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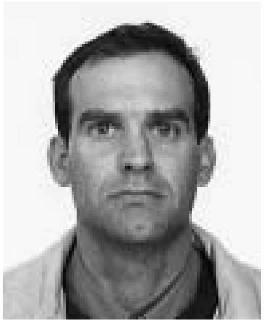
Assessment of Offshore Sand and Gravel for Dredging



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Abstract

Reliable assessment of offshore sand and gravel resources permits efficient dredging, the maintenance of cargo quality control and the effective mitigation of environmental impacts. Site investigation should be based on the interpretation and correlation of high resolution seismic profiling and CPT/sampling data.
A preliminary interpretation of the seismic data reveals the geological setting of the sand bodies and leads to the selection of appropriate sampling methods and the recognition of key sampling positions. Geologically complex sand bodies demand phased data acquisition to delineate geometry, physical properties and compositional variability. The alternative approach of grid-based sampling using a predetermined sampling density is costly at best and probably misleading.
A 3-dimensional model is created from the integration of acquired data and a resource volume calculated. Dredging constraints and overflow losses are applied to the model resulting in the determination of a reserve volume and critical dredging parameters. It is advisable to carry out a wide-ranging testing programme on the recovered samples to ensure compliance with relevant standards or requirements. The potential penalties for superficial site investigation include delay, unpredictable cargo quality and unforeseen environmental problems.
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Introduction

Offshore sands and gravels lying at depths of less than 60 m on the inner shelf form an important economic resource. The last twenty years has witnessed an escalation in the value of offshore deposits as demand and extraction rates have significantly increased for a wide range of uses. Sand and gravel deposits are dredged for four major applications:
– for use as fill in reclamations: pressures arising from population and development in many ports and coastal communities around the world, for example the Middle East, Hong Kong, Singapore and Taiwan, have lead to a demand for land through reclamations, (e.g. Ooms *et al.* 1994) together with the redevelopment of existing port sites;
– for use as aggregates for construction and concrete: as land-based extraction has become environmentally less acceptable, an increased quantity of fine and

coarse marine aggregate is being used in concrete and as fills. Currently in Japan about 85% of aggregates are supplied from marine sources (Tsurusaki *et al.* 1988) compared with about 18% in the UK (Parrish 1987), whilst many other countries have investigated potential offshore resources, for example Suter *et al.* (1989);
- for beach replenishment: it is now recognised that soft, natural solutions, eg. beach recharge, rather than costly, hard, structural solutions to coastal protection often offer significant environmental and economic advantages. Beach replenishment schemes around the world use a variety of methods (van Oorschot and van Raalte 1989) on a range of scales (for example Murray *et al.* 1994), typically resulting in the deposition 0.5-10 million m^3 of sand and gravel supplying starved and eroded beaches; and
- to extract placers: including precious stones and mineral sands (eg. Hein *et al.* 1993), occurring in fluvial and marine sands and gravels.

This paper examines the origins and assessment of sands and gravels dredged for fill, aggregates and beach replenishment. Dredged sand and gravel resources must satisfy a wide range of specifications for various uses. Sands dredged as fill for reclamations may contain up to 20% or more fines (<63Ám), depending on the works programme and planned use of the area. If the area is to be developed upon completion of the reclamation works, a high bearing capacity is required at an early stage. This can be achieved by using a well-sorted, coarse-grained sand with a low fines content, although ground improvement methods are also used to enhance strength and stiffness characteristics. Reclamations allowing larger settlements over a longer period before construction begins may utilise sands with a higher fines content. Sands and gravels dredged as concreting aggregates require a very low fines content (<5%), must satisfy colour and grading criteria and should not contain deleterious lithologies. A wide range of gradings may be specified for beach nourishments, from fine-grained sands, encouraged as a beneficial use of sediments dredged for other projects (PIANC 1992) to well-sorted gravels.

