# Guidelines for the beneficial use of dredged material

**T N Burt**

**Report SR 488**
**November 1996**

HR Wallingford

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## Contract

The work described in this report was funded by the Department of the Environment Construction Directorate under research contract PECD 7/6/297. The DoE, nominated officer was Mr P B Woodhead and HR Wallingford's nominated officer was Dr W R White. The report is published on behalf of DoE but any opinions expressed are not necessarily those of the funding department. The research was carried out by members of the Ports and Estuaries Group at HR Wallingford which is managed by Dr J V Smallman. The HR job number was DBS 40.

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Date ...16...July...1997

## *Summary*

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Beneficial uses of dredged material is by no means a new concept, indeed it is probably as old as dredging itself for applications such as reclamation. However, there is now a developing emphasis on environmental management which has resulted in a change in approach whereby dredged material is regarded as a resource rather than a waste. Many beneficial uses have now been tried in different parts of the world, the largest schemes being in the USA; others are under consideration. The guidelines presented here are the result of three years of literature research, discussions with a wide range of organisations in Europe and the USA, observing some schemes at first hand and in a few cases studying them in detail using numerical models.

The guidelines seek to present in a consolidated form the experience gained as a basis for assessing what the realistic options presently are. The dredging industry will benefit from these guidelines as they are now required by MAFF to demonstrate that possible beneficial uses have been considered before a disposal licence will be granted. They will also benefit those with a responsibility for planning and management of dredging works and coastal defence.

Chapter 2, gives guidance on how to characterise the material for assessment purposes. Also in Chapter 2, guidance is given on some general issues concerning contamination, transport, dewatering, storage and environmental value, all having cost implications. A check list of beneficial use options is then presented as an introduction to the detailed guidance given in the subsequent Chapters. Each Chapter thereafter gives specific guidance on a particular class of beneficial use, subdivided where appropriate. For each type of use a description of the use is given followed by guidance on the type of material which is suitable, design criteria and monitoring. These are sometimes illustrated by example to aid understanding.

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# 1 Introduction

## 1.1 Purpose of the guidelines

Beneficial uses of dredged material is by no means a new concept, indeed it is probably as old as dredging itself for applications such as reclamation. However, there is now a developing emphasis on environmental management which has resulted in a change in approach whereby dredged material is regarded as a resource rather than a waste. Many beneficial uses have now been tried in different parts of the world, the largest schemes being in the USA; others are under consideration. The guidelines presented here are the result of three years of literature research, discussions with a wide range of organisations in Europe and the USA, observing some schemes at first hand and in a few cases studying them in detail using numerical models.

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## 1.2 Background

It is a requirement of the London Convention 1972, the Oslo Paris Convention and a statutory requirement under the UK's Food and Environment Protection Act that in considering whether to licence disposal at sea, the Licensing Authority has regard to any alternative means of disposal. There has been considerable recent pressure from bodies such as English Nature, from the House of Commons Environment Committee on Coastal Zone Protection and Planning and others for the use of dredgings where possible in a beneficial way. The changing approach sees dredged material as a resource rather than a waste.

The Licensing Authority, as part of their assessment now ask the licence applicant to give consideration to other possible disposal routes, including the use of material beneficially (Murray 1994). In this way the UK is seeking to encourage the development of these options. Many such options are only at the development stage at present. As might be expected there is more success in finding uses for granular material, sands and gravels, than fine silts which form the majority of maintenance dredgings from the UK.

In terms of sheer quantity, dredged material outweighs all other materials disposed of in the marine environment so it is not surprising that it has come under close scrutiny in recent years. Yet most dredged material is natural sediment and should not be considered as a waste. Certainly any material resulting from an earth moving operation on land, say for road building, would not be considered as a waste but rather as a resource, perhaps for landfill, landscaping, topsoil or other construction works. Why should underwater earth moving be philosophically considered any differently?

One reason is almost certainly cost. The promoter of the dredging works is primarily concerned with both achieving a certain depth of water and removing the excess material in the most cost effective way. If the material is not able to be sold, then there is little motivation to do anything with it, other than dispose of it in the most economical manner. It is the factors that govern the economics that will bring about the most significant changes in the future. Perhaps the saleability of dredged material will change as new technologies open up more options for beneficial uses and as the value of the environment enters the equation. Legislation and licensing requirements are beginning to change the economics. In many parts of the world dredging operators are required to demonstrate that other options have been properly considered before a disposal licence is granted. Conversely, the placement of dredged material above Low Water may require the approval of the local planning authority under the Town and Country Planning Act 1990, the permission of the land owner and the consent of the Environment Agency (formerly the National Rivers Authority). English Nature, and possibly others as local conditions dictate. The Crown Estate Commissioners may also decide to take a royalty if beneficial use is made of the material and there is an increase in value of the asset (Ash 1994).

As more research is being carried out, more and more options are beginning to open up. These are discussed in the guidelines but before going into detail there are some fundamental practical problems and some more philosophical principles to consider.

Defining "beneficial" is not a simple matter. The context in which the phrase has been coined probably gives it the emphasis "beneficial to the environment" rather than "beneficial to man in particular". It poses the question of who or what will benefit. For example, the construction of an offshore berm using dredged material to reduce coastal erosion may at the same time obliterate an important fishing ground. Beneficial use could be seen as that which gives net environmental gain within the overall context of the dredging (Ash, 1994). This definition would include finding an alternative means of disposal which is less detrimental than the existing practice. Whilst commendable in itself this does not, in the authors' view, constitute a beneficial use. The authors' preferred definition arises from the context of the concept: "any use which does not regard the material as a waste". Having considered possible beneficial uses by this definition it may still be necessary to dispose of some or all of the material and this should then be carried out with minimum detriment to the environment commensurate with reasonable cost.

Introducing cost raises the issue of what value we place on the environment and may lead us to consider such difficult issues as indirect environmental compensation, ie would the money be better spent on some other project totally unrelated to the dredging, from which the environment would obtain greater benefit. Clearly the cost issue cannot be ignored.

Moving on to the practical difficulties, the first one to be considered is scale. Taking the UK as an example about 40,000,000 tonnes of sediment are disposed of at licensed sites around the coast each year. In the USA the figure is about ten times higher. It is difficult to conceive of sufficient schemes that could utilise this quantity every year even if all of the material were to be suitable. In fact most of the material in the UK is cohesive "mud" and therefore generally unsuitable as aggregate or for reclamation. Only a few schemes such as wetland restoration appear to have the potential to absorb significant quantities of mud.

The next problem is that the cohesive fraction of sediments contains the highest proportion of contaminants such as heavy metals so mud from a contaminated estuary is likely to be unsuitable for most "beneficial" purposes. Processes exist which are able to separate the mud fraction from the coarser sediments. It is therefore possible to consider using sand from a contaminated estuary although the cost is inevitably higher.

Of course some of the "beneficial uses" are not new but rather a new name has been applied to established technologies. The most obvious examples are beach nourishment and aggregate dredging. However, it must also be said that in most cases the material for these has been sought from convenient and/or licensed extraction sites rather than it being the result of maintenance or capital dredging works. The future challenge of beneficial uses is to match the resource with the requirement. Research is required into methods and possible locations of stockpiling for future use as supply and demand for dredged material rarely coincide.

A final point in discussing the underlying principles of beneficial uses is that the potential coast protection benefit of retaining sediment within a coastal cell should not be overlooked (Murray, 1994). An example would be an estuary entrance channel where sediment is carried into the channel by a coastal drift process. If the material is taken out of the area for disposal then the downdrift coast is deprived of its source of replenishment. A beneficial use of the dredged material would be to place it on the downdrift side of the channel so as to maintain the natural processes as far as possible.

## 1.3 Construction control

Some beneficial use schemes have failed, not because the material is unsuitable or the scheme badly designed but rather a lack of proper control on the handling or placement of the material. An example would be in the creation of wetland or saltmarsh habitat where it is essential to the ecology that the material is inundated at the right frequency and to an appropriate depth. This may require the dredged material to be placed and levelled to within fairly narrow tolerances.

It is therefore a feature of some beneficial use schemes that the work should be well supervised and controlled as well as being well designed.

## 1.4 Monitoring

Although there have been thousands of beneficial uses of dredged material over the last century, only in the last 20 years have environmental concerns required technical monitoring of such projects (Landin 1992). Both engineering and environmental monitoring is needed in an interdisciplinary effort that documents whether or not a site is meeting its goals and objectives, and blending with its surrounding environment.

There are three reasons why monitoring is essential. First, it is needed to acquire baseline site data. How can an environmental project involving beneficial uses of dredge material be judged successful in meeting its goals if no one knows what conditions and biotic communities existed prior to construction? It is also just as important to acquire baseline data during and after construction, to have a basis for comparison with pre-construction conditions. In other words, did the project improve surrounding habitat conditions, blend with the existing ecosystem and compare favourably with existing natural habitats of similar community structure? Did it meet its goals?

Second, monitoring is needed to document success, failure and/or changes over time. Many sites continue to evolve and have not reached ecological maturity. Only long term monitoring has allowed changes to be documented and provide a basis for improving technology and cost effectiveness.

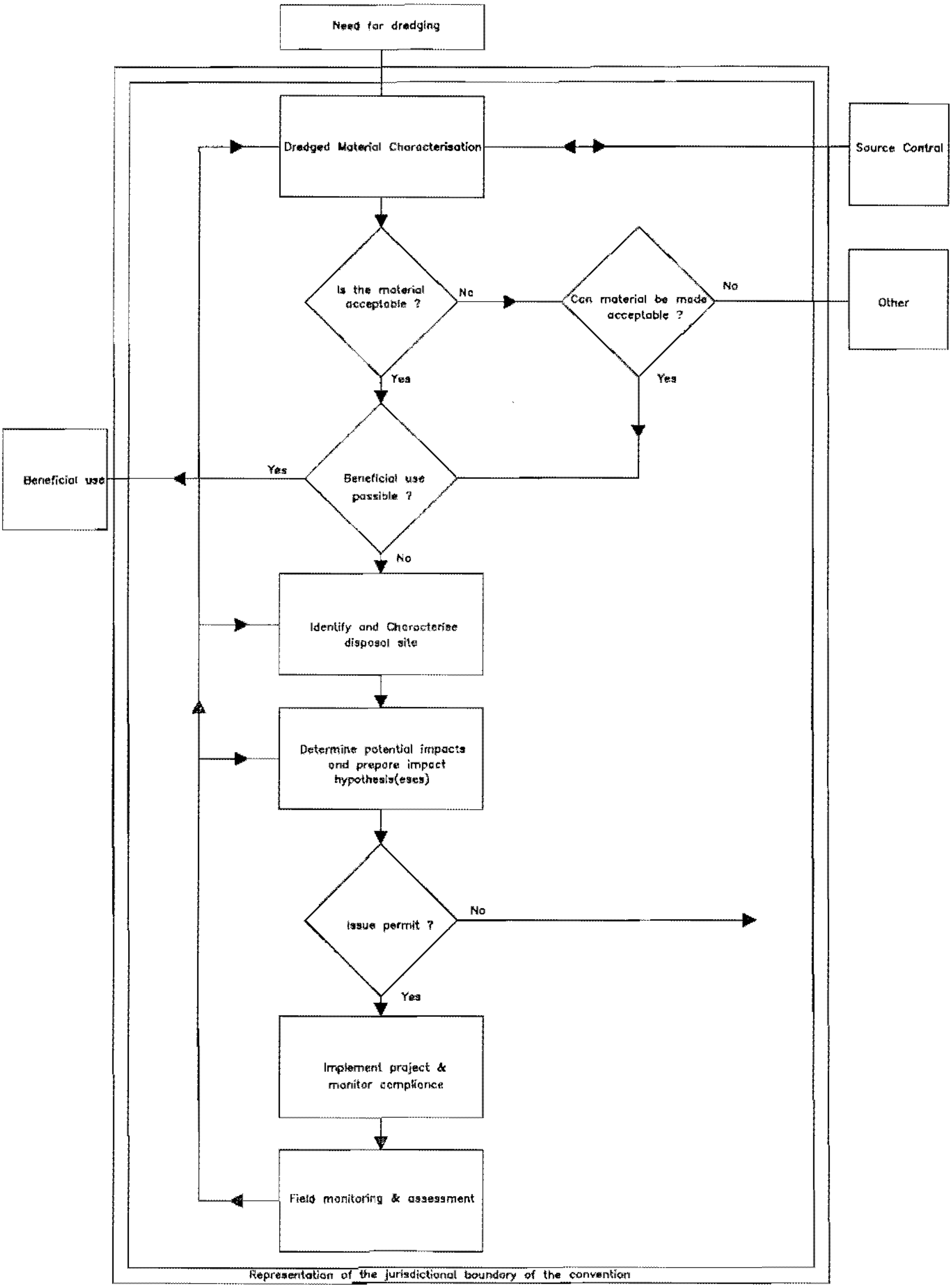
Third, monitoring is needed to provide justification of applying similar techniques to future projects. Unless it is known whether a project has succeeded or provided valuable habitat and information, it is difficult to convince the appropriate authorities and the general public that similar projects should be carried out.

The problem with long term monitoring is obtaining the commitment, both interest and financial, of those with the responsibility. Once a project has been completed and the public has got used to the scheme being there, there is little interest in monitoring. Most, if not all, of the funds for a project are linked to the capital cost of a dredging project and the promoter does not want a long term financial liability with no obvious financial benefit. Government agencies and even the pressure groups who have such a high profile involvement in consent stage seem to lose interest once the project has been constructed.

In the context of producing these guidelines a number of schemes in the UK have been monitored for a relatively short time and it has become clear that there is still much to learn. It is strongly recommended that any beneficial use scheme includes a period of monitoring so that appropriate adjustments can be made if necessary and so that future schemes may benefit from the experience. Guidance on suitable monitoring programmes is given where appropriate in this document.

### 1.5 Structure of the guidelines

The guidelines are structured to parallel the dredged material assessment framework of the London Convention 1972. This is summarised in Figure 1.1 overleaf.




# Figure 1.1 Dredged material assessment framework

However, this gives no guidance on the beneficial uses available and how to assess suitability of the material for such uses. Chapter 2, therefore, gives guidance on how to characterise the material for assessment purposes. Also in Chapter 2, guidance is given on some general issues concerning contamination, transport, dewatering, storage and environmental value, all having cost implications. A check list of beneficial use options is then presented as an introduction to the detailed guidance given in the subsequent Chapters. Each Chapter thereafter gives specific guidance on a particular class of beneficial use, subdivided where appropriate. For each type of use a description of the use is given followed by guidance on the type of material which is suitable, design criteria and monitoring. These are sometimes illustrated by example to aid understanding.

## 1.6 The UK dredged material resource

Collins (1979) reviewed the British resource. At that time more than 30 million tonnes of wet silt were dredged every year as necessary maintenance. On average silt contains about 60-70% water, but even allowing for both this and loss on ignition there was sufficient silt available to produce 8 Mt of aggregates or bricks (see Ch 4.4). Collins presents tables giving the total dredgings port by port and an analysis of samples from London, Humber, Manchester, Tees, Forth and Bristol. The properties measured included physical attributes, chemical and mineralogical constituents. This gave grounds for concluding that virtually all dredged material could be used from a technical standpoint but that the economics may not be favourable. In 1979 large scale use of maintenance dredged material for coast protection, habitat creation or salt marsh restoration was not being considered. The pressures of environmental controls and changing economics described by Burt and Dearnaley (1994) are changing so that there is now much more potential for beneficial uses but it is unlikely to result in the production of 8Mt of synthetic aggregates or bricks.

A review of the demand and resources of beach recharge material was carried out in 1995 (CIRIA 1995). Most of the material, by far, used for beach recharge in the UK comes from marine dredged sediments. Some schemes, however, have used material won from land sources such as sand and gravel pits, and quarried hard rock is widely used for armouring in coastal and harbour protection schemes. The presence of large stockpiles of waste materials from such industries as china clay production and slate quarrying has led to speculation about their suitability for use in beach recharge. Similarly, there is interest in the use of navigation dredging, which are at present dumped as a waste material, as a potential source of material for beach recharge purposes. There is, therefore, a need to investigate the quality, quantity and potential in-service performance of these alternative sources of materials, to consider also the economic and environmental effects of their extraction and usage. These considerations need to be balanced with the similar constraints involved with the use of marine materials in beach recharge.

An assessment has been made of the volumes of material disposed offshore as a result of maintenance and capital dredging operations in the UK. This analysis has been undertaken using data available in the public records maintained by MAFF. These records indicate the volumes of material annually dumped at the licensed offshore sites around the UK. There are approximately 150 of these sites in use in any one year. The analysis has been carried out using data from 1985 to 1992. The public register does not contain information concerning the nature of the material dumped.

For this analysis the licensed sites have been grouped into 30 regions around the UK. For the 30 regions of this breakdown, the average annual disposal of maintenance and capital dredged material for the period 1985-1992 is given in Table 1.1.

An assessment has been made of the type of material (cohesive or sandy) dumped in the 8 regions that account for about 85% of the annual average disposal of maintenance material. This information is presented in CIRIA (1995).

MAINTENANCE DREDGED MATERIAL

Table 1.1 indicates the main areas of maintenance dredging in the UK. The majority of material dredged for maintenance is cohesive (Table 1.2). The estuaries of the Humber and the Severn account for about 60% of the entire UK dredging and marine disposal. The approximate breakdown of cohesive and non-cohesive material dumped in these regions has been determined through discussions with the Port Authorities. This breakdown indicates that about 20% of the material dumped offshore is sand. However much of the sand that is disposed offshore is in the form of mud/sand mixtures rather than in a form where the sand could be dredged separately.

## *Table 1.1 Average annual disposal tonnages 1985-1992*

| Region | Maintenance Tonnage | Capital Tonnage |
|---|---|---|
| Thames | 57,000 | 78,000 |
| Harwich | 1,224,000 | 1,074,000 |
| Great Yarmouth | 115,000 | 6,000 |
| The Wash | 130,000 | 133,000 |
| Humber | 11,201,000 | 535,000 |
| Scarborough | 83,000 | 16,000 |
| Tyne and Tees | 1,711,000 | 1,384,000 |
| Berwick-upon-Tweed | 7,000 | 0 |
| Forth | 1,499,000 | 137,000 |
| Dundee | 198,000 | 4,000 |
| Moray Firth | 522,000 | 36,000 |
| North West Scotland | 63,000 | 95,000 |
| Clyde | 465,000 | 52,000 |
| Solway Firth | 197,000 | 46,000 |
| Morecombe Bay | 1,186,000 | 1,255,000 |
| Isle of Man | 7,000 | 0 |
| Liverpool Bay | 2,374,000 | 11,000 |
| Anglesey | 6,000 | 101,000 |
| Pembroke | 1,000 | 52,000 |
| Outer Bristol Channel | 2,614,000 | 37,000 |
| Inner Bristol Channel | 6,739,000 | 7,000 |
| Plymouth | 219,000 | 196,000 |
| Lyme Bay | 61,000 | 3,000 |
| Poole | 150,000 | 220,000 |
| Isle of Wight | 692,000 | 301,000 |
| Brighton | 378,000 | 32,000 |
| Dover | 493,000 | 36,000 |
| Irish Sea 0 | 18,000 | |
| Northern Ireland (East) | 367,000 | 141,000 |
| Northern Ireland (North) | 82,000 | 104,000 |
| TOTAL | 32,906,000 | 6,110,000 |

*Table 1.2 Breakdown of maintenance dredged material*

| Region | % of Total | Average annual Tonnage (thousand) (1985/92) | cohesive | non-cohesive | unknown |
|---|---|---|---|---|---|
| Humber | 34.0 | 11,201 | 9,300 | 1,900 | |
| Inner Bristol Channel | 20.5 | 6,739 | ~6,700 | | |
| Outer Bristol Channel | 7.9 | 2,614 | | | 2,600 |
| Liverpool Bay | 7.2 | 2,374 | | 1,100 | 1,300 |
| Tyne and Tees | 5.2 | 1,711 | 500 | 900 | 300 |
| Forth | 4.6 | 1,499 | 1,400 | 100 | |
| Harwich | 3.7 | 1,224 | 1,200 | | |
| Morecombe Bay | 3.6 | 1,186 | | | 1,200 |

Dredging volumes can be measured in many forms including hopper tonnes, hopper volumes and insitu volumes. As a consequence the accuracy of the absolute values presented in the Tables is questionable. However, for the purposes of comparing volumes available from around the UK and changes from one year to another the data is adequate and represents the most complete data set available.

Annual maintenance disposal on the south coast of England is about 2 million tonnes. This disposal is concentrated between the Isle of Wight and Dover. Between the Thames and the Humber about 1.5 million tonnes of material are disposed. Nearly all of this material is cohesive. Between Scarborough and Berwick-upon-Tweed 1.8 million tonnes of material are dumped offshore and the indications are that at least half of this material is sandy.

It is important to note that at present in only a few instances is maintenance dredged material used in a beneficial manner. In the Liverpool Bay region about 1.5 million tonnes of dredged material is taken onshore and there the sand fraction is separated for use in the construction industry. Most of the time the material is regarded as unsuitable for beach nourishment purposes or the timescales for the letting of contracts associated with maintenance works are too short to consider options, other than disposal.

CAPITAL DREDGED MATERIAL

Capital dredging works around the UK may be a more suitable source of material for nourishment purposes. By their very nature capital schemes are more likely to result in the production of coarse material than maintenance works. The plant that is used can be adapted to pump material ashore. Unfortunately capital dredging projects are not evenly distributed around the coast or through time and cannot therefore normally be considered a reliable source of material for nourishment schemes. In the years 1985 to 1992 over 60% of the UK capital dredging was undertaken in the three regions, Tyne/Tees, Harwich and Morecombe Bay. Tyne/Tees and Harwich were schemes associated with major port development works and in Morecombe Bay the capital dredging was associated with deepening the approach channels for the Admiralty at Barrow.

An example of the use of capital dredged material for beach nourishment is the port of Poole. Here capital works in the approach channel to Poole Harbour in

1988/89 resulted in 604,000m$^3$ out of 675,000m$^3$ dredged being pumped onto Bournemouth beaches. Further capital works the following winter resulted in 420,000m$^3$ out of 510,000m$^3$ dredged being pumped ashore. The second scheme was only realised following the success of the first development. In 1991/92 developments to the navigation channel inside Poole Harbour resulted in 40,000m$^3$ of fine sand being jetted onto the beach at Sandbanks for Poole Borough Council. The operation was economically beneficial in terms of both the dredging cost to the port and the recharge cost to the Borough Council.

# 2 General guidance

## 2.1 Is the material suitable for beneficial use?

This section describes the sort of information which will be needed about the material itself to decide which use (if any) it is suitable for. The amount of detail and level and type of analysis required will vary from case to case.

The material should be characterised in terms of its physical, chemical and biological properties. Each of these are discussed in turn.

In order to consider and plan potential uses it will usually be necessary to investigate the characteristics before the dredging is carried out. The sampling procedure should:

- guarantee a representative description for the planned dredging and disposal project by taking a sufficient number of samples to cover the thickness and extent of the layer to be dredged;

- limit the cost of analyses by combining samples into fewer samples (unless there is reason to believe there are "high spots" in which case the dredging operation may be designed to exclude them);

- give reproducible data. (PIANC 1992).

It is to be noted that contaminants in dredged material, after placement, may be altered by the physical, chemical and biochemical processes in the new environment to more or to less harmful substances. The susceptibility of the dredged material to such changes should be considered in the light of the eventual use of the material. In this context field verification of predicted effects is important. Later Chapters give guidance on appropriate monitoring for each use.

If the material is known to be seriously contaminated (a relatively rare situation in the UK) then this will be the primary consideration and will probably rule out beneficial use. Nevertheless the same characterisation will be necessary in deciding how to dispose of or treat the contaminated material. Even contaminated material can be used beneficially (Paipai 1995). Guidance on this is given in Section 2.3.

### *2.1.1 Physical properties*

In general it is the physical properties which will determine which of the possible beneficial uses are appropriate. Chemical and biological properties may impose additional limitations.

There are several classification systems in use internationally. Two of the better known ones are the Unified Soil Classification System (USCS) and the PIANC system "Classification of Soils and Rocks to be dredged" (PIANC 1984). The following sections are based on a synthesis of these.

It is important to remember that some of the physical properties will be altered by the dredging process. For example, most dredging processes will reduce the bulk density.

1. Form and composition

This is a general description which can be given based on visual assessment. It includes, for example, terms such as rock, fluid mud, sand with clay lenses, and silt containing organic material.

2. <u>Grain size</u>
   Grain size is the principle characteristic to be determined. It is the basis for most dredged material classifications. A number of samples should be analysed to give a reasonable representation of the material available for beneficial use. If there is more than one type of material in the area to be dredged the sampling should represent that variation and define spacial boundaries (including defining layers at different depths) so that only appropriate material is supplied to the beneficial use scheme.

   The analysis is usually carried out by sieving for particles down to 0.06 mm. Below that size the traditional method is by settling tube analysis but new methods such as laser particle sizing equipment are now commonly available.

   The particle size distribution is usually described by the percentage by weight which passes each sieve size. The material is generally described using the following threshold sizes:

| | |
|---|---|
| boulders | > 200 mm |
| cobbles | < 200 mm |
| gravel | < 60 mm |
| sand | < 2.00 mm |
| silt | < 0.063 mm |
| clay | < 0.002 mm |

   From gravel downwards these are often subdivided into coarse, medium and fine.

   Material in the silt and clay size bands generally exhibit properties of cohesiveness, ie the interparticle forces are sufficiently strong to bind them together. They are often described as "mud" which has no precise definition. So called "mud" often contains quite a high percentage of sand.

3. <u>Specific Gravity</u>
   This parameter affects the consolidation of placed material and is required in calculation of void ratio. A range of values is given in Table 2.1:

## *Table 2.1 Specific gravities of minerals (Lamb & Whitman 1969)*

| **Mineral** | **Specific Gravity** |
|---|---|
| Quartz | 2.65 |
| K-Feldspars | 2.54 - 2.57 |
| Na and Ca Feldspars | 2.62 - 2.76 |
| Calcite | 2.72 |
| Dolmite | 2.85 |
| Muscovite | 2.7 - 3.1 |
| Biotite | 2.8 - 3.2 |
| Chlorite | 2.6 - 2.9 |
| Pyrophyllite | 2.84 |
| Serpentine | 2.2 - 2.7 |
| Kaolinite | 2.64 |
| Halloysite | 2.55 |
| Illite | 2.60 - 2.86 |
| Monmorillonite | 2.75 - 2.78 |
| Attapulgite | 2.3 |

4. Bulk Density
   Bulk density is a weight measurement by which the entire soil volume is taken into consideration. It is usually low for fine-grained materials which generally contain a large proportion of water. It is an important parameter for determining volumes in situ, in transport and after placement. Some examples are given below in Table 2.2.

## *Table 2.2 Examples of bulk densities (Bray 1979)*

| Material | Density before excavation tonnes/m$^3$ |
|---|---|
| Igneous rock | 2.0 - 2.8 |
| Sedimentary rock | 1.9 - 2.5 |
| Metamorphic rock | 2.0 - 2.8 |
| Gravel | 1.75 - 2.2 |
| Sandy gravel | 2.0 - 2.3 |
| Medium sand - silty fine sand | 1.7 - 2.3 |
| Cemented fine sand | 1.7 - 2.3 |
| Silt | 1.6 - 2.0 |
| Firm or stiff gravelly or sandy clays (boulder clays) | 1.8 - 2.4 |
| Soft silty clays (fresh harbour sediment) | 1.15 - 1.6 |
| Soft silty clays (alluvial clays) | 1.2 - 1.8 |
| Firm or stiff silty clay | 1.5 - 2.1 |
| Peats | 0.9 - 1.7 |

Bulk density is usually affected by the dredging process. Some typical bulking factors for mechanically dredged material are given below in Table 2.3.

## *Table 2.3 Typical bulking factors (Bray 1979)*

| Material | Bulking factor (dredged vol/in situ vol) |
|---|---|
| Hard rock (blasted) | 1.50 - 2.00 |
| Medium rock (blasted) | 1.40 - 1.80 |
| Soft rock | 1.25 - 1.40 |
| Gravel, hardpacked | 1.35 |
| Gravel, loose | 1.10 |
| Sand, hardpacked | 1.25 - 1.35 |
| Sand, medium soft - hard | 1.15 - 1.25 |
| Sand, soft | 1.05 - 1.15 |
| Silts, freshly deposited | 1.00 - 1.10 |
| Silts, consolidated | 1.10 - 1.40 |
| Clay, very hard | 1.15 - 1.25 |
| Clay, medium soft - hard | 1.10 - 1.15 |
| Clay, soft | 1.00 - 1.10 |
| Sand/gravel/clay mixtures | 1.15 - 1.35 |

There is considerable confusion about density measurements and some attempts have been made to standardise on dry density to avoid such variable dimensions as "hopper tonnes", a common dredging measurement which relies on observation of vessel displacement in the water but which gives no direct indication of the amount of solids contained. To aid understanding the following figure shows the relationship between bulk density, dry density and void ratio for a material having a specific gravity of 2.65.

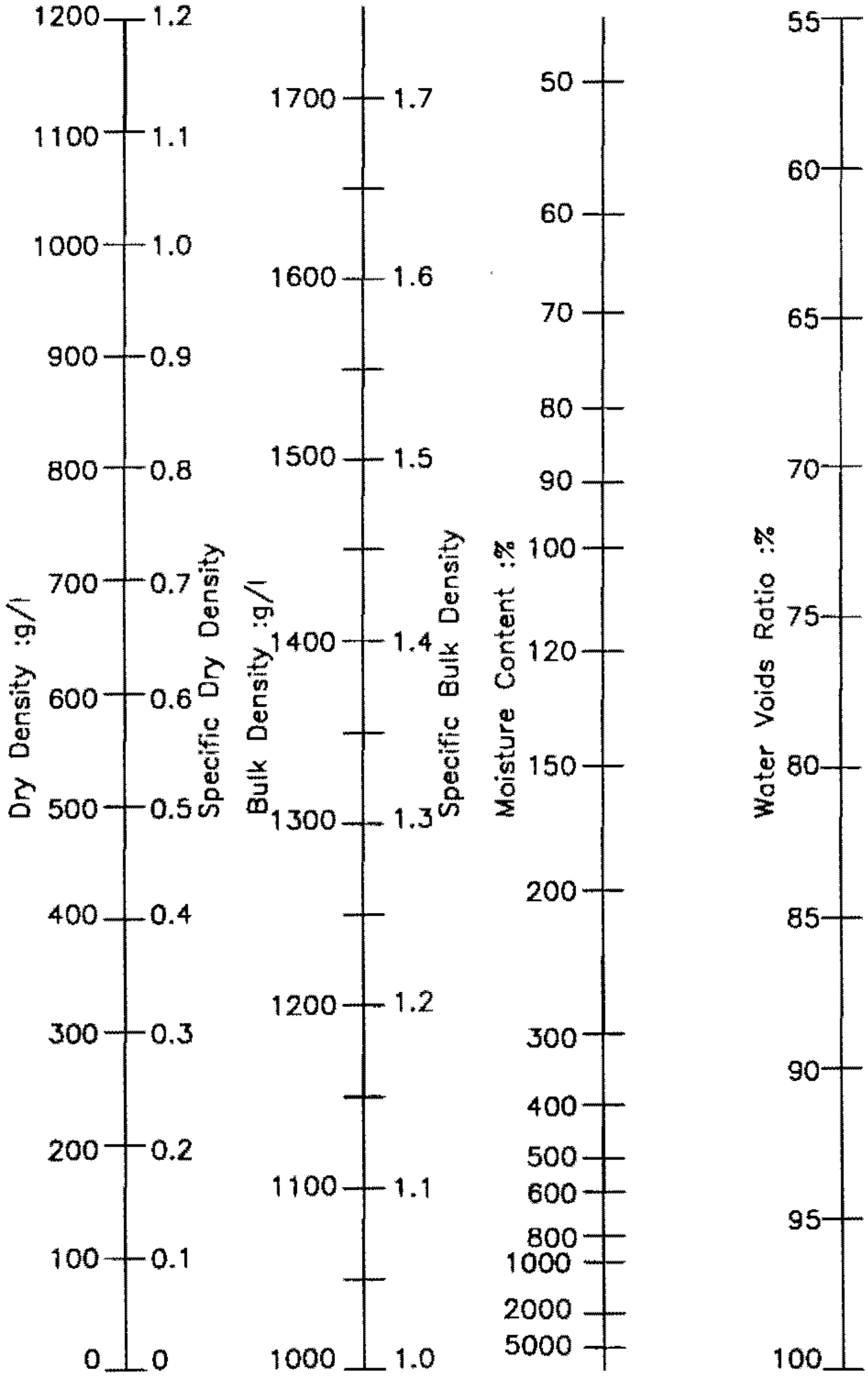



**Figure 2.1** **Conversions between dry density, bulk density moisture content, and water voids ratio**

5. Plasticity
This is relevant only to the fine fraction of the sediment samples. The most commonly used descriptors are the Atterburg liquid limit and plastic limit (LL and PL). The LL is that water content above which the material is said to be in a semiliquid state and below which the material is in a plastic state. The water content which defines the lower limit of the plasticity state and the upper limit of the semi-solid state is termed the plastic limit. The plasticity index (PI), is used to express the plasticity of the sediment.

6. Water retention
Water retention characteristics are relevant to the ability of the dredged material to sustain plant life. The potential available water capacity of a material used as soil is defined as the amount of water a crop can remove from the soil before its yield is seriously affected by drought. It is strongly influenced by the arrangement of the solid components and the quantity of fine particles and organic matter. The US Army (1986) Manual gives the following tables for guidance.

## *Table 2.4 Available water capacity of soils*

| **Grain Size Range** | **Available water capacity at saturation mm of water/mm of material depth** |
|---|---|
| sand | 0.015 |
| loamy sand | 0.074 |
| sandy loam | 0.121 |
| fine sandy loam | 0.171 |
| vary fine sandy loam | 0.257 |
| loam | 0.191 |
| silty loam | 0.234 |
| silt | 0.256 |
| sandy clay loam | 0.209 |
| silty clay loam | 0.204 |
| sandy clay | 0.185 |
| silty clay | 0.180 |
| clay | 0.156 |

## Table 2.5 Water capacity required for agricultural crops

| Available water capacity mm water/m depth material | Recommended plants |
|---|---|
| <50 | Not suitable for most agricultural crops unless irrigated |
| 50 - 75 | Best suited for grasses |
| >75 | Suitable for most agricultural crops |

7. Permeability

The permeability and sorptive properties of the material express the ease with which water passes through it. It is determined mainly by the particle size of the material and (for cohesive sediment especially) the degree of consolidation. Consolidation is discussed in more detail in Section 2.1.4. The coefficient of permeability is defined as the rate of flow per unit area of material under unit hydraulic gradient and therefore has the dimensions of velocity.

For granular material it varies inversely with the specific surface of the particles (ie the surface area per unit weight of material). A range of average values is given in the following table:

## Table 2.6 Typical permeability ranges

| Material | Permeability cm/sec |
|---|---|
| Clean gravel | 100 - 1<br>good drainage |
| Clean sands and mixtures of clean sands and gravels | $1 - 10^{-3}$<br>fair drainage |
| Very fine sands, silts, mixtures of sand silt and clay, glacial tills, stratified clays etc. | $10^{-3} - 10^{-7}$<br>poor drainage |
| Unweathered clays | $10^{-7} - 10^{-9}$<br>virtually impervious |

8. Volatile solids
Volatile solids are important in determining contaminant retention within the material and for the material's capacity for plant growth.

### *2.1.2 Chemical properties*

The chemical constituents of dredged material affect the suitability of the material for some beneficial uses. Most dredged material arrises from maintenance of existing channels and ports and is therefore sediment which has been exposed to anthropogenic contaminants. The chemical characteristics will be strongly influenced by the type of population, the industry and the agriculture of the region. Capital dredging in uncontaminated natural situations is comparatively rare. Nevertheless even in natural situations it may still be appropriate to carry out chemical analyses because even natural chemical characteristics may be unsuitable for some applications. The potential problems arising from chemicals in the material are:

Plant toxicity
Animal toxicity
Surface water contamination
Groundwater contamination

Even if plants or animals themselves are not directly affected their uptake of contaminants may be passed on via the food chain to higher organisms.

Contaminants are generally classified into four major groups (PIANC 1996), nutrients, metals, organics and radioactive substances.

<u>Nutrients</u>
Eg phosphorus and nitrogen compounds like ammonium.
The release of untreated municipal wastewater and agricultural and industrial effluents containing large amounts of organic compounds, phosphates, nitrates and ammonia is considered to be the oldest and most widespread threat to the quality of surface waters and sediments. As soon as the capacity of the aquatic system to oxidise this material has been exceeded and eutrophication has taken place, lack of dissolved oxygen will kill animal life in the water. A concentration of <5mg/l limits certain aquatic life.

<u>Metals</u>
Usually the heavy metals; cadmium, chromium, copper, lead, mercury, nickel, zinc and arsenic are analyzed in environmental impact studies for dredged material. The levels of metals or their combinations in certain organs at which they damage the individual and later the whole ecosystem vary considerably. Some metals may have carcinogenic and mutagenic properties.

Heavy metals are reported in many navigable channels and ports. The major sources are sewage and industrial discharges. Wastes from metal plating industries contain significant amounts of copper, chromium, zinc, nickel and cadmium. Chemical partitioning studies of sediments have shown that these metals occupy the least stable of the sediment fraction and that the sediment chemistry dominates the mobility and availability of the contaminant as well as the indigenous metals.

The solubility of specific metals whose concentrations are high in a particular sediment under consideration for beneficial use is important because soluble forms are readily available to the food chain. The potential of a heavy metal to become a contaminant therefore depends greatly on its form and bio-availability rather than on its total concentration within the dredged sediment. Heavy metals may be fixed in a slightly soluble form in dredged material containing excessive sulfide. The placing on land of dry oxidised dredged material may increase the solubility of heavy metal sulfides. However, under oxidising condition, the levels of pH and heavy metal hydroxyl and oxide formation become important factors and sulfur no longer governs the solubility and availability of heavy metals.

<u>Organics</u>
This group includes a variety of organic compounds (eg PAH's and certain mineral oil products). They are clearly toxic and some are carcinogenic (PAH's). Generally they are more easily decomposed and therefore less prone to bioaccumulation than other organic contaminants like PCB's.

Organic contaminants also comprise less volatile, highly accumulating, non bio-degradable toxic substances such as the DDT group, HCB, PCB's, dioxins and furanes.

Radioactive substances
These have a preferential affinity for the fine grained sediments which can be transported long distances from the source and therefore increase the risk of exposure of humans, animals and plants. A dredged material containing radioactive substances is unlikely to be considered for beneficial use.

The interactions between the dredged material and the contaminants are influenced by the following factors which should be taken into account in considering possible beneficial uses (PIANC 1996):

**Type and amount of clay:** the higher the clay content, the higher the adsorptive capacity of the sediment (montmorillonite has a larger internal adsorptive surface than kaolinite).

**Cation exchange capacity:** The capacity of soil particulates to adsorb nutrients which become available for plant growth is called the cation exchange capacity. Adsorbed or sorbed nutrients are readily available to higher plants and easily find their way into the soil solution. The grain size and organic content of sediments determine to a large extent the capacity of that material to sorb and desorb cations, anions, oil and grease and pesticides. A high capacity will remove potentially toxic metal cations from solution but can also cause a long-term release of adsorbed toxic metals.

**Organic matter:** the higher the organic matter the lower the levels of biologically available contaminants.

**pH:** there are possible direct and indirect effects on animals and plants that attempt to colonize a placement site (applicable mainly to upland sites).

**Iron and manganese oxides:** the greater the content of active iron oxide, the greater the immobilising capacity for potentially toxic metals.

**Redox potential:** the release and fixation of potentially toxic substances from dredged sediment will be affected by oxidative (presence of oxygen) and reducing (absence of oxygen) conditions respectively. This activity is greatly influenced by the sulphur content and chemistry of the sediment.

**Salinity:** seawater can flocculate fine particles thus contributing to the removal of contaminants from the water. It is possible that abundant magnesium, sodium and calcium ions in the seawater displace the toxic metals and thus make them bioavailable. This is particularly true for contaminated dredged material from inland waterways when placed at sea.

### *2.1.3 Biological properties*

Depending on the potential use of the material it may be necessary to analyse the biological properties. This means testing for the presence of viruses, bacteria, yeasts and parasites. Where the biological (and/or chemical) properties are not well understood or if there is concern of possible harmful effects it may be appropriate to carry out tests:

- acute toxicity tests;

- chronic toxicity tests capable of evaluating long-term sub-lethal effects such as bioassays covering a life cycle of appropriate flora or fauna;
- test to determine the potential for bioaccumulation of the substances of concern.

### *2.1.4 Engineering properties*

By this stage the user will have sufficient knowledge of the material to begin to consider which beneficial uses may be applicable. After the broad classification by particle size the engineering properties will further narrow the options. The importance of the engineering properties relate very much to the intended use of the material. Specific guidance is given in relation to each defined beneficial use in subsequent Chapters. In this section, general guidance is given for rock, sand/gravel, consolidated clay and mud.

Rock

Dredging of rock is always capital dredging and may involve blasting, cutting or ripping. The rock may vary from soft marl to hard granite with sandstones and coral in between. It may also vary in size depending on how it was dredged and the type of material. Because of size and weight the occurrence of boulders and cobbles tends to improve the stability of foundations. Angularity of particles increases stability.

Many engineering uses require rock of a certain size range and it may therefore require sorting or processing (ie crushing).
Possible uses include:

- coast protection (armouring, breakwaters)
- offshore berms
- foundation material
- fishing reefs
- aggregate
- construction material

Sand and gravel

Sand and gravel may be produced in the course of capital or maintenance dredging. Considering that aggregate dredging is an industry in its own right it is not surprising that this is generally considered to be the most valuable material to arise from a dredging project. The main difference is that there is less control over the particle size grading of the material.

Gravel and sand have essentially the same engineering properties differing mainly in degree. The defined classification boundary particle size has no engineering significance. They are easy to compact, and little affected by moisture and are not subject to frost action. Gravels are generally more perviously stable and resistant to erosion and piping than are sands. Well graded sands and gravels are generally more stable than those which are poorly graded. Irregularity of particles increases the stability slightly. Fine, uniformly graded sand approaches the characteristics of silt, ie a decrease in permeability and reduction in stability with increase in moisture.

The engineering properties of dredged sand and gravel can be assessed using the same standards and design manuals as for land based aggregates. Removal of salt is important if the material is marine in origin and is to be used in structural concrete.

The engineering properties of marine sands in a hydraulic environment are described in the HR Wallingford "Manual of marine sands" (Soulsby 1994)

Further reference to this is made in sections concerning schemes where sand is exposed to erosion by flowing water.

A very approximate guide for the thresholds of erosion and deposition of material sizes ranging from clay to gravel is given in the following diagram reproduced from US Army 1986 but should be used with caution. Site specific studies and thorough analyses are always necessary where these parameters are of any significance. The velocities are those measured about 10cm above the bed.

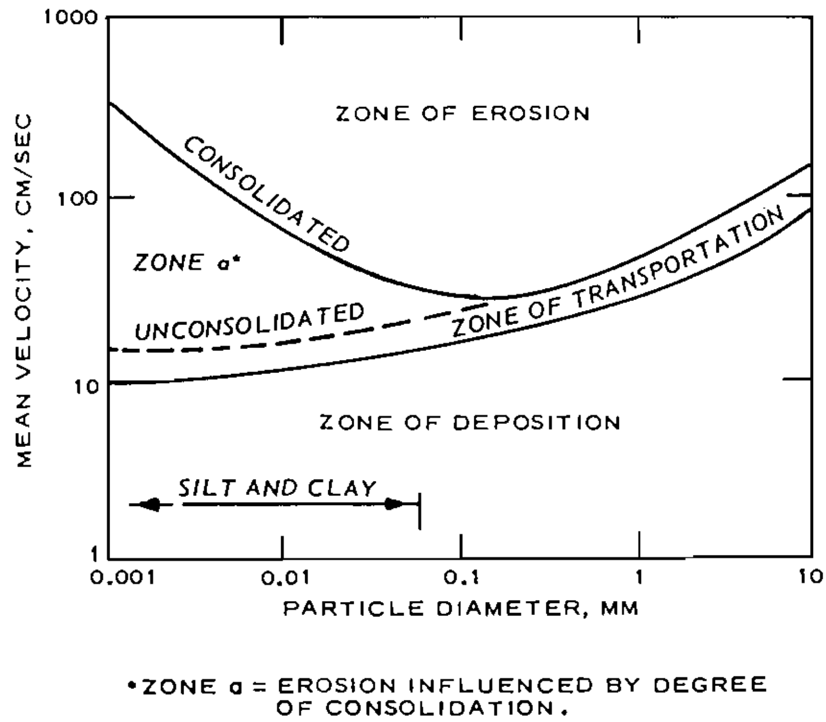



**Figure 2.2 Erosion-deposition criteria for different grain sizes**

Possible uses of sand and gravel include:

- construction material
- aggregate
- beach nourishment
- offshore berms
- shore protection
- reclamation
- capping
- habitat creation
- wetland restoration

<u>Mud/silt</u>
Silt is inherently unstable, particularly when moisture is increased, and has a tendency to become "quick" when saturated. It is relatively impervious, difficult to compact, highly susceptible to frost heave, easily erodible and subject to piping and boiling. Bulky grains reduce compressibility. Flaky grains (eg mica) increase compressibility and produce an elastic silt.

This is the most common material to arise from maintenance dredging. Lacking structural strength it is most suited to agricultural use and habitat development. Dewatering is invariably necessary and takes a long time, perhaps years.

The engineering properties of mud in a hydraulic environment are described in the HR "Mud Manual" (Delo and Ockenden 1992). An approximate indication of thresholds for erosion and deposition is given by the diagram in the previous section.

Possible uses include:

- topsoil
- habitat creation
- wetland/salting regeneration
- bricks and ceramics
- "Mudcrete"
- "Geotubes" (registered trade name)
- coast protection (mud profile engineering and soft berms)

<u>Consolidated clay</u>
The distinguishing characteristic of clay is cohesion which increases with decrease in moisture content. The permeability of clay is very low. It is difficult to compact when wet and impossible to drain by ordinary means. When consolidated it is resistant to erosion and piping, is not susceptible to frost heave but is subject to shrinkage and expansion with changes in moisture. The properties are influenced not only by the size and shape (flat, plate-like particles) but also by their mineral composition; ie the type of clay-mineral and chemical environment (see cationic exchange capacity). In general montmorillonite has the greatest adverse effect on engineering properties and illite and kaolinite the least.

Consolidated clay comes only from capital dredging and may be hard or soft. Depending on the material type and the equipment used it may emerge from the dredging process in lumps or as a homogeneous mixture of water and clay. Possible uses include:

- construction materials (eg bricks and ceramics)
- as an impermeable material for dykes and berms
- capping
- habitat creation
- wetland restoration

### *2.1.5 Processing (hydrocyclone)*
In cases where the dredged material is not suitable for beneficial uses it can sometimes be made more suitable by processing. Dealing with contaminated sediments is covered separately in Section 2.3. Treatments to produce synthetic materials such as the addition of concrete to produce "mudcrete" or heat treatment to produce synthetic aggregates or bricks are covered in Chapter 4. In this section we consider the technology for separating coarse from fine material.

Generally sands and gravels have more applications than mud so the removal of fines to an acceptable level will sometimes be economically justified, especially if there is a local shortage of sands and gravels.

One of the most established forms of processing is the use of the hydrocyclone. Hydrocyclones have wide use in the sand, gravel and mineral processing industries. Its primary use is for separating different density or weight materials within a slurry mixture.

Operation of the hydrocyclone is based on the principal of centrifugal force. It has no moving parts and requires relatively low energy to perform its primary function. The technique has been used in some European ports to increase solids concentrations in dredged slurries. The figure below illustrates a typical hydrocyclone. A slurry mixture is introduced to the feed chamber under pressure. The tangential entry causes the slurry to rotate at a high angular velocity, forcing coarser or heavier particles to the side walls where they continue downward with increasing velocity to the bottom of the cone section. This material then exits through the apex as a denser, higher percent solids, material, called the underflow. The cyclonic flow creates a centrally located low pressure vortex where the lighter, finer grained sediments and water flows upward and exits the top through the vortex finder. This finer grained, reduced percent solids slurry is called the overflow.

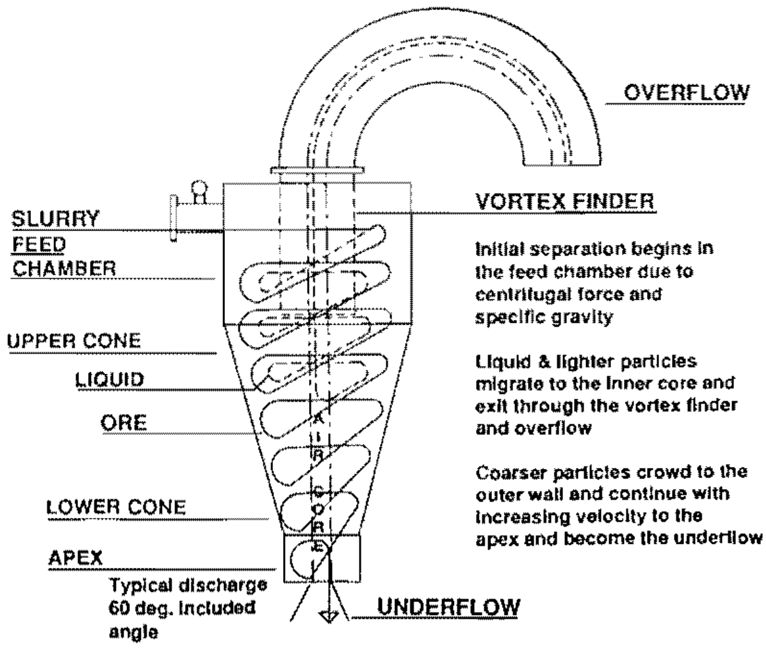



**Figure 2.3 Hydrocyclone in operation from METPRO Supply, Inc., Bartow, Florida**

A desired separation and production rate can be achieved by carefully designing the required hydrocyclone system to include suitable size devices. The table below provides examples of hydrocyclone sizes, defined by the diameter of the feed chamber, and associated operational characteristics. As indicated, typical size devices can range from 0.76 - 0.91m with respective capacities ranging from 0.3 - 252.4 l/s

## Table 2.7 Hydrocyclone size and capacity (Heibel et al 1994)

| Size (m) | Capacity (l/s) | Inlet pressure (kPa) | Separation Size (micron) |
|---|---|---|---|
| 0.076 | 0.3 - 2.2 | 68.9 - 482.6 | 10 - 40 |
| 0.102 | 1.3 - 5.7 | 68.9 - 413.7 | 10 - 40 |
| 0.152 | 2.5 - 12.6 | 68.9 - 344.7 | 15 - 40 |
| 0.203 | 5.7 - 18.9 | 34.5 - 275.8 | 20 - 44 |
| 0.305 | 12.6 - 50.5 | 34.5 - 206.8 | 30 - 44 |
| 0.457 | 18.9 - 94.6 | 34.5 - 179.3 | 44 - 53 |
| 0.610 | 50.5 - 151.4 | 34.5 - 172.4 | 53 - 74 |
| 0.762 | 94.6 - 220.8 | 34.5 - 172.4 | 74 - 100 |
| 0/914 | 113.6 - 252.4 | 34.5 - 137.9 | 100 - 149 |

Operationally hydrocyclones function efficiently with slurry concentrations of about 20% solids by weight. A properly designed device can operate between from about 5% to 50% solids. It operates best at constant pressure and flow rate. They can be stacked in parallel to achieve higher production rates if necessary. For example, to handle the discharge from a dredger with a 0.61m discharge pipe would require about 20 hydrocyclones in parallel, each having a 0.61m dia inlet. It should be technically feasible to mount this number on a floating barge or mobile shore-based trailer.

## 2.2 Is the use environmentally acceptable?

Simply calling a use of dredged material "beneficial" does not mean it is automatically acceptable from an environmental viewpoint. In considering possible uses it will be necessary to carry out an assessment of the impact (Environmental Assessment - EA) and possibly produce a formal Environmental Statement (ES). This may involve substantial time, effort and money. There are no formal guidelines specifically covering beneficial uses in existence although many authorities now have general policy statements on environmental matters. PIANC (1992) suggest the following steps.

Step 1: General description of the ecosystem

A description is required of all the involved trophic chains based on population analyses.

Step 2: Assessment of **all** potential impacts

Using the general description in Step 1 the potential short and long term impacts are predicted for both the operation and the final scheme. In the UK it will involve discussions with official bodies such as the Environmental Agency (formerly NRA), local authorities, local interest groups, English Nature, land owners etc. It is important to include all likely interested parties as an objection at a late stage is difficult to deal with and may delay or jeopardise the whole scheme. The impacts are wide ranging and concern:

- Fauna (bioaccumulation, ecotoxicity and biomagnification);
- Flora (bioaccumulation and ecotoxicity);
- Groundwater (contamination of groundwater and of the food chain);
- Soil (contamination and erosion);
- Air (contamination, dust, and odour);
- Landscape (visual);
- Land-use (planning);
- Politics (National and local policies)
- Economics (benefits, losses,)

Step 3: Study of significant impacts
This phase involves identification of the significant impacts and further studies. If no impacts are identified further studies are not required. Each identified impact is analysed following standard test procedures. Subsequent processing of the results gives an evaluation of the impact which will be included in the ES.

If significant impacts are identified or measured during testing the only choices are to abandon the scheme or provide mitigation in some way (eg in the operational stage by better control over selection of the material to be used, its method of transport and placement etc.)

As far as possible the impacts should be stated by comparison with standards or using risk analysis methods.

## 2.3 Options for contaminated dredged material (cdm)

### *2.3.1 Possible beneficial uses*

There are few options open for beneficial use of highly contaminated dredged material: they are generally restricted to those where the contaminants are "fixed" by heat treatment. This would include manufacture of ceramics and bricks. However, experience has shown that there is consumer resistance to bricks made of contaminated material, however safe they may be.

Slightly contaminated material may be considered for use on land where there is no likelihood of the contaminants getting into the food chain, eg where land-use is restricted to timber growing or crops such as cotton. It can also be used where the material is confined in some way. This includes geotextile filled tubes (see Ch 4.5) or certain reclamation areas.

The productive use of confinement facilities is not a new concept (PIANC 1996). The majority of ports around the world have used dredged material as engineering fill. What is relatively new is the conscious use of contaminated material for a subsequent land use with potential benefits to society. This type of beneficial use requires a balance between the environmental, technical, socioeconomic, legal and policy incentives. The concept of using cdm for use on land does not differ from that of using clean material eg for industrial/commercial and agricultural use and for habitat creation. In the case of agricultural use there are two major factors to consider, the nature and extent of impermeable soils and their susceptibility to pollutant uptake and the public perception coupled with the local economic situation. The following aspects should be considered in assessing potential for beneficial use of cdm for land creation or improvement.

- The characteristics of the dredged material in terms of the engineering strength of the material and therefore the suitability of the land to various types of development;
- The biological properties of the material and those of the surrounding area;
- Proper site selection based on balancing environmental, operational, social, legal and financial constraints and opportunities, appropriate to local circumstances;
- Timing of dredging operations (ie the time between cycles) as it may interfere with the time required to condition the material for end use (eg settlement and consolidation);
- Compartmentalisation of a site to separate new from old cdm deposits and achieve progressive conditioning;
- Efficient and safe transportation of the cdm and possible temporary storage facility;
- Foundations of the site (which may limit the final use);
- Site preparation to prevent leakage and to facilitate drying.

### 2.3.2 *Treatment*

The aim of treatment in this context is to render unsuitable material suitable for beneficial use. In some cases it may be necessary to make it suitable even for disposal. The options for treatment have been reviewed by HR Wallingford (HR 1996) and by PIANC Working Group 17 (PIANC 1996). HR research is continuing and a further report is expected in 1998. The reader is referred to these reports for more detailed guidance. Only a summary is provided here for ease of reference.

Costs are at present high and will in most cases rule out beneficial use but as pressure on disposal sites becomes greater, and costs continue to rise, the treatment option is likely to become more attractive.

There is no single "cure all" treatment available because of the wide variety of contaminants which exist in dredged material. Treatment techniques are available for different contaminants but most are still in the experimental or demonstration phase of development. Some have been used with some success at full scale.

For all projects, where treatment is being considered, a broad 'treatability' study will be required. This study will determine whether the contaminants are adsorbed preferentially to a certain fraction of the cdm, whether standard dewatering techniques will be applicable, how leachable the contaminants are, at what temperature the contaminants will become volatile and whether biological treatment is feasible.

The next step may be to carry out bench tests of each of the possible treatments. These steps will save time and money later when the processing begins.

Treatment processes may be subjectively classed as follows:

- Pretreatment
- Biological
- Chemical
- Thermal
- Immobilisation
- Water treatment

Pretreatment

Pretreatment aims to reduce the volume of material to be treated. Some separate the contaminated fractions from clean fractions (taking advantage of the preferential attachment to fine cohesive material). One method is the use of the hydrocyclone described in Section 2.1.5. Others separate the water from the solids. The main classes are:

- Dewatering
- Size separation
- Washing
- Density separation
- Magnetic separation

Biological

Biological techniques are based on the degradation of organic substances by micro-organisms. They accelerate the natural decomposition of organic contaminants and are particularly useful for contamination with petroleum hydrocarbons and PAH's. The main types of biological treatments are:

- Land-farming
- Bioslurry systems
- Plant cultivation

Chemical

Chemical treatment is based on chemical-physical interactions such as adsorption/desorption, oxidation/reduction reactions, pH adjustment and ion exchange. The processes can be divided into two categories, those that seek to extract contaminants and those that try to destroy or alter them.

Thermal

Thermal treatment can be very effective but is expensive and is usually reserved for very seriously contaminated sediment. The treatments available are:

- Desorption
- Incineration
- Thermal reduction
- Vitrification

Immobilisation

This treatment method attempts to prevent contaminants from moving out of the solid matrix of the cdm. This is done either by chemically binding the contaminants to the solid particles (fixation) or physically preventing the particles from moving (solidification). Some countries allow immobilized soil or cdm to be used as construction material or fill. In the Netherlands and Belgium these products have to meet Building Materials Regulations.

Water treatment

Treatment of cdm usually involves the release of large volumes of contaminated water which must be treated before discharge into sewers or watercourses.

Water treatment is much more advance than cdm treatment and many commercial treatment options are available.

### *2.3.3 Cost of treatment*

It is difficult to generalise but the following Table from the HR research (HR 1996) indicates the broad range of costs experienced.

## *Table 2.8 Cost of Treatment*

| | COSTS US $ PER TONNE (wet weight) | £/m$^3$ |
|---|---|---|
| Mechanical | | |
| Separation | $5-44 | £5-35 |
| Sediment washing | $28 | £25 |
| Physico-chemical | | |
| Extraction | $40-268 | £30-210 |
| Wet air oxidation, base catalysed decomposition | $34-945 | £30-735 |
| Biological | | |
| Microbial degradation | $39-181 | £30-140 |
| Thermal | | |
| Thermal desorption | $70-257 | £55-200 |
| Immobilisation | $33-158 | £30-125 |
| Incineration | | £1000-2000 |

Reference: (Galloway, 1992)
Approximation derived from literature

Conversion: Exchange rate $1.55:£
Bulk density 1200kg/m$^3$

## 2.4 Is it available?

It has to be acknowledged that at the present time the beneficial uses of dredged material are generally driven by the need to do something with the material arising from a dredging operation rather than a demand for the material. There are exceptions such as the Great Lakes in the USA where the demand for material to create wetland habitat exceeds the supply of suitable material but in the UK this is not the case. The example of dredged material from deepening of the Poole Harbour channel being used for beach replenishment at Bournemouth (see Ch 5) is rare. The problem is having the material (which must be suitable for the purpose) available at the same time and place as the need arises for its use.

### *2.4.1 Storage and rehandling*

There is a need for more economic, engineering and hydraulic studies to investigate options for stockpiling.

Ideas have been suggested for long term sub-tidal storage in coastal areas where the material would stay until re-dredged and brought ashore. For the purposes of the regulatory authorities this would probably be regarded as a disposal operation requiring a licence (which it would be if the material is never re-dredged) and the re-dredging would probably also require a licence because the material would be classed as part of the sea bed. This together with the cost of double handling would probably make it uneconomical. On land storage of sand and gravel is more likely to be reasonable if space is locally available.

When the material to be used is remote from the placement area, eg for reclamation or beach nourishment, it is not uncommon to use a short term rehandling pit. Although temporary, the formation of such a pit may require formal consent.

A common combination of plant employed is a trailing suction hopper dredger and a cutter suction dredger. The "trailer" dredges the material and deposits it on the sea bed close to the boundary of the placement area. The material placed on the sea bed is then re-dredged using a cutter suction dredger or stationary suction dredger and pumped via a floating pipeline to the area of reclamation. When this system is employed the point of temporary deposition should ideally be accessible at all stages of the tide.

Losses from the rehandling site may be reduced if it takes the form of a pre-dredged pit, referred to as a rehandling pit. The pit size should be sufficient to avoid interference between the items of plant and have sufficient capacity so that, if one item of plant stops work, the other may continue for a reasonable time so as not to interrupt the overall progress of the works.

The maximum elevation of the material stockpiled in the rehandling pit should not interfere with the operation of the primary dredger.

The hydraulic conditions at the site (waves and currents) must be taken into consideration with regard to possible losses of material (and consequential impact where the lost material goes to). The dispersion of placed material, particularly fine sand, increases with water depth. Serious losses may occur if the depth is excessive.

### *2.4.2 Transportation*

Transportation is of course possible but may be prohibitively expensive. The options are considered below.

Hopper pump discharge

Dredged material delivered to the placement site by a trailing suction hopper dredger or by hopper barges may be pumped directly into a placement area without intermediate handling. This may be done by the trailing suction hopper dredger using its own pumps.

During discharge the dredger is usually moored securely and connected to a discharge pipeline. Sometimes this may be achieved for land reclamation work by mooring at an existing pier or quay. However, for beach nourishment work such facilities are rarely available. The link between the discharging dredger and the pipeline is normally the weakest and most vulnerable part of the system.

It is generally considered that for exposed sites the most suitable type of mooring and pipe connection consists of a heavy sea bed anchor block or pile, on which is mounted a swivel connection for both the discharge pipe and mooring line. From the anchor point a fixed sea bed pipeline runs to the shore and a short flexible floating pipeline leads to the sea surface. On arrival the loaded dredger picks up and connects to the mooring line and then picks up and connects to the floating pipeline. The swivel connection allows the dredger to "stream" into the prevailing wind or current .

When material is delivered to the site by hopper barge, the hopper may be discharged by a barge unloader, sometimes called a reclaimer. Such methods require sheltered conditions.

The barge unloader is a fixed pump-set, normally floating, alongside which the barge is moored. The cargo is fluidized by water jets and discharged via a pipeline by a solids-handling centrifugal pump.

The following points should be considered:

a) Proximity to the placement site.

b) Climatic factors (down time).

c) Availability of existing jetty or mooring facilities.

Hydraulic pipeline
This is a shore based version of the method described above and is the only reasonable form of transport for material in slurry form. Unless the dredging work and beneficial use coincide precisely it will be necessary to re-dredge the material from a lagoon in a similar operation to that described for a marine rehandling pit in Section 2.3. Small cutter suction dredgers are on the market which are suitable for this purpose. An example of this secondary dredging takes place at Hamburg Germany where dredged material is pumped from the plant dredging the port into a lagoon where it is re-dredged at an appropriate rate to feed the processing plant which separates the contaminated sediment from that which can be used. Special care and appropriate plant is needed when dredging from lined basins not to damage the lining. A water supply is needed to produce the right density of material for transport in the pipeline. The pumping of water by the dredger in a confined basin will lower the water level so the supply must be sufficient to maintain the required level.

The pipeline to the placement site will require at least one pump and possibly several booster pumps depending on distance. The following points should be considered in planning transport by pipeline:

a) Saline material should not be moved to a fresh water environment in this way.

b) Dewatering will be required at the point of receipt. The water may require treatment before return to watercourses or drainage systems.

c) Confinement dykes or bunds will be necessary at the point of receipt.

d) Rights of way for the pipeline and access for maintenance.

e) National and local regulations and planning requirements.

Rail
US experience is that rail transport can be economic for a regular maintenance dredging operation. It requires dedicated units (eg tippler trucks) to run on a tightly regulated schedule. Similar systems operate in the UK for aggregate and coal transport. Facilities are required for rapid loading and unloading. Generally existing track would be used but it may be necessary to construct short spurs to the placement site.

The following points should be considered:

a) Material must be dry enough to free fall from the wagons;

b) The length of train will be limited;

c) The number of trains/day and timing will be limited and tightly controlled.

d) Regulations may require the wagons to be covered;

Barge

In the right circumstances barge transport can be the most economic. Access to inland waterways is clearly a necessity which makes this method more appropriate to European and American dredging projects than the UK. Experience, particularly in the USA, has shown that as far as possible it is most economic to use familiar and available equipment. Loading and unloading docks should have sufficient space and equipment to handle two barges at a time. Road links to the placement site are another obvious necessity.

The following points should be considered:

a) Thorough information must be obtained about the waterway: ie navigation depth and width, allowable speed, lock size, traffic density and patterns etc.

b) Regulations exist in some countries concerning responsibility for spills and clean up.

c) Climatic conditions may affect operational schedules.

Truck

This can be the most economical for distances up to about 50 miles. For greater distances transport by truck is too labour and fuel intensive and becomes uneconomic. The simplicity of loading and unloading and the extensive network of roads in most areas make it technically attractive. The relative costs given in the next section are based on 25 tonne trucks carrying $8.5m^3$ of material. They include driver and fuel costs.

The following points should be considered:

a) Regulations concerning size and axle weight of vehicles on public roads.

b) Environmental standards on noise and emissions.

c) Weight limits on bridges.

d) Spillage (especially if material is contaminated).

Belt conveyor

These can be employed to transport relatively dry material for short distances. They are technically feasible and cost competitive. Typical ranges of sizes are:

| | |
|---|---|
| width | 0.75 - 1.75m |
| flight length | 275 - 800m |
| speed | 10 - 15 km/hr |

The following points should be considered:

a) Local planning requirements etc.

b) Material pile-up due to system failure.

c) Breakdown of one flight stops the whole system.

## 2.5 Will it cost more than disposal?

There are costs associated with disposal of dredged material linked primarily to the cost of transporting the material to the designated disposal site. There is considerable scope for diverting the money associated with obtaining licences, assessment of material, and monitoring into beneficial uses of material. For example the Port of Truro, Cornwall, estimates that about 60 - 70% of its dredging costs are attributable to disposal (Brigden 1996).

An economic appraisal of the disposal and beneficial use of dredged material has been undertaken (EFTEC, 1996). The study reports the findings of a survey conducted at 15 ports and harbours. The data collected via the survey and literature review regarding the financial and environmental costs of dredging and disposal of dredged material are used within a cost benefit analysis framework. The objectives of the study were to assess the cost of alternative options for disposal; assess and, where possible, assign monetary values to the environmental costs and benefits of each option; make recommendations on the feasibility of quantifing environmental costs and benefits.

There are three disposal options for dredged material which are assessed in the study; beneficial use of dredged material, disposal of dredged material at sea and disposal of dredged material on land. The costs and benefits of each option are assessed within the cost-benefit analysis (CBA) framework. The CBA is a procedure for:

1. measuring the costs and benefits to all individuals, i.e. society, using money as the measuring rod of those costs and benefits; and

2. aggregating the money valuations of the costs and benefits of individuals and expressing them as a net social cost or benefit

Concentrating on assessing beneficial use in terms of financial performance, the benefits are the cost of the next best alternative of achieving the same beneficial use. for example, in the case of building sea defence, the benefit of using dredged material is the avoided (saved) cost of not using rocks quarried on land.

The following beneficial use categories were specified to the participating ports; beach nourishment, landfill cover, habitat creation, sea defence, other land reclamation, mineral sales and recycling (bypassing) of sediments. Although strictly not a beneficial use, the latter may have less environmental impacts in the dredging area and hence be included in the questionnaire.

Only four of the 15 ports questioned regularly provide, or have some time in the past 10 years provided, dredged material for beneficial uses specified above. One port dredged material for beneficial use with five projects between 1989 and 1995 including habitat creation, sea defence, land reclamation, mineral sales and recycling of sediments. On a regular basis, two ports provide dredged material for land reclamation and for landfill cover as top soil substitute, respectively.

The following points have been identified as the main obstacles to wider use of dredged material for beneficial use. The numbers in brackets show the number of times ports indicated each points as being a problem.

unsuitable particulate size of material (8);

the main concern is that the type of material may not be suitable for the purposes of beneficial use such as difficulty in finding sand suitable for building purposes

lack of demand fro the material (6);

demand for the dredged material is either non-existent or is suitable to the type and the quantity of material extracted, and the price at which it can be made available

additional cost of beneficial use (6);

the main cost items mentioned are the costs associated with handling dredged material ashore, storage on land, travel between the port and the place of use and pumping requirements

unsuitable quantity of material (4);

ports stated that there is no capacity to utilise the enormous quantities of dredged material in any of the specified beneficial uses

contaminated material (3);

some ports have areas where the dredged material is contaminated to an extent which may restrict certain beneficial uses.

others;

an alleged lack of support by Government Departrments and local authorities was mentioned as another problem. Negative public perception of the use of dredged material in beaches and other community spaces was also mentioned.

The results of the cost benefit analysis show that beneficial use produces potential net benefits, i.e. benefits exceed costs. The most important assumption in the beneficial use scenario is the technical feasibility of beneficial use. However, beneficial use may not always be feasible depending on the characteristics of the dredged material, the local requirements and the market for the product.

In conclusion the report states that a ranking option emerges from the CBA. this ranking in the order of increasing costs is as follows:

1. beneficial use (net benefits) where such uses are technically feasible
2. sea disposal (lowest net costs with unquantified environmental impacts)
3. land disposal of uncontaminated dredged material
4. land disposal of contaminated dredged material

Sensitivity analysis show that the above ranking is not sensitive to the discount rate, the relative costs of dredging activity and sea disposal, and the distance travelled between the port and the landfill. Even if it is assumed that the financial costs of landfilling are zero, the financial and environmental costs of transport exceed the cost of sea disposal.

Despite generating net potential benefits, there are feasibility problems with the beneficial use of dredged material which prevented it from being more widely practised. Work by a working group of the Permanent International Association of Navigation Congress (PIANC) and experience from recent examples show that a number of factors influence the choice of a beneficial use (Murray, 1994); material type, location for use, scheme design, timing, dredging method, contamination and funding. The utilisation of beneficial use options in practice face difficulties which will depend on the type of beneficial use employed. These are generally associated with the factors below;

- the cost of handling dredged material so that it becomes suitable for a chosen beneficial use option
- excess supply of the dredged material compared to the potential demand
- suitable uses for large volumes of non-cohesive fraction of sediments
- material may be contaminated and dredging can actually lead to decreasing natural protection of the coats line.

It seems beneficial use of dredged material suffers what recycling of many products suffer: the lack of an efficient market. Better promotion of beneficial uses by providing support to ports and willing users of the dredged material may improve the existing conditions.

Over the next 20 years, it was reported that 3 of the 4 ports in the UK which are already providing dredged material for beneficial uses expect to carry on with their current practices without any change. One of these ports expects to provide material for land reclamation and beach nourishment. Ten of the 11 ports which have not provided material for beneficial use before are not planning to do so over the next 20 years. Only one of these ports expects to provide material which will be used for land reclamation. Greater incentives such as high sea disposal license fees and landfill tax are likely to encourage a diversion of dredged material for beneficial uses. In addition the legal requirement under the licensing system to explore beneficial uses are aimed at altering existing practices and perception over the next 20 years.

<u>Cost of transport</u>
Transport may the most significant cost element in a beneficial use scheme, experience in the USA suggests up to 90% or more. The following relative costs are given as a guide for planning purposes. They should not be used to provide definitive estimates.

## *Table 2.9 Relative costs of transport methods (based on US DRP analysis)*

| Annual quantity m$^3$ | Transport distance miles | Pipeline | Rail | Barge | Belt | Truck |
|---|---|---|---|---|---|---|
| 500,000 | 10 | 1.0 | * | 1.0 | 3.6 | 1.8 |
| | 20 | 1.3 | * | 1.3 | 6.1 | 2.7 |
| | 100 | 3.9 | 2.9 | 1.9 | * | 5.5 |
| | 250 | * | 3.8 | 3.0 | * | * |
| 1,000,000 | 10 | 0.6 | * | 1.2 | 2.2 | 1.5 |
| | 20 | 0.8 | * | 1.3 | 5.4 | 1.7 |
| | 100 | 2.6 | 2.2 | 1.8 | * | 5.2 |
| | 250 | * | 3.1 | 2.9 | * | * |

* Unreasonable

## 2.6 What are the options?

This section is intended as a first line guide to which options should be considered before going into too much detail in a feasibility or design study. The PIANC guide (PIANC 1992) lists the options available for different classes of material. Reference has already been made to this but whereas the PIANC guide is material based, this guide is project based, so for each type of beneficial use a description of possible materials is given.

Sediment cell maintenance (putting it back where it came from)
The material will have to closely match the natural material in its physical response to waves and currents.

Construction
Reclamation

Virtually any material but depends on intended use. Mud is unsuitable for buildings but may be suitable for recreation land after a period of consolidation.

Aggregate

Natural sand and gravel;
Artificial materials such as pellets made from clay/mud (includes vitrified contaminated material);
Rock (may require crushing and sorting)

Mudcrete

Mud mixed with cement

Synthetic material

Bricks or pellets made by firing silt

Filled Geotextiles

Mud and sand (including contaminated)

Dykes

Clay (where impervious dykes are required)

Bunds

Rock, gravel, sand, clay depending on function.

Roads

Rock, sand, gravel, artificial materials made from clay/mud

Coast Defence
Beach creation (recreation)

Sand

Beach nourishment

Sand/gravel (generally the grading has to be similar to the natural material)

Managed retreat

Mud placed behind existing defences before breaching

Mud-shore profile engineering

Mud placed on intertidal mudflats to change the shape from concave to convex

Offshore berms (hard and soft)
- Rock (permanent)
- Sand (semi-sacrificial)
- Mud (energy absorbing)

Agriculture

Agriculture
Horticulture
Forestry
- sand and mud

Amenity

Landfill
Landscaping
Recreation areas
- Virtually any material depending on application.

Habitat

Aquatic habitats for fish etc
- Gravel for reefs, sand for oyster beds, mud for seagrass beds.

Bird habitats (nesting islands etc)
- Virtually any material depending on application. Sand/shell mixture is particularly good.

Wetlands
- Clay, mud

Saltmarsh protection/regeneration
- Clay, mud

Intertidal mudflats
- Mud

Capping

sand, clay

# 3 Sediment cell maintenance

This applies exclusively to maintenance dredging.

There exist a number of situations where removal of sediment by dredging and placement at a designated disposal ground, however well studied and recommended they may be, effectively removes the sediment from its natural path or cycle and may itself have environmental consequences.

## 3.1 Tidal Estuaries

It is a common misconception that the siltation which occurs in estuaries is almost entirely caused by the sediment carried down the freshwater river. We were taught that when the river meets the great expanse of the sea it slows down and deposits its sediment load. While this may be true on a geological time scale it does not describe the estuary dynamics of most British estuaries. Taking the River Thames as an example the oscillating load which passes the Thames Barrier site with each tide (springs) has been estimated at in excess of 100,000 tonnes compared to the daily fresh water river input of a few hundred tonnes during peak months and less than 10 tonnes during low flow months.

Studies have been carried out to try to determine whether there is a net inflow of sediment from or outflow to the sea in the Thames at Southend. The difficulties of total sediment load measurements in a wide and deep estuary together with the problem of seasonal variations has prevented any definitive conclusions being reached. It is clear that large quantities do move around within the estuary and can cause siltation in any low energy regions such as dock entrances or dredged berths. The total dredging requirement historically greatly exceeded the sediment load of the river implying that either there was a net removal of sediment from the estuary or that there was a significant input from the sea.

Similarly in the Tees Estuary in the North East of England the riverbourne sediment can only account for about 2% of the annual dredging requirement, indicating that the source of the sediment is marine. The opposite appears to be true for the River Clyde in Glasgow where the majority of sedimentation is from riverbourne sediment.

<u>Regime concept</u>
It could be said that most tidal estuaries in Britain are "in regime", ie. there is a net balance (averaged over say a year to take account of seasonal variations) between the amount of material deposited and the amount eroded. It is a dynamic, self-regulating process. If excess erosion takes place (eg during a period of high velocity flow) the fact that the river bed is deeper reduces the speed of subsequent flow and this allows deposition to occur. If excess accretion occurs the flow is forced through a smaller cross section and therefore speeds up and therefore is capable of re-eroding the accreted material.

Such a balance is disturbed when an estuary is dredged. The artificially enlarged cross section reduces flow velocity and deposition takes place, attempting to restore the regime balance. This material has to be removed to maintain navigation. Taking the above example of the Tees the vast majority of the sediment removed comes from the sea bed (principally during storms when the sea bed is disturbed by wave action and the flood tides carry the sediment into the estuary). This is not a natural situation. If the natural regime were in total control any material so entering the estuary would be flushed out by the combined effects of river and tidal flow.

Design criteria
Continuing with the above example, the issue to be resolved is where should the material, which has been removed from the sea bed by an indirect consequence of dredging in the estuary, be placed.

The study must answer the questions:

> Where would the sea bed material have gone if it had not been conveyed to and trapped in the estuary?
>
> What are the potential consequences of the deprivation? These may include downdrift coast erosion and loss of sea bed habitat.

The answer to these questions may lead to the conclusion that it would be beneficial to return the sediment to the cell. This may actually be a cheaper option than removing altogether from the cell (eg into deep water).

There is an instinctive desire to avoid placing the material where it can reenter the dredged area, so total removal from the system is the usual practice. This is based on a simple appraisal of economics. It should be challenged if only because the transport cost of removing from the system may outweigh the cost of redredging a proportion of it. Another major factor in some cases is that the source of sediment is so large that the amount removed by dredging and placement outside of the sediment cell affords no significant reduction in its size and therefore the potential for resiltation.

Where the offshore sediment movement has a net drift in one direction it should be possible by hydraulic studies to identify the most suitable location to place the material on the downdrift side. The criteria would be optimisation of the following parameters:

- Minimum disruption of normal sediment cycles;

- Avoid substantial alteration to existing contours at the selected point. This may be achievable by not placing all loads at the same point but rather over a design area.

- As close as possible to the dredging area to minimise transport costs but not so close as to encourage immediate return of the material to the estuary.

- The material placed must have the same physical characteristics as the material in the cell. For example, if the material in the cell is sand, then the placement of mud in that cell is unlikely to have the desired result.

- Particularly if the material is mud and the estuary is polluted the adsorption of contaminants onto the mud during its time in the estuary may render it unsuitable for placement in the marine environment.

## 3.2 Longshore drift
On many stretches of the British coastline and many other parts of the world significant quantities of sediment, particularly sand and gravel, are moved by oblique wave action with a resultant net drift in one direction. The visible evidence is often seen where groynes have been placed on beaches in an attempt to arrest the material. Where such a drift crosses a river mouth the result is often a bar formation just seaward of the mouth. This can present a navigation

hazard, particularly as it is also likely to be in the location where a vessel leaving a port first encounters significant waves.

The capital solution is usually to build a large groyne or mole on the updrift side of the channel. This can be very effective but has two major disadvantages:

a) It has a limited life. Material gradually accumulates on the updrift side and eventually bypasses the mole causing a new bar seaward of its original location;

b) It deprives the downdrift side of its supply of material, resulting in some cases in severe erosion.

An extreme example is Lagos in Nigeria where the updrift beach has moved seaward at least 1km and the downdrift beach has receded a similar amount. Another example (in Westbay, UK) is shown in the photograph below:

The dredging/beneficial use options to deal with this problem in a sustainable way are:

a) sand bypassing scheme;

b) dredging from the bar and placement of the material on the downdrift side.

<u>Sand bypassing schemes</u>
A possible coastline management strategy involves sand bypassing, ie the supply to downdrift beaches by disposing of dredged material within the sediment transport system. Sand bypassing may be performed in various ways. The sediments may be intercepted updrift of a navigation channel by a fixed pumping installation, transported by pipeline and discharged on the downdrift side of the channel. If volumes are small and concentrated, such as in a very localised channel bar formation, the sediment may be moved by the regular use

of a bed-leveller. If volumes are large or if site condition do not favour the use of a fixed pumping installation, sediment may be dredged from the channel, transported, and discharged at a suitable location on the downdrift side.

A technique gaining in popularity for this type of dredging is the use of the thrust or jet pump. One of the principal advantages is that it has no moving parts and is therefore much less susceptible to breakdown than many previous attempts at sand bypass schemes.

A scheme consists of:

i) Creation of a sand trap on the updrift side to intercept the drifting material before it enters the navigation channel;

ii) A sand bypassing system comprising:

  a) A shore based mobile sand pump operating from a fixed trestle perpendicular to an updrift breakwater;

  b) A pipeline (usually underwater) to transfer the material to the downdrift side.

Such a scheme is in operation at Paradip, India (Panda et al 1995). One disadvantage of the jet pump is its relatively poor hydraulic efficiency. A solution is to incorporate a centrifugal pump. In hybrid form this system gives a high overall efficiency (Wakefield 1995).

## 3.3 Resuspension

In situations where there are very high fine suspended solids concentrations, often associated with the formation of fluid mud under certain tidal conditions, siltation rates can be extremely high. In such situations the source of sediment (ie natural cyclic resuspension of deposited mud) is likely to be extremely large. Attempts to remove sediment from the system in sufficient quantities to deplete the source are futile and there seems to be little point transporting it large distances in an attempt to do so. In such a case it may be considered more sensible to simply resuspend the material by some form of dredging process and allow the currents to carry it away from the site. Whether or not some of the material later returns to the site is virtually irrelevant as it would make only a marginal difference to the siltation rate.

The "benefit" in this case is mainly economic due to the huge saving on transport costs. However, if it avoids having to place the material in a marine disposal area it could be argued that the operation is overall a beneficial use of the material and is certainly an option which should be considered before conventional disposal is allowed. It is probably indeterminate at the present time whether there is any benefit to the system in retaining material within it.

<u>Design criteria</u>

- possible impact on marine life of temporarily increased sediment concentrations;

- selection of appropriate plant and operating rate to control concentration increase to an acceptable level;

- optimising the time in the tidal cycle when the work is done to:

a) minimise the risk of immediate return of sediment to the dredged area;

b) minimise the risk of increasing siltation of adjacent structures, eg. berths, locks or dock entrances.

# 4 Construction

Construction use of dredged material is deemed to include reclamation, aggregate, mudcrete, filled geotextile containers, and synthetic building materials.

## 4.1 Reclamation

Generally coarse materials, sands and gravels, are more suitable for reclamation schemes, especially if the land is to be used for buildings or other purposes which involve heavy loadings. The reason is primarily that silts and clays consolidate over a long period and so are unsuitable for foundations. Because most maintenance dredged material is of this type most reclamation schemes will involve prospecting for suitable sources of material to be dredged or will be related to capital dredging schemes where the material is more likely to be suitable. Nevertheless there are schemes, such as for parkland where settlement can be accommodated without concern, where silty materials can be used. If this is supplied from maintenance dredging it should be noted that the rate of supply is dictated by the siltation/maintenance dredging rate.

Techniques exist for speeding the consolidation process. This can be enhanced by horizontal layering with sand or gravel or by inserting vertical drains on a grid pattern. It is obviously best to consider this at design stage rather than after the event. A lesson is to be learned from the reclamation associated with the development of Osaka South Port (Japan) (Ohnishi and Sasaki, 1990). It was necessary to keep the cost of reclamation as low as possible so it was decided to use the clay dredged from channel and berth areas as the fill material. In the reclaimed area the original ground consisted of a very soft alluvial clay stratum 15 - 20m thick over which the softer dredged clay was placed for reclamation. This brought about serious problems of subsidence and inadequate bearing capacity. Excellent results were achieved with the remedial action for about 100ha of the reclamation but the authors point out that many other schemes in Japan have not been successful.

### *4.1.1 Granular material*

BS 6349: Part 5: 1991 provides general guidance on reclamation using dredged material.

Site preparation

Site preparation may be unnecessary if the ground upon which the dredged material is to be placed is firm and provides a reasonable foundation.

Where the site is overlain by weak deposits it may be necessary to remove these before filling commences. The decision will be influenced by both economic and engineering factors.

In order to determine the rate and amount of settlement that will result if strata are surcharged by placing of material the characteristics of the soil to be surcharged and of the fill material have to be determined. This is normally done through a site investigation and subsequent laboratory testing. Fill materials may undergo a change of density resulting in the final placed density being greater or, more commonly, less than the in situ density of the source material (see bulking factors Section 2.1.1). Calculations to determine the rate and extent of foundation settlement should be based on the maximum density of the placed material as determined by laboratory testing. (BS 1377: Part 4 : 1990 provides guidance on this).

Materials
For beneficial use applications the material available may be less than ideal and there may be cost implications in "making do". An economic material is a well-graded, free-draining sand with particle sizes in the range 0.10 - 0.60mm. Sand and gravel mixtures are normally also suitable. Materials with a significant content of particles coarser than 0.60mm may cause problems if the material is to be conveyed by pipeline as described in Section 2.3.

Materials finer than 0.10mm may be subject to excessive losses during dredging handling and placing.

The maximum percentage fines that is acceptable in materials for land reclamation depends to some extent on the overall grading of the material. A well graded material containing a high percentage of coarse particles may be better able to absorb higher percentages of fines without any adverse effect due to the greater voids ration. A difficulty that arises whenever significant percentages of fines are present, however, is the natural tendency for the fines to segregate during hydraulic placing.

Materials that are not well graded may consolidate less well and require dewatering.

If the material is to be placed by pumping, fines may also be released with the draining water when flow velocities within the area of reclamation are sufficiently high to maintain fine particles in suspension. When material is placed hydraulically without containment bunds, the free escape of draining water normally removes most of the fine particles.

When the reclamation area is remote from the dredging operation rehandling may be necessary, Guidance is given on this in Section 2.3. Guidance is given on transport alternatives in Section 2.4.

Containment
It is usual but not always essential to contain the reclamation material by means of a boundary structure. This may take the form of temporary or permanent embankments, sheet steel piling or concrete structures. If the material is not confined considerable losses may occur especially if the site is exposed to waves or currents.

Segregation of fines
When dredged material is transported hydraulically into the reclamation area, there is a natural tendency for separation of the various component particle sizes to occur. Coarse material is deposited close to the point of discharge and particles of smaller size or lower specific gravity are transported further. This may result in pockets of fine material forming which may not achieve the required strength within an acceptable time.

Fines may also accumulate in front of the advancing face of denser fill with the consequent formation of weak deposits immediately in advance of the main filling. Concentration of this material may eventually be overtopped by coarser material and hidden from view. The finished reclamation surface may then appear uniform and sound but may conceal pockets, perhaps quite extensive, within which bearing capacities may be very low. This situation should be avoided where reclamation is for development purposes.

Consolidation
The consolidation of granular materials which are properly placed by hydraulic methods when particle size is in excess of 0.10mm is normally rapid, and

improvement in density is normally good without further treatment. However, when the material permeability is low, or when the filling has been carried out in fully or partly submerged conditions, consolidation may be poor. IJRM (1978) gives common relative densities for hydraulically placed fine to medium sands as 35-40% if placed in submerged conditions and 50-65% if placed above water.

<u>Compaction</u>
Where compaction is necessary the surface layer of 300 - 400mm can be most effectively compacted by using a vibrating plate or roller compactor. For maximum effect, the frequency of vibration should be selected to suit the characteristics of the reclamation material.

The effectiveness of surface vibration compaction decreases with depth. Increasing the vibrator mass will extend the depth of influence, but if the depth to be compacted exceeds about 2m alternative methods, such as vibroflotation for dynamic compaction, may be necessary.

Further guidance on compaction may be found in BS 6349 Part 1 and BS 6031 Clause 9.

<u>Settlement</u>
Well placed hydraulic fill on firm ground is not normally subject to significant settlement. If the material has been compacted subsequent settlement is normally negligible.

When the material is placed upon weak ground, such as unconsolidated silts, clays or peats, the weight of the fill results in consolidation of the foundation materials with consequent settlement of the reclamation. The settlement can be predicted using conventional soil mechanics theory, provided that the properties of the foundation material and the load overlying them are known. The amount of settlement predicted may influence the amount of material placed. In areas of complex ground conditions (common in estuarial areas) differential settlement may occur.

These problems are not unique to beneficial uses of dredged material and the reader is referred to standard civil engineering manuals for further guidance on calculation methods and ways of dealing with the problems.

<u>Protection</u>
In sheltered situations it may be acceptable to allow the material to form its own defence by a natural adjustment of slope in response to local wave activity (as natural beaches do). However, in exposed situations (eg at coastal sites) the reclamation will probably require protection against waves and currents.

Protection may take many forms depending on the proposed land use and the sea conditions that prevail in the area. Protection is most commonly achieved by some form of armouring, which may include sand asphalt, pressure-grouted concrete mattresses, concrete block revetment or riprap rock. Design guidance is given in the Shore Protection Manual (1984).

<u>Wind erosion</u>
Large areas of land reclaimed with fine or medium sands which are exposed to strong winds will suffer erosion when the surface is dry. Apart from the problem of loss of material from the site there may be sensitive areas downwind which could suffer.

Estimates of the rate of sand transport by wind may be made using Bagnold's formula (Bagnold 1936). This assumes sand to have zero moisture content (which is rarely the case). Work by Terwindt provides a relation between moisture content on a beach and the minimum shear velocity needed to initiate sand transport by wind. From this the rate of sand transport under various moisture conditions anticipated can be estimated (Kerckaert et al 1985).

Wind erosion can be controlled to some extent by the erection of sand fences to trap the mobile material. To achieve a permanent solution it may be necessary to seal the sand surface with an erosion-resistant layer. This may consist of top-soiling and the establishment of vegetation or, in areas of commercial development, the formation of a bituminous or concrete wearing surface. In areas which are not subject to heavy wear a temporary seal can be achieved by spraying with a bituminous emulsion.

### *4.1.2 Cohesive material*

Consolidation of mud

As new layers of unconsolidated mud are placed on top of a mud bed the weight squeezes water out and crushes the flocs as more weight is transferred to them. At this stage the sediment ceases to behave as a suspension of individual flocs and starts to behave as a soil with behaviour described by effective stress theories. However, the soil skeleton in these circumstances is extremely compressible and strains are large. Thus suitable theories to describe this behaviour must include large strain and the body forces of self weight. Traditional soil consolidation theories are inadequate in both of these respects.

A fully saturated soil may be considered as incompressible particles forming a framework whose pore spaces are filled with an incompressible fluid (water). At equilibrium the framework is subjected to a system of stresses. The stresses at any point of a section of the framework can be computed from the total principal stresses (ie in each directional plane), which act at this point. The voids filled with water are also under a stress which acts in all directions in the water and solid. This is termed the pore water pressure. The difference between this and the principal stress is the effective stress.

Thus it follows that at equilibrium the total stress in any direction at a point can be expressed in terms of the effective stress.

If there is an instantaneous increase in the total stress such as that which would be caused by placement of a hopper load of mud, the pore water pressure is seen, by experiment, to rise immediately. With time, the pore pressure returns to its equilibrium value as water drains from the pore spaces. The loss is therefore gradually transferred to the particle framework. With this increasing effective stress the particle framework strains and this is accompanied by a decrease in porosity and an increase in density. When consolidation is complete the pore water pressure is at its equilibrium value and the effective stress is equal to the total stress.

It is evident therefore that changes in soil structure are achieved by changing the effective stress. This cannot be measured but can only be derived from measurement of the total stress and pore pressure.

Looking down into a consolidating mud bed there is a transition from a suspension where pore pressure equals total stress and the effective stress is zero, to a situation where the pore pressure becomes less than the total stress and effective stresses start to develop between the particles. As drainage proceeds the effective stresses between particles increase as the submerged weight of the overlying material is transferred to the soil skeleton. When the pore pressure returns to hydrostatic, the effective stress is equal to the submerged weight of the overlying particles and the pore pressure is zero.

Burt and Parker (1984) describe experiments on the settlement and density in beds of natural mud during successive sedimentation. Fixed masses of mud at a fixed concentration were added at 24 hour intervals to a settling column 10m high. A total of 7 beds were added and density profiles measured 24 hours after each addition and immediately; before the next one. Density was measured 24 hours and 15 days after the last bed was added. They observed that the degree of consolidation of the uppermost layer 24 hours after placement became less with each successive layer. This was attributed to the fact that the lower layers were not fully consolidated and therefore there was an upward flow of pore water which hindered consolidation of the layers above. After 22 days from commencement only the first layer had fully consolidated.

It was also concluded that the absolute thickness of the layers affects the rate of dissipation of pore water pressure.

In the long term the rate of consolidation is controlled more by the rate at which water is evaporated from the surface than the self weight consolidation. It is therefore often the case that the surface forms a crust. The crust is usually overconsolidated due to the increase in effective stress caused by high negative pore pressure resulting from evaporation. Below the surface crust, however, the mud is extremely soft, with water content usually showing little change from the time of deposition. Density and shear strength increase only slightly, if at all, with increasing depth. In a reclamation area fed hydraulically (ie mud discharged via a pipeline) the engineering properties are generally better near to the discharge pipe. This is because the coarser material tends to settle first and the finer material travels furthest.

Dewatering

Dewatering is not required for all types of beneficial use such as wetland and aquatic habitat development and aquaculture. It is required for nesting islands, upland habitat, most kinds of recreational use, agriculture, forestry, horticulture etc.

The material is usually placed hydraulically into the disposal area in a slurry state. Although a significant amount of water is removed through the overflow weirs of the confinement the material usually consolidates to a semi-fluid consistency that still contains a large amount of water. This makes it unsuitable for most development works. There are two basic methods to accelerate natural dewatering, surface drainage and bottom drainage.

**Surface drainage/evaporation**

As described in the section on consolidation, a surface crust forms which can inhibit further drying and consolidation. Natural shrinkage and cracking allows drying to a greater depth and this can be encouraged by providing good surface drainage. This prevents ponding of rainwater which would inhibit drying.

This can be further aided by trenching but requires heavy plant and it may take one or two years before sufficient consolidation has taken place to allow the plant onto the site. Special plant with wide tyres (to distribute the weight) is available and can be used for this purpose.

## Table 4.1 Trenching methods

| Equipment | Min crust m | Max crust m | Max trench depth m | Trenching rate m/hr | Relative cost/hr |
|---|---|---|---|---|---|
| Low ground pressure tracked vehicle + rotary trencher | 0.10 | 0.61 | 0.61 | 600+ | 1.0 |
| Small dredge | 0.10 | 0.25 | 0.76 | 8 | 1.4 |
| Amphibious dragline | 0.15 | 0.46 | Crust + 0.46 | 12 | 1.4 |
| Small dragline on double mats | 0.30 | 0.46 | Crust + 0.46 | 9 | 1.0 |
| Medium dragline on double mats | 0.30 | 0.46 | Crust + 0.46 | 12 | 1.2 |
| small dragline on single mats | 0.46 | 0.61 | Crust + 0.46 - 0.61 | 15 | 1.0 |
| Medium dragline on single mats | 0.46 | 0.76 | Crust + 0.46 - 0.61 | 18 | 1.2 |
| Large dragline on single mats | 0.61 | 0.91 | Crust + 0.61 | 24 | 1.3 |

In general trenching should be carried out at intervals of between 2 weeks and 1 month to begin with then gradually increasing to about 4 months until the required dewatering has been achieved.

**Bottom drainage**
This involves the placement of porous pipes, tiles or sand layers at the bottom of the site. This enables dewatering and therefore consolidation to take place at the lower levels. Sometimes vertical sand drains have also been used to speed consolidation. The technique has been used successfully in a scheme in Surabaya, Indonesia where fine dredged material was placed in a reclamation area adjacent to a new jetty and berth construction. It has also been used to remedy part of a reclamation site for the Osaka Airport, Japan although installing drains after the material has been placed is expensive and difficult.

### 4.2 Aggregate
The UK is one of the largest marine aggregate producers in the world. This has partly been driven by dwindling land based sources and greater environmental constraints, together with increasing demand. The potential for beneficial use of suitable material is therefore considerable. However, in most cases the desired material has been prospected for and the necessary permissions obtained to dredge the identified area. For the purposes of this manual this is not regarded as a "beneficial use" although it clearly is just that. The question addressed in this manual is whether material dredged for other reasons is suitable for use as aggregates. If the material is suitable then the techniques and experience of the marine aggregate industry are highly relevant.

In the UK most maintenance dredged material contains a high proportion of silt which is not suitable. Material arising from capital dredging and maintenance of certain sites where the predominant maintenance dredged material is sand or (very rarely) gravel is therefore, the most useful in this respect. Logistics and economics then becomes the biggest issues. For example, predominantly sandy material from the Manchester Ship Canal has been sold as commercial sand but the supply greatly exceeds the demand.

Some dredged material can be used as aggregate but in most cases will require some treatment. Generally the fine cohesive fraction is not acceptable and therefore must be removed. Separation methods include hydrocyclones (see Section 2.1.5) and differential settling.

Salt is not acceptable in aggregate to be used for reinforced or other structural concrete so if the source of the material is marine it will require washing before use. The safe discharge of saline water from the processing plant will be an issue requiring attention if it is a fresh water environment.

If the salinity is not too high the sandy fraction can be used as backfill material or in the production of bituminous mixtures or mortar.

Once the material is in the form of clean sand and/or gravel it may require screening to achieve the desired grading for a specific purpose.

## 4.3 Mudcrete

"Mudcrete" is marine mud stabilised with ordinary Portland cement. This gives it the advantage of greater strength while minimising the leaching of contaminants.

Laboratory tests

Extensive laboratory test have been carried out to ascertain the additive which would best improve strength and contaminant binding properties when mixed with marine mud (Priestley 1995). The additives tested were ordinary Portland cement, lime, pulverized fuel ash, and a proprietary product. Ordinary Portland cement proved to be the most effective additive. The optimum ratio of cement to mud was 20% based on dry solids weight. The gain in shear strength was from an average of about 5kPa in the muds natural state to 100kPa with cement added. It was also found that the cementatious process produced a material of very low permeability.

Mixing and placement

The method used in Auckland, New Zealand, was tried and refined off site. All plant used to dredge and stabilise the sediment was operated from flat top barges. Dredging was performed using hydraulic excavators discharging to shallow mixing bins on the barges. Cement was sprinkled over the surface of the dredged material and mixing was performed using a modified stabiliser hoe adapted to fit on the beam of a hydraulic excavator. Once mixed the mudcrete was placed using hydraulic excavators operating either from the barges or from within the reclamation. When the material had to be placed below water level a clam shell bucket was used.

Problems were experienced at the beginning of this operation with the mixing consistency of the mudcrete. This was overcome by specifying the cement content in terms of bulk quantity rather than dry weight. It was found that an application rate of about 100kg of cement per cubic metre of dredged material achieved the target shear strengths. The clam shell bucket also had to be modified to prevent the mudcrete sticking to the bucket and not being released.

Once mixed and placed the mudcrete set sufficiently so that it could be walked on after one day and could be subjected to construction plant after 3-4 days.

Shear strengths of over 200kPa were usually obtained after 7 days curing. On completion a layer of road basecourse aggregate was placed and compacted on top of the mudcrete and was sealed with a layer of bituminous chip seal.

Geotechnical properties
An investigation was carried out at the Auckland site 6 months after placement with the following results.

Two boreholes were made. The material encountered in each was variable. It ranged from well mixed cemented material through to cemented material and further to soft clay. Some voids were also observed. The shear strength of the well mixed and cemented material was high at around 400kPa. Placement of the material while in a more or less liquid state during construction influenced the final geotechnical properties. It appears that the well mixed material within the clam shell remained intact but on the perimeter of each load the material had a lower strength or was a soft clay material. In effect, the reclamation is competent lumps of material surrounded by a weakly cemented matrix. This structure is analagous to large boulders placed in a stack pile surrounded by a weakly bonded material.

Contamination
The stabilisation process has been found to reduce the contaminated discharge in two ways, firstly by reducing the leachate strength and secondly by reducing the permeability of the material. Nevertheless the contaminants in mudcrete may be higher than in the marine mud because of the chemical processes which take place on mixing. Experience at Auckland was that the leaching strength from standard TCLP tests were higher for zinc but generally lower for all other contaminants. The results of seawater elutriation tests showed that for all materials except copper the results were less than the detection limits. For copper, however, relatively high concentrations of leachate were released and this was consistent with earlier laboratory studies. The remedy was to ensure sufficient dilution to meet USEPA standards for marine waters.

Mudcrete has the potential to be used on much larger structures. With suitably selected design criteria such structures could be lighter than conventional quay structures. Research is needed to define strength parameters such as effective cohesion and effective angle of friction for its long term use. While mudcrete appears to be chemically stable, the leaching strength of copper appears to exceed marine discharge standards. Research should aim to find additives to suppress this.

## 4.4 Other building materials
Investigations have been carried out on the possible use of dredged silt for making building products such as bricks and synthetic aggregates (Collins 1979).

Historically very little use has been made. Some rare examples are early cement works on the banks of the River Thames which used mud in cement production up to about 1930 but abandoned it in favour of excavated clay (IGS 1978), and Limerick works of Cement Ltd, Ireland where geologically recent deposits laid down by the River Shannon have been used (Lea 1970). Maintenance dredged material from the Humber was once considered for use in cement manufacture but, although of acceptable composition was rejected because no guarantees could be given of future quality.

## Bricks

Collins (1979) reports that small test bricks were extruded from combined samples of silt representative of 3 ports using a Rawdon vacuum extruder, and dry firing at 1000-1050°C. Higher temperatures caused the bricks to bloat and become distorted, although this might be reduced by slower heating rates. Cubes were sawn from each brick and tested for compressive strength by crushing using an Instron Universal testing machine. The results were:

| Source | Strength (MN/m2) |
|---|---|
| Manchester | 23.4 |
| Tees | 10.0 |
| Forth | 19.3 |

These were lower than strengths reported by Rhoads et al (1975). Drying shrinkage was rather large at 10% and caused two full-size bricks to crack on drying. This could possibly be improved by using a drier material in the extruder and adding a water reducer to increase elasticity if necessary (Heller and Thelan 1971), or by admixing a material with less shrinkage such as pulverized fuel ash.

## Synthetic aggregate

Collins (1979) also investigated synthetic aggregates. Hand rolled pellets 10-15mm in diameter were produced from each silt sample after drying in an oven to a water content of 25-50%. The pellets were then completely dried and fired for 30 minutes on silica trays in a muffle furnace at 1000-1100°C. Above that range the silts began to melt. The aggregates were tested for relative density and water absorption according to BS 812 Part 2 1975. Most of the aggregates fell in the lightweight range (a relative density on an oven dried basis of about 1.6 or less can give a bulk density of less than 1000 kg/m$^3$ for uniform spherical aggregates). The water absorption is high unless the silt is heated until it nearly melts.

An indication of strength was obtained by crushing using an Instron Universal machine. Compressive strengths ranged from a few grams to more than 200kg. The average was about 30kg. Results of less than 5kg were obtained for a few pellets with structures that had become friable after melting and for coarse silts.

Except for the coarse silts, the melting temperatures were all quite close together but appeared to correlate more with port of origin than any other factor. At 1100°C, silts from Manchester and the Forth showed only slight bubbling and bloating and those from the Thames and Tees slightly more. Bristol silts showed partial melting and some of the Humber silts became almost completely molten.

Removal of sea salt from the silts could alter the properties of the aggregates considerably but apart from a general increase in the melting temperature no consistent trend was found.

Chloride has a deleterious effect on reinforcing steel in concrete but virtually all the chloride was found to be driven off by the firing process. (Permissible levels of chloride are specified in BS CP 1100 "The Structural Use of Concrete").

Another way of attempting to improve the bloating characteristics of aggregates made from dredged silts is the addition of pulverized fuel ash (pfa). This might also partly solve the problem of dewatering wet silt, which could be costly in terms of equipment (filter presses, band filters or centrifuges) (Collins 1979). Aggregates fired at a number of temperatures were compared with those produced from silt and pulverized fuel ash alone, but no major difference in properties was evident, except for an increase in melting point with increasing pulverized fuel ash content, presumably due to its higher alumina content. The flux contents of English pulverized fuel ashes are very similar to those of dredged silts and, according to Riley (1951), both materials should not have sufficient viscosity at the temperatures at which gases are liberated to cause bubbles to be trapped and bloating to occur. Scottish pulverized fuel ashes are generally lower in fluxes and even higher in alumina than English pulverized fuel ashes and mixtures with dredged silt could be within Riley's range of bloating clays.

Silt/pulverized fuel ash mixtures do not appear to produce significantly better aggregates but they may be advantageous in other respects. From the point of view of silt utilisation, addition of pulverized fuel ash leads to a reduction in the drying requirement per tonne of aggregate produced. For wetter silts this would result in beneficial use of more pulverized fuel ash than dredged silt.

Dredged silt aggregate compares favourably with many lightweight aggregates in its capability of being used in structural concrete as well as block manufacture, and also because of its proximity to large ports demand for aggregate is high and transport costs can be relatively low. The aggregate has very little water-soluble impurity which could be deleterious in concrete (eg chloride, sulphate, alkalies) and is not affected by an alkali-aggregate reaction.

Colins found that all silts with a specific surface of greater than about 200 $m^2/kg$ produce reasonably strong aggregates which would appear to be suitable for use in concrete. Apart from this, fineness does not seem to have much effect on the quality of the aggregate, except perhaps for a slight tendency to lighter weight or lower water absorption for the finest silts. The coarse silts had a high quartz content and sintering would have to be carried out at higher temperatures. In general it can be said that aggregates made from dredged silt have a higher strength than many lightweight aggregates but they are adversely affected by coarse fractions and shell fragments in the raw material.

## 4.5 Filled geotextile containers

Synthetic fabrics have been used for the past 30 years for various types of containers such as sandbags, geotextile tubes and geotextile containers. In recent years geotextile containers filled with fine dredged material have begun to be used in construction (Fowler et al 1996).

Geotextile containers filled with granular dredged material have been successfully used in constructing groynes (Harris 1994), but filling these containers with fine grained maintenance dredged material and contaminated dredged material has been very limited. Beneficial uses of fine-grained dredged material in construction have been fairly limited because of the high water content and low strength. Confinement in geotextiles has improved the potential use.

Filling and placement

The material is placed in bags, tubes or large containers either in situ or in split hull barges. The tubes can be filled hydraulically with dredged material straight from the delivery pipe of a cutter suction dredger or other slurry pump system (see Ch 2 "transport methods"). They can be placed using a cradle bucket on a barge mounted crane or they can be installed using a continuous position-and-fill procedure. When using the hopper barge technique a geotextile sheet is placed over the whole hopper and the dredged material is then loaded in the normal way (taking care not to damage the fabric). The two long sides are then drawn together along the centre line of the barge and joined using portable industrial stitching equipment. The tube is then allowed to free-fall through the bottom opening doors of the split hopper barge.

Fabric design

A variety of textures are available, woven and non-woven, with a range of porosities and strengths. The design parameters to be considered are:

- contain sufficient permeability to relieve excess pore pressure;
- retain the dredged material (non-woven liners retain virtually 100% of fine grained material);
- resist the pressures of filling and active loads without failure of the fabric or the seam;
- resist mechanical abrasion during filling;
- survive construction abuse during placement;
- resist puncture and tearing;
- resist ultra violet light.

Guidance on the design of geosynthetic material in civil and marine engineering is given in the UTF Geosynthetics Manual (Rankilor, 1994)

Field tests

The Waterways Experiment Station (WES, Vicksburg, USA) recently filled four tubes about 150m long with fine grained dredged material for potential use by the Corps of Engineers Mobile District for dyke construction and wetland creation at Gaillard Island. It was found possible to pump material into the tubes at a density of 1.2 - 1.3 $t/m^3$, directly from the point of dredging in the navigation channel. After 4 - 6 weeks of drainage the density in the tubes had increased to 1.4 - 1.5 $t/m^3$, and the tubes had flattened to about half of the original height. The tubes were then filled a second time.

Pressures measured in the tubes ranged from 28 - 34 kPa and strains were less than 3%.

WES also instrumented geo-bags and geo-containers with pressure cells and strain gauges in a sedimentation control project on the Mississippi River at Red Eye Crossing, Los Angeles. This consisted of 6-9m high underwater control dykes between 180 and 425m long. Over 40,000 bags and 700 containers were dropped in 18m deep water with a current strength of 1.2 m/s without failure of any units or inaccuracy of placement.

River applications

The most prevalent use to date has been in river training works. Usually, flow training structures have traditionally been constructed with rock. As an alternative, a structure can be built up by one or more dredged material-filled fabric tubes. By varying the size, number, and composition of the tube units, virtually any structure can be produced, including revetments, groynes and longitudinal dykes.

They can also be used for scour protection, eg adjacent to a weir. Normally this is done with rock of a certain size grading with filter layers underneath to prevent sediment passing through the rock layer. By filling in and covering a depression in the riverbed with dredged material-filled fabric tubes, the same result can be achieved. In this case the tubes have to be placed close together.

Estuary applications
Projects to protect, reclaim or enhance estuaries often require long dyke structures where traditional construction techniques are ill-suited or the cost is prohibitive because the bed material is soft mud. The dykes can be constructed with dredged material-filled tubes. Because they are easy to place underwater they can be used to construct dredged material containment areas into the sub-tidal regions.

Coastal applications
Beach nourishment projects often incorporate groynes, breakwaters or sill structures as tools for trapping littoral drift sediments which stabilise the shoreline. Because of their flexibility, integrity and large mass dredged material-filled tubes are very suitable in some situations for use as groynes, breakwaters or sills (Harris 1994).

They can also be used to form offshore breakwaters (see Ch 5), and to protect sand dunes along coastal areas where hurricanes and storms continually destroy them. The tubes can be placed and buried within the dunes more economically than some other methods of stabilisation.

Habitat
The use of these flexible fabrics has added a new dimension to wetland stabilisation technology (Landin et al 1994). Geotubes can be built and filled with dredged material to the exact contour and configuration needed for the wetland. The largest tested to date for this application are 152 x 6 x 3m. However, they may be:

- designed to be larger or smaller;
- stacked and layered;
- form rings to be filled for island creation;
- used detached from the shoreline;
- shaped to allow high and low spots after filling to better accommodate intertidal flow.

The literature cites many other applications, notably in Brazil, Netherlands, Germany and the USA. The performance of a number of the US projects is being documented under the CPAR Program (Construction Productivity Advancement Research) so that improved design and construction methods can be recommended. 'GeoTube' and 'GeoContainer' are copyrighted trade names registered by Nicolon Corporation to market this method of construction.

# 5 Coast protection

There are several ways that dredged material can be used in coast protection schemes. These include the direct replacement of eroded beach material (beach nourishment), encouragement of the development of new, unenforced coastlines (managed retreat), adjustment of intertidal mud profiles, and the formation of offshore berms designed to modify the wave climate. The latter may be hard, designed to withstand wave energy or soft, designed to absorb wave energy. Some of these options are illustrated in the two figures below reproduced from Kirby (1996).

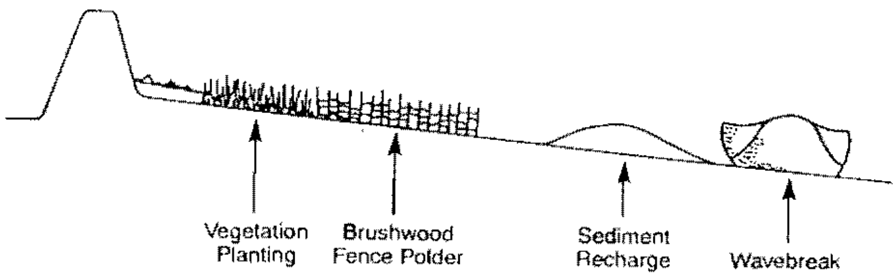



**Figure 5.1 A range of alternative techniques aimed at marsh restoration or maintenance.** The wave break is provided by a grounded barge

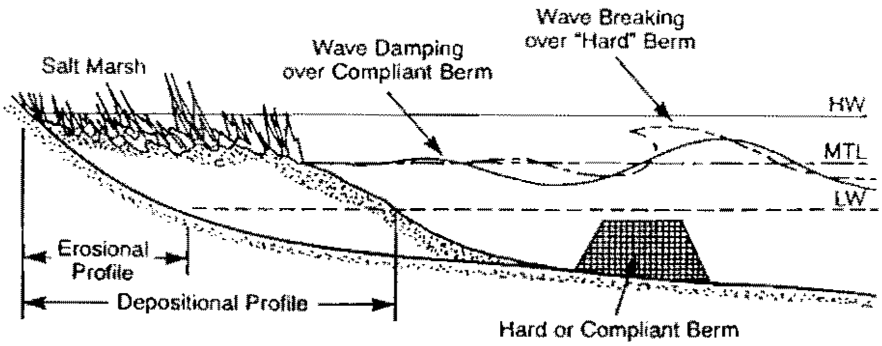



**Figure 5.2 Applications of hard or compliant berms for reducing inshore wave energy.** Inshore a low and concave tidal flat can be changed to a high and convex shape using muddy dredge material. Shore protection and enivornmental value are both enhanced

## 5.1 Beach nourishment

Beach nourishment is now an accepted form of "soft" coastal defence. In the past the specification has usually required that the beach is nourished with similar material to that which has eroded. This usually means that the contractor prospects the immediate area for a source of sufficient size. The real challenge is to use maintenance or capital dredged material. This may mean more research is necessary into stability criteria. The historically pertaining beach profile might not be achieved but a more stable beach with a different profile may be created.

Perhaps one of the most imaginative schemes in this respect is the beach resort at Koge Bugt (Denmark) (Kaalund et al, 1991). A new coastline of dunes and sandy beaches was created. Sand and clay from dredging was used for the reclamations and landscaping. Artificial bird islands and flood protection schemes were also built.

A good example of cooperation is the recharge of Bournemouth beach by sand dredged from the Poole Harbour approach channel, the Swash Channel. The deepening of the channel resulted in the need to dispose of 1,182,000$m^3$ of sandy material. Use of the material for aggregate was examined but dismissed since no user was found who could take the material at the rate it would be necessary to dredge. It was known that Bournemouth Borough Council had a problem with their beach: erosion was occurring following the stabilisation of nearby cliffs. By setting up a special form of tender and contract it was possible to use just over 1,000,000$m^3$ for beach nourishment. It is interesting to note that the cost of the research necessary to achieve a satisfactory and environmentally acceptable scheme was about 20% of the capital cost but this was compensated by the savings to both parties in reduced cost of dredging and reduced cost of beach nourishment (Appleton 1991).

### *5.1.1 Technical specification*

The principal physical characteristic of a material which affects its performance in beach recharge is its grading. It is generally accepted that the recharge material should be at least as coarse as the existing beach material. Specific recharge schemes usually specify a sediment grading, although this may be to some extent modified to match the grading of the most suitable supply of material. The material should also be clean and non-toxic. In the case of shingle beaches, particle shape may also be specified (i.e. the material should be rounded). In addition, it is usual to specify that the materials should be of a similar nature to those occurring naturally on the local coastline.

Even when a material is technically suitable for a particular scheme, there may be resistance to its use due to a perception of inferior quality. In order for the customer to accept the material, it must be fully demonstrated that it is both reliable and consistent.

Where suitable material is in short supply it is technically feasible to reduce the fines content of the material using hydrocyclones. This may render maintenance dredgings more suitable. In the state of Florida, quantities of readily available suitable sand for beach nourishment purposes are dwindling and adequate borrow areas are becoming scarce. The Canaveral Port Authority in conjunction with a number of other bodies sponsored an investigation into separating beach quality material from material containing a mixture of sand, silt and clay dredged from the approach channel during routine maintenance. The method of separation investigated was the use of a bank of hydrocyclones. The study concluded that it was technically feasible but that the economics would vary considerably depending on the situation. Disposal of the separated fines may still be a problem environmentally. Each case should be judged on its own merits (Heibel et al 1994). A description of the hydrocyclone and performance indicators are given in Section 2.1.5 of this report.

Comprehensive advice on assessing beach recharge volumes may be found in CIRIA(1996). In this manual several methods were identified. Briefly these methods fall into the following categories:

i) Simple recharge calculation methods. These are appropriate where the matching material is available to restore a beach to historically recorded profiles, or match existing more healthy beaches nearby.

ii) Profile design methods. These are based on calculations of the response of a typical beach profile to design wave/tidal conditions, taking into account sediment sizes or gradings which are different to native beach material, and which would therefore result in a different beach profile shape.

iii) Detailed computational or physical modelling methods. These consider both the plan shape and profile of the new beach, the need for control structures and the future maintenance strategy.

The first two types of methods are appropriate for small scale schemes. In the context of beneficial use these may only apply to maintenance dredging arisings. For large studies, where a comprehensive understanding of the coastal processes is required, the third type of method is appropriate. This may correspond to large capital dredging schemes.

These three types of methods are discussed below in more detail.

*i) The simple recharge calculation methods*

The simple recharge methods fall into two categories.

The first is an observational approach undertaken by comparing the current day reduced profile with the historically healthy profile at the same or adjoining locations. Comparisons can also be made with the performance of any adjoining recharge schemes. Information can also be gathered on the size and grading of the indigenous beach material. This will lead to a first good estimate of the quantity and type of material required to revive the beach. However, this approach may not be feasible due to a lack of historical information.

The second is a the Dutch Design Method (Verhagen, 1992) which is used in the Netherlands on most coastal erosion beach recharge schemes. The method is simple but again requires significant monitoring and assumes a good match between the indigenous material and the dredged recharge material. This method as summarised in CIRIA (1996) consists of the following steps:

1. Regularly (at least once a year) measure beach profiles for a period of at least ten years.

2. Calculate sand losses in $m^3$/year per coastal section.

3. Add 40% to account for losses as the profile adjusts to allow for the increased exposure of the recharge profile.

4. Multiply this quantity by a convenient life time (eg ten years).

5. Place material between the low-water-minus-1m line and the dune foot on sandy beaches. Shingle beach should in most cases be concentrated on the upper part of the beach.

*ii) Profile design methods*
Sand beach recharge

CIRIA (1996) and Davison et al (1992) suggest that a range of methods should be used to identify the range of recharge volumes that may be required. Caution should be adopted when using these methods not to infer that coarser material will necessarily last longer than native material. The methods identified in CIRIA (1996) are briefly described below:

Dean's equilibrium profile method (Dean, 1991) is the most widely used method in the USA. The method centres on calculating the volume of recharge sand, of a given grain size, that will need to placed on a beach to increase the dry beach width by a given amount.

Pilarczyk, van Overeem and Bakker (1986) equilibrium slope method. This method considers the response of the beach to prevailing hydraulic conditions and the depth to which the profile will develop.

Overfill factor or overfill ratio methods assume that the indigenous sediment material at any site represents the most stable sediment grading for that site. The method also assumes that the natural conditions sort the grain size distribution and that coarser grain material is more stable. This method awaits to be proven with any reliability.

Shingle beach recharge

Powell (1993) derived an equilibrium slope method specifically for shingle beach recharge with sediment of a dissimilar grading. Although this method has yielded encouraging results the method is yet to be fully tested to provide confidence in the results.

*iii) Computational or physical modelling of a recharge scheme.*

This method is well regarded in the UK as it has been proven successfully to refine the beach recharge scheme. However, in the US this approach has been criticized. Many of these schemes have had inadequate post-project monitoring and therefore it is difficult to assess whether this criticism is valid. However, in the UK, where schemes have failed it can be attributed to movement along the coastline rather than offshore.

### *5.1.2 Monitoring*

Monitoring of beach nourishment projects has traditionally been primarily oriented towards engineering evaluations to determine beach stability, consolidation rates, sand drift and erosion rates, and suitability of donor sites and beach sites. In recent years monitoring will also entail environmental components. Biotic impacts and sand placement on both the donor site and the beach site require monitoring to determine organism losses, recruitment and colonisation success (Landin 1992).

Underwater biotic component monitoring is especially important at the donor site for non-motile biota (sediment dwellers, seagrasses etc) and at the beach site for critical beach nesting use by endangered sea turtle and other beach components.

Dredging windows that avoid primary nesting areas and seasons are the norm in many affected countries. Monitoring is required on a regularly scheduled basis (eg annually) to determine immediate and long term use and trends by biological communities on and near the donor site or project site. In the US the presence of endangered species also invokes a special set of criteria and monitoring requirements.

Monitoring technology currently practised includes a wide variety of standard scuba and underwater testing, as well as ecosystem computer modelling. Permanent bottom markers are used as well as the release of floaters to determine underwater currents and sediment movements and to determine where marked sediments are accumulating along shorelines in beach nourishment or beach stabilisation efforts. Bottom grid systems are used to canvass both donor site (pre and post dredging) and placement sites (underwater berms and other topographic changes) for non-motile and colonising biota. Using sophisticated sampling strategies that can be tied into computer models can optimise the amount of data collection necessary (US Army 1989).

## 5.2 Coastal realignment

On eroding muddy coasts backed by low value land one approach to the erosion problem is coastal realignment (also sometimes termed managed retreat). The objective is to create a buffer zone by setting back the defence works and breaching the existing wall. Experiments to evaluate the concept are in progress in several areas of the world. Two experiments in the UK are Tollesbury and Orplands in Essex.

One method in use is to place untreated dredged material behind a temporary bund which is removed after the material has consolidated (Krone 1985). Such an experiment, aimed at raising the backshore areas to keep pace with sea level rise, is in progress in San Francisco Bay in the USA.

## 5.3 Mud-shore profile engineering

### *5.3.1 Changing the profile*

Where managed retreat is not possible, for example where high value land backs onto the eroding muddy foreshore, another option under investigation is profile engineering (Kirby 1996).

One traditional approach in the past had been to deliberately induce a salt marsh immediately in front of a defence. These have only been successful where tidal flat elevation has not already fallen below Mean High Water Neaps, which is the lower limit of growth of Spartina Anglica. Such inducements have been temporarily successful in some areas but are now mainly failing due to Spartina die-back (for reasons which are much researched but not yet established) or erosion of the margins (the cause of the original problem).

Such schemes have formerly relied upon trapping and accumulating the natural fine sediment. Today, thin layer feeding methods are being developed in the USA using dredged material, although in rather small quantities.

The main limitation of saltmarsh inducement arises from the fact that it serves to enhance the "coastal squeeze" of muddy foreshores and is an inherently destabilising technique. Marine transgression results in continued degradation of the outer shore during the rather short period (a few decades) whilst the salt marsh is in place, leaving the shore even more degraded than before inducement commenced.

It is now becoming established from field measurements (Kirby 1989 & 1992), from worldwide literature reviews (Lee 1995), from theoretical studies (Friedrichs & Aubrey 1994), laboratory flume studies (Lee and Mehta 1996) that muddy shores behave differently from sandy shores and that consequently they may have a different profile. Accretion dominated shores on a straight coast tend to be high and convex in cross sectional shape when in equilibrium. In contrast, erosion dominated coasts at equilibrium are low and concave. Low, concave shapes are considered bad from the standpoints of sea defence, land loss, port operations etc, whereas high convex profiles are desirable.

Based on this new understanding, the Bruun Rule, widely applied in the last 30 years to define the stability of sandy shores and their response to sea level rise, can be modified and redefined in order to apply it to muddy shores (Mehta & Kirby 1996). A new factor is emerging to permit mud shore stability to be quantified, so permitting appropriate management of erosion. The main finding is that mud shores need to managed as integral units. Dredged material may be most beneficially used in eroding concave muddy beaches.

A small scale experiment on this technology, funded by the Ministry of Agriculture Fisheries and Food, is presently being carried out in a tidal creek on the River Medway, in Kent, UK. Results are not yet available.

### *5.3.2 Onshore feeding*

Another variation on this technique is shoreline feeding. In this it is necessary to construct an offshore berm and simultaneously long-term-feed the foreshore with unprocessed, low density muddy dredged material. This can be done cheaply once the breakwater is in place using pumping or bottom dump techniques. The breakwater itself may consist simply of weighted and sunk barges.

This technique has the advantage that a large quantity of dredged material from a contract maintenance operation can be placed in a short time and left to adjust under the action of waves and tides.

A limitation is that the revised profile will only arise slowly and that until consolidation takes place high losses of material can be expected due to the low resistance to erosive forces. The material so lost may also cause an unacceptable level of turbidity from an ecological point of view. This would need to be assessed on a case by case basis.

A similar technique is described below for onshore feeding of sand, the feeder berm. The hydraulic conditions for either of the two to be appropriate are quite different. An essential difference is that with the muddy shore a fixed breakwater is also necessary to provide the right wave conditions for the scheme to work.

## 5.4 Offshore berms

Three types of berm are considered, feeder berms, hard berms and soft berms. The latter two are offshore berms which can be used to reduce the force and vary the direction of waves striking the shore, thereby reducing shore erosion. The first is sacrificial in that it supplies sediment designed to move onshore.

A wide protective (perched) beach or shallow offshore shoal can be retained by terracing with beach retaining sills. Wave energy is dissipated while propagating over this shallow region by breaking and bottom friction. Hence waves have a reduced effect upon the shoreline.

These breakwaters and sills can be constructed in a variety of ways using dredged material ranging from rock to filled tubes (See Section 4.5) and placed cohesive sediment.

Generally the berm is aligned roughly parallel to the beach but the best alignment should be studied carefully and will probably be most effective if it is aligned to modify the most destructive waves which are not necessarily from the same direction as the most frequent waves. The height must be designed so as to achieve the depth of water which will cause the required amount of wave modification. By definition of their function, offshore berms are subject to high energy dissipation forces so unless very coarse or rock materials are used erosion is likely. This need not necessarily be a problem with regard to the dispersed material, which will probably still be a benefit to the coast protection function, but it implies a certain amount of maintenance.

In the case of dredging the Harwich channel (Allen 1994) several berm sites were considered. For each of the sites the mobility of the placed dredged material under the influence of waves and tidal currents was predicted. The effect of the berms on local wave conditions was predicted using a computational model representing wave refraction, shoaling, diffraction, friction and breaking. The effect of the berms on coastal sediment transport was examined using a computational model of littoral drift. As it became evident that much of the dredged material was mobile under frequently occurring conditions further calculations were made to estimate dispersion. The study led to some of the options being abandoned because of potentially dangerous wave focusing and the sediment transport paths were uncertain.

### *5.4.1 Feeder berms*

The construction of feeder berms involves the placement of beach quality sand in relatively shallow water, eg depths ranging from 5 - 8m. With proper planning and design considerations, the dredged material will be transported downdrift and toward the beach by littoral currents and storm wave action. The objective is to provide supplemental material in repetitive annual operations which, over a period of time, will create a more gentle underwater slope and reduce the extent of beach erosion.

In many situations this may afford a reduction in dredging costs because the feeder berm site is likely to be much closer to the navigation/dredging site than the historical offshore placement site (Murden 1995).

Feeder berms should be a possible use even in cases where the dredged material is a composite of beach quality sand and unsuitable silts and muds. The same processes which cause drift and onshore movement may be capable in many situations of sorting the sediment so that the silt fraction is carried away in suspension by the littoral currents leaving the sand to move onshore in the way described above. No such schemes have been found in the literature but as many ports do have sand/mud mixtures to deal with it must be a suitable case for research. One problem may be the inevitable increase in turbidity during storms.

### *5.4.2 Hard berms*

The construction of hard berms involves the placement of suitable material in depths ranging from about 10 - 13m. The objective is to create a relatively permanent feature on the sea bed approximately parallel to the shore line with gentle side slopes which will intercept the troughs of incoming storm waves and decrease erosion of the shoreline.

The essential difference between hard and soft berms is that soft berms (made of mud/silt) are designed to absorb wave energy, hard berms are designed to cause the waves to steepen and break prematurely by increasing bottom friction (ie by reducing the depth of water) so that energy is dissipated as turbulence and the wave that reforms is of lower height.

If the berm is made of sand it is to be expected that as it modifies the storm waves it will itself be modified in profile and some of the material will be lost. This implies that some maintenance will be necessary but the technique may still be cheaper and more convenient (ie less disturbance of recreation) than direct beach nourishment.

If the berm is to be constructed of rock the threshold shear stress for motion can be derived using standard design methods such as Shields (1977) or Neill (1973). The maximum stress exerted by a given wave climate can be derived from published tables and formulae.

An alternative to rock in erosive environments may be dredged material filled geotextiles. Sand filled containers may be used in conjunction with beach nourishment as either terminal groynes, breakwaters, sills for perched beaches or other structures used in stabilisation (Gutman, 1979 and Laustrup, 1988). The manufacture and use of these is discussed in Section 4.5.

Construction

Particularly for hard berms it is important that the material is accurately placed. Hopper dredgers and positioning equipment routinely used by dredging firms are capable of achieving the necessary standards but proper control of the operation is necessary.

Berms can be built by bottom dump barges and even by pipeline dredge but hopper dredgers are the most common method and hard to beat where the haul distance is significant, say up to 15 miles (Parry 1994). One major advantage is that they carry their own electronic positioning system.

Placement can be by side dumps while stationary or on the run down the length of the berm. The side by side method is susceptible to drifting in the current, especially side currents. However, side currents can be overcome by the dredger starting upcurrent and "sliding" down the berm. In currents parallel to the berm, dumping on the run down the berm is the better method. When the berm is in shallow water it is safer to have the vessel's propellers away form the beach. For berms parallel to the beach this means that the side by side method is required.

Losses may be high (up to about 20%) as berms are often placed in areas of high currents.

### 5.4.3 Soft berms

Naturally occurring underwater mudbanks are known to absorb water wave energy and thereby attenuate waves that pass over (Mehta and Jiang 1993). Energy reduction of the order of 30% to 90% are not uncommon even in the absence of any measurable wave breaking. In recent years engineering efforts have been made to make use of this property of bottom mud by creating underwater mud berms to mitigate wave impact in areas leeward of the berm. Thus, for example, by appropriately placing fine-grained dredged material from navigation channels in this way the disposal site can be made to serve beneficially.

An offshore mud berm to absorb wave energy constructed using maintenance dredged material was built in the Gulf of Mexico off Mobile Bay (US Army 1992), the aim being to reduce wave erosion of the coast. The design concept necessitated the berm being placed in waters shallow enough to absorb wave energy via penetration of wave orbits into the mud bottom, but also deep enough such that wave-induced shear stresses never exceeded the bottom shear strength of the berm. Guidance on shear resistance of mud is given in the HR Mud Manual (Delo and Ockenden 1992). The implication of this is that the technique is only applicable to sites where wave action is moderate and where tidal currents are weak.

The design parameters for a mud berm have been studied using a shallow water wave-mud interaction model (Mehta and Jiang 1993). The model determines the elevation of the berm crest and the water column height above the crest in a given coastal environment. The model considers water to be inviscid and mud to be a highly viscous fluid. The latter can be a reasonable assumption in an environment where the top layer of mud that participates in the dissipation process remains in a practically fluidised state. Such is for instance the case in Lake Okeechobee, Florida, where the bottom mud is composed of fine-grained sediments with 40% by weight organic matter. On the other hand, in more typical coastal situations the elastic properties of mud must be included in the rheological description. Since the Voigt viscoelastic description, the most commonly used constitutive model for mud rheology in wave-mud interaction studies, is not fully applicable over the range of natural forcing frequencies and mud densities, a new model has been produced based on experiments using a controlled-stress rheometer, Carri-Med CSL, at Waterways Experiment Station, Vicksburg. The Voigt model is a special case of the new model at comparatively high forcing frequencies.

For deeper water the model is modified by including a turbulent diffusion coefficient for the water column. This model has been previously tested against laboratory flume data and can be used to calculate wave attenuation at certain highly mobile monsoonal mud banks off the southwest coast of India. There the damping is often so significant that offshore storm waves practically vanish by the time they arrive at the shoreline.

The above model was used to calculate wave attenuation over a non-sacrificial mud berm designed by the Army Corps of Engineers in the Gulf of Mexico, off Dauphin Island in Alabama. Fine-grained material for the berm was derived from dredging the ship navigation channel into Mobile Bay. The berm has been effective in reducing wave energy in the sheltered area. In two cases studied the measured reduction was 29% and 46%. Considering the nature of the wave field and the water depth over the berm crest at the site, the high degree of wave damping is believed to be mainly due to wave energy absorption by the berm. The model gave reasonably good correlation between predicted and measured wave spectra in the sheltered area.

When subjected to wave action, bottom mud responds by oscillating predominantly at the forcing wave frequency, although as a result of high viscosity the oscillations (particulate orbits) attenuate much more rapidly with depth within mud than in the water column above. The high rate of dissipation in turn causes the wave height to decrease rapidly with onshore distance. Thus, given the wave amplitude at the seaward edge of the berm crest, the amplitude at any distance depends on the wave attenuation coefficient which relates directly to the rigidity of the bottom. Thus where the bottom is sandy the attenuation effect is much less. On the other hand the wave celerity (speed) is higher when mud is the substrate because the available depth for wave propagation is effectively greater than the water depth. Consequently an important parameter that requires specification is the depth corresponding to the thickness of the mud layer that effectively participates in the dissipative process through mud motion. This parameter appears to depend, among other factors, on the rate of wave energy dissipation.

[Fig 1.2 from Mehta and Jiang 1993]

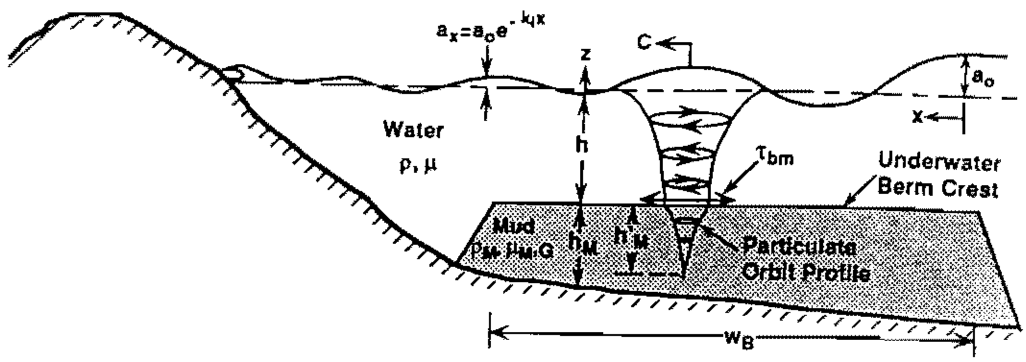



**Figure 5.3 Schematic sketch showing wave propagation over an underwater mud berm**

Mud oscillation primarily occurs as a result of wave-induced pressure work within the body of the mud, while the effect of shear stress is more important at the mud surface where it can cause particulate resuspension. Thus, under continued wave action the equilibrium water depth above the crest is that depth at which the wave-induced stress (amplitude) is equal to the erosion shear strength of mud. This being the case, in many naturally occurring environments mud oscillations under typical fair weather wave conditions occur without much particulate resuspension and associated turbidity (Jiang and Mehta 1992). In turn this condition can be used to design the berm crest elevation so that the berm can fulfill its role as a wave attenuator without generating excessive turbidity and self-dissipating in the process through transport of the eroded sediment.

For a given crest elevation the slope from crest to toe is determined by the thixotropic yield strength, which for design purposes can be approximated to the upper Bingham yield strength of the pseudoplastic material (Migniot 1968). However, the stability of the berm crest is not assured solely through this criteria because the residual velocity can cause the mud mass to be transported landward. The impetus for this motion is the net wave-induced thrust that occurs in the mud due to the rapid wave attenuation with distance. The equilibrium condition occurs when the hydrostatic gradient induced by the sloping bottom is balanced by the adverse wave-induced thrust. This is illustrated in the following figure. Slopes in the case of the Mobile study varied in the range 1:24 to 1:130.

[Fig 1.3 from Mehta and Jiang 1993]

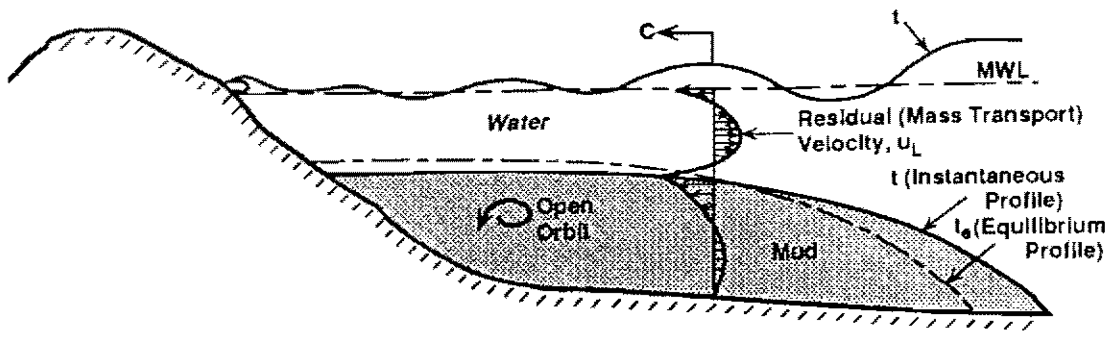



**Figure 5.4 Elevation sketch showing mudbank and its motion due to Stokes' drift**

Mass transport due to Stokes' drift is important in situations such as the Indian coast which is subjected to monsoon wave conditions for several months at a time. However, movement onshore during high wave conditions may be balanced by a gravity slide into deep water at the onset of calmer conditions.

Research on the use of mud berms to modify waves has not reached the point where the design can be generalised and each case must be studied on its merits.

# 6 Agriculture, horticulture and forestry

Dredged material has been used in each of these industries. Some disposal sites, especially in river systems, have provided livestock pastures. These pastures have not been developed in any way except by allowing natural grass colonisation or by planting pasture grasses on them. Other uses involve actively incorporating dredged material into marginal soils. An attractive alternative for disposing of dredged sediments is to use these rich materials to amend marginal soils for agriculture, forestry or horticulture. Marginal soils are not intensively farmed because of inherent limitations such as poor drainage, unsuitable grain size and poor physical and chemical conditions. They may also be of low productivity because of high water tables or frequency of flooding. In the US there are millions of acres of these marginal soils located near waterways (US Army 1986).

## 6.1 Agriculture

When dredged material is free of nuisance weeds and has the proper balance of nutrients, it is similar to productive agricultural soils and can be beneficial for increasing crop production when incorporated or mixed. By the addition of dredged material the physical and chemical characteristics of a marginal soil can be altered to such an extent that water and nutrients become more available for crop growth. In some cases, raising the elevation of the soil surface with a cover of dredged material may improve surface drainage and reduce flooding and therefore lengthen the growing season. Dredged material characteristics which influence plant growth and guidance for dredged material incorporation and cover use are discussed in this section.

### *6.1.1 Planning considerations*

Chemical and physical analyses of the dredged material, site locations, weed infestation potential and possible salinity problems must be considered before deciding upon the suitability of a specific dredged material as a medium for agricultural purposes.

<u>Chemical analyses</u>

Dredged material may contain heavy metals, oil and grease, high nutrient concentrations from fertilizer runoff and other contaminants.

**Heavy metals:** Heavy metal uptake by plants is dependent on a number of factors, primarily the form and concentration of metals in the rooting media and the type and variety of plant. The heavy metal uptake of plants is generally less than the concentration in the rooting media. The following table shows the range in the concentration of heavy metal uptake by agronomic and common vegetable food crops grown under normal conditions and the suggested plant tolerance levels. These data are important if a food crop is to be grown, but are less important when non food crops are to be produced, for example Christmas trees or pulpwood. Another example is the uptake of minimal amounts of heavy metals in the heads of grain plants, making them a good food crop selection even if larger amounts of heavy metals are present. However, the higher concentrations in the leaves of grain crops make these less desirable when harvested as forage.

## Table 6.1 *Average range of heavy metal uptake for selected food crops and suggested plant tolerance levels*

| Element | Range (ppm) | Suggested tolerance level (ppm) |
|---|---|---|
| Cadmium | 0.05 - 0.20 | 4 |
| Copper | 3 - 40 | 150 |
| Iron | 20 - 300 | 850 |
| Manganese | 15 - 150 | 325 |
| Nickel | 0.01 - 1.0 | 4 |
| Lead | 0.1 - 5.0 | 10 |
| Zinc | 15 - 150 | 350 |
| Boron | 7 - 75 | 200 |
| Chromium | 0.1 - 0.5 | 2 |

*Foodcrops used: Corn, soybeans, tomatoes, beets, lettuce, peas, potatoes, melons, squash, alfalfa, clover, wheat, oat, barley, and pasture grasses.*

**Nutrients:** Nutrient analyses of dredged material should provide data to determine nutrient availability and to establish recommended fertilizer applications for vegetative production. The nutrient constituent of dredged material which require greatest attention are nitrogen, phosphorus, potassium, metallic metals, and organic compounds. Although medium and fine-grained dredged material is normally high in nutrients available for plant uptake, the levels of these nutrients are usually not high enough to limit plant growth. However, nitrogen, which is usually in the ammonia form, will undergo nitrification rapidly in aerobic soil. Nitrate is the readily available form of nitrogen for plant uptake or loss by surface runoff and leaching into ground water. Sterile clean sand is of little value for agriculture.

**Oil and grease:** Possible effects are slower wetting of the soil materials, a smothering effect on plant parts and a tendency to restrict water uptake by the plants.

**Lime requirements:** Lime requirements for dredged material vary but if the pH of the material is below 6.5 it should be amended with ground agricultural limestone before being applied to marginal soil for agricultural production. Large amounts of sulphur in the dredged material will require heavy applications of lime to neutralise the acidity as well as succeeding applications to maintain neutral conditions. A soil pH below 4.0 indicates the presence of free acids resulting from the accumulation of sulphate and nitrate ions. A pH below 5.5 suggests the presence of toxic quantities of exchangeable aluminium, iron and manganese. A pH from 7.8 to 8.2 may indicate an accumulation of the bicarbonate ion and the uptake of elements will be detrimental to plant growth. Gupta et al (1978) provides specific recommendations on rates of both fertiliser and lime to apply to various dredged material deficiency levels. A rule of thumb for lime requirements of high sulphur dredged material is to double the usual lime requirement.

Physical analyses

The physical characteristics of the material must be known to ensure the best agricultural use and to guard against adverse impacts on agricultural land. The texture and water content are essential tests to aid in characterisation. Guidance on assessment of physical properties is given in Section 2.1.1. Their application to agricultural use is discussed here.

**Texture:** Textural classification helps to determine not only the nutrient-supplying ability of soil material but also the supply and exchange of water and air that are so important to plant life. Therefore an important criterion is to adjust the texture of the final mixture of dredged material and marginal soil to approximate a loam soil (ie silts and clays whose liquid limit is less than 50). Mixing a fine textured dredged material (silt and clay) with a coarse textured marginal soil (sand) to the proportions of loam would improve its physical and chemical characteristics for crop production. Sandy, coarse-grained dredged material is generally low in organic matter, available nutrients and heavy metals. It may have potential as an amendment to heavy impermeable clay soils, improving structure and permeability. Sandy loams are generally preferred for vegetable root crops, orchards and small grained cereals.

**Water content:** When placing dredged material on agricultural lands it is desirable to have the water content of the material within the plastic range. This will present fewer problems in handling, placing and mixing. In general this means a moisture content of 30-40%. If dredged material is to be placed in slurry form the layer thickness should be limited to about 0.25 - 0.5m. This thickness of dredged material will usually dry within 10 weeks to 6 months, depending on the material texture, to the point where mixing and farming can begin. The provision of underdrainage has been found to be beneficial (Riddell et al 1988). Experiments on dewatering sediments from the River Scheldt, Belgium (Van Mieghem et al 1995) showed that it was possible using underdrainage to dry up to 750kg (dry weight) material/m2 and consolidation from 1.1 t/m3 to 1.4 t/m3 was achieved in 1 year. Taking all into account it was estimated that to dry 1 tonne of solids (dry weight) required 2 m2/year. Full test results are given in IMDC (1992).

Weeds

Weed infestation is a serious problem in many dewatered, inactive, fine-grained dredged material containment areas. Treatment prior to the transport of dewatered dredged material to an agricultural site may avoid problems to the farmer later, for example, an application of herbicide or removal of the top 150mm vegetation layer of the containment area with a bulldozer.

Salinity

If the dredged material is from a coastal or tidal region special attention must be given to salinity because crops will not grow on highly saline soils and few agronomic crops will grow in brackish soils. The electrical conductivity of a soil water extract gives an indication of the total concentration of soluble salts in the soil. The term "soluble salts" refers to the inorganic soil constituents that are soluble in water. Excess soluble salts not only limit the availability of water to plants but also restrict growth. Salt-tolerant species are available and research on salt-tolerant agricultural crops is underway but none have been found to be economically viable. Techniques for treating dredged material with high salinity are available and should be completed before the material is transported to the agricultural site.

With saline dredged material there is a major conflict of interest in that drying is essential to successful handling whereas wetting with fresh water is required to reduce salinity (Riddell et al 1988). Because of poor diffusivity associated with fine grained material, wetting of the dredged material in its initial state may not result in any significant reduction in salinity. Leaching of the salt may only be effected after the material has been dried and rotovated to a crumb-like structure. Thus effective management requires rapid drying followed by rapid leaching. Riddell recommends the following procedure:

1. Spreading of a thin layer (say 0.3m) of coarse material (sand) on a flat surface.

2. Spreading of a layer of fine dredged material (silt) on top of the sand. The thickness of this layer is critical: depths greater than 0.5m do not dry out quickly. At the same time the proportion by weight of the dried silt in the final mixture of fine and coarse materials must be such as to give an acceptable soil particle size distribution.

3. Through a combination of surface drainage, underdrainage through the sand and evaporative drying, the silt develops surface cracking down to the sand layer in approximately 2 months. This drying is not dependent on precipitation but is highly dependent on mean daily temperature.

4. Once crack formation is complete and the water content of the silt has reached about 60% the silt and sand layers are mixed and respread as a layer approximately 0.4 - 0.5m thick. This mixture has the required particle size grading for a good soil.

5. Irrigation of the mixture is then commenced to leach out the salt. Short periods of spray irrigation undertaken at regular intervals were found to most effective.

6. Sampling and analysis of the mixture is carried out to monitor salinity and pH.

7. Once salinity has reached the required level, the material is recovered from the drying area and stockpiled; if necessary lime can be added at this stage to control acidity.

8. The stockpile then contains a good soil which readily supports growth and the additional advantage of being weed free.

### *6.1.2 The Clyde experience*

A full scale soil factory was set up on a former quay on the Clyde which was capable of producing 2000 tonnes/week of topsoil selling at £5.20 per tonne excluding delivery (1988 prices). This more than covered the costs of drying, leaching and handling the material. The material was supplied free by the Port Authority who had the benefit of reduced costs through not having to transport the material to the licensed disposal site.

### *6.1.3 The Truro experience*

The Port of Truro, Cornwall, UK has begun an investigation which will take things a stage further and examine composting dredged material with a number of waste products such as sewage sludge, leaf mould, fish waste, bark shreddings and seaweed as well as sand from chin clay production. It is thought that the addition of these will give a better texture to the proposed topsoil substitute and help to improve its organic content. Although composting has yet to be tried two sites have been treated with dredged material. The first used the basic material and took about 3 years to become established with native grasses through windborne seeding. The second used a mixture of sediment and sand and was sown with grass sed. This proved to be very quick in establishing itself but some patches had too high a sand content which inhibited growth (Brigden 1996). Further research is in progress, funded by European Union (Objective 5b).

## 6.2 Horticulture

Horticulture crops are generally considered to be vegetable, fruit, nut and ornamental varieties of commercially grown plants. Dredged material applications on soils for vegetable production, orchards and nurseries will not differ from the guidelines given for agriculture. Some additional comments are given for special crops.

Vegetable production

All commercially grown vegetable crops can be produced on dredged-material-amended soils. Vegetables grow best on sandy loam soils of good texture, drainage and aeration. The best types of dredged material mixtures for such crops would be sandy silts or silty dredged material which can be incorporated into an existing sandy site. Clays in general are too heavy for good vegetable production but could be improved by the addition of sand.

Orchards

No documentation has been found of any schemes using dredged material for orchards. While technically feasible the sites suitable for orchards are generally well away from areas where dredging takes place. Fruit and nut trees are not very tolerant of changing ground level so the addition of any dredged material should be limited to about 150mm to prevent root damage.

Ornamental plant nurseries

These require a high quality soil but in small quantities. While technically feasible and possibly very beneficial it seems unlikely to be economically justified.

Turf farms

Urban and suburban areas require large quantities of readily available grass for such uses as residential lawns, parks, golf courses etc. Marginal soils near urban areas may be brought into turf production through applications of dredged material. Since grass is less exacting in its growth requirements than most food crops, the type of dredged material used is not as critical. However, the material should be a loamy or silty sand substrate to ensure the best growth.

Christmas tree farms

Another specialised use of dredged material is the cultivation of Christmas trees. This has been successfully carried out in Baltimore, US (Spaine et al 1978). Christmas trees require 5 - 8 years to reach marketable size and have the advantage that they can be grown on more contaminated material than would be acceptable for food crops.

## 6.3 Forestry

The improvement of marginal timber land by the application of dredged material shows promise. It would be expected to be received with enthusiasm by Forresters who have the problem of trying to produce timber on poor soil. There are several rapid growing pulpwood species that may be grown in dredged material. The most appropriate method would be road transport of already dewatered material.

The same physical and chemical material properties discussed for agriculture would apply to forestry, except that the trees could be grown safely on dredged material with higher contaminant levels than would be acceptable for food crops. No documentation has been found of tolerance levels for heavy metals which may limit growth.

Commercial tree species that would be suitable for timber production on dredged material would be Eastern Cottonwood, American Sycamore, Eucalyptus, Green Ash, Water Oak and Sweet Gum. These are tolerant of periodic flooding. These species have a rotational life of 5 - 15 years. For upland sites enhanced by dredged material pines, walnut, ash and several oak and hickory species would be more appropriate.

# 7 Amenity

Amenity in this context means the improvement or provision of facilities which are designed to be enjoyed by people. It thus includes regeneration of derelict land, landfill, landscaping and creation of recreation areas. There is clearly some overlap with other chapters of the guidelines, for example the use of dredged material to create a garden festival site in Glasgow has been discussed in the section on agriculture (6.1) and is not repeated here. Another example is beach nourishment or creation which has obvious amenity value but which is covered in Chapter 5 - Coast protection. Many amenity schemes will involve reclamation, the design considerations for which are discussed in Chapter 4

Probably a unique feature of amenity schemes using dredged material not covered elsewhere is landscaping, the deliberate creation of contoured sites. Some design aspects are discussed here.

For creating small hills, dykes or mounds it has been found that the most effective method of construction is alternate layers of silt of up to 2m with layers of stabilising sand 0.5m thick. The intermediate sand layers are necessary to provide access to the hill for plant during construction. Thicker layers of silt may be possible in dry climates (Van Mieghem 1995).

The silt must be free from pollution if it is to be used for amenity. To protect groundwater against infiltrating pollutants, special attention should be given to the bottom layers. As an example 0.5m of fresh clay can be heavily compacted with bulldozers and rollers. Care should be taken to avoid the presence of vegetable matter in this layer because it can decay and leave voids and drainage paths in the substrate. A layer of sand on top of this layer will then act as a drain for any leachate from the dredged material above it. From there it can discharge into surrounding ditches where it can be collected for purification if necessary.

The precise contours and vegetation (see chapter on agriculture) can be chosen to blend in with the surroundings

A recreational hill has been created on the banks of the River Elbe in Hamburg, Germany using maintenance dredged material. This material has been processed through the MEHTA plant which separates the contaminated mud from the relatively clean silty sand (see Section 2.3.2). Such is the success of the scheme that local people now use the hill for walks and picnics. It has pleasant views of the river in an otherwise flat area (Glindemann and Csiti 1996).

This illustrates that it is possible to give visual proof to local communities and to policy makers that disposal of fine-grained sediments can be turned into an ecological and socially acceptable project.

# 8 Habitat

## 8.1 Introduction

This section covers various ways in which dredged material has been used to create or maintain wildlife habitats. It includes five types - aquatic habitats for fish and benthic organisms, bird habitats (upland habitats and nesting islands), wetlands, saltmarshes and intertidal mud flats. The development of this technology has been almost exclusively in the USA although a few projects are underway in the UK and Europe. The guidance in this chapter, therefore, relies heavily on US literature.

The creation of any new habitat means replacing an existing one. A full environmental benefit study will be necessary before making a decision and any scheme will inevitably mean some losses as well as gains. It is interesting to note that many areas which were simply disposal grounds (sometimes for contaminated sediment) in a less environmentally conscious age have been designated as conservation areas because of the richness of the habitat which has been inadvertently created, one example being the Seal Sands area in the Tees Estuary (UK). Because of this, disposal is not allowed there today. If such habitats can be created almost by accident how much more we should be able to achieve by deliberate and careful design.

## 8.2 Aquatic habitats

Aquatic habitat development is the establishment of biological communities on dredged material at or below mean tide level in coastal areas and in permanent water in lakes and rivers. Fishery resource improvement can take many forms. Ecological functions of fishery habitat can be obtained by appropriate placement of dredged material. For example, bottom relief created by mounds of dredged material may provide refuge habitat for fish. In shallow or intertidal waters, subject to erosion, mounds composed of fine-grained sediment can be stabilised by planting seagrasses or capping with shell or other coarser material. These will also enhance the habitat (PIANC, 1992).

### *8.2.1 Seagrass habitat*

Seagrass can be used to stabilise dredged material, either sands or silts, through the binding of roots and rhizomes and by dissipating wave and current energy. Suitable sites for seagrass growth will have the following characteristics:

<u>Location</u>
Seagrasses normally occur along shorelines with low wave and current energies. Development of seagrass habitat in higher energy areas will require permanent protection with breakwaters or planting within lagoons created within dredged material islands.

<u>Depth</u>
Bottom elevations within seagrass beds extend from mean low water to about (-0.2m in estuaries and -10m in coastal environments.

<u>Water quality</u>
Frequent surveys will be needed to predict annual fluctuations in water quality. The presence of natural seagrass beds in the vicinity will be a strong indicator of suitability of water quality.

> **Light:** The foremost need of seagrasses is sufficient light penetration through the water column to support growth. High water column turbidity is an indication that a site is not suitable.

**Salinity:** Most of the common species of seagrasses require salinities greater than 20 ppt, though some local variations may exist where plants tolerate salinities as low as 10 - 15 ppt.

**Temperature:** Though seagrasses require relatively low energy environments the area needs to be well flushed and currents must circulate to prevent lethal temperature extremes occurring.

Sediment type

Sediment grain size is not usually a limiting factor as most seagrasses can tolerate a wide range in sediment from coarse sand to mud.

Propagation

**Propagule selection:** Seagrass habitat development is almost exclusively restricted to transplanting mature plants from a donor bed. Mature plants reproduce by branching. Methods using seedlings have not yet been successfully developed.

**Spacing:**The rate at which seagrasses will cover the bottom is dependent on the species. Further guidance is available in Thorhaug (1981).

**Handling plants:** The plants need to be handled carefully to avoid damage to roots and shoots. Turtle grass meristematic tissue protection is critical for that specie's reproduction. Short term storage (a few hours) can be in well aerated containers, while longer term storage (days or weeks) should be in floating pens or flowing seawater tables. Plants should never be directly exposed to sun and air for more than a minute or two.

**Time of planting:** Almost without exception spring is the best time for planting seagrasses.

### *8.2.2 Gravel bar habitat*

Dredged material has been used in the construction of submerged gravel bar habitats in the USA (Miller, 1988). Gravel bars are notable natural features of rivers and streams that have not been altered by development. Gravel and cobble sized materials provide points of attachment and anchorage for aquatic organisms such as larvae, snails and worms. Coarse-grained particulates stabilise fine substrate and allow colonisation by long-lived invertebrates such as freshwater mussels. Particle size distribution, degree of embeddedness and presence of attached organic matter and plants determine the characteristics of invertebrate communities in flowing water systems. When gravel shoals are dredged to improve river navigation the material can be placed in side channels (ie the channel around islands that does not include the navigation channel). These coarse grained sediment mounds in flowing water are potentially valuable habitat for a number of riverine fishes and invertebrates, including ecologically and commercially species. Payne and Tippit (1989) studied such a scheme on the Tennessee River. They suggest some general guidelines. First, disposal sites should be selected based on knowledge of the distribution of important aquatic resources. Burial of all or a portion of the dense and diverse mussel bed in the deep portion of the side channel was avoided by selection of disposal sites along the shoreline. Disposal along the shoreline had the added benefit of stabilising eroding banks and creating a stable gravel shoal. The potential for bank and shoreline stabilisation should be considered during the site selection. By creating a stable gravel shoal where none otherwise existed, disposal added mussel habitat to the side channel. Site selection should consider bathymetric and hydraulic conditions in an attempt to create gravel disposal mounds that will neither be severely eroded nor covered by silt.

An aquatic habitat was created on the Lower River, Kentucky (Landin, 1989) after the construction of a barge loading facility damaged existing mussel beds. After research into mussel habitat a gravel bar was constructed to reduce sedimentation and promote the mussel habitat. Homziak and Veal (1992) point out the benefits to a fish farmer of having dredging works in close proximity in order to supply suitable material for habitat construction.

### *8.2.3 Oyster beds*

Dredged material can be used to develop oyster habitat, particularly in areas where the lack of suitable intertidal habitat limits production. These areas offer oysters a competitive advantage by reducing predation pressures and enhancing growth (Priest 1994).

Normally dredging is considered deleterious to oysters. The siltation from the resuspended sediments can smother oysters, particularly recently settled spat. High concentrations of suspended solids from dredging operations can also hinder larval development and stress oysters by clogging gills, making feeding and respiration difficult.

The best dredged material is sandy with some shell. The idea is to replace soft bottoms with hard intertidal sand bottoms. This can be achieved by gradually raising the level over a number of dredging cycles. The site can either be left to be colonised naturally or treated with oyster shell cultures to encourage growth.

<u>Management</u>
An area may be designated near to a maintenance dredging area and subdivided into compartments which can accommodate say 30 - 50 years dredging in total. Each site would be used in rotation for successive maintenance cycles. After each site has been used to its design capacity, ie raised to a level that would provide a predetermined area of intertidal habitat, it would be left alone to develop naturally as an oyster resource or enhanced by the placement of oyster shell cultures to stimulate oyster production. The area would remain in production until needed in the normal rotation of the placement sites.

When the developed site is again needed for dredged material placement, several of the other areas developed adjacent to it should be in production. If necessary the existing resource can be removed to another site and transplanted. The old site can then be refurbished (ie compensating for erosion or settlement) or extended and brought back into production.

<u>Monitoring</u>
Pre-dredging physical and biological surveys should be conducted of potential placement areas. The physical surveys should include both bathymetry and surface sediment types. The sediments to be dredged should also be sampled and characterised by grain size.. The biological surveys should attempt to identify potential sites that would have minimal impact on existing ecological and fishery resources.

After the initial placement of the dredged material, the site should be periodically monitored for physical and biological changes which occur between dredging cycles. This will provide information on the temporal changes in bathymetry, sediment types and benthic community. It will also help to improve predictive capabilities for future projects and will indicate modification to the management procedures.

### 8.2.4 *Dredged material containment areas*

Commercial fish farming in ponds has been in existence for many years. Dredged material containment areas provide some new sites for such development. Dyked disposal areas share many features with aquaculture ponds: level sites, good foundation soils, water holding capability and a water control structure.

The use of dredged material containment areas for both disposal and aquaculture has many benefits. Aquaculturists gain access to good sites and benefit from reduced costs for pond design, engineering, permits, construction and other site improvements.

Clearly at planning stage compatibility with the dredging operation must be assured, in particular the frequency and duration of use, sediment type, presence of undesirable substances in the sediments and the depth of material placed each time (Homziak and Veal 1992).

<u>Design features</u>

- The bottom should slope to a drain by gravity flow (1:1000 to 1:50).
- The type and size of drain will vary, depending on the size of the pond, harvest method and time needed to drain.
- Drain outlet must be at least 0.6m above the surface of the water in the drainage ditch to prevent wild fish from entering the pond.
- Levee crest widths should be at least 5m and topped with gravel to accommodate traffic.
- Side slopes should be 3:1 with proper compaction. However, slopes greater than this are common in large ponds.
- Freeboard should between 0.3 and 0.6m.
- For fish ponds, depth should be at least 1.0m at the toe of the slope at the shallow end and not exceed 2.0m at the toe at the deep end. Crawfish ponds are shallower.
- The shape of the pond will be determined by topography, land ownership and dredging needs. Fish do not appear to be sensitive to shape.

### 8.2.5 *Artificial reefs*

Although the conventional definition of an artificial reef is sufficiently broad to include materials as disparate as quarrystone rock, prefabricated concrete units, obsolete oil rigs or steel ship hulls, dredged material is not readily perceived as artificial reef substrate. Artificial reefs are generally thought of as hard structures that provide three dimensional relief. Although dredged material does occasionally consist of rock rubble, it more typically consists of sands, silts and clays.

Significant progress has been made in recent years with regard to artificial reef technology toward a basic understanding of how reefs function and why they are attractive to particular fish and shellfish species (Clarke and Kasul 1994). A number of factors contribute to the performance of constructed habitat (Bohnsack et al 1991). Among the primary factors are location, nature of substrate in the surrounding area, prevailing water depth and hydrodynamic regime, degree of isolation from similar habitats and level of primary productivity. Secondary factors which contribute to increased habitat complexity include 3-D shape, height, profile, size, material composition, interstitial space size, spatial scale and dispersion. A reef comprising dredged material represents a different mix of these factors from other basic reef forms.

In addition to the above factors the economics may lead to the location being as near inshore as possible to reduce the transport costs for the dredged material and to make the site accessible to fishermen if it becomes a haven for sportsfish.

One way that dredged material can potentially increase habitat complexity is by forming reefs that differ from surrounding substrate with respect to sediment type. In theory (Rhoads et al 1978 and Rhoads and Germano 1986) placement of dredged material can lead to enhanced secondary production which in turn may represent increased availability of prey items for foraging by demersal fish and shellfish.

Design criteria

**Structure height** relative to water column depth has not yet been well researched. However, there is reasonable consensus that relief greater than 10% of the water depth attracts mid water fishes whereas lower reefs with substantial horizontal spread seem to attract Dorsal fish (Grove and Sonu 1985).

**Profile:** The combination of height and profile may be critical to the performance of a stable reef in serving as a fishers habitat.

**Side slopes** will be determined by the character and condition of the dredged material which will be affected by whether it is capital or maintenance dredging and the method by which it was dredged (see Chapter 2). For fine materials a side slope of 1:100 to 1:20 can be expected. For sands and gravels much steeper slopes can be achieved. The factor that seems to affect the fish is described as the lee wave phenomenon. This occurs as shed eddies form both up and downstream of a structure placed in a current field. A key question is whether reefs having gradual slopes can produce similarly attractive current field alteration to which fish would respond.

**Current shadow** occurs when high velocities are dissipated by the reef providing shelter in the near-bed zone which attracts some demersal species.

**Interstitial spaces** or rather the lack of them is perhaps the most striking difference between artificial reefs with dredged material and natural reefs. If large topographic features can be created it is advantageous. These can be armoured using smaller volumes of gravel or rock. Addition of surficial layers of coarse material would enhance the performance of the reef by creating habitat for cryptic fishes and shellfishes as well as providing appropriate substrate for development of fouling communities having ecological value in themselves.

**Size** does not seem to be an issue. There is no obvious limit to size or shape except that imposed by neighbouring habitats or other legitimate uses of the sea.

## 8.3 Bird habitats

### *8.3.1 Introduction*

The second type of habitat creation refers to islands and upland habitats for birds. Some of the most useful experience comes from the US Army Engineer's "Environmental Effects of Dredging" programme (Landin, 1986). One hundred years of dredging and open water disposal operations has resulted in the creation of over 2000 man-made islands throughout US coastal waters, inland waterways and the Great Lakes. This process is continuing because of the increasing shortage of upland disposal sites, the need for habitats and the islands' recreational potential. As the population in coastal areas has increased, natural areas have been altered and occupied by man. Dredged material islands have provided vital habitat in many areas. The primary wildlife species needing habitat in the US are pelicans, cormorants, anhingas, herons, egrets, ibises, spoonbills, gulls, terns and skimmers. Several of these are rare or endangered. An estimated 1,000,000 of these are nesting on dredged material islands each year especially along the Atlantic and Gulf coasts. Management of these schemes involves a broad spectrum of techniques: habitat establishment, habitat manipulation and protection of bird colonies.

### *8.3.2 Design considerations*

The PIANC guide (1992) lists seven technical criteria:

- Gradually sloped shorelines.
- Suitable substrate for nests and young chicks.
- Access to the water/shoreline.
- Not less than 1 - 3m above highest water level to prevent nest washout. At least 0.3km from the mainland to prevent egg and chick-eating predators from swimming to the island.
- Suitable vegetation (or lack of vegetation) that meet a species' nesting requirements.
- Close proximity to feeding grounds and brood cover so that chicks do not have to travel long distances to obtain adequate food items for nest-bound chicks.
- Isolation, or at least restrictions, to prevent high human use during the nesting season.

These are expanded below.

<u>Assessing the need</u>

It is outside the scope of these guidelines to give advice on how the need should be assessed. It is sufficient to note here that as man has encroached more and more into the natural environment the number and size of places where birds can successfully nest and breed has similarly reduced. Consultation with knowledgable ornithologists would be an obvious starting point.

An example of such an assessment was carried out in Galveston Bay, Texas (Glass 1994). Population trends of three selected nesting groups of waterbirds and the trends in their favoured habitat were studied resulting in a recommendation to cater for a lack of suitable nesting sites in the lower estuary to halt a perceived decline in numbers of colonies. The availability of suitable dredged material was also an obvious issue.

<u>Location</u>

Again the advice of ornithologists is required. The islands must be placed in areas where the birds will be isolated from predators and human disturbances. However, greater flexibility can be achieved by protecting an area.

Timing
An artificial island will not be colonised until after initial sorting of fine material by wind and water. Construction work should be avoided during the nesting season.

Size
New islands should be no smaller than 2 ha and no larger than 20ha; however, birds have nested successfully on smaller and larger islands. Islands larger than 20 ha are difficult to manage and would be more likely to support predator populations. The greater the amount of habitat diversity required, the larger the island should be.

Shape
The configuration will depend on the target species. Steep slopes such as those found on dykes should be avoided for all species. A slope no greater than 1:30 has been recommended (Chaney et al 1978).

Substrate
Substrate configurations for the ground nesting species are shown in the following table reproduced from US Army (1978b).

## *Table 8.1 Preferred configuration of nesting bird substrates for nesting species on dredged material islands*

| Species | Flats | Slope | Domes | Ridges | Lumps | Other |
|---|---|---|---|---|---|---|
| White pelican | # | | # | | | |
| Brown pelican | # | | # | | | # |
| Glaucous-winged gull | # | # | # | | | |
| Great black-backed gull | | # | # | # | | |
| Herring gull | | # | # | # | | |
| Western gull | # | # | # | | | # |
| Ring-billed gull | # | # | # | | | |
| Laughing gull | # | # | | | | # |
| Gull-billed tern | # | # | # | # | # | # |
| Forster's tern | # | | | | | # |
| Common tern | # | # | # | # | # | # |
| Roseate tern | # | # | # | # | # | |
| Least tern | # | # | | # | # | |
| Royal tern | | # | # | | | |
| Sandwich tern | | # | # | | | |
| Caspian tern | # | | # | # | | |
| Black tern | # | | | | | # |
| Black skimmer | # | # | | # | # | |

# denotes occurrence

Generally coarser material due to its greater stability makes better nesting substrate than fine material which is subject to wind and rain erosion. A mixture of sand and shell material makes good nesting substrate for most ground nesting species which nest in bare substrate or sparse herb habitats.

Fine unstable dredged material may be stabilised by adding coarse material such as shell over its surface. Arboreal species prefer woody species and if plant propagation is to be part of the scheme these should be given the first consideration in order to select appropriate varieties.

Elevation
Elevations should be high enough to prevent flooding of the colony site, but not so high that the substrate will not become destabilised due to wind erosion. Generally the optimal level will be between 1 - 3m above high water level. Coarser materials may stabilise at higher elevations. The elevation will affect which species nest there. Ground nesting birds requiring sparse herb habitats will be better catered for on islands with levels at the top end of the range whereas those preferring dense herb cover will prefer a lower level.

### *8.3.3 Vegetation propagation*
This will be governed by the choice of habitat selected.

Ground nesting
For bare substrate no plantings are necessary, rather the removal of excess plants is recommended. For sparse herb and medium herb the following species are suggested: seaside paspalum, saltmeadow cord-grass, saltgrass, evening primrose, amphorweed and horseweed. These species can be propagated by seeds or transplants, will tolerate saline stressed conditions, and occur over wide ranges. For dense herb habitat high marsh grasses and giant reeds can be added though giant reeds can take over and displace other varieties. These will take 5 to 17 months to establish

Arboreal nesting
This habitat requires several years to establish. Some suggestions are: huisache tree, Brazilian pepper, mangrove, oleander, eastern red cedar, live oak, salt cedar, sand pine, loblolly pine, hackberry, Australian pine, eastern cottonwood and peachleaf willow. These will take 3 to 10 years to establish mature habitat.

Planting
Establishment of plants on a site can be costly so good planning is essential to avoid heavy losses. Plant spacing depends on the density of cover desired. For 2 year ground cover (grasses and forbs) using vegetative propagules one plant/m$^2$ is suggested. For 1 year cover, 4 plants or clumps/m$^2$ is suggested.

### *8.3.4 Protection*
While legislation can provide a basis of enforcement the best method is public awareness and sympathy. This can partly be achieved by notices and publicity. Education from an early age is more likely to achieve long term results.

## 8.4 Wetlands
### *8.4.1 Introduction*
The third type is creation or restoration of wetlands. From papers presented at a conference in London (ICE, 1994), it was clear that there is no consensus on what the objectives are since wetland habitats are very different and various different ecosystems develop accordingly. Nevertheless, dredged material has been used extensively to restore and establish wetlands. Over 16,000 hectares have been restored or created in the US. It is a relatively common use of dredged material and fulfils a need created by the degradation or destruction of many of the world's wetlands (PIANC, 1992). Dredged material can readily be used to stabilise eroding natural wetland shorelines or nourish subsiding wetlands. Dewatered dredged material can be used to construct erosion barriers and other structures. Some types of restoration are more feasible than others. Spreading the material in thin layers to raise the general level up to an intertidal elevation has been successful in Louisiana (USA). An important feature of using dredged material is that hydric soil conditions (ie containing hydrogen) are necessary and the literature suggests that dredged material may take 15 years

or more to achieve this state. Thus it will probably be necessary to import hydric soil and wetland vegetation as well as creating the right hydrologic conditions.

Wetlands or marshes are considered to be any community of grasses or herbs that experience periodic or permanent inundation. They are recognised as extremely valuable natural systems and are accorded importance in food and detrital production, fish, wild life cover, nutrient cycling, erosion control, flood water retention, groundwater recharge and aesthetics.

### *8.4.2 Design considerations*

The conceptual design is divided into four parts, location, elevation, orientation and shape, and size. These have been researched by US Army (1978) and Newling and Landin (1985).

The elements of substrate design include configuration, elevation, protection and retention. "Substrate" refers to the dredged material upon which a marsh will be developed. The design must provide for placement of the dredged material within the desired limits and to the required elevations, allowing for settlement due to consolidation of both the dredged material itself and the foundation soils. Adequate surface area or detention time must be provided for fine grained material to allow settling of suspended solids in order to meet effluent criteria during construction.

<u>Location</u>

The location of the new marsh may be the most important decision. Low energy areas are best suited and sandy dredged material has been found to be the ideal substrate. Departure from these conditions will require a careful evaluation of the need for structural protection and containment. High waves or current energies may prevent the formation of a stable substrate and the establishment of vegetation, making various forms of protection necessary. Another major factor regarding containment or protection is the grain size distribution. Hydraulically placed clay will usually require temporary or permanent containment, regardless of wave or current energy. Silt in low energy areas may not require confinement but it will in moderate energy conditions.

The proximity of the site to the source of material is likely to be a significant factor in the cost.

Care should be taken not to destroy an existing rich habitat in the process of creating a new one.

<u>Elevation</u>

The final elevation of the marsh substrate is largely determined by settlement and consolidation and is the most critical of the operational considerations. It dictates both the amount of material and the biological productivity of the habitat established. Guidance on estimation of consolidation is given in the HR Estuarine Muds Manual (Delo 1992). The final level should be designed on the requirements of the desired plant community. For salt marshes the top 30% of the tidal range is most productive. For fresh water marshes inundation of about 0.6m is the maximum acceptable. Variation in topography will produce habitat diversity and is encouraged, provided the main objectives are also met. It is quite possible to create the required height over a number of successive placements of dredged material. If too much material is placed (eg if consolidation is less than expected) the height can be reduced by mechanical plant.

Orientation and shape
The shape should minimise impact on drainage or current patterns in the area surrounding the site and allow it to blend into the local environment. If high energy forces are anticipated the marsh should be shaped to minimise exposure. This will reduce the cost of providing protection. Efforts should be made to take advantage of natural protection or existing structures as well as the bottom topography. If ring dykes are required to contain the material it should be remembered that a circle gives the minimum perimeter for area contained and that construction in shallow water is much cheaper than in deep water.

Size
The objective is to match the size of the new marsh with the volume of dredged material available or requiring disposal. This may be in a single dredging operation or over several years of maintenance dredging. Phased construction is an option whereby compartments are established to final level in a single operation. New compartments are added as material becomes available. This allows a more gradual development of the marsh and is to be recommended where possible.

Sedimentation design
Confined substrates composed of fine-grained dredged material must be designed for retention of the solids by gravity sedimentation during the placement operation. Design for sedimentation is directly related to the area of the containment, the inflow rate, operational conditions, the physical properties of the sediment and the salinity of the water (which causes flocculation and speeds settlement). Standard design procedures are available which relate primarily the area to the settling velocity. However the design should take account of possible short circuiting (ie the flow does not expand from the inlet to fill the whole area of the containment but finds the least hydraulic gradient). If the area is basically not large enough to control sedimentation and therefore concentration in the effluent the options are to reduce the rate of inflow or have intermittent operations.

Weir design
Retention structures used for confined substrates must provide a means to release water from the site. This is best accomplished by placing a weir in the containment structure. It must have the capability of selective withdrawal of the clarified upper layer of ponded water without excessive resuspension of the settled solids. Designing outfall weirs is a standard procedure, eg in Walski and Schroeder (1978).

They should be well anchored and collared. Two basic types are the drop inlet and the box. The drop inlet consists of a half cylinder corrugated metal pipe riser equipped with a gate of several stop logs or flash boards that serve as a variable height weir. A discharge pipe leads from the base of the riser through the dyke to the exterior. The box weir consists of an open cut through the dyke section. The cut is usually lined with timber. They are not often used but have the advantage of being able to discharge large volumes of water rapidly.

Retention and protection works
Sites may require protection from erosion caused by currents, waves (including ship waves) and tidal action. The same structure may also be required to retain the dredged material until it consolidates and to control the migration of fines. The designer should keep in mind that the structure itself may modify the waves and currents.

The factors to be taken into account include the material to be retained, the maximum height of dredged material above firm bottom, degree of protection required, permanence of the structure, foundation conditions and availability of material.

A number of options are shown in the following diagram reproduced from Eckert et al (1978).

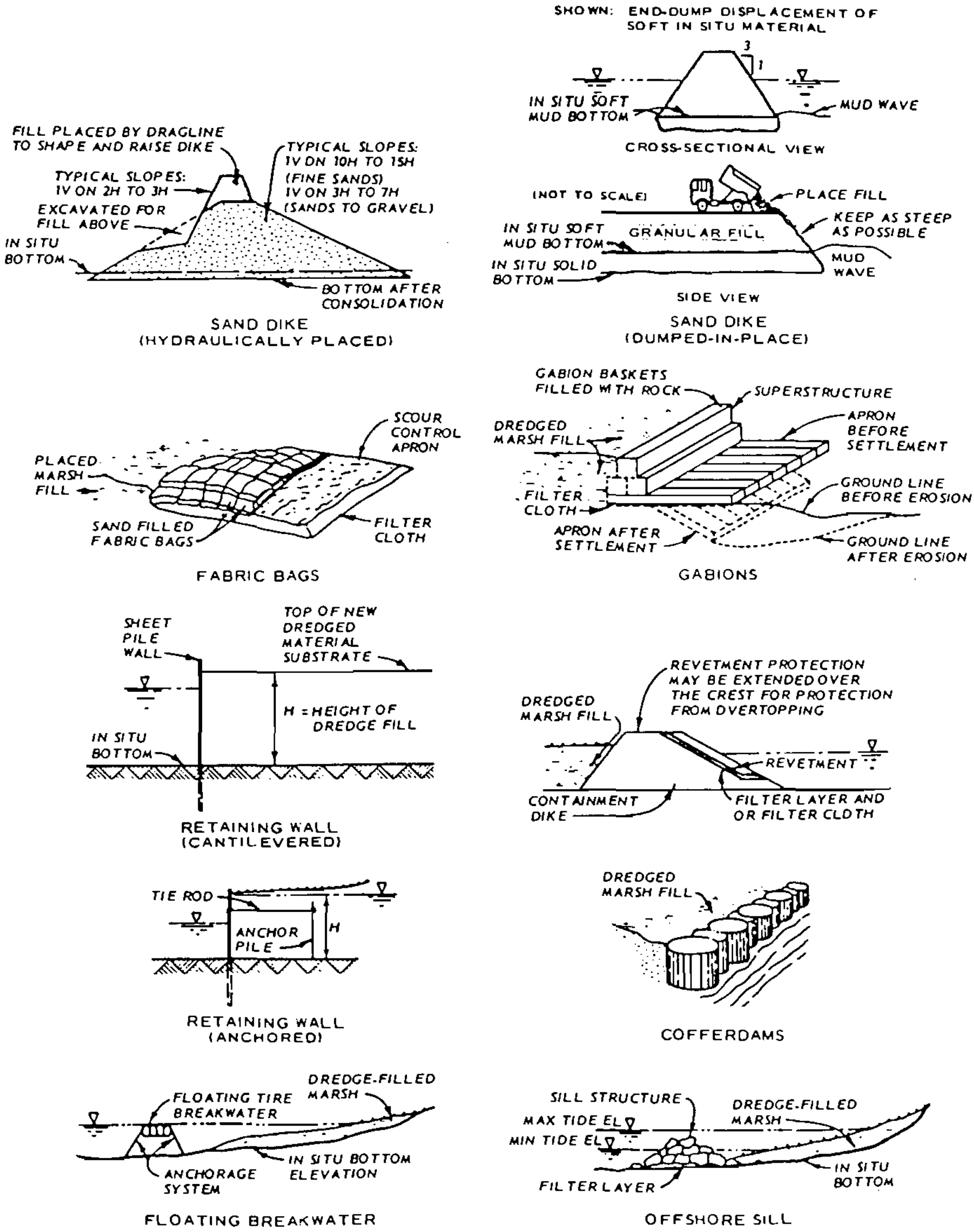



**Figure 8.1 Retention and protective structures**

### 8.4.3 Construction considerations

Contract

Marsh construction contract procedures may be difficult because of the general lack of experience and because the final product is not entirely predictable. This means that it is particularly important that the contractor should have some understanding of the intricacies of the project as well as a detailed contract specification. Scheduling is important: for example, to obtain maximum vegetative cover within the first year it is necessary to have the dredged material in place and with a relatively stable surface elevation by the beginning of the growing season. Delays will affect the initial success of the project and may result in loss of nursery seed stock, replanting costs, adverse public reaction and unwanted erosion at the site. The importance of construction control has already been emphasised in Section 1.3 and is restated here. The success of the whole operation depends on achieving the right level, not too high and not too low. The contractor must be aware of this and not try to maximise dredged material disposal at the expense of jeopardising the whole scheme.

Dredged material placement

Material may be placed within the disposal site using either hydraulic or mechanical methods. The hydraulic pipeline is the most commonly used. Pipeline length can be several kilometres with the use of booster pumps but at substantial additional cost (see Sections 2.4.2 and 2.5). The details of an operation are site specific. If more detailed guidance is required the reader is referred to US Army (1978).

At the beginning of the placement operation the outlet weir is set at a predetermined elevation that will ensure that the ponded water will be deep enough for settling of the sediment. As the containment fills no effluent is released until it reaches the level of the weir, thereafter the outflow rate is approximately equal to the inflow rate. The depth of water then decreases as the sediment level builds up. Use can be made of the ponded water for floating the delivery pipeline to any desired location to ensure an even distribution of the dredged material.

### 8.4.4 Vegetation establishment

Propagation of marsh plants can be attained by natural invasion or artificial propagation. Natural establishment of plants can be expected if the environmental requirements for a marsh community, including a source of propagules, are present at the site. In many fresh water marshes natural invasion will occur on a site within a few months. Establishment will be accelerated by seeding or sprigging.

In selecting species for artificial propagation every effort should be made to ensure that the selected species represent a natural assemblage for a given area. Exotic or offsite species will not generally be able to compete with natural invaders. An exception may be an instance in which a species is selected for temporary cover or erosion control until natural invasion has colonised the site. For example, smooth cordgrass is planted in Florida with mangrove seed pods. The smooth cordgrass provides protection for the mangroves seedlings until they become firmly established.

Seven types of propagules are available for vegetation establishment, seeds, rootstocks, rhizomes, tubers, cuttings, seedlings and transplants (sprigs). The most commonly used is transplanted sprigs.

Plants themselves may be used as protection by planting the more erosion resistant large transplants on the outer fringe of the marsh.

Young plants are particularly vulnerable to wildlife feeding and browsing. Herbivores such as Canada geese, muskrats, nutria, rabbits, goats, sheep, and cattle can rapidly destroy a newly established marsh. If necessary trapping and fencing should be used to control this problem.

Further guidance on plant selection and planting is given in US Army (1986).

## 8.5 Saltmarshes

The saltmarshes that fringe the Blackwater Estuary on the east cost of the UK are declining in area due to net erosion (Pye and French 1993). This loss is detrimental to navigation, sea defence, aesthetics, conservation and recreation and so any economically viable scheme that slows or reverses the loss of saltmarshes may be deemed to be beneficial.

### *8.5.1 Design criteria*

To allow colonisation by saltmarsh plants the height of the mudflat should probably be within the range of elevations between MHWS and MHWN (which at Maldon is approximately 1.7m ODN to 2.7m ODN).

### *8.5.2 The Maldon experience*

Dredged material from a boatyard in Maldon, at the head of the Blackwater, has been used creatively to mitigate the erosion of saltmarsh opposite the yard and at several locations downstream. This management has been conducted in a piecemeal, small-scale approach, for more than a decade (Dearnaley et al 1995).

The aims of the remedial work on the Maldon saltmarshes is to reduce erosion and to create saltmarshes. Two years ago there were four breaches in the Maldon saltmarshes separating the main channel from Heybridge Creek. The breaches were getting bigger and it was considered that if this trend of erosion continued it might lead to major changes in the hydraulic and sedimentation regimes in the area. A possible consequence of this was a general loss of depth alongside the Maldon Quay in addition to accelerated loss of the remaining saltmarsh area.

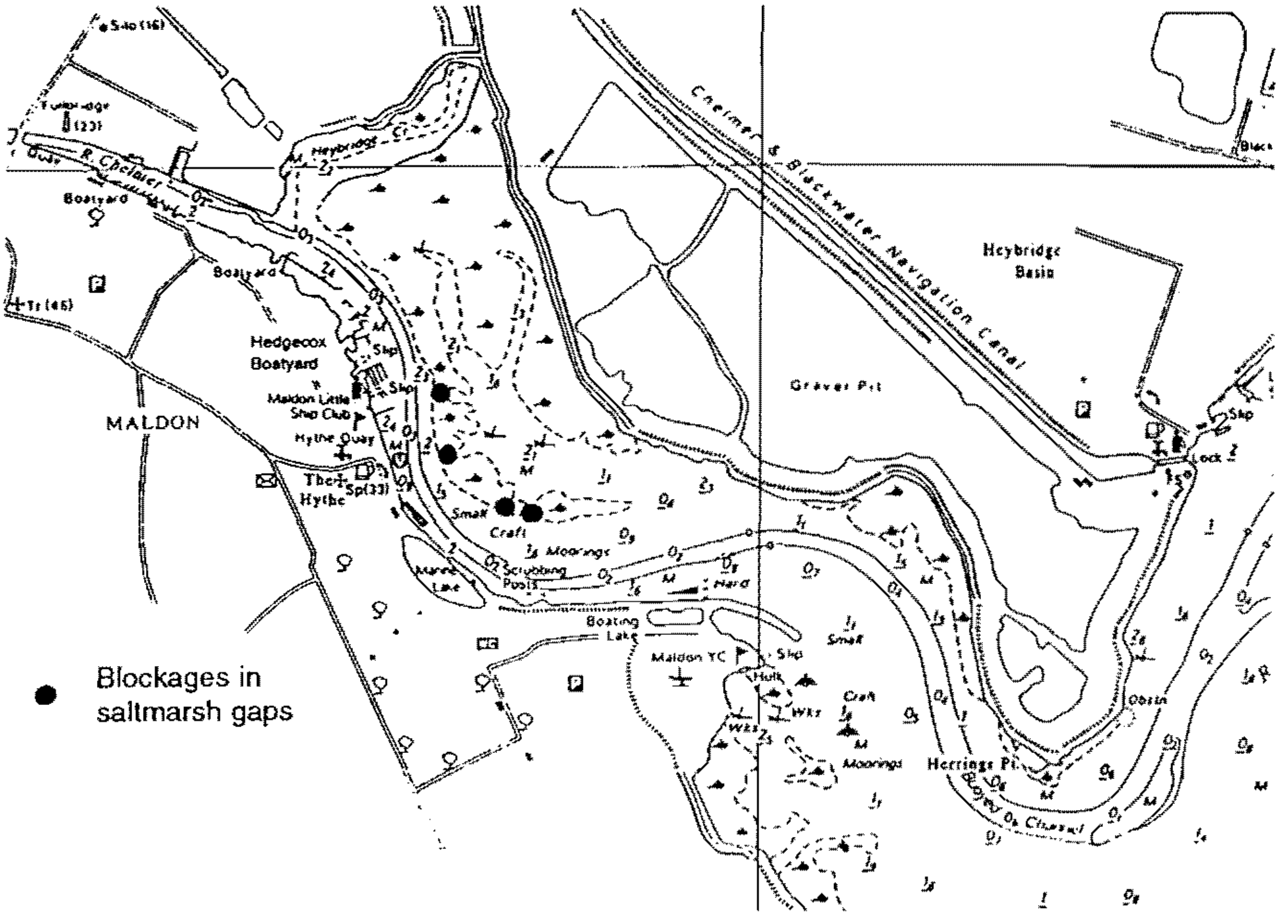



**Figure 8.2 The Blackwater Estuary, Maldon**

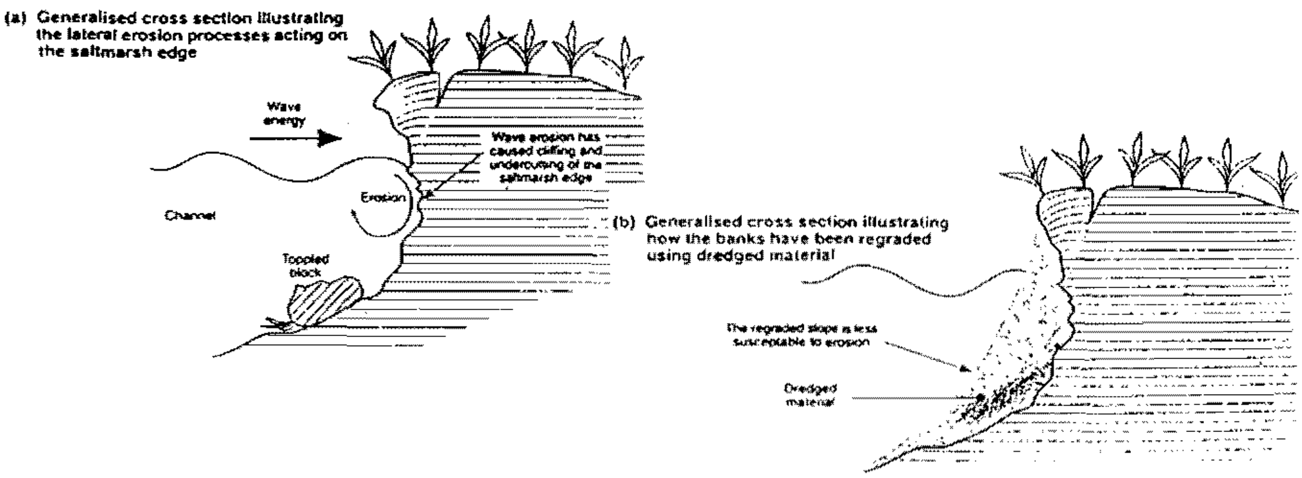
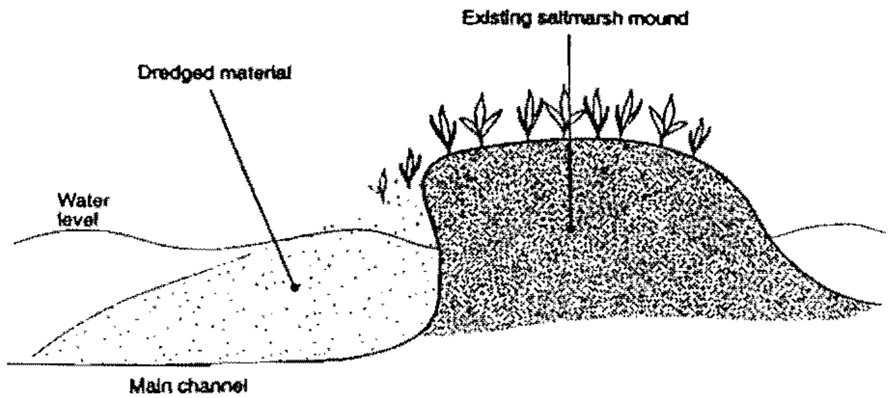



**Figure 8.3 Cliff regrading**




## Figure 8.4 Saltmarsh extension

In the spring of 1993 the four breaches were plugged with wooden planking bolted to timber piles at 2.4m centres, and infilled either side with dredged material from berths at the Quay. The contractor who undertook the work suggested that ongoing erosion, if remedial action had not been taken, would have soon made the work impossible to carry out, in the economical fashion employed.

In the engineering sense the remedial work has undoubtably been successful (HR Wallingford 1995). It has blocked the gaps and eliminated the tidal flow. There is also evidence of re-colonisation of the infill areas with saltmarsh growth. The infilled areas are not as species rich as the adjacent natural saltmarsh, which is to be expected given their relative ages. However, in general, revegetation has been extremely successful and it is difficult to distinguish the infilled areas from the established saltmarsh.

A further use of the dredged material has been to combat lateral erosion of the saltmarsh adjacent to the main estuary channel by regrading the unstable banks so that they are less susceptible to damage from wind and vessel-induced waves (Figure 8.2). Where such cliff regrading has been undertaken observations indicate that this management technique appears to be successful in engineering terms. However, detailed profile monitoring would be required to determine whether the dredged material had halted lateral erosion.

In areas downstream of Maldon where limited placement of dredged material has been undertaken over the last 12 years to extend the margins of the remaining saltmarsh (Figure 8.3). At some of these sites there appears to be little revegetation of the placed material. This seems to be because the elevation of the placed mudflat surface is too low, hence the frequency and duration of flooding is not suitable to allow the development of higher plants (algal mats being the only form of plant life over the majority of the mud mounds). It is inferred that either consolidation or erosion resulted in a lowering of the initially placed mud mound or that the initial height of the placed material was insufficient.

### 8.5.3 Monitoring

The purpose of monitoring is to assess the degree to which the schemes have been successful. A monitoring programme to investigate the plant colonisation and potential ecotoxicology of the dredged material used to block the breaches should include the elements as listed below. These should be used for comparison with a control site in an area of natural saltmarsh with similar elevation and proximity to the channel to the infilled areas.

A typical monitoring programme (eg 6 monthly observations) may include:

i) Chart plant colonisation on the deposit sites

- Time series photography
- Record species frequency using 1$m^2$ fixed quadrats with 0.1m subdivisions

ii) Establish whether concentration of contaminants in the placed material are below the Netherlands standards for the aquatic disposal of dredged material

- Analysis of contaminant concentration (heavy metals and TBT) in sediment samples from the oxic and anoxic zones
- Comparison of contaminant concentrations to some recognised standards (eg Netherlands) by converting the results of the analysis to a standard soil type (in order to do this percentage of fines and percentage of organic content must be known)

iii) Estimate the potential ecotoxicology

- Measurement of pH and redox potential profiles. This data, in conjunction with the measurements of contaminant concentrations in the oxic and anoxic zones, indicates the availability of the contaminants, and hence the potential risk, to biota.

iv) Investigation of bioaccumulation

- Comparison of the concentration of contaminants (heavy metals and TBT) in the sediment with those in samples from the different species of plants growing on the site (note that all species will be analysed individually as it is known that there is significant variation in bioaccumulation between species).
- In order to see whether the roots accumulated contaminants to a different degree than the shoots (which would affect the impact that the bioaccumulation had on grazers) the roots and shoots are separately analysed for selected examples.

v) Determination of whether the concentration of heavy metals and TBT in the placed material decreases over time

- Comparison of contaminant concentrations in fresh deposits to those in a range of historically placed deposits.

## 8.6 Intertidal mudflats

Intertidal mudflats are an essential source of the invertebrates on which many species of wader such as Dunlin and Redshank feed during migration. They support softshell clam (Mya arenaria) and baitworm (sandworm Neris virens and bloodworm Glycera dibranchiata). They also provide feeding grounds for commercially important fish species such as winter flounder (Ray et al 1994).

The development of many estuaries, including the construction of tide excluding barrages, has reduced the extent of such mudflats. The deliberate creation of new mudflats is one means of compensation being tried. Because it is new technology there is little available in the way of design guidance but a scheme in Poole, UK currently being monitored is reported so that the reader may benefit from the experience gained so far.

### *8.6.1 Design criteria*

If the primary purpose of the intertidal mudflat creation is the provision of alternative feeding grounds for wading birds the following criteria apply:

- the mud used must be of a type which will sustain the appropriate invertebrae (Ray et al (1994) found that an artificial mud flat in Maine consisting of >80% silts and clays had an abundance of baitworm and soft clams after 3 years);

- the mud should be free from contaminants toxic to the birds;

- wading birds tend to feed along the waterline so the length of shoreline is a more significant criteria than the width of the mudflat (ie perpendicular to the shore);

- the mudflats should be in relatively calm water (ie not exposed to severe waves);

- the area should be reasonably free from predators and/or human activity;

- in engineering terms the flats should be at a stable slope;

- it is not always necessary to provide exposed mud at all stages of the tide, indeed in many situations the most productive area is that between mid tide and the high water line (this depends on the local conditions and especially the tidal range).

### *8.6.2 The Parkstone experience*

In 1990 Parkstone Yacht Club obtained planning permission for development of a Yacht Haven at their site on the northern shore of Poole Harbour, UK. Because of its considerable environmental value Poole Harbour is designated a Site of Special Scientific Interest and has been proposed for designation as a Special Protection Area under the European Community Directive on the Conservation of Wild Birds and as a wetland of international importance under the RAMSAR convention. As part of the planning consent the design for the Yacht Haven included the provision of an area of intertidal mudflat to replace that portion of the existing intertidal zone lost to the development (Figure 8.5) (Dearnaley et al 1995).

The Yacht Haven was constructed in the winter of 1994/95. The mudflat has been built on the inside of a rubble mound breakwater which protects the Haven from wave action from the south and west and is held in position by sheet piling inshore of the breakwater. The mudflat is about 325m long by 20m wide. The sheet pile wall is at level of +1.2m CD, which is the level of mean low water on a neap tide, and at the breakwater edge it is +2.0m CD, slightly below mean high water on a spring tide (Figure 8.6). During a typical spring tide the whole of the mudflat is submerged for about 2 to 3 hours, and during a neap tide the lower section will be submerged for 10 or 11 hours, and the upper half will remain dry.

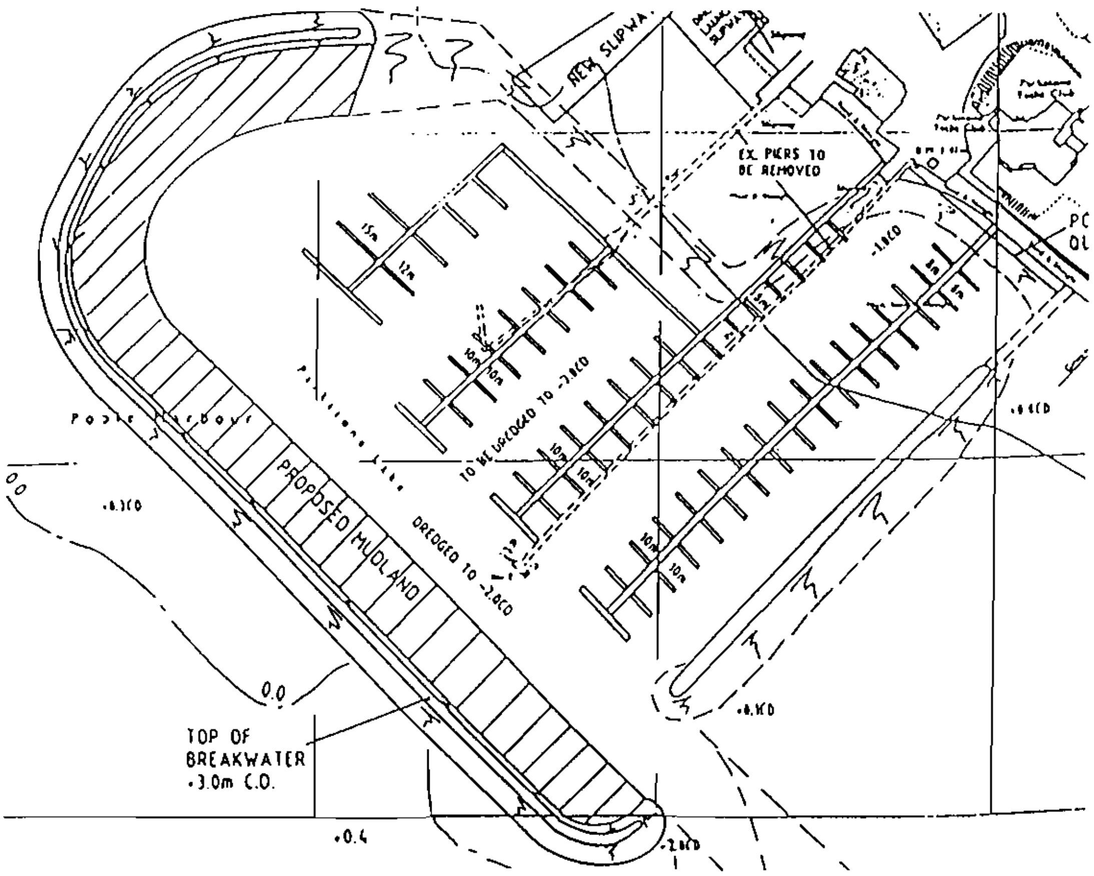
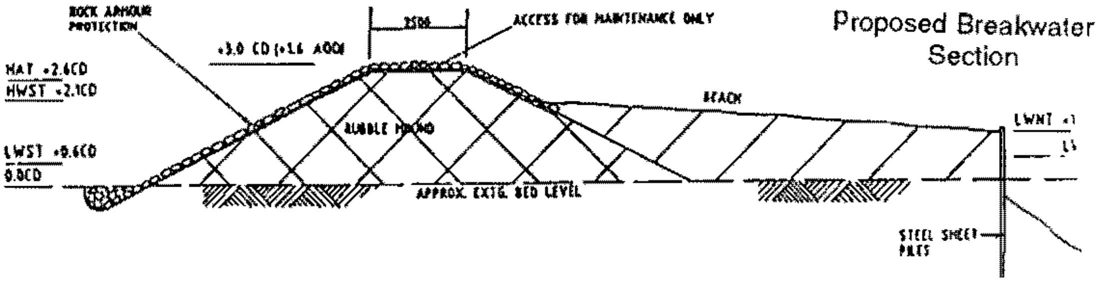



**Figure 8.5 Proposed Haven with mudflat**




## Figure 8.6 Section through mudflat

The initial tasks were dredging the approach channel and the Haven basin, and the construction of a temporary roadway. The approach channel and most of the haven were dredged by trailer suction hopper dredger to about -2.5m CD. Two areas were left undredged at this stage. The combined quantities from these two areas, about 10,000 $m^3$ were ultimately used for the construction of the mudflat. Only mud dredged from existing intertidal areas was used for the top layer.

### *8.6.3 Construction problems*

The following potential problems should be considered regarding the planning and execution of construction works:

- if a retaining wall to retain the toe of the mudflat is to be constructed at or near to low water level, (as in the case of a perched mud flat like Parkstone), the time for access is severely limited;

- for work in an environmentally sensitive area the time of operation may be restricted for example to daylight hours and certain seasons (eg not nesting seasons).

- if the mud is to be placed by hydraulic methods it will be very difficult to create a slope greater than about 1:50 - 1:100. Placement at, or close to, in situ density is advisable. Final profiling can be achieved by dragline. Use of graders, bulldozers etc will be restricted because of the low load bearing capacity of the placed mud (see Section 2.1.4).

### *8.6.4 Monitoring*

Monitoring should be undertaken at approximately three monthly intervals throughout the first year of construction and then annually (unless there are particular seasonal factors which would require more frequent observation).

Monitoring should include the physical, chemical and biological development of the mudflat to compare these characteristics to an adjacent area of natural mudflat in order to assess how successfully the replacement habitat has been created. Such monitoring will establish the benefits of the habitat creation scheme and may have many other potential applications in terms of considering and justifying other applications for recreation of intertidal zones lost to development.

The following schedule is suggested:

i) In-situ measurements of bulk density of the placed material

- Density measurements of the placed material may be made with a radio-active density probe in order to investigate consolidation of the placed material, which is likely to be low, and the rates at which any erosion or deposition on the mudflat occur.

ii) Surface sediment analysis

- Particle size analysis and characterisation in order to establish whether deposition is occurring at the site. The information will also be required to normalise observed metal concentrations found in the samples to a format that is comparable with other standards in common use (eg the Netherlands Standards for dredged material use in aquatic environments).

- Analysis of the organic content to investigate colonisation of the mudflat.

- Analysis of heavy metal concentrations in the surface sediments.

iii) Biological sampling

- Sampling of meiofauna and macrofauna to investigate the colonisation of the mudflat

iv) Photographic record of the development of the mudflat

- Careful visual records should be obtained throughout the initial period of development of the mudflat. This will support other monitoring activities and help in the consideration of issues of potential importance for other habitat creation schemes.

## 8.7 Monitoring

Monitoring of habitat creation schemes generally should include at least the following components (Landin 1992):

a) Site stability and critical elevations;

b) Substrate suitability to accommodate successful biotic components;

c) Erection and monitoring of temporary and permanent breakwaters and other structures to ensure establishment of vegetation in the habitat built of dredged material;

d) Consolidation and settling tests to determine exact elevations after consolidation of dredged material for wetland construction;

e) Hydraulic and hydrology components necessary to achieve habitat objectives, especially where wetlands restoration or creation is the project goal, and

f) A combination of techniques known as bioengineering, in which structures are combined with planted material to provide greater stability and a more natural appearance.

There are other engineering parameters to be evaluated as they relate directly and indirectly to habitat development. Environmental engineering guidelines are published by the US Army Corps of Engineers (US Army 1986 and 1989).

Nesting and wildlife construction and monitoring guidelines are published in Soots and Landin (1978) and more recently in Landin (1992 a).

# 9 Capping

Capping has become an accepted means of isolating contaminated dredged material from the aquatic environment (Sumeri 1995). It involves placing a layer of sand over the contaminated material which may have been placed in an underwater pit or simply placed on the aquatic bed. The material used in capping must have the properties of sealing the contaminants but that does not necessarily imply that it must be totally impervious. Experiments in the USA have found that dredged sand can be used satisfactorily for this purpose. Studies have also been carried out to determine the feasibility of using a layer of dredged clay (HRW (Asia) 1993).

A simple definition of subaqueous capping is the controlled accurate placement of contaminated materials at a disposal site followed by a covering or cap of clean isolating material. The two Figures below illustrate two types of capping, level-bottom capping and contained aquatic disposal (CAD) (US Army 1987).

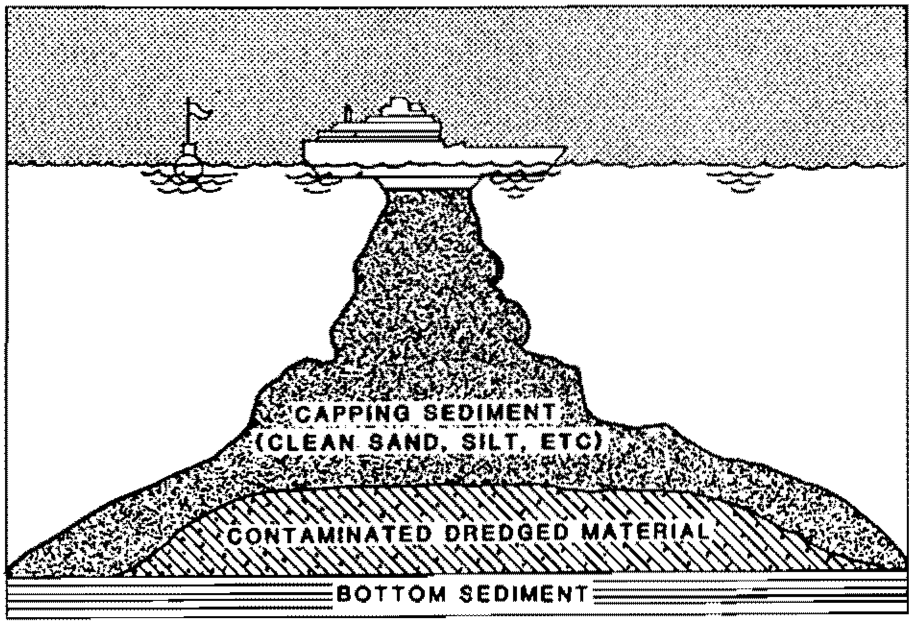



**Figure 9.1 Schematic of typical level-bottom capping operation (adapted from Shields and Montgomery 1984)**

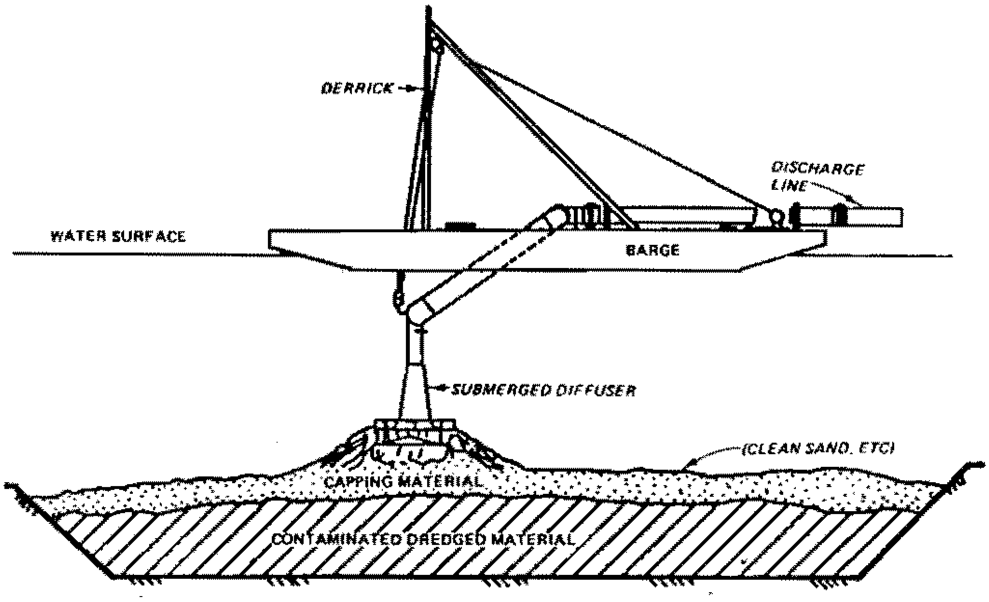



**Figure 9.2 Schematic of contained aquatic disposal (CAD) project also showing use of a submerged diffuser for placement**

As the name suggests, level-bottom capping projects attempt to place a discrete mound of contaminated material on an existing flat or very gently sloping natural bottom. A cap is then applied over the mound by one of several techniques, but usually in a series of disposal sequences to ensure adequate coverage. CAD is generally used where the mechanical properties of the contaminated material and/or bottom conditions (eg slopes) require positive lateral control measures during placement. Use of CAD can also reduce the required quantity of cap material and thus cut costs. Options may include the use of existing depressions, pre-excavation of a disposal pit or construction of submerged dykes for confinement.

## 9.1 Design considerations

### *9.1.1 The site*

Bathymetry

If the bottom in a disposal area is not horizontal then a component of the gravity force will influence the energy balance of the bottom surge. It is difficult to estimate the effects of the slope alone, since bottom roughness plays an equally important role in mechanics of the spreading process. Gordon (1974) described the results of monitoring barged disposal operations at a level bottom site on Long Island Sound, US, and concluded that 81% of the original volume of sediment released was deposited within a radius of 30m from the point of impact and 99% within a radius of 120m. Truitt (1986) similarly found 93% within 30m of the injection point.

Currents

Basic current information should be collected at prospective sites. However, based on observations at several sites, Bokuniewicz et al (1978) concluded that the principal influence of currents is to displace the point of impact of the descending jet. They stated that even strong currents in the receiving water need not be a serious impediment to accurate placement, nor do they result in significantly greater dispersion. Further, currents do not appear to affect the surge phase of the disposal.

The long term effects of currents at the site will affect the stability of the capping material.

Average water depth
Apart from the effect that depth has on the current profile there appears to be little additional short-term influence on placement. Bokuniewicz et al (1978) observed the same general physical processes occurring with water depths ranging from 15 - 60m. In deeper water more entrainment occurs in the descent phase and there is more bulk dilution of the dredged material before it reaches the bottom but there is no increase in the jet impact speed, nor does the bottom surge spread at a faster rate.

The initial thickness of the spreading surge above the bottom has been shown to be a function of water depth.

Stratification (due to salinity or temperature)
A sufficiently great density gradient in sufficiently deep water can result in arrest of the descending jet. The depth at which this occurs can be calculated. Bokuniewicz (1978) suggested that although highly stratified conditions may be encountered, it is most unlikely that water depths would be great enough at most sites to cause collapse in the upper water column. Johanson et al (1976) present an empirical formula for estimating the conditions under which a descending jet would penetrate a stratified layer.

Other factors

- wave erosion (possibly in conjunction with currents);
- propeller wash erosion;
- bottom sediment characteristics;
- type of contaminants;
- future site use;
- ground water conditions;
- recontamination potential;
- risk of burrowing animals compromising the cap;
- desired cap thickness;

### *9.1.2 Cap design*
There are two main design criteria: the cap must provide an adequate seal and it must remain intact under all site conditions (US Army 1987b).

Isolation
The effectiveness of inert sediment as a contaminant-isolation technique has been evaluated by Brannon et al (1985). Their experiments used modified flow-through reactor units containing contaminated sediment and various capping materials. Effectiveness was assessed by chemical analysis on water samples

from the water column and uptake by clams and polychaetes. Samples of sand, silt and clay were all tested with and without the effects of bio-turbation organisms. The results showed that materials containing the highest percentages of silt and clay were generally more effective than sand in preventing the movement of contaminants into the water column. However, the thickness of the cap was more important than material type.

A procedure for more precise determination of cap thickness is given in US Army (1988). This involves laboratory testing of the contaminated sediment and capping material and gives guidance on the interpretation of the results.

However, Murray et al (1994) refer to an "effective" cap thickness, being the thickness below the bioturbated zone. Detailed studies were made of the diaganetic process of molecular diffusion of pore water through sediment caps which showed that it would take 50 years for a 0.5m cap to become fully saturated. In many situations this rate would be much less than natural sedimentation over the cap.

Thus bioturbation and physical disturbance are the more significant parameters in determining cap thickness. For practical reasons of construction and reasonable tolerance (allow say 0.5m) a minimum cap thickness of about 1m is recommended.

Stability

Cohesionless sediments (sand and some silts) transport as individual grains typically in a continuing series of discrete erosion and deposition events. The erosion rate is primarily dependent on the size, shape and weight of sediment particles and on the shear force exerted on them by the flowing water. The orbital motion of waves also produces oscillating flow at the bed depending on depth of water and wave height and period. This may add to the maximum shear stress. Sediment transport is a highly complex subject and it is not possible to give an adequate description of reasonable length in the context of this document. A slightly fuller description is given in Section 5.4. The reader is referred to the HR Manual of Marine Sands (Soulsby 1994) which provides methods of calculating thresholds for and rates of transport for currents, waves and a combination of the two. HR Wallingford have also produced software (SANDCALC) which enables the user to vary parameters and compare results using different formulae.

For cohesive material the transport is more dependent on the cohesive bond than the particle size. A more detailed description is given in the section on soft berms (Section 5.4.2). For estimating thresholds and rates the reader is referred to the HR Estuarine Muds Manual (Delo and Ockenden 1992).

Volume of capping material

Layout of the cap perimeter must take into account the method of placement. For side-pushed barges the area should be as rectangular as possible. The volume required should include where barge loads overlap the perimeter. For non-rectangular areas this can be considerable. For towed barges the site should take into account the turning radius of the barge/tug combination and should avoid acute angled corners. Manoeuvring limitations will increase out of area (off target) discharge.

Several other factors affect volume computations. One is off site drift of material. Current data must be provided to allow upcurrent placement to reduce losses. Even then, losses will occur. Allowance should also be made for off site losses due to the difficulty of maintaining position along the site boundary. An even bigger allowance should be made if the design tolerance is only positive (ie if a minimum thickness is specified). Total losses can be expected to be in the range 10 - 20%.

Finally the design calculations should allow for the natural angle of repose side slopes to develop.

## 9.2 Construction

A number of placement methods have been tried. The choice will be based on material properties and the compatibility of placement for both the contaminated material and the capping material (Palermo 1994). The main options are given here together with comments on some of the problems as well as the advantages.

### *9.2.1 Sand capping using dump barges*

Split hull or bin bottom dump barges are very effective tools but have some limitations. It is impossible to get the sand to discharge uniformly, either over the length of the barge or over time (Parry 1994). The barge is hard to get uniformly loaded, even if the dredger is careful. This is especially true at the ends of the barges. Sands, especially riverine sands, are not homogeneous, and small changes in the amount of fines affects discharge rate. Water will collect in pools. When the barge opens, these pools will locally accelerate the discharge until drained and then the loading along the barge axis is even less uniform.

The problem of non-uniform discharge is caused by the mechanics of the placement. At the start of the discharge the sand "bridges" the gap at the bottom of the hopper and a few degrees of opening are necessary just to get the sand flowing. As the weight of the "bridges" decreases the hopper must be continuously opened in small increments. Finally, a point will come when bridging does not occur and sand will flow freely down the sides of the hopper. This can result in the remainder of the material "bombing" the bottom with a risk of displacing the material being capped. Experience has shown (Parry 1994) that an average discharge rate of 0.5 - 0.7$m^3$/s to reduce this pulse to an acceptable size. a rate of 10$m^3$/s will result in 30% of the volume being dropped in the last few seconds of discharge. Monitoring and controlling the discharge rate requires a high level of operator skill.

If the capping site is small or confined, pushing the barge sideways is very effective. The capping site is simply divided into rectangles for each barge load, according to the size of the barge and the desired thickness. Two tugs are needed, one on the side and one on the end. Either tug can be the master tug. High precision electronic position fixing is essential and the master tug must have a visual display. Because of the discharge rate problem it is necessary to make several passes over the incremental area during each load to reduce unevenness of the cap thickness. The best tolerance on cap thickness that can be reasonably expected is about 0.15m. This requires interim surveys for adjusting placement.

For larger capping sites room to manoeuvre only one tug is necessary. The tug operator tries to fill the capping site with uniformly distributed track lines. Multiple passes are needed over the same area which also helps in gaining a more uniform distribution. Side by side tracklines are not feasible due to the turning radius of the tug/barge combination. A tug towing a 1000$m^3$ barge needs 120m to turn while maintaining speed and control. This technique is less likely to produce an even cap than side pushing

### 9.2.2 *Sand capping using flat scows*

This involves washing the sand off flat scows using a high pressure jet. It used to be a common method before the widespread use of bottom dump barges but the associated high turbidity and the manpower intensive costs virtually ended the practice. An 130l/s jet can be expected to move 240 $m^3$/hr of sand. It is approximately twice the cost of bottom discharge. However, washoff can be very effective in achieving a more uniform distribution since the discharge is more diffuse and does not have the end pulse at the end of each track. It is particularly effective over soft substrate.

### 9.2.3 *Capping with a submerged diffuser*

A submerged diffuser has been successfully tested in the Netherlands at Rotterdam Harbour and as part of a demonstration project at Calumet Harbour, Illinois (McLellan and Truit 1986). The diffuser minimises upper water column impacts and especially improves placement accuracy and controls sediment spreading. This in turn reduces benthic impacts. By routing the slurry first through a conical expansion and then a combined turning and radially divergent diffuser section, the discharge is released parallel to the bottom and at a lowered velocity. The design can be modified to suit project needs.

The diffuser can be employed as a direct connection to a pipeline dredge or as a modification to hopper dredged or mechanically dredged material disposal techniques. For the latter cases, a reslurrying pump-out capability would be required. The pipe connecting the surface support barge to the diffuser head can be of relatively small diameter (ie conventional pipeline size) and can be semi-rigid or flexible if the head is controlled independently by cable or other moorings.

### 9.2.4 *Gravity fed downpipe (tremie)*

This consists of a large diameter conduit extending from the surface through the water column to some point near or above the bottom. Dredged material is placed into it either as a slurry or by being mechanically removed from a scow. Isolation from the water column is achieved and placement accuracy improved. Because of its rigidity and large size it is difficult to use in strong currents and high waves or in deep water.

### 9.2.5 *Hopper dredge pumpdown*

Some hopper dredgers have pump-out capability by which material from the hoppers can be discharged like with a conventional hydraulic pipeline dredge. Some also have modifications that allow pumps to be reversed so that material can be pumped down through the dredger's extended dragarms. Because of the expansion at the draghead the result is similar to using a diffuser.

## 9.3 Measurement

Some contracts may require all of the material to be accounted for. This is usually for environmental reasons rather than as the basis for payment. However, it is fraught with problems.

Barge volumes are usually measured at the dredging site by displacement or in-situ hydrographic survey. Cap volume is measured in a bulked or semi-bulked condition by hydrographic survey which takes no account of settlement of the original substrate or the material being capped. Settlement can be measured using staff gauges or settlement plates but it is difficult to provide enough of these and inevitably some get knocked over. Sub-bottom profiling is another option but its interpretation is as much an art as a science at the present time. Each method has its limitations and accuracy and comparison between results obtained by different methods should be made with great caution.

It is, however, essential to determine cap thickness since this is the criteria for successful completion of the scheme. While the same accuracy arguments apply taking the conservative value on each one will ensure that the thickness meets the specification even if it results in higher contingency volumes.

## 9.4 Monitoring

Monitoring must address the same two main parameters as the design, namely the effectiveness of isolation and the stability of the cap. Additionally the effects of the construction itself should be monitored.

### *9.4.1 Construction phase*

Monitoring should take place before, during and immediately after the construction operation. Background chemical characterisation of the site will be necessary to serve as a baseline for comparisons. Water samples should be taken during the placement of the contaminated dredged material and during capping, primarily looking for resuspension of sediment. The main attention should be on bathymetry, accurate positioning during discharge and accounting for the mass/volume of sediment handled. See Section 9.3 on measurement problems.

Side scan sonar and video equipment can be used to verify conditions.

Cores should be taken through the completed cap to verify thickness and for sediment chemistry characterisation.

### *9.4.2 Long term*

Similar water column sampling and sediment core series should be completed periodically after construction. Bathymetry and consolidation should also be measured at these intervals. Special monitoring may be appropriate after extreme events to ensure the integrity of the scheme and delineate remedial action if necessary.

The results of several years of monitoring a number of capping schemes in the US are given in Sumeri (1995). He reports that confined aquatic disposal and capping of contaminated sediments with clean sandy dredged material has been satisfactorily carried out in a number of projects in the Puget Sound. Sandy dredged material caps with low silt content are providing adequate substrates for biological recolonisation. Generally, with the exception of some clays balls with low levels of contaminants in the capping material and some minor instances of mixing of cap and contaminated bottom material, sediment chemical analyses indicate that the caps of dredged material are functioning as intended in separating contaminants from aquatic organisms. In many of these projects dredged material was beneficially used for economic capping of contaminated sediments utilising conventional or easily fabricated equipment. Some evidence of recontamination of cap surfaces has been noted from

- adjacent contaminated areas
- construction activities in adjacent contaminated area such as pile extraction
- propwash from ferries
- sources that have not been sufficiently controlled.

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## 11 Acknowledgements

HR wishes to acknowledge with gratitude the following organisations who contributed their resources of time, data and facilities to this project.

- Construction Industry Research and Information Association (CIRIA).
- New Ross Harbour Commissions (Ireland).
- Harwich Haven Authority (UK).
- Central Dredging Association (Netherlands).
- International Association of Dredging Companies (Netherlands).
- Ministry of Agriculture Fisheries and Food (Marine Environmental Protection Division) (UK).
- Mr S Priestly, Ben Carter Hollings & Ferner Ltd (New Zealand).
- US Army Engineer, Waterways Experiment Station, Vicksburg (USA).
- Water & Power Development Agency (WAPDA), (Pakistan).
- Economic & Social Commission for Asia and the Pacific (ESCAP), Bangkok (Thailand).
- Maldon District Council (UK).
- Geotec Associates (USA).
- Parkstone Yacht Haven (UK).