentation rather than particular issues associated with the management of the sedimentation.

<u>Location of development</u>
For new harbour development the key factor associated with optimising the future harbour sedimentation is usually the actual siting of the development. In cases where there is some flexibility in the location of the development this aspect should be considered in detail. Consideration of all potential sources of sedimentation is crucial at this stage. However, often other factors will be overriding, for example political, economic, navigation and berth tenability.

<u>Training wall/deflection works</u>
The use of training walls and current deflection walls to enhance the natural scouring of dredged areas and prevent the formation of zones of recirculation, is an option which has been successfully applied at some locations (perhaps most notably at Hamburg, Reference 27). In order to optimise the design, detailed predictive model tests are required. Consideration must be given to the choice of model used for such tests as the flow patterns will be complex and a high resolution will be required (see Sections 8.5.2 and 8.5.3).

<u>Alignment of dredged areas with natural flow direction</u>
Where possible dredged areas should be aligned with the dominant flow direction so as to maximise the natural scouring of the area. The alignment of channels and berths with respect to the tidal flow can be examined in detail using physical or computational modelling techniques (see Chapter 8).

Alignment of dredged channel perpendicular to natural bed slopes
In areas where there is a risk of substantial fluidisation of a muddy bed by tidal or wave action, it is beneficial for a dredged channel to be constructed perpendicular to the natural bed contours so that the flux of sediment that is intercepted by the channel is minimised. Whilst modelling of fluid mud movement is specialised it is an important technique to apply in cases where both hydrostatic and gravitational forces will be important in moving the mud (see Reference 22).

Underkeel allowance
With any dredging operation it is important to establish the minimum requirement for the dredged depth. This is most important for ports where wave action is significant. There is a potential for considerable savings in both capital and maintenance expenditure in such cases. Underkeel clearance studies will be required for this (see Reference 28). Prediction of wave conditions in the approach and manoeuvring areas will be required (see Section 8.6) Consideration can also be given to operating in tidal windows. This will require detailed information on water levels in the area (see Section 7.3).

Manoeuvring requirement
Unnecessary capital and maintenance dredging can be avoided by considering the requirements for manoeuvring of the proposed vessels at the port. In the past dredged approach channels were constructed in straight sections to simplify navigation. However, in terms of minimising dredging requirements a smooth curving channel is more efficient. Simulation of the passage of the design vessel through an approach channel and berthing and unberthing can be used to determine the requirements for safe navigation. For further details see References 2 and 4.

Locking/impounding operations
At locations where there is a large tidal range, or where suspended solids concentrations are naturally high, it may be necessary for berths to be created in an impounded area. The level in the impounded area may be controlled by pumping operations or by locking operations. In both cases operation and design of the impounding system can lead to significant reductions in the amounts of sediment drawn into the berths area. This will require long term measurements of suspended sediment concentrations (see Section 7.4). It may also be possible to construct the locks and lock gates so as to be able to scour away deposits of material that accumulate in the bellmouth.

Construction of sediment traps
In some port areas it may be beneficial to create over deep areas to act as sediment traps. The aim of such areas is that they are able to concentrate the areas in which high sedimentation occurs. Consequently removal of the material is usually more efficient than dredging a larger area. It can also be the case that, by concentrating the sedimentation in a number of locations, different dredging operations can be undertaken efficiently, such as the use of static cutter suction or bucket dredgers.

The effect of a sediment trap on tidal flows and consequent sedimentation pattern can be examined most effectively in an appropriate computational model (see Chapter 8). A sediment trap will be most beneficial when, due to the layout of the port area, there are locations through which sediment is advected by natural currents (wave or tidal driven). However, these are often busy approach channels where frequent dredging operations may be impractical or uneconomic.

A further application of a sediment trap is to undertake over dredging of an area or construction of a specially designed section to an approach channel. This approach has been shown to work for sedimentation during a monsoon or winter period, when maintenance dredging is impractical.

Sand bypassing

At coastal ports where littoral drift from a dominant direction occurs, it may be beneficial to undertake a dredging operation where material is extracted from the approaches, or possibly from a specially constructed trap and thence placed on the down drift side of the port. This process of sand bypassing has the advantage that static plant can be use, pumping distances are usually quite short and there is no requirement for disposing of material offshore. A further advantage is that the impact of the port on the adjacent coastline is minimised by such action. In order to optimise the design of such a sand bypassing operation it is necessary to determine the rates of drift, and magnitude of drift that might occur during a storm or monsoon period. The practicality of this system in terms of dredging plant and the need for associated engineering works will need to be assessed.

Location of disposal grounds

It is important to consider whether the location of the disposal site is such that any material can return from the disposal site to the harbour. In some cases it is accepted that there may be an environmental benefit if material is disposed within the same coastal or estuarine cell as the harbour so that material is not removed from the system entirely. A consequence of this is that material placed at the disposal site may return to the area from which it was dredged. In other cases the requirement may simply be that material removed from the harbour is placed at a location from which it will not return to the harbour.

Locating a disposal site requires detailed consideration of environmental factors such as dispersion of fines, smothering of benthic fauna and flora and consideration of other users of the site such as fisheries interests. Both computational modelling and detailed field investigations will be required to progress this type of study.

Change in dredging strategy

In some cases the actual dredging strategy employed may contribute to sedimentation rates. At some sites it may simply be unnecessary to dredge continually. Identifying whether the dredging operation itself is contributing to the sedimentation rates usually requires an in depth review of the dredging strategy and sedimentation regime (which will require detailed measurements, see Section 7.3).

Changes to dredging strategy can be employment of different size plant, different combinations of plant or even entirely different practices. Agitation dredging may often appear cost effective but a full assessment of the impacts and the areas to which the material is redistributed should be undertaken.

Upgrading of harbour owned dredging plant

Upgrading of harbour owned dredging plant is an option which will usually be subject to periodic review. The introduction of more sophisticated positioning, measurement and surveying techniques are all beneficial and may lead to identification of improved techniques. In some cases, however, the training and support that is needed to maintain the optimum operation of such systems is a major consideration in their effective application.

Beneficial use of dredged material
It is now a requirement in some countries to consider possible beneficial uses of material that is to be dredged. Such consideration needs to take into account the suitability of the material for alternative uses, whether or not there is a market or need for the material and whether the cost is acceptable. Further guidelines on the beneficial use of dredged material is provided in Reference 29.

5.6 Requirements for field investigations and predictive modelling

In the preceding sections comments have been made regarding the appropriateness of applying models or further field investigations within the assessment process. Broadly speaking hydrodynamic modelling will be required for all cases where the layout of an existing harbour or a new site is being altered significantly or in cases where options for reducing sedimentation are being proposed. Exceptions to this are generally the simplest of developments, for example a small amount of deepening or extension at a riverside berth or deepening of a berth within an enclosed basin. When other studies are also required, such as navigation or environmental assessment these may necessitate the application of modelling.

The requirements for collecting field data are more obvious. There will always be a requirement for collecting a minimum amount of field data on the sediment regime at a site. Further data collection will be required to set up and verify any hydrodynamic modelling that is undertaken. In some cases more detailed measurements of natural variability of the sediment sources will be required in order to quantify sedimentation rates.

In Chapters 7 and 8 further details of field investigations and modelling techniques are provided. The chapters provide an insight into the techniques available and the level of specialism associated with different techniques. The information is presented to facilitate incorporation of the techniques into the overall assessment process rather than to prescribe, for example, the modelling approach to a particular problem. The choice of approach and overall design of a study will nearly always be a matter of experience based on the particular site, the issues and the Client's demands.

6 Desk study of harbour sedimentation

6.1 What is desk study?

Desk study of harbour sedimentation implies an assessment based upon available information without recourse to the predictive modelling techniques or detailed field measurements described in Chapters 7 and 8. The desk study may utilise existing information from field investigations and modelling previously undertaken at the site but those techniques would not have been applied specifically for the purposes of the study. On this basis desk study is generally the lowest cost option for an assessment of harbour sedimentation. However, if a lot of data is available, for example bathymetric charts to be analysed, then the overall cost of a desk study at one site might be as much as modelling at another site. Again the implication is that for a desk study the timescales will be shorter than for other types of study. A desk study may be an appropriate level of study at the feasibility stage of a large project or it may be the only requirement for a smaller development.

A desk study seeks to address all the elements of the assessment process with data that is available. Obviously there are circumstances where such an approach is unworkable and in those cases the desk study is really an initial scoping exercise.

The minimum aim of the desk study is to identify the important sedimentation mechanisms at the site which will be responsible for sedimentation in the harbour facility under consideration. A desk assessment can therefore only be undertaken by individuals with a full understanding of the processes and mechanisms described in Chapters 3 and 4.

A desk study will require application of various algorithms found in References 20 and 25 to consider the importance of different mechanisms. It may use simple equilibrium approaches to consider exchange between a basin and adjacent tidal waters and the impacts of changes in flow associated with deepening. A desk study can consider all aspects of the assessment process and define the requirements for further work. In the timescale of an overall development project an initial desk assessment of harbour sedimentation can be the most useful investment.

6.2 When is a desk study appropriate?

A desk study may be an appropriate means to consider the important sedimentation mechanisms at a site. It may also be possible to quantify sedimentation and the approach to optimising the harbour layout. However, there are significant limitations in what can be achieved quantitatively through a desk study. A situation where a desk study might be an appropriate means to consider all aspects of the sedimentation process is the scenario previously discussed of siltation in an enclosed basin. Different dimensions of basin could be considered satisfactorily in a desk study. However, if the basin were to have two entrances and significant internal flows then the assessment will require the appropriate application of predictive modelling to consider alternative harbour layouts.

A desk study however, is the most appropriate means for scoping the options for a development without recourse to great expense. Depending upon the diversity of the options then it may be appropriate to develop the final scheme based upon qualitative analysis only. For example in some cases the different options for development will be associated with siting a new port at a number of different locations. In other cases the options may be dominated by the requirements for safe navigation or berth tenability.

6.3 Stages of a desk study

A desk study will need to follow the assessment process presented in Chapter 5 making full use of the different sources of data referred to in Chapter 4. The desk study will either be complete in itself or it will be a scoping study leading on to recommendations for further study (see Section 5.1).

In cases where the objective of the desk study is to define the requirements for further work the information in Chapters 7 and 8 discussing field investigation and modelling techniques should be referred to.

7 *Field data collection for assessment of harbour sedimentation*

7.1 Minimum requirements for field data

The requirements for field measurements at a particular site will depend to a large extent on whether the hydrodynamic and sedimentation mechanisms are understood and on the options for harbour development which are being considered. There is, however, a minimum amount of field information which is always required at a site before an assessment of harbour sedimentation can usefully be undertaken. This has been reviewed in Section 4.1 and is summarised here:

- bathymetric survey data
- tidal range and current strengths
- salinity/density variations at the site
- information on bed material
- information on suspended sediment concentrations
- wind/wave conditions
- river discharges in the area
- seasonal variability in the above

This information, other than the bathymetric survey, if not available before an initial site visit, can be established during a site visit. The level of detail required does not have to be high at the onset of a study. Prior to recommendations being made for more detailed measurements, for example of river discharge, consideration will need to be given to their potential importance. If it is not possible to judge whether processes associated with a particular mechanism are important, then further measurements will probably be required.

In the following sections a discussion of additional data that may be required is provided. Data outlined in this section may already exist and require collating (Section 7.2) or may need to be specified (Sections 7.3 and 7.4). Where the data specified is described as routine (Section 7.3) it is assumed that any established field survey organisation throughout the world will have the equipment and staff to satisfactorily undertake the measurements without significant supervision. Only minimal detail is given of the measurement techniques and instrumentation. In Section 7.4 specialist field measurement techniques are briefly described. In cases where such measurements are required it is assumed that all those involved will be able to appreciate the requirements for such measurements.

7.2 Data that may exist and will require collation

Data described here has been discussed in Chapter 4. It may be obtained during an initial site visit but more likely it will require collation by the Client or their representative prior to forwarding to the Consultant undertaking the sedimentation assessment.

- historical bathymetric data
- historical dredging records
- information on present and past dredging strategies
- information on river discharges and sediment load
- information on historical changes in coastline
- information on historical changes in inter-tidal areas

None of this data is necessarily vital to an assessment of harbour sedimentation. However, in cases where the assessment is to form part of an environmental impact assessment the addition of this type of data can lend credence to the studies and help to place predicted impacts into the context of natural variability.

7.3 Field data that can be routinely obtained by most marine survey organisations

This type of data can be collected as a matter of routine by most good marine survey organisations:

- bathymetric survey
- topographic survey
- through-depth measurements of tidal current speed and direction
- measurements of river discharge
- deployment of self recording current meters
- undertaking tracking of drogued floats
- through-depth measurements of salinity and temperature
- through-depth measurements of suspended sediment concentrations
- particle size analysis of suspended sediment samples
- particle size analysis of bed samples
- bulk density analysis of bed samples
- deployment of instrumentation for self recording water levels
- deployment of instrumentation for self recording wave height and period

Specification for the requirements of all these measurements in terms of positions, density of sampling, times of sampling and number of samples will vary for each sedimentation assessment. There are also likely to be other requirements of a field survey in terms of input to other aspects of the design and environmental studies. Care should therefore be taken when considering the specification for an extensive field survey.

If further detail is requested by an organisation apparently capable of undertaking the measurements and analysis it must be assumed that the organisation is not used to this type of data collection and alternative surveyors should be found.

7.3.1 Survey specification

With any field survey undertaken by another party it is important to specify everything that must be measured. Opportune measurements are rarely beneficial unless full understanding of the reasoning behind the measurements is held by the observers. If this is not the case the opportune measurements will invariably fail to deliver useful information. The location for measurements will require careful consideration particularly if they are to be used for subsequent modelling. Measurements from structures should be avoided unless it is considered that the measurements will be unaffected by the presence of the structure.

When specifying field measurement positions remotely it is difficult to identify locations where strong shear in the velocity field might exist. These locations should also be avoided and ideally representatives of the survey organisation will be able to identify such positions and will move the location accordingly. A similar issue arises with respect to bed sampling. In many locations the bed sediment composition will vary only slightly from one position to another. In these cases obtaining a limited number of samples can be acceptable.

However, in some locations the bed material is highly variable and in these cases more samples should be obtained. Obviously the way round this dilemma is to initially specify collection of many samples and assume that someone on site can take responsibility for reducing the number of samples analysed if appropriate.

Often with technology transfer projects (see Section 2.4) one of the objectives of a programme is to provide a local organisation with the capability to undertake these routine measurements. It should be acknowledged that those capable of undertaking these measurements may not be aware of the reasons for making the measurements, the use to which the measurements will be put nor of their importance.

For any survey that is taking place over a number of days it useful to be provided with meteorological data, including available information on freshwater discharges for the periods, of the survey.

7.3.2 Instrument calibration

Evidence of calibration of the key instruments such as current meters should be requested since large amounts of time can be wasted in considering unreliable field data. Note also that in situation where currents are very weak (less than 0.2m/s) consideration may need to be given to the accuracy of the current meters. The measurements, particularly with propeller meters, will be affected by the resistance of the propeller and the instrument may often swing out of alignment with the flow making all measurements meaningless.

7.3.3 Measurements of suspended sediments

When suspended sediment samples are being obtained by a third party it is often most sensible to insist that the suspended sediment concentrations are determined gravimetrically in a reliable laboratory. The use of optical silt monitors is generally more cost-effective but there can be considerable difficulties in the calibration of such instruments.

Suspended sediment sampling requires care especially when samples are being obtained near bed. If the sampling device touches the seabed it may resuspend material rendering the sample unreliable. This said it is always important to try and obtain such samples close to the bed. Sediment samples taken at mid-depth are indicative of variability but do not provide information about vertical variations in suspended sediment concentration profiles. The simplest specification is to suggest samples 0.5m/1m below the surface and 0.5m/1m above the bed. A further sample at mid depth can be beneficial in deeper water.

If the samples are being analysed gravimetrically it is important that the samples contain sufficient sediment for accurate determination of mass. If particle size determination of the material in suspension is required then even larger volumes of water will be required. The volume requirements should be agreed with the laboratories undertaking the analysis.

7.3.4 Logistics of field measurement programmes

The logistics of field measurement programmes can become very complex. For example in a tropical delta there may be a requirement to make simultaneous measurements at a number of points on spring and neap cycles during wet and dry seasons. Note that the dry season measurements are likely to be representative but the wet season measurements are likely to only provide indicative information concerning the variability of the system. Determining the impact of freshwater discharge on the hydrodynamics usually requires information concerning the time history of freshwater flow and salinity fields for the previous weeks. Since two separate measurement campaigns have to be undertaken to establish wet and dry seasonal data it makes sense to undertake dry season measurements first and to use these, if appropriate, in a computational model. The calibrated dry season model can then be used to simulate conditions during representative wet season conditions by including effects of freshwater discharge. With this information from the model it is possible to focus the requirements for wet season measurements to areas where the effects of stratification are likely to be greatest. If wet season data is collected first such an integrated approach cannot be taken. It is very unlikely that a satisfactory calibration will be achieved based on wet season data only.

When non simultaneous measurements are made and are to be used as being representative of particular conditions it is important that the conditions under which the measurements are being made are placed in a wider context. For example spring tide measurements on the largest tides of the year may be quite different to those made on a mean spring tide. Another factor which may be important is that the sequence of tides close to the measurements are similar. For example suspended sediment concentrations on a tide rising towards springs may be lower to those on a similar range tide following springs. This is because the largest tides will tend to resuspend more material which will then take some time to find a new location in which to deposit.

7.4 Specialised field measurements

This type of data will require specialist organisations to be involved in the collection. Consideration should be given to the practicality of making such measurements in remote and overseas locations:

- geophysical measurements
- geotechnical measurements
- ADCP measurements of tidal currents
- VMADCP measurements of tidal fluxes
- VMADCP measurements of suspended sediment backscatter
- OSCR measurements of tidal currents
- sediment tracer studies
- near bed measurements of suspended sediment concentrations
- long term bed frame measurements (water level, waves, currents, suspended sediment)
- in-situ fluid mud measurements
- in-situ density measurements
- in-situ erosion threshold measurements
- in-situ settling velocity measurements
- laboratory measurements of cohesive sediment properties
- long term suspended sediment monitoring

Collection of these more complex field measurements should be considered from the onset of the studies in order to make any major field measurement campaigns as effective as possible. However, in order to identify the dominant sedimentation mechanism(s) it is often unnecessary to undertake such extensive field measurements. For example, based on a generic understanding of a particular mechanism it is possible to suggest a sensible range of values for many of the properties that the above observations seek to measure. These values can be used to consider the relative impact of different options. Note, however, that in cases where quantification is of upmost importance then it may be necessary to make specialist measurements.

At large ports there is usually a value in undertaking some of these specialist measurements within the framework of a strategic study, as a means of adding to the understanding of the sediment regime at the site. This understanding, as outlined elsewhere, is important for optimising future operations and developments. In a commercial environment, where the onus is on the port operator to demonstrate that the functioning of the port is environmentally acceptable a long term plan of field measurements may also be an asset.

In the following sections a short description of these specialist services is provided:

<u>Geophysical and geotechnical measurements</u>
These are mentioned under specialist services because an organisation which generally undertakes marine hydraulic measurements may not undertake geophysical and geotechnical services.

<u>ADCP measurements of tidal currents</u>
The use of the Acoustic Doppler Current Profiler (ADCP) for routine marine measurements of current speed and direction is becoming widespread. The instrument can be fixed to a single position (including the bed) or can be vessel mounted (VMADCP). Deployment of such instruments provides a simultaneous through depth measurement of current speed and direction. Note that in most cases it will not be possible to measure close to the instrument or close to the bed. Typically 2-3m of the water column cannot be profiled with this instrument.

<u>VMADCP measurements of tidal currents and fluxes</u>
In many circumstances vessel mounted deployment of the ADCP (VMADCP) is more useful. In these cases a careful operator can record currents whilst transiting a preset course at speeds of up to about 4 knots. Accordingly it is possible to gather current data over large spatial areas. This is particularly effective when considering the difficulties in making fixed point observations of local features such as tidal eddies. The VMADCP technique is also an excellent technique for making discharge measurements across the mouths of harbours and for obtaining river discharges.

All ADCP techniques result in very large quantities of digitally recorded data. To optimise on the use of such techniques it is often cost-effective for the organisation who will use the data (perhaps for model calibration or further analysis) to be involved in specifying the data and the field data collection.

<u>VMADCP measurements of suspended sediment backscatter</u>
Recently research has been undertaken investigating the use of the backscatter signals recorded by the ADCP for inferring suspended sediment concentrations. Dredging Research Limited have progressed furthest with this technique and have used it effectively in measuring the resuspension of material during dredging activities in Hong Kong and for investigating fluxes in the Mersey Estuary (Reference 30). The technique presently requires the collection of numerous calibration samples using standard water sampling techniques. The technique offers an ideal combination of sediment and current measurement particularly when used for calculating fluxes.

OSCR measurements of tidal currents

Ocean Surface Current Radar (OSCR) is a shore based remote sensing system designed to measure sea surface currents in coastal waters. It uses high frequency radar to map current patterns over a wide area without seaborne or submerged equipment. Measurements are carried out from two arrays some kilometres apart, which produce output which are combined to give speed and direction of the surface currents.

OSCR data is useful because it provides simultaneous spatial data, however, because it only gives and indication of the surface speeds its use must be considered carefully. It is vital to be supplied with simultaneous meteorological data for the period of OSCR measurements.

Sediment tracer studies

A variety of techniques (including biological, florescent and radioactive) exist for establishing the movement of bodies of water and of sediments in the water column or on the bed. With respect to sediment transport studies it is of prime importance that the tracer employed satisfactorily reproduces the characteristics of the material in question. For sandy material this is more straightforward than for cohesive material.

For any application of a tracer it is important that information pertaining to the hydrodynamic regime is available for the duration of the study.

Generally tracer studies should be employed to provide qualitative data rather than quantitative data. The tracer experiment may be used to demonstrate a phenomenon which can be reproduced within a predictive model. Uncertainties both in nature and the tracer technique make the predictive model much the best tool for exploring variability.

Near bed measurements of suspended sediment concentrations

It is often important to measure near bed suspended sediment concentrations. Fluxes of sediment in the bottom 0.5m of the water column may be significant with respect to the total water column and inaccuracies associated with approximations can be misinterpreted.

Normally the only technique for satisfactorily measuring near the bed is to deploy instrumentation which sits within a frame which rests on the bed during the measurement period. Such tethered measurements have the inherent problem that the conditions during the measurements must be satisfactory (ie relatively calm) for work to proceed. As a consequence quantification of the importance of waves on sand transport is practically difficult to measure in this manner. However, the technique enables details of the tidal mechanisms to be quantified to high degrees of accuracy.

Long term bed frame measurements (water level, waves, currents, suspended sediment)

Longer term measurements made with instrumentation mounted on a bed frame can provide insight into the relationships between sediment transport and the hydrodynamic regime. Careful consideration needs to be given to any long term deployment so that the instrument is able to measure over the various ranges of environmental conditions to be encountered.

The Minipods and Tetrapods developed jointly by MAFF and Cambridge University (Reference 31) are good examples of what is currently state-of-the-art in this field. These instruments were developed for deployment in coastal waters and their use in port related measurements has only just commenced.

In-situ fluid mud measurements

Where the presence of fluid mud is expected and a requirement exists to make measurements of the fluid mud a number of techniques can be applied. Note that when the formation of the fluid mud is thought to be by episodic wave action alone, anything other than opportune measurements of the density of the bed material after the wave action are unlikely to be effective.

In situations where tidal mechanisms are responsible for the formation of fluid mud a suitably instrumented bed frame can be employed to observe near bed measurements of suspended solids and current speed and direction. It is important to obtain some samples of the high concentrations encountered because of difficulties in calibrating the instrumentation for high concentrations.

The main difficulty with making measurements of fluid mud is in identifying the locations where fluid mud is present or moving on the sea bed. Often the use of dual frequency echo sounders can help but other geophysical techniques can be employed and improve the likelihood of obtaining results.

In-situ density measurements

The facility of making measurements of the vertical profile of bed density at fixed locations is particularly useful when considering the masses of sedimentation. The technique can also be used for considering the potential mobility of areas of cohesive sediment particularly when the issue of fluidisation of the bed is considered. The measurements can be made with a number of techniques and are one of the few specialist measurements where it is sensible to consider the deployment of the instrument on an opportune basis.

In-situ erosion threshold measurements

Recent years have seen the development of techniques for employing methods developed in the laboratory in the field to directly measure the erosion thresholds of cohesive sediments. These techniques were developed for inter-tidal measurements but recently in conjunction with MAFF an instrument developed at HR Wallingford has been used on large diameter cores of undisturbed sea bed material (Reference 32).

This type of measurement is only just becoming available as a practical means of measuring site specific sediment properties. In the future the data bases built up form investigations into natural sediments will replace those developed over the past thirty years based on laboratory measurements of disturbed sediment.

In-situ settling velocity measurements

Since the 1960's gravimetric techniques have been employed for inferring the settling properties of cohesive material. Recent work using video imaging techniques has demonstrated that the gravimetric methods may be under estimating the settling velocities of the largest flocs of sediment in suspension (and therefore most significant in terms of mass flux) (Reference 33).

Video imaging is now available as a practical technique for determining both the size of the sediment in suspension and the settling velocity of individual particles. The cost of undertaking such measurements, and the application of the results to the present state-of-the-art computational sediment transport models, means this technique should be regarded in most cases as desirable rather than necessary.

Laboratory measurements of cohesive sediment properties
It is not presently possible to determine all the important behavioural properties of cohesive sediment properties based upon simple in-situ measurements or sampling. When considering the consolidation, erosion rate and depositional threshold of most cohesive sediment it is generally necessary to resort to laboratory measurements. Such measurements have evolved over the past forty years and are well documented elsewhere. They have one main disadvantage compared to in-situ measurements in that quantities of natural material are taken to the laboratory and processed in some way before measurements are made. As a consequence the measurements may be misleading and the usefulness of such measurements should be carefully considered.

Long term suspended sediment monitoring
In many harbour sedimentation assessments the key to understanding and quantifying the sedimentation mechanisms is establishing the natural variability of the suspended sediment concentrations at the harbour. If variability exists, it can be correlated with tidal and meteorological phenomena to determine the important mechanisms responsible for generating the sources of material at a particular site.

At present most deployments of long term silt monitoring equipment require servicing at regular intervals. They also require a convenient location from which to deploy the equipment. In remote areas both of these can present difficulties. If there are doubts about the reliability of the data collection then there is probably no justification in utilising this method. Ideally long term data is collected for a period spanning the potential variability at the site. In the UK, which is largely tidally dominated, monitoring for periods of 3-4 months over the winter period is generally recommended (Reference 15). Ideally measurements should be undertaken for an entire year or longer.

Measurements have been made from piers, jetties, light towers and piles installed specifically for the measurement period. It is important when choosing the site for such measurements that the measurements at that location will apply to the area of interest or can be used within a computational model. It is notoriously difficult to keep the instrumentation well serviced at sites which dry out. Sites with strong tidal currents are also difficult to operate unless a substantial installation is made.

7.5 Integration of field measurements with other studies

Field measurements will provide input into parallel studies on port design and environmental impact in addition to the assessment of harbour sedimentation. This factor should not be overlooked. However, it is important that the field measurement programme is well focused. Field data that is collected that does not contribute to the understanding of processes at a site or cannot be used for model comparison is valueless.

8 Predictive modelling techniques for assessment of harbour sedimentation

8.1 The application of predictive models

The application of modelling techniques to the assessment of harbour sedimentation might, to the outsider, appear to have become routine on all but the smallest of developments in the last decade or so. An important aspect of the present work is to place the use of modelling tools in its proper context within the assessment procedure. Modelling is not always required and any model used is only as good as the physics and assumptions that it reproduces. In selecting a model for a particular application it is important that the engineer be aware of the range of models available, the processes they can represent, the underlying assumptions on which the models are based, their limitations and the solution method used.

This chapter first discusses the situations where modelling may be appropriate (Section 8.2). It then goes on to review the cases where physical modelling may be effectively applied (Section 8.3). In Section 8.4 the calibration and validation of flow models is reviewed. In Section 8.5 the situations where 3D models are required are described. In Section 8.6 computational modelling of waves and wave induced flow is reviewed. In the final section of this chapter the use of computational models of sediment transport in the assessment of harbour sedimentation is described.

If predictive modelling is to be applied within the assessment process it will require at least the use of a suitable flow model. If wave action is an important aspect of the hydrodynamic regime then a suitable wave model will also be needed. There may not be a requirement to apply an appropriate sediment transport model. In some cases analysis of the results of hydrodynamic modelling will suffice. However, if required a sediment transport model representing the important sediment physics will also be necessary.

8.2 Appropriate application of models

8.2.1 Identification of important sedimentation mechanisms

Figure 1 has indicated the role of modelling in the three stages of the assessment process. Pilot modelling (ie use of an uncalibrated or simplified model) can be helpful in identifying the important sediment transport processes. Pilot modelling will nearly always be by means of a computational model.

8.2.2 Quantification of sedimentation rates

There is more likely to be a requirement for modelling when it comes to quantifying the rates of sedimentation for an existing or proposed harbour development. For example a sediment transport model can be applied to investigate the importance of different supplies of material and the impacts of episodic conditions.

8.2.3 Optimisation of harbour layout and operation

When it comes to optimising the layout or operation of a harbour a model may be an absolute necessity. For example if siltation is caused by an area of recirculation in the mouth of a dock it will be necessary to use a flow model to consider the impact of various schemes to alleviate the problem. Of the twelve scenarios for optimising harbour sedimentation described in Section 5.4.2

modelling may not be necessary for: defining the location of the development (in general terms); for considering the phasing of locking or impounding operations; for considering a change in dredging strategy; for upgrading dredging plant or for examining some options for beneficial use of dredged material. In all other cases of optimising the design and operation modelling would be beneficial and in many circumstances necessary.

8.3 Physical or computational modelling?

In the past most hydraulic modelling of harbours was undertaken with physical models. Such models, in their day, were the only tools available and until recent advances with finite element computational modelling were the only tools available for accurately resolving the important flow features of the harbour layout. This is no longer the case and in most assessments the application of computational modelling techniques will be more cost-effective. The following factors render the use of physical models inappropriate in many cases:

i) Most harbours suffer from the deposition of muddy material. Physical models cannot correctly simulate mud transport because the floc size, settling velocity, turbulence and bed stresses cannot be scaled properly.

ii) For physical models in which wave action has to be accurately reproduced it is necessary to use an undistorted model. This may be at variance with the requirements for tidal flow modelling, where a distorted scale is necessary to achieve the correct flow conditions over a large area.

iii) A distorted model exaggerates upwelling and distorts the secondary circulation at bends. The side slopes of channels and berths are artificially smoothed. To obtain correct energy dissipation requires the model friction factor to be exaggerated in proportion to the distortion ratio.

iv) The rate of transport of fine sediment in suspension is grossly underestimated if the rate of energy dissipation, which is related to the friction factor, is too low.

However, the use of physical models for coastal sediment transport studies and modelling the flow around complex harbour structures (such as lock gates, piled jetties and bridge piers) can still be the best approach.

Physical models have traditionally had an advantage over computational models in that they present the harbour layout and hydraulics in a format which is readily understood by lay people. The presentation of results from computational models has, until recently, limited the value of these types of models as a means for conveying information to large groups of interested parties. As a consequence a physical model of a harbour can be considered as a strategic tool for initially examining and presenting options for development to interested parties.

At present there are no practical means of taking spatial information on tidal hydrodynamics from a physical model and using those within a computational sediment transport model to investigate spatial sediment transport processes. The most that is normally undertaken is to use changes in flow patterns at a number of fixed locations to infer changes to periods of deposition and consolidation in a point model.

8.4 Calibration and validation of flow models

It is generally necessary when using a tidal flow model to demonstrate that the model can represent realistically the flows that are observed in the field. This requires a calibration phase when the model's sensitivity to parameters (usually bed friction and turbulent diffusivity) is used to obtain agreement with observations for a particular set of conditions. The model can then be validated by comparison with another set of data (if such exists) while using the same values of the calibrated parameters. Such an exercise creates the confidence that the model is able to be used for engineering purposes.

A variety of the data sources described in Chapter 6 can be used for purposes of calibration:

- through-depth measurements of tidal current speed and direction
- measurements of river discharge
- deployments of self recording current meters
- tracking of drogued floats
- through-depth measurements of salinity and temperature
- ADCP measurements of tidal currents
- VMADCP measurements of tidal fluxes
- OSCR measurements of tidal currents
- long term bed frame measurements (water level, waves, currents)

Fixed station current metering is most commonly used. Where spatial calibration data is to be obtained (drogues, VMADCP or OSCR measurements) special consideration should be given to the deployment in order to maximise the value of the measurements and ease of comparison with the model. For example re-release of floats from a given section in the area of interest is generally more useful in terms of presenting a calibration than a selection of float tracks over the whole model area at different stages of the tide.

8.5 Application of 2D or 3D flow models

8.5.1 Types of computational flow model

Computational flow model were reviewed in References 6 and 34 and the following main types identified:

- fully hydrostatic
- hydrostatic pressure 3D flow models
- Boussinesq 2DH models
- hydrostatic pressure 2DH models
- 2D 2 layer models
- hydrostatic 2DV models
- 1D models

(The description 2DH or 2DV signifies a two dimensional model developed in plan or in the vertical)

Further details of the different kinds of model are provided in Reference 6.

The relevant model types for sediment transport in coastal and estuarial regions are the 2DH and 3D hydrostatic pressure model types. The other kinds of model will not be considered further here as they have less application for harbour studies. The most commonly applied form of flow model is the 2DH model that solves the shallow water equations to obtain the water elevation and depth-mean current at each point of the model at each timestep through the simulation. While such two dimensional modelling is very often wholly adequate for the purpose of an engineering study there are also circumstances where three dimensional modelling is required. This is discussed in Section 8.5.2. The differences between the different kinds of computational model (finite difference, finite element, curvilinear grid etc) are described in Section 8.5.3.

8.5.2 When it is necessary to use a 3D flow model

In a 3D model, water movements in the vertical are represented by use of a series of layers. This allows the current speed and direction and salinity to vary between the layers. In a 2D model only one layer is considered in the vertical and the flow is taken to be averaged throughout the depth. It can be seen that 3D modelling is therefore more complex than 2D and, in general, it is more cost-effective to use a 2D flow model than a 3D one. If five layers are used in the vertical direction in a 3D model the model is likely to take ten times longer to run. More layers may be required if very strong vertical stratification is encountered. Hence it is practically important in a particular case to decide whether for the purposes of the study a 3D model needs to be run or whether a 2D model is sufficient.

If there are only or mainly tidal effects then a 2D model would be considered to be acceptable. The following should be evaluated for each study to consider whether the three dimensional effects are great enough to render the conclusions drawn from a 2D model run to be invalid.

<u>Density effects</u>
Density variations may occur in the horizontal or vertical direction. In modelling the marine environment it is common to check the Hunter-Simpson parameter,

$\log10(\text{depth}/(\text{max velocity})^3)$

If this parameter is less than about 2, stratification will be destroyed by tidal mixing. Generally thermal stratification occurs in areas of rather deep water (more than 20m) and not in shallow coastal and estuarine waters. If thermal stratification does occur then a 3D model may be needed, for example to model the flows driven by wind as the vertical diffusivity is very greatly reduced by the vertical stratification.

In the coastal region and near to estuaries and river outflows, there can also be areas where gravity currents are present resulting from salinity variation. In normal tidal conditions this would take the form of a residual current over and above the tidal residual. Where the horizontal or vertical salinity gradient is considerable it may require a 3D flow model to predict accurately the residual flows.

<u>Wind stresses</u>
Wind can give rise to currents through the depth that can be modelled in a depth integrated model. They are not more than 1% of the wind speed and possibly considerably lower. Three dimensional flows may also arise. They are not likely to be greater than 3% of the wind speed. Note however, that the wind will often produce flows around a bay rather than a true downwind flow at the surface and upwind flow underneath. Wind induced flows are normally not important where the tidal current exceeds 1m/s but may be rather important as far as residuals (which affect sediment transport) are concerned. Also an offshore wind may not be uniform in the presence of hills, cliffs and buildings for example. It can then

give rise to complex wind-induced current fields that make calibration against nearshore current meters a near impossibility. Note also that wind induced currents are likely to be small and therefore errors in their measurement may be significant.

Secondary flows

Where the flow turns a sharp corner the surface and bed flows may point in different directions. This can be important for sediment movement which is dominated by the near bed current speed and direction. If such sharp bends occur in the area of interest then it may be wise to make sensitivity tests with a 3D model.

8.5.3 Finite difference and finite element flow models

Most of the computational models available today use either a structured finite difference grid (of squares or curvilinear grid) or an unstructured finite element grid. The finite element grid has much more flexibility by virtue of the unstructured nature of the grid. Thus a coastline or structure can be accurately simulated. With most curvilinear grid models the cells are required to be orthogonal which places limits on how the grid can vary. It is more straightforward to use a finite element grid, for example to include a reclamation. The shape of the reclamation can be accurately represented without needing to change the mesh elsewhere (which will affect the solution).

For many purposes it is found that the finite difference and finite element approaches yield practically similar results (see Section 5.4 of Reference 6), but nevertheless it is recommended to use finite element based models where there is a need to quantify small changes in the flow caused by engineering works.

Specific advice on the use of 2DH models for tidal flow problems is provided in Reference 6.

8.6 Application of wave models

Computational wave models in general use knowledge of offshore wave conditions to drive the computation of the behaviour of waves closer inshore or in an area of particular interest. The offshore wave conditions are generally obtained from the sources such as the Meteorological Office Model and Observational data bases or from long periods of wave measurements (see Section 4.2.3).

Computational wave models can initially be split into the following two categories:

i) Wave transformation models
ii) Wave disturbance models

The difference between these two types of model is that wave transformation models are able to model the effect of wave shoaling and refraction (and in some cases diffraction due to changes in bathymetry), while wave disturbance models include the effects of diffraction and reflection which are important for studies including surface piercing structures. The wave transformation models are less computationally expensive than their wave disturbance counterparts and are commonly used where nearshore wave conditions are required (extremes or climates) and often to establish boundary conditions for detailed wave disturbance models of waves in and around harbour structures.

These two types of computational model can be further categorised into three groups:

i) Ray tracking models
ii) Finite difference/Finite element models
iii) Non-linear models

Ray tracking models use a technique which comes from the theory of light. This type of model can either use a forward tracking technique or a back tracking technique and are useful in different circumstances. The forward tracking models track wave rays shorewards in the direction of wave propagation. The wave rays provide information on how wave energy is redistributed and the wave height and direction of a particular wave component can be calculated quickly over a large area. The back tracking wave models track wave rays seawards from an single inshore point at which the wave conditions are required. The results can be used to calculate the wave height and direction for a spectrum of wave conditions at the point in question. For this reason back tracking ray models are extremely useful where wave climates are required at a number of discrete points, however, where sea bed friction is important these models may tend to over-estimate wave heights.

Finite difference/finite element models solve the governing equation, usually the mild slope equation, numerically at each point on a grid. For an incident wave condition, the wave height period and direction at each point in the grid can be predicted. The effects of sea bed friction and wave breaking can be incorporated into this type of model. These models are more computationally intensive than the ray models because of the computation of wave behaviour everywhere within the model area and the necessity for a minimum number of grid points per wavelength. This type of wave model can provide information in terms of wave orbital velocities and wave radiation stresses for input to flow and sediment transport models.

Non-linear models, such as those based upon the Boussinesq equations, are expensive in computer memory and processing time and are therefore only suited to conditions where non-linear wave-wave interaction is likely to be important such as in the case of harbour resonance in regularly shaped harbours exposed to long period incident waves.

Further information on the nature and suitability of each of these types of model is given in Reference 35. When computational wave modelling is required for a study, it is important that the important features of the existing and possible resulting wave processes are included in the selected model. It is also advisable to chose the least computationally expensive model that will carry out the job effectively.

8.7 Computational modelling of sediment transport

8.7.1 Integration of hydrodynamic model results

Whilst the flows that occur in estuaries and coastal situations are frequently very repetitive, the rate of sediment transport may be a great deal more variable. It depends not only on the currents but also on the waves present, other features such as wind and vessel movement and most importantly the sediment properties. For these reasons predictive sediment transport modelling is at a much lower level of certainty than the modelling of waves and flows.

In the first instance it is possible to calculate certain properties based on the hydrodynamics alone to infer some aspects of sediment transport. For example by integrating the bed shear stress predicted by a 2DH flow model and assuming a constant suspended sediment concentration and appropriate settling velocity it is possible to infer patterns and quantities of deposition of mud over the model area. Similarly by taking the fourth power (for example) of the predicted velocity it is possible to infer the relative magnitudes of the potential sand transport at a site. In many cases this approach will be sufficient for the purposes of the assessment of sedimentation because of limited field data or the nature of the proposed development and no further modelling activity is justified.

Another approach which utilises the results of the hydrodynamic models without recourse to spatial sediment transport modelling is to feed hydrodynamic climate data into an appropriate sediment transport formula to determine probabilistically the potential erosion, deposition or transport of sediment at a point. If this approach is used for different layouts of a proposed development it is possible to infer the optimum scheme.

8.7.2 Types of sediment transport model

Sediment transport models can be classified like flow models according to dimensionality. However, for the prediction of sediment transport it is not only important to understand the hydrodynamics (which are driving the sediment transport) but it is also important to adequately represent the physics of the sediment transport mechanism. Inaccuracies in the representation of the hydrodynamics will lead to uncertainties in the magnitude of the sediment transport and identification of the most important sediment transport mechanisms. However, inadequate representation of the physical properties of the sediment itself may lead to greater uncertainties.

Much research work is being undertaken to examine the important physical processes and sediment properties which control the different sediment transport mechanisms described in Sections 3.7 and 5.3. In the 1980's much of this work was undertaken in laboratory settings. More recently it has been accepted that in-situ measurements have to be made to ensure that the properties of natural, undisturbed sediments are being examined. Some of these in-situ measurements are relatively straightforward others require specialist instrumentation (see Sections 7.3 and 7.4). In the absence of detailed information on the sediment properties at a particular site, it is possible to make useful predictions of sediment transport by applying some sensible assumptions on the nature and properties of the sediment and to use this as a basis for a series of sensitivity tests. Indeed this is an approach which can help to identify the requirements for a field monitoring exercise. However, applications of appropriate assumptions need to be undertaken with care. Therefore, sediment transport models, rather more so than flow and wave models, are only useful engineering tools in experienced hands. In such hands they can usefully be applied in the overall assessment process to optimise the design of engineering works and to quantify (within certain limits) the likely rates of accretion and erosion.

In order to focus on the requirement of using a sediment transport model that represents the required mechanisms it is more useful to group sediment transport models depending on the processes represented, in particular:

- bedload (sand) models. Saturated and unsaturated
- littoral drift models
- suspended load (mud) models
- models including formation, flow and entrainment of fluid mud
- models which represent mixtures of mud and sand
- models which represent the evolution of the muddy bed at a single location
- models which represent the dispersion of a plume of sediment at concentrations above background
- models which represent the long term dispersion of material placed on the sea bed
- models which can predict bypassing of sand around a coastal structure
- models which can predict the long term morphological evolution of an area

These model types have been discussed in Reference 34. Selection of the appropriate type of model will depend upon a thorough understanding of the important sediment transport mechanisms occurring in the area to be modelled as described in Chapters 3, 4 and 5.

8.7.3 Guidance on selection of type of transport model

Nearly all sediment transport modelling requires the results of both wave and flow models as input. As a consequence different commercially available hydrodynamic modelling packages are supported by different sediment transport modules. In some special cases there will not be an appropriate sediment transport model to compliment the wave and flow models for the mechanisms required. Examples of this are models for prediction of long term morphological evolution and the movement of fluid mud. Another mechanism which may not be available is the inclusion of the effect of wave driven flows in the basic flow model. Consequently adoption of some hydrodynamic modelling packages will limit the extent and potentially the value of the sediment transport modelling studies that can be undertaken.

Most commercially available hydrodynamic modelling systems will support 2DH sediment transport modelling packages that can:

- represent saturated sand transport
- represent the transport of mud in suspension
- represent the dispersion of a plume of sediment
- predict the littoral drift at a particular location based upon an input wave climate

As with the field measurements described in Chapter 7 it can be considered that most competent organisations with hydraulic modelling skills will be able to offer all of these modelling services. However, specialist laboratories are presently required when it comes to modelling sediment transport in 3D or modelling of the following in 2DH:

- representation of unsaturated sand transport
- interactions between sand and mud particles
- representation of the formation and transport of fluid mud
- representation of the evolution of a muddy bed at a point
- representation of the long term dispersion of material form a location on the bed
- prediction of bypassing of sand around a coastal structure
- prediction of morphological evolution of the bed

Specialist sediment transport modelling should be viewed with a certain amount of caution. It is important that the model is applied as a tool within the assessment process and does not become an end in itself. Sediment transport modelling tools need to be flexible and computationally efficient because more sensitivity tests should be undertaken than with hydrodynamic models.

In some cases the particular mechanism and issues at a site will immediately identify that the problem requires one of these specialist sediment transport models and therefore recourse should be made to an appropriate laboratory. In other cases a variety of modelling approaches may suggest themselves. In these cases the approach to the sediment transport modelling and the justification for that approach are really issues to be presented in the proposal from the organisation hoping to undertake the studies. Different combinations of modelling and field data collection may lead to similar conclusions with respect to identification of important mechanisms, quantification of sedimentation and optimisation of harbour layout. There may however be considerable cost benefits in undertaking particular approaches. In cases where a particular sediment transport mechanism is known to be important it is essential that this process is represented to some extent (either by desk study or modelling) within the assessment procedure.

8.7.4 Guidance on application of a sediment transport model

Because of the uncertainties associated with the understanding of sediment transport all sediment transport modelling input to the assessment process should include sensitivity tests concerning key parameters in the particular model selected for use. For example with a sand transport model the grain size of the sand represented should be varied. With a mud transport model the critical bed shear stresses for erosion and deposition, the erosion rate, the settling velocity and a representation of the consolidation process should be considered through sensitivity tests. Based upon the outcome of these sensitivity tests predictive tests can be considered.

8.7.5 Verification of sediment transport models

Within this study a variety of potential sources of data with which to calibrate and validate a sediment transport model are described. In reality calibration is not usually possible because of the limited extent to which the models represent some of the important physical processes. It is more appropriate to use the term verification.

Whilst it is satisfying to be able to demonstrate that a sediment transport model adequately reproduces the observations of suspended sediment and the areas where net deposition occurs it should be borne in mind that there will be considerable natural variability in the observed sediment measurements. Consequently care should be taken in extrapolating from limited tidal observations to account for an observed requirement for annual dredging. It is very important that all potential mechanisms are considered and that episodic sedimentation or different processes to those represented in a model, such as the movement of fluid mud, are investigated.

9 Conclusions

The aim of this study has been to distill the best current practice based on HR experience and recent research output, to identify a common approach to practical consideration of issues associated with sedimentation in harbours. An approach to assessment of harbour sedimentation is presented, which is appropriate for both rapid and in-depth studies. Harbour design must address the inter-related issues of navigation and berth tenability as well as sedimentation. This study addresses only the sedimentation aspects, concentrating on timescales typically associated with the maintenance dredging operation, anything from a few days to a few years. Long term morphological change is becoming an increasingly issue with respect to assessment of environmental impact, but is outside the scope of this report.

Although the complexity of sedimentation processes may be independent of the sedimentation volume, the financial implications of sedimentation may determine the appropriate scale of studies.

At most of the major european container ports a strategic approach to management of sedimentation is being adopted. The value of such an approach can be enormous when the cost of maintenance dredging and the benefits in being able to progress port development works quickly are considered.

A broad system of classification is suggested in this study, as follows:

Harbours	-	Coastal	-	protected by breakwaters
			-	nearly enclosed
	-	Tidal	-	estuarine
			-	locked
			-	natural lagoon

This breakdown provides a useful background, in the context of this study, for considering some of the various mechanisms leading to sedimentation in different types of harbour.

The assessment process consists of four main stages:

i) Understanding the layout and operations of the existing/proposed development
ii) Identifying the important sedimentation mechanisms at the site
iii) Quantifying where appropriate the magnitude of the sedimentation associated with the different mechanisms
iv) Optimising the harbour layout (possibly in combination with navigation and berth tenability studies).

The methods used to carry out each of the four stages depend upon the existing knowledge of the site and the degree of detail required by the Client. For all studies, the first stage is a review of available data, and wherever possible a site visit is recommended, which can incorporate simple measurements and consultations.

Subsequent to the initial review and site visit, five main options exist:

i) Carry out a scoping study to define requirements for further studies;
ii) Use existing data to carry out a desk assessment;
iii) Carry out detailed field measurements, followed by a desk assessment;
iv) Carry out an assessment including a modelling study based on existing data;
v) Carry out detailed field measurements, which provide input data for a modelling study and using these together to make the required assessment.

A series of check lists have been presented to help with each stage of the assessment: see Tables 1 to 5. Discussion of each item in the lists is found in the main body of the report.

Table 1	Important sedimentation mechanisms
Table 2	Information requirements for the harbour layout and operation
Table 3	Information requirements and sources on the local hydrodynamic regime
Table 4	Information requirements and sources on the local sediment regime
Table 5	Types of routine and specialised field measurements

Quantification of sedimentation will not normally lead to a single answer. In nearly all cases it is most appropriate to provide an answer in the form of a range or an upper limit. It is acceptable to quote ranges because this represents the uncertainty in the understanding of many of the processes involved and also their natural variability. Often, comparison of relative sedimentation rates associated with different options is sufficient, for instance how a new development would change sedimentation compared with the existing situation.

The requirements for field measurements at a particular site will depend to a large extent on whether the hydrodynamics and sedimentation mechanisms are understood and on the options for harbour development which are being considered. The basic types of field data are as follows:

- bathymetric survey data
- tidal range and current strengths
- salinity/density variations at the site
- information on bed material
- information on suspended sediment concentrations
- wind/wave conditions
- river discharges in the area
- seasonal variability in above

The report describes the methods available to obtain these data if they are not already available, by means of standard or specialised techniques as appropriate. Cautionary advice on possible difficulties which can be encountered with particular types of measurement or with large and complex measurement programmes is also provided. It is important that field measurement programmes are well focussed and that data are collected with proper consideration as to how they will be used to improve the understanding of the site or utilised in modelling work.

As with field measurements, a variety of types of computational modelling can be used in assessment of harbour sedimentation. An important aspect of this study has been to place the use of modelling tools in its proper context within the assessment process. No model represents all possible physical processes, therefore it is essential that the engineer has an understanding of the most important processes influencing the sedimentation at a site and how these processes are represented in each type of model . The reader is referred to recent guideline reports prepared for the DoE on this matter (See References 6, 34 and 35). It is important that models should be viewed as tools to be used as part of the assessment process, in combination with other sources of information. In this context, they can provide a useful means to test hypotheses on sediment transport mechanisms and to quantify rates of sedimentation associated with particular processes.

In the past most hydraulic modelling of harbours was undertaken with physical models. In most assessments the application of computational modelling techniques is now more cost-effective, although for some applications, such as transport of beach material around harbour structures or flow around bridge piers or piled jetties, a physical model can still be the best approach.

Predictive sediment transport modelling is at a much lower level of certainty than the modelling of waves and currents. This is because sediment transport movement depends not only on the hydrodynamic conditions but also on other features such as wind and vessel movement and most importantly the sediment properties. In some cases it is efficient and effective to use the results of hydrodynamic modelling to infer residual movements of sediment and the likely areas of accretion and erosion without use of sediment transport models.

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Tables

Table 1 Important sedimentation mechanisms (see Section 5.2)

Mobilising Forces	Mobilising mechanisms	Advection mechanisms	Mechanisms resulting in sedimentation
Wave action alone	Wave breaking	Wave-driven flow	Reduction of wave breaking
Waves and Currents	Wave stirring	Littoral drift	Reduction of wave-driven flow
Currents alone	Fluidisation by waves	Wind driven flow	Interception of littoral drift
Wind	Deposition of fluid mud	Meteorological induced flow	Reduction of wave stirring
Operational activities	Erosion by currents	Tidal currents	Reduction of tidal flows
Bank stability	Pick up by wind	Near bed flow	Interception of fluid mud
Ecological processes	Fluvial discharge	Density currents	Interception of bed load
	Resuspension by dredging	Mixing/dispersion of material in suspension	Deposition form suspension
	Resuspension by vessels	Localised secondary flows	Interception of wind load
	Slumping of sea bed	Fluvial flow	Interception of material form slumping
	Bioturbation	Vessel induced flow	Ecological stabilisation of sediments
		Movement of fluid mud	

Table 2 Information requirements for the harbour layout and operation

- Drawings showing the layout of the harbour
- Aerial photographs of the site
- Bathymetric surveys of the site
- Information on harbour operations (lock operation, turning areas, ferry traffic)
- Information on past and present dredging requirements
- Information on dredging volumes
- Information on material dredged
- Information on disposal site(s)
- Information on episodic sedimentation rates
- Information on seasonal variations in conditions
- Information on river discharges in the vicinity of the harbour
- Information on local coastal processes (erosion of cliffs, intertidals, marshes, mangroves)
- Information from other local harbours
- Information on navigation issues at the port (currents, waves and wind)
- Information on the types of vessels using the harbour
- Anecdotal information from other users of the local waters (normally fishermen)

Table 3 Information requirements and sources on the local hydrodynamic regime

Information required

- Tidal range at the harbour
- Tidal volume of harbour (if enclosed)
- Tidal currents (direction and speed) in and adjacent to the harbour
- Flow patterns throughout the tide in and adjacent to the harbour (eddies etc)
- Wave climate (height, period and % occurrence) in and adjacent to the harbour
- Density variations in the harbour and adjacent waters (importance of stratification)
- Importance of wind induced flows in the harbour area

Useful sources for such information include:

- Admiralty Charts
- Admiralty Tide tables
- Admiralty Pilot
- Data from local Harbour Authority
- Data from local Pilots
- Previous studies and measurements
- Data from local research organisations (typically Universities)
- Observational data from the Meteorological Office
- Data from Meteorological Office wave model
- Data from local airports (wind speeds)
- Aerial photographs
- Remote sensing images (Satellite, CASI data)

Table 4 Information requirements and sources on the local sediment regime

- Identification of material causing sedimentation
- Natural suspended sediment concentrations at the site
- Natural variability of suspended sediment concentrations at the site
- Potential sources of suspended sediment adjacent to the harbour
- Magnitude and direction of littoral movements adjacent to and within the harbour
- Importance of river flow on sediment supply
- Importance of wave action on sediment supply
- Importance of fluid mud as a sediment transport process
- Importance of vessel operations as a mechanism for re-distributing sediment
- Potential for slumping of sea bed

Useful sources for such information include:

- Admiralty Charts
- Ordnance Survey maps (for low and high water positions)
- Admiralty Pilot (information on anchorage areas and requirements for dredging)
- Data from local Harbour Authority (dredging and type of material)
- Data from MAFF public record of offshore licensed disposal sites
- Information from Dredging Contractors concerning materials dredged
- Data from local Pilots (seasonal changes in navigability etc)
- Previous studies and measurements
- Data from local research organisations (typically Universities)
- Aerial photographs
- Remote sensing images (Satellite, CASI data)
- Information from geological surveys
- Information from geotechnical surveys for existing and proposed structures

Table 5 Types of routine and specialist measurements

Field data that can be routinely obtained by most marine survey organisations:

- bathymetric survey
- topographic survey
- through-depth measurements of tidal current speed and direction
- measurements of river discharge
- deployment of self recording current meters
- undertaking tracking of drogued floats
- through-depth measurements of salinity and temperature
- through-depth measurements of suspended sediment concentrations
- particle size analysis of suspended sediment samples
- particle size analysis of bed samples
- bulk density analysis of bed samples
- deployment of instrumentation for self recording water levels
- deployment of instrumentation for self recording wave height and period

Field data that requires specialist organisations to undertake the measurements:

- geophysical measurements
- geotechnical measurements
- ADCP measurements of tidal currents
- VMADCP measurements of tidal fluxes
- VMADCP measurements of suspended sediment backscatter
- OSCR measurements of tidal currents
- sediment tracer studies
- near bed measurements of suspended sediment concentrations
- long term bed frame measurements (water level, waves, currents, suspended sediment)
- in-situ fluid mud measurements
- in-situ density measurements
- in-situ erosion threshold measurements
- in-situ settling velocity measurements
- laboratory measurements of cohesive sediment properties
- long term suspended sediment monitoring

Figures

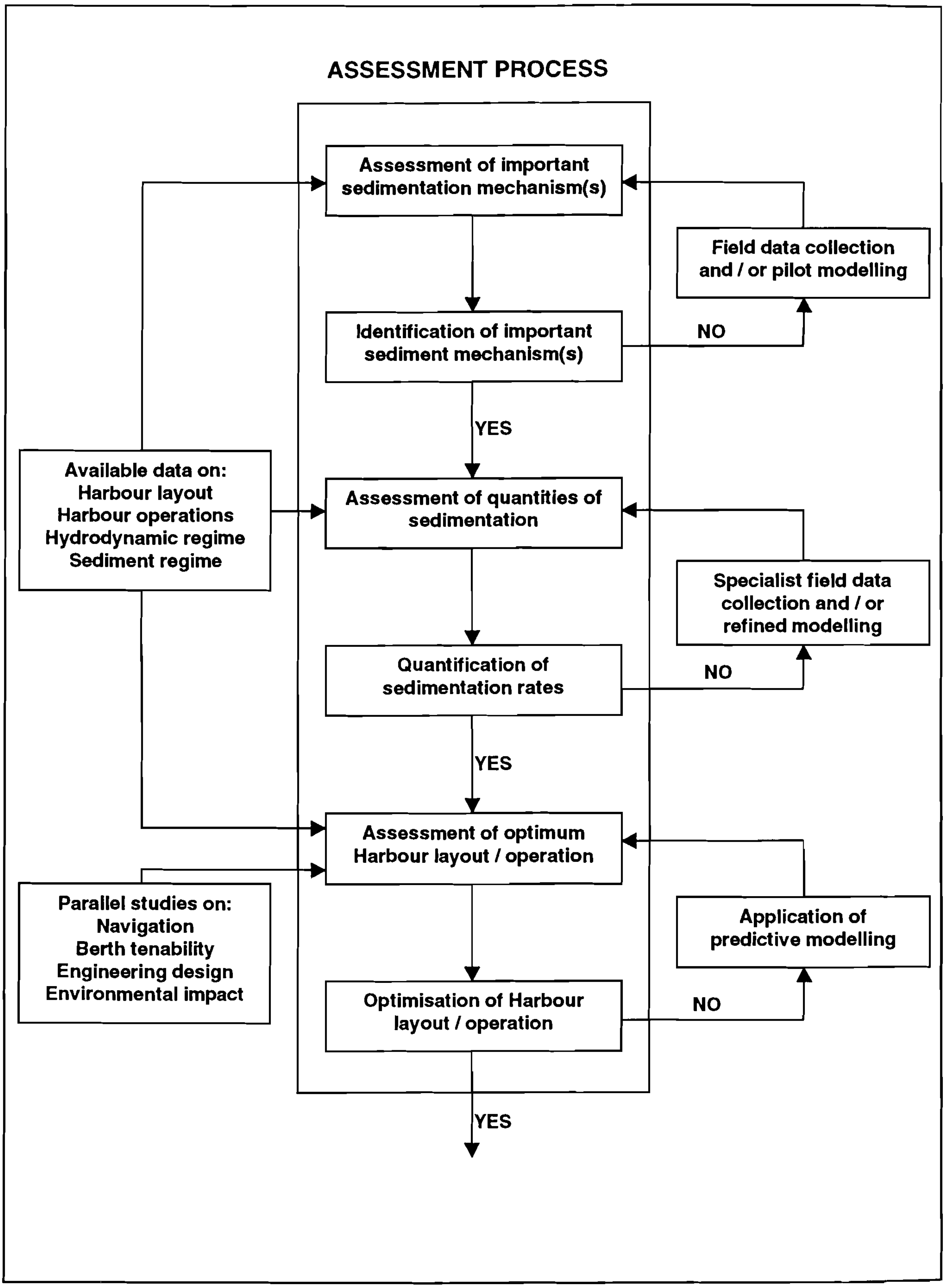

Figure 1 Schematic flow diagram of the Harbour sedimentation assessment processes

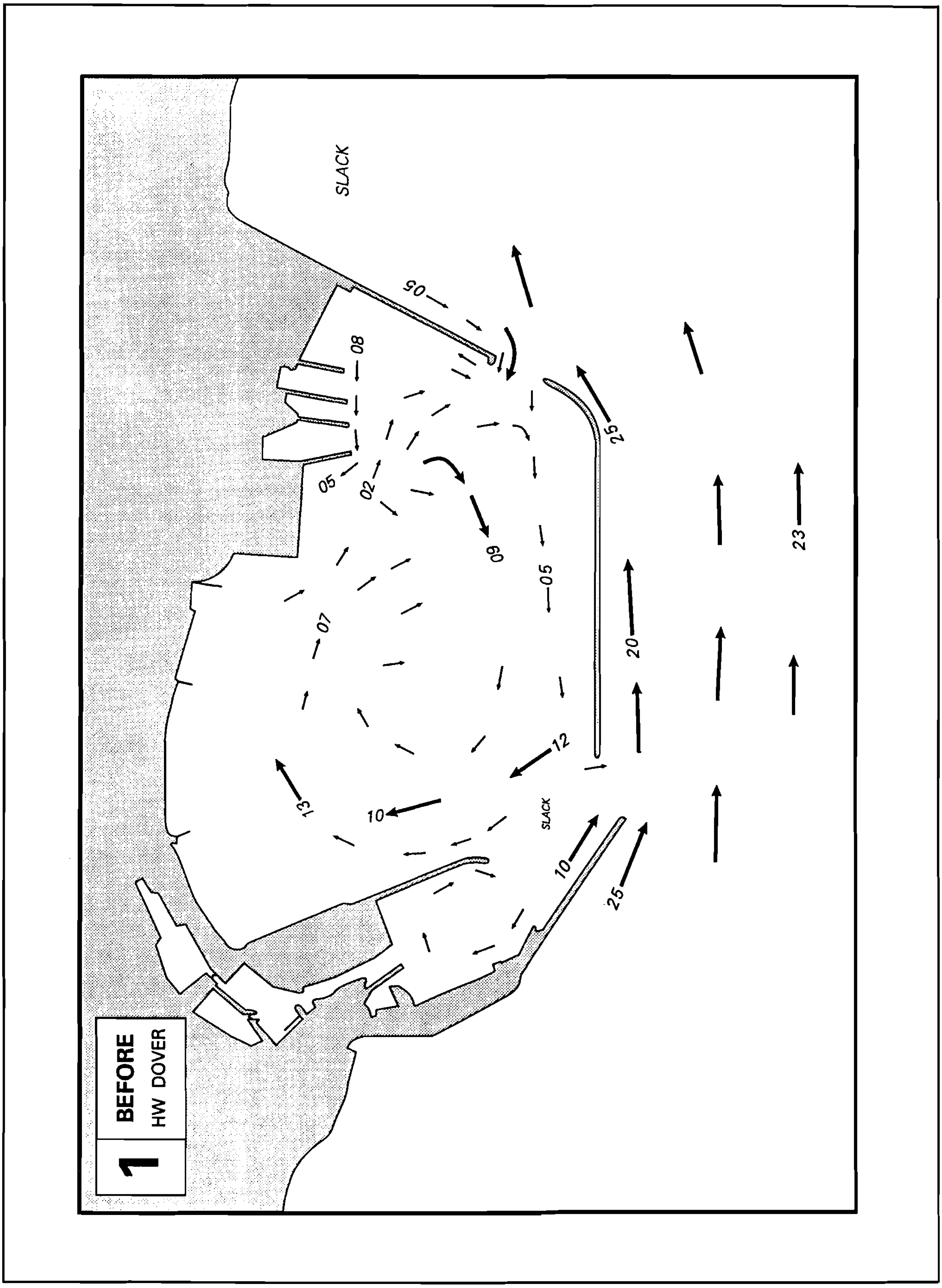

Figure 2 Flow Patterns in Dover Harbour at one hour before High Water (Taken from Port of Dover Tidal Flow Atlas)

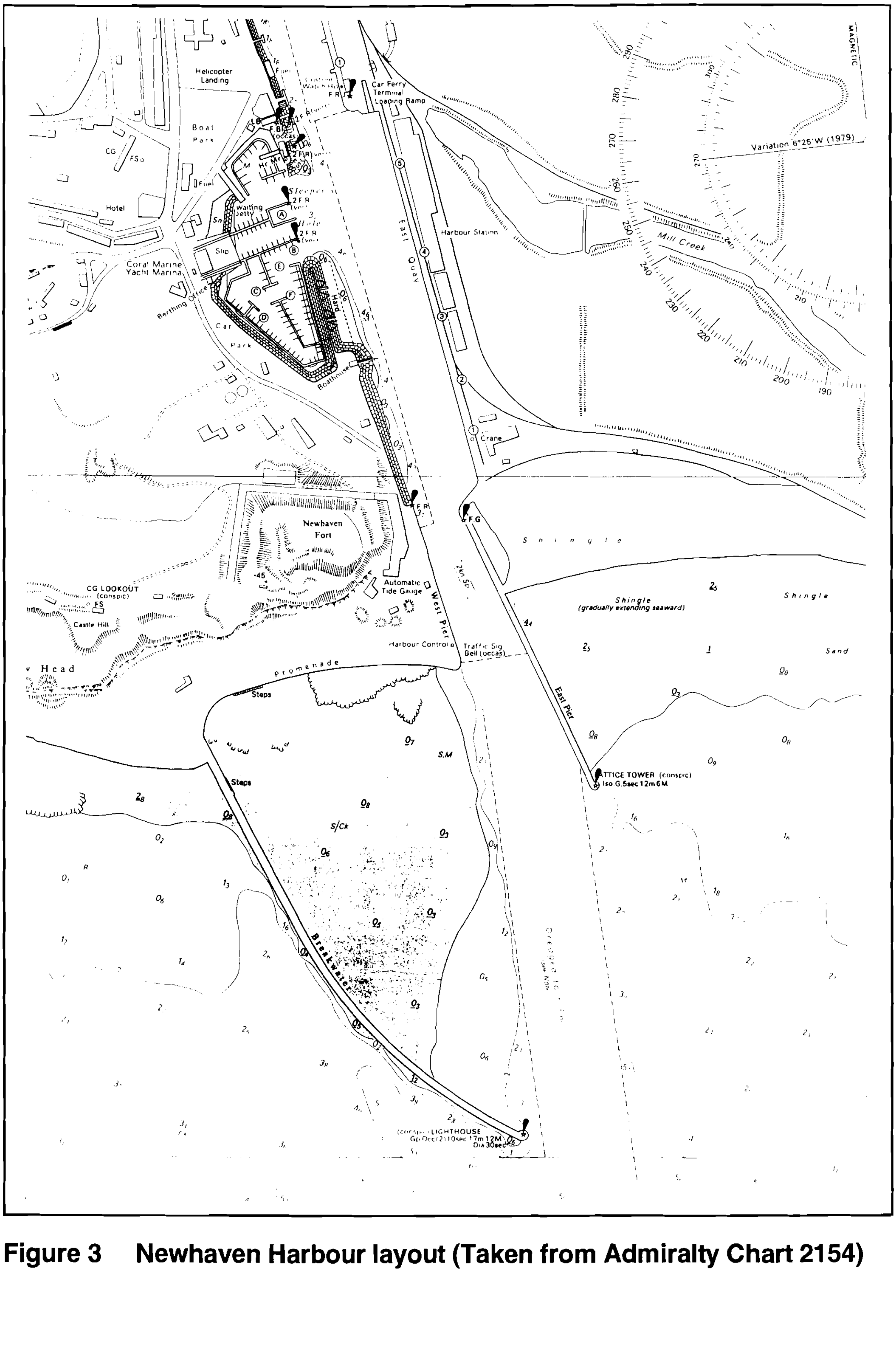

Figure 3 Newhaven Harbour layout (Taken from Admiralty Chart 2154)

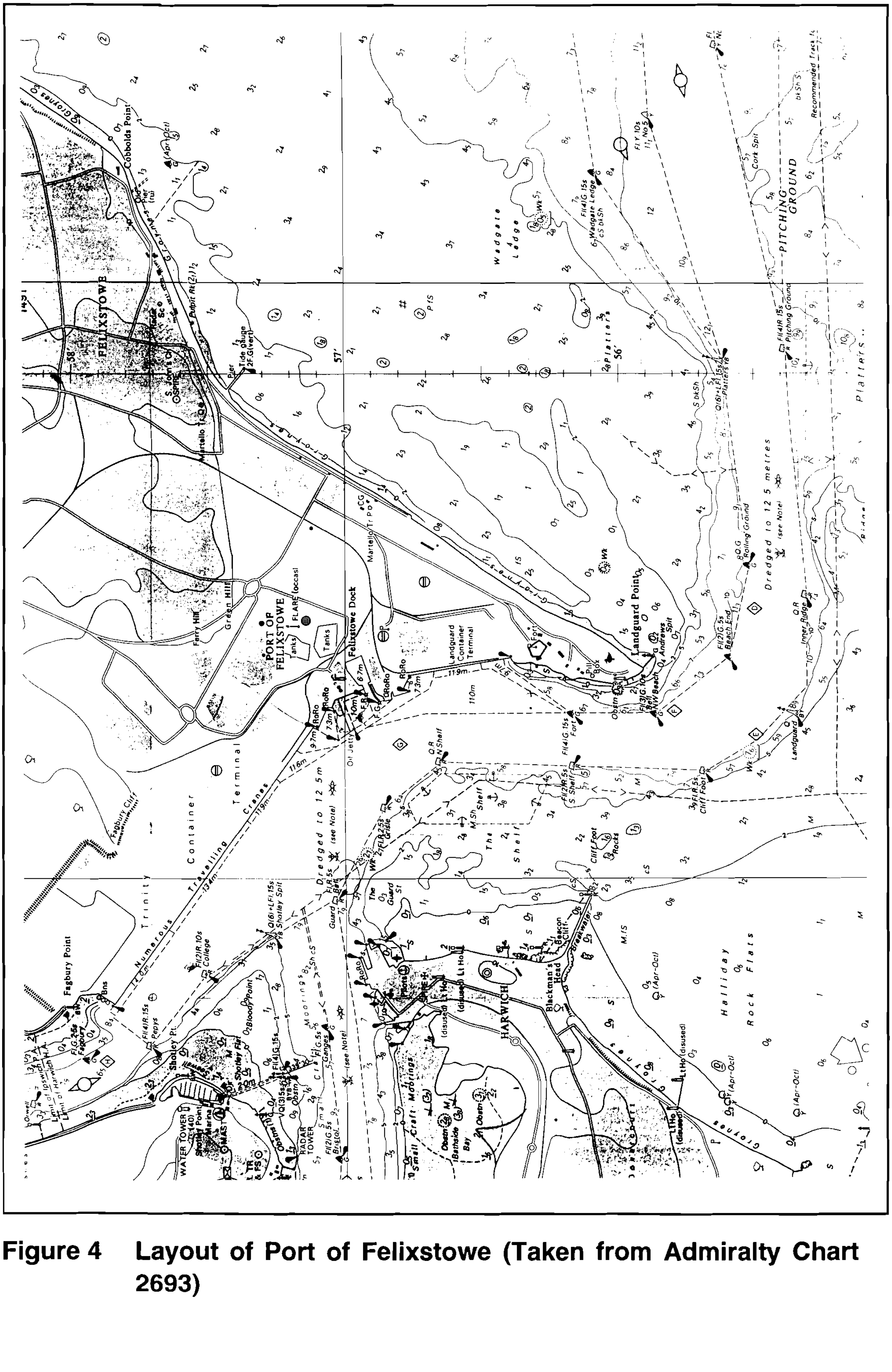

Figure 4 Layout of Port of Felixstowe (Taken from Admiralty Chart 2693)

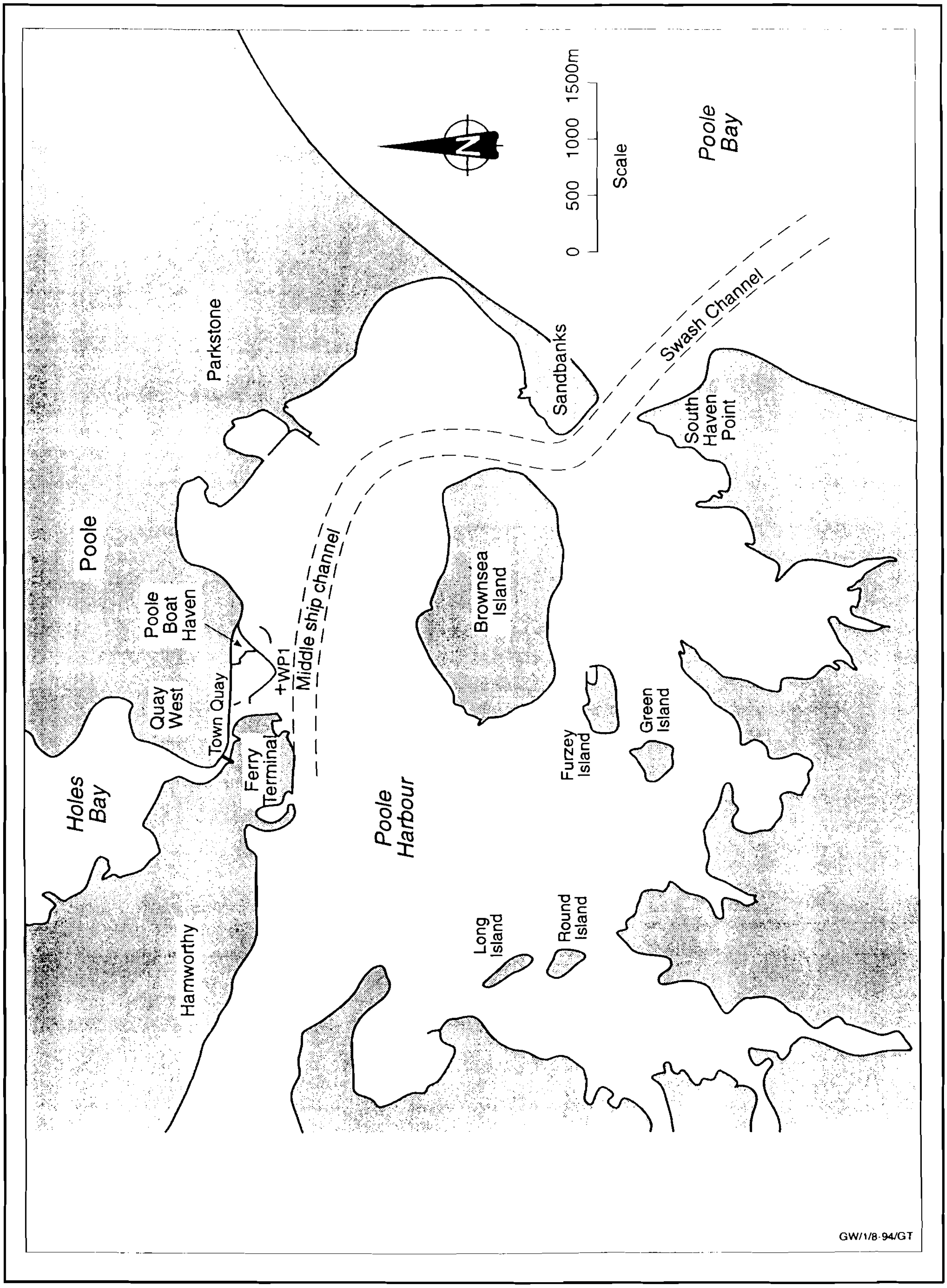

Figure 5 Poole Harbour layout

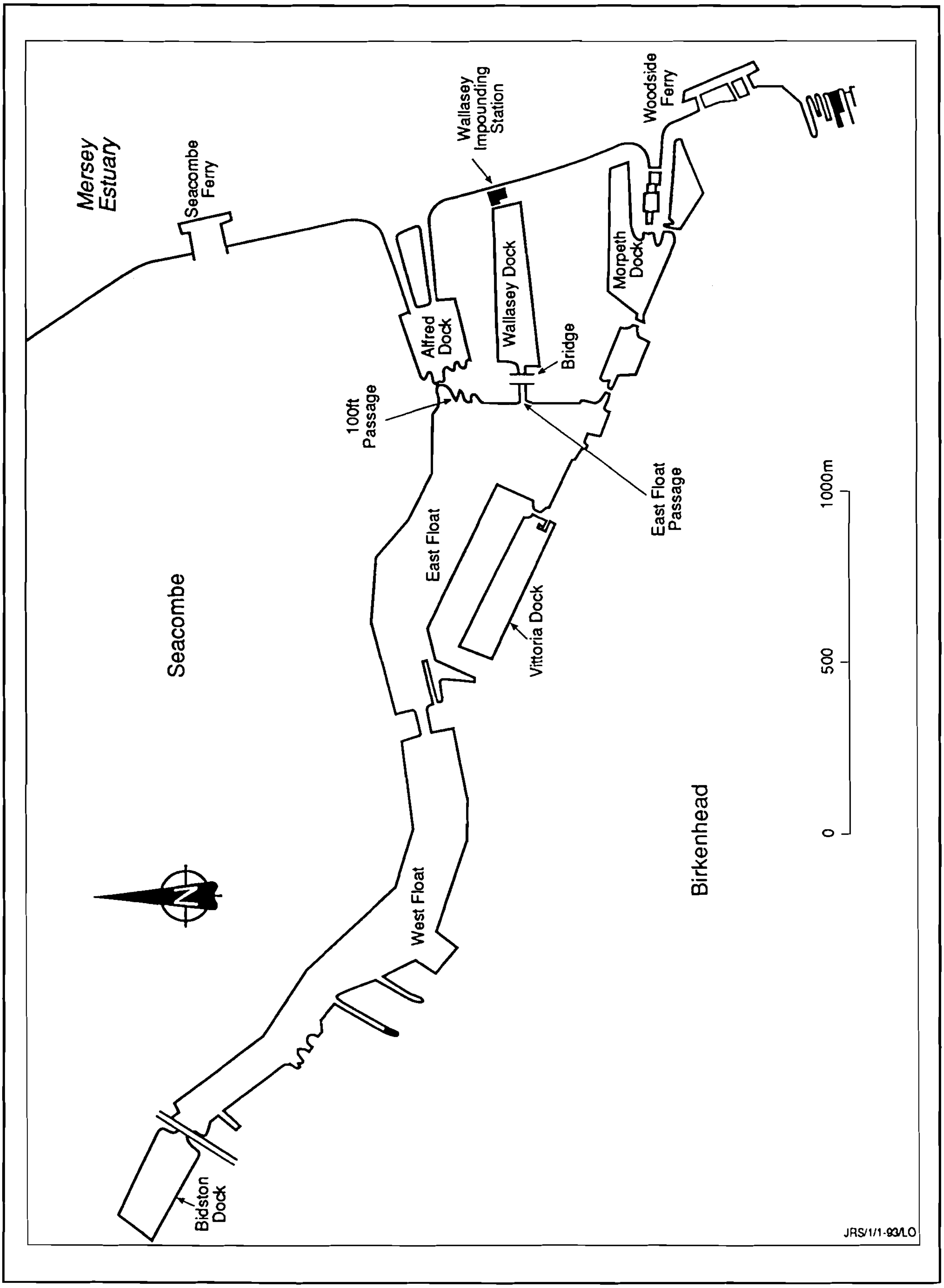

Figure 6 Birkenhead Docks