Dredging is a large international business with over 1000 million m^3 of sands and gravels being dredged annually. The advantages of dredging in comparison to quarrying have long been recognised, and dredging will continue in the foreseeable future to rapidly, reliably and economically deliver large volumes of sands and gravels to the developing areas of conurbations, thus ensuring good progress of projects. For example, at Chek Lap Kok airport in Hong Kong, over 70 million m^3 of sand was delivered in about two years to form a platform measuring 2 km x 1 km, in an area of sea formerly 4-6 m deep. For the majority of these requirements, trailer suction hopper dredgers (TSHDs) are used to dredge sand from the licenced borrow areas

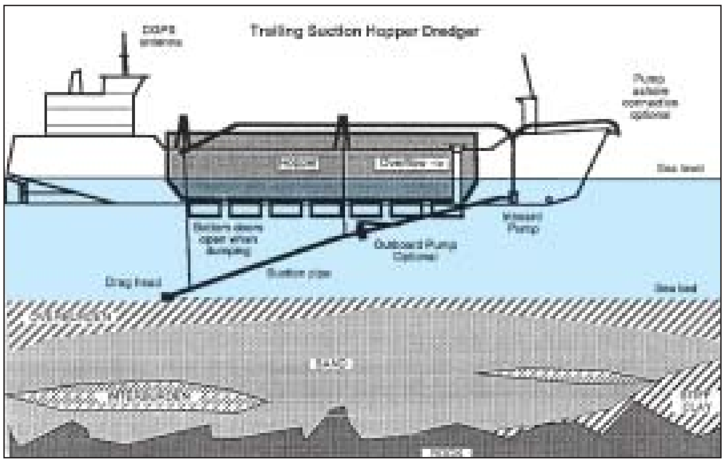


Figure 1. A typical TSHD with a 8000 m^3 hopper capacity is 125 m long x 21 m across with a loaded draft of 9 m. Dredged slurry is discharged in the rear of the hopper. Overflow from the hopper is regulated by adjusting the height of the overflow tubes. TSHDs dredging aggregates have a single dredge pipe, overflow through spillways in the top of the hopper above the waterline, and discharge by pump and bucket wheel or scraper and conveyor.

and discharge their cargo at the site or wharf (Figure 1). TSHDs used for capital projects typically have hopper volumes of 4000-10000 m^3, and are soon to be as large as 23000 m^3. Aggregate dredger hopper volumes are generally smaller, around 1000-3500 m^3, largely due to the restrictions imposed by tidal berths. This paper only considers dredging by TSHDs. In the past extraction by TSHD has been limited to depths of about -50 m, but several dredgers may now operate at -60 m and deeper as a result of outboard pump systems, and the trend towards deeper dredging continues.

Given the investment in TSHD technology, it is critical to maximise the utilisation of finite geological resources. However during dredging operations (Bray 1979), production and quality problems often arise which can be directly attributed to a poor understanding of the geological context of the dredged deposit. This is often a result of an inadequate site investigation which has lead to an incorrect interpretation. Coupled with uncompromising restrictions being imposed as a result of the developing environmental awareness of dredging impacts, it is considered that the inefficiency arising from poor resource assessment is becoming increasingly unacceptable. This paper highlights the potential benefits of a thorough site investigation, which will result in a confident prediction and assessment of resources, permits optimal production and mitigation of environmental impacts. The methods outlined are based on experience of resource and reserve assessment in the UK and Hong Kong for sand and gravel deposits dredged for aggregates, fill and beach replenishment. Figure 2 illustrates the assessment methodology. Aspects of the geology of offshore sands and

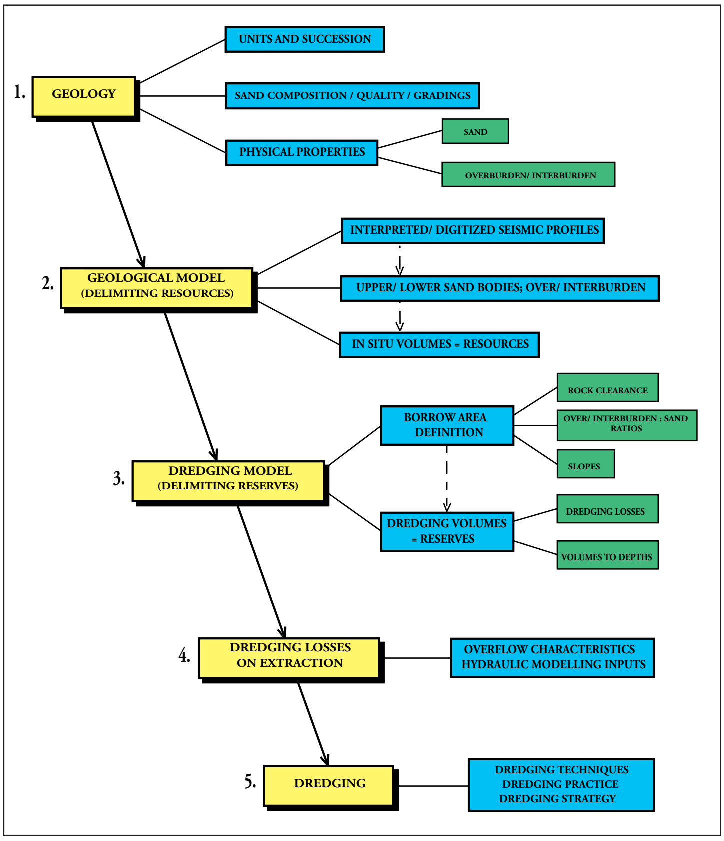


Figure 2. Proposed methodology for the assessment of volume and quality of offshore sand and gravel deposits. When combined with physical and biological measurements and observations, the data derived from this assessment allows the prediction of environmental impacts.

gravels, with examples from Hong Kong, and each stage in the assessment process are outlined in the following sections.

Occurrence of Sands and Gravels on the Inner Shelf

Offshore sands and gravels are a finite resource. The majority of the sands and gravels currently dredged from the inner shelf are relict and were deposited as a result of the numerous major sea level and climatic changes that have occurred during the alternating glacial and temperate episodes of the past 1-2 million years. Throughout this time sea levels have regularly fallen (lowstands), rarely to a maximum of around -120 m, sub-aerially exposing the shelf, and have risen (highstands), occasionally above existing sea level (Shackleton 1987). In high latitudes during cold stages, glacigenic (subglacial, proglacial and glaciofluvial) and periglacial processes (Boardman 1987; Drewry 1986) have resulted in intensified erosion, transport and sedimentation rates of sands and gravels, which then may become available for reworking during the following warm stage highstand. In the lower latitudes, shifts in the climatic belts have resulted in changes in precipitation and vegetation leading to periods of intensified erosion of deeply weathered rocks and reworking of existing sand deposits. Throughout this time, climatic changes in hinterlands have resulted in changes in river sediment loads, composition and deposition rates.

Sands and gravels have been deposited in a wide variety of high energy, fluvial, coastal and marine settings which have been influenced by the numerous changes in relative sea level. Typically, sand and gravel bodies are characterised by complex depositional geometries and histories. Offshore, the shelf often slopes seaward at very low angles, eg 1 in 1000, and consequently even if a minor sea level fall occurs, wide expanses of shelf become sub-aerially exposed and rivers flow across the plains. Fluvial incision occurs as base levels fall and the channels of braided and meandering systems migrate and infill (Miall 1992). Coarse-grained sediments by-pass the exposed inner shelf during a lowstand. Terraces preserved along the channel margins (Bellamy 1995) provide evidence of further minor sea level changes and estuaries and deltas become sediment traps, where the rivers enter the sea (Orton and Reading 1993). Rising sea levels result in estuarine sedimentation backstepping coastwards, forming the late stage infills of the fluvial channels, whilst concurrent erosion of the transgressed land surface forms a planar ravinement surface. The ravinement surface is commonly associated with overlying veneers of sand, locally up to a few metres thick, deposited in a nearshore, shallow shelf environment (Stride 1982). Stillstands in the transgression leads to the development of coastal depositional systems including beaches, bars and barriers, which may be partially preserved on the shelf (Nummedal *et al.* 1987), whilst shallow marine currents may lead to the formation of offshore sand banks.

Sands from the Inner Shelf Around Hong Kong

The sands lying offshore Hong Kong provide a good example of the variety of inner shelf sand bodies. Around 250 Mm^3 of sand has been dredged in Hong Kong to provide fill for the reclamation programme since 1985. Hong Kong lies on the stable passive margin forming the northern shelf of the South China Sea, on the eastern side of the mouth of the Zhujiang (Pearl) Estuary (Figure 3). Within territorial waters, depths attain -33 m (all depths are below Chart Datum) and the seabed is typically underlain by a 5-15 m thick mud sheet deposited during the final stages of the Holocene transgression (Fyfe *et al.* in press). The mud sheet overlies a sub-aerially weathered succession of interbedded muds and sands incised by fluvial processes during at least two major sea level lowstands. A significant difference between resources in Hong Kong and elsewhere, for example in the UK (Selby 1992), is that gravels are rare. This is attributed to the intensity and depth of the weathering of the bedrock in

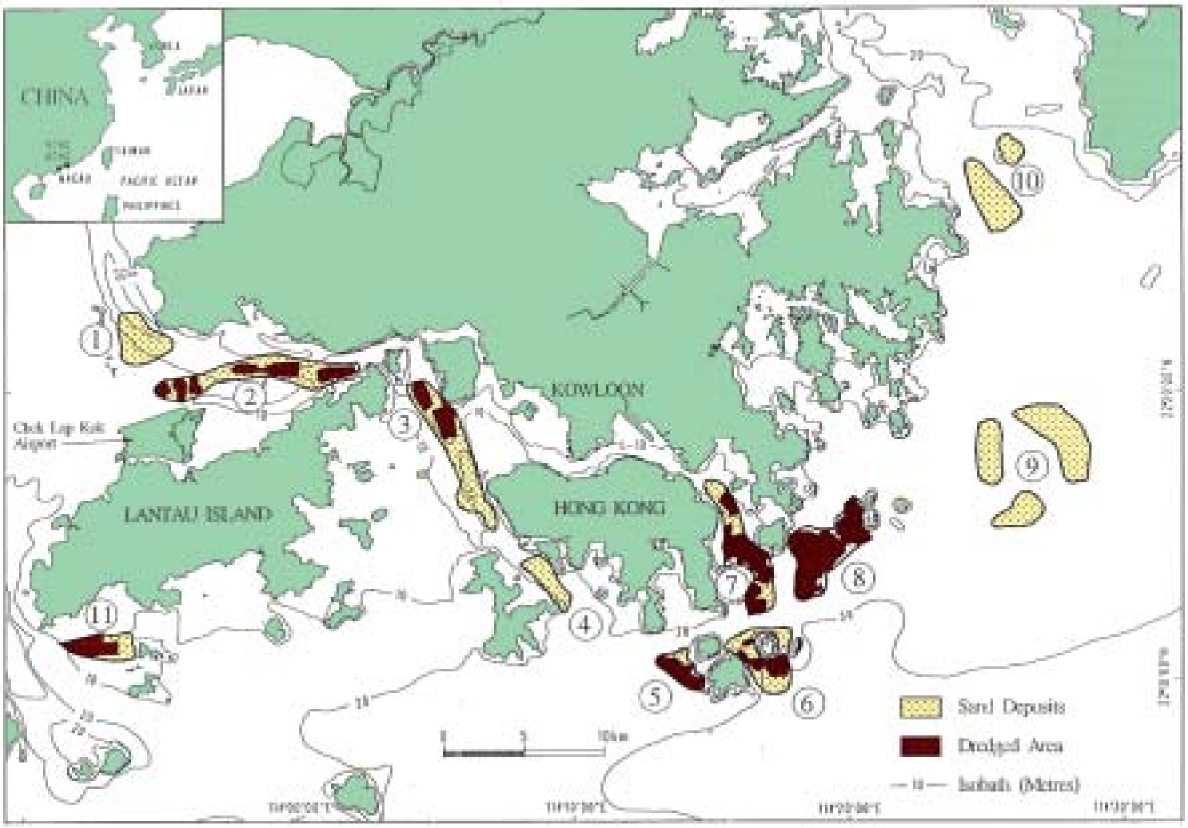


Figure 3. Location of sand deposits used for the reclamation at Chek Lap Kok and for projects at the harbour. The sand bodies are: (1) Urmston Roads, (2) Brothers, (3) Tsing Yi, (4) East Lamma Channel, (5) West Po Toi, (6) East Po Toi, (7) Tathong Channel, (8) West Ninepins, (9) Eastern Waters, (10) Mirs Bay and (11) Sokos. Mirs Bay sand deposits remain undeveloped for environmental reasons.

Hong Kong, which is dominated by silicic magmatic lithologies.

In Hong Kong, inner shelf submarine sands have been deposited in fluvial, estuarine and marine environments, however two major types of sand body have been dredged to depths of -50m: (i) seabed marine sand sheets, and (ii) fluvial channel sands, which have commonly required the removal of overburden.

Seabed marine sand sheets
The seabed sands form mounds and sheets typically up to 5 m thick lying in restricted channels and around islands and headlands, eg. East Po Toi, Tathong Channel and Urmston Roads (James 1993) at depths of -30 m (Figure 3), and may grade laterally into mud sheets. These restricted tidal channels correspond with the highest existing tidal currents in Hong Kong, which reach about 1.0m/s. Sand grain size varies across the sheets, whilst fines contents increase at the base of the sheets and channel margins where currents are reduced. For example, in the Tathong Channel the sands are grey, poorly sorted, fine to coarse-grained, shelly, occasionally gravelly with a fines content of 10-20%, but become very fine-grained with fines contents >30% at the margin of the sheet.
The sheets were deposited in the final stages of the last transgression, probably as a result of current and tidal winnowing of coastal and seabed sands by the enhanced currents flowing through the shallow channels, when sea levels were 15-25 m below present levels. Sandbanks formed locally (eg. Evans 1988), and often became partially buried by the mud sheet that accumulated as sediment supply became predominantly fine-grained and current speeds reduced with increasing sea levels. As the sands overlie the flat-lying ravinement surface, dredging of underlying sand occurs below the erosion surface in places. Dredging has now removed the majority of the marine sand sheets in Hong Kong.

Fluvial channel sands
Two types of fluvial sand are present infilling channels: (a) Type I channel sands lie in relatively narrow channels, often constrained by steep bedrock valley sides eg. East Lamma Channel, Tsing Yi and Tathong Channel (Figure 3). The sands have been deposited to depths of >-70 m, commonly within linear and continuous channels. Seismically, the sands are homogeneous and characterised by a high amplitude backscatter, although prograding and flat-lying reflectors are occasionally present. In the East Lamma Channel, the very poorly sorted, medium to coarse-grained yellow sands and fine gravels (d50 0.8-1.0 mm) are apparently

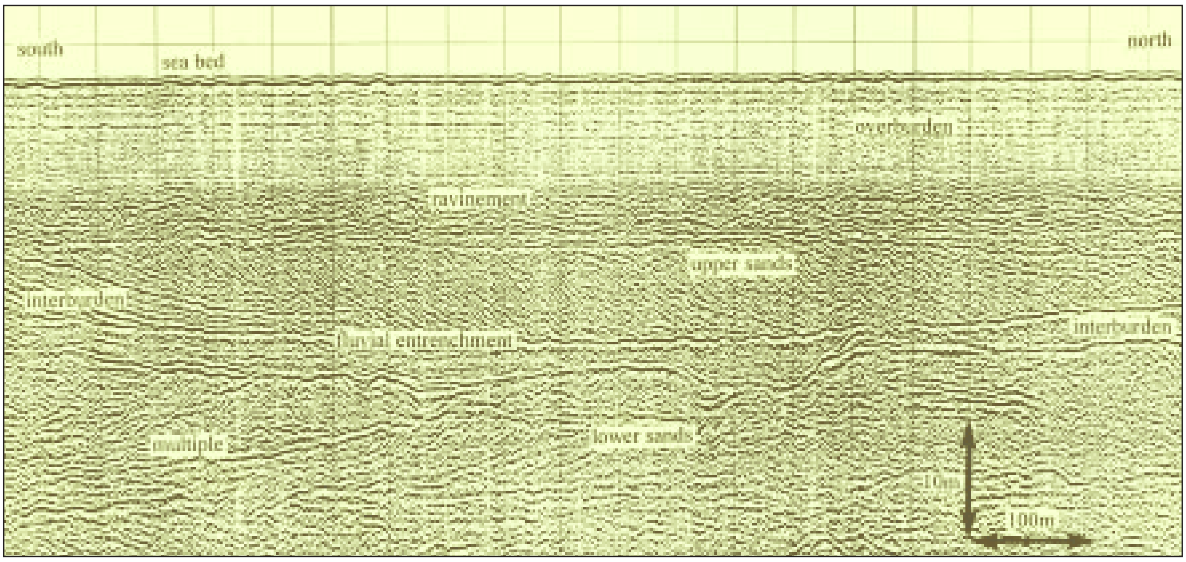


Figure 4. A surface-tow boomer profile across sands infilling a north-south trending channel in the eastern waters of Hong Kong at a depth of 28m. The overburden is characterised by a series of parallel, continuous, low amplitude reflectors and consists of soft silty clays. The flat lying discontinuous reflector, interpreted as a poorly defined ravinement surface, was formed during the Holocene transgression and truncates a 10m thick channel infill forming the upper sands. The upper sands accreted following channel incision during the Last Glacial Maximum. The prograding reflector configuration is interpreted as representing lateral accretion. The interburden was deposited following an earlier phase of fluvial entrenchment.

massive and dense (SPT-N value 20-80), subangular-subrounded, of moderate sphericity and contain less than 5% fines. The fines contents increase towards the channel margins. Thin (<2.0m thick), firm-stiff, silt/clay lenses are rare, weathered yellow and red, and are generally overconsolidated due to dessication (undrained shear strength up to 70kPa). The sands are interpreted to be autochthonous and deposited in braided, possibly seasonal, fluvial channels characterically infilled by lateral and downstream accretion and have been subjected to prolonged, possibly repeated periods of sub-aerial exposure. It is likely that the sands were deposited by the fluvial system that drained through Hong Kong, prior to the development of the Zhujiang (Pearl) Delta, since the last glacial maximum (Long and Huo 1990). Strong tidal currents in the areas restricted the deposition of the mud sheet and consequently these sands are associated with minor thicknesses of overburden.

(b) Type II channel sands infill fluvially entrenched channels and are often overlain by up to 10 m of overburden deposited during the final stages of the Holocene transgression, for example at West Ninepins and Eastern Waters (Figure 4). Seismic profiles reveal channels up to 3 km across incised to depths of -58 m and courses locally controlled by bedrock configuration. The sand bodies form lenses up to 15 m thick lying at the channel margins. The sand lenses may coalesce and are characterised internally by a series of prograding packages of reflectors. Samples reveal the sands are often grey, well-sorted, medium-grained (d50 150-220Ám), moderately dense, (cone resistance occasionally up to 40MPa) subrounded and contain less than 2% comminuted shell. Fines contents are generally less than 10%, although occasional mud partings and interburden lenses are present in the uppermost and basal sections of the channels. The sand lenses at the margins contrast the final infilling of the centre of the channel, which consists of fine-grained sediments. The sand bodies are interpreted as lateral accretion deposits including giant point bars, deposited in fluvial and locally estuarine channels. Overlying sands associated with the ravinement surface add to the thickness of the dredgable resources, together with the underlying poorly sorted, fine to coarse-grained, angular sands containing less than 15% fines and up to 30% gravel (Type I sands). Type II fluvial sands lie within channels commonly incised during the last glacial maximum (18,000 yrBP), although it is possible minor incision and limited deposition occurred during the other lowstands following the oxygen isotope stage 5e highstand of about 125,000 yrBP.

Site Investigation

Site investigation begins with a desk study of available data. Although this may include reconnaissance surveys, e.g. Harrison (1988) and maps, e.g. Balson (1990), large areas of seabed remain unexplored and it is reasonable to assume a comprehensive investigation will be required. However, the desk study does provide an indication of the characteristics of the local geological sequence to be expected and should be considered when planning the forthcoming surveys. Offshore site investigation consists of seismic acquisition, which is relatively inexpensive, and sampling, which is generally expensive. In the past, it has been common to drill boreholes on a pre-determined grid, e.g. a 500 m spacing, in an attempt to determine the geological structure, whilst the information provided by seismic data has been overlooked or ignored (see Orlic and Rosingh 1995). The previous section outlined the depositional environments and superimposition typically associated with seabed sands and gravels which strongly suggests that grid sampling is only reliable for resource assessments of seabed sand sheets and mounds. The complexities of variable bedrock levels, courses of infilled channels, together with sand body geometry, internal structure and variability, and the margins of all other types of sand body remain undefined using the grid method. Unfortunately the grid sampling concept persists (Stone 1992 and IADC 1995), demands high sampling densities and is therefore costly at best and probably misleading (Figures 5 and 6). It is proposed that the grid sampling technique has been superceded and this section describes the essential site investigation elements required for a confident resource assessment.

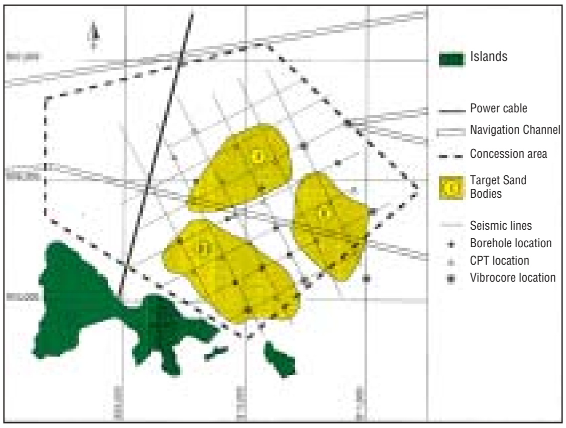


Figure 5. A chart indicating locations of target sand bodies forming potential borrow pits. The example site investigation consists of seismic profiling, sampling and CPTs, however the grid sampling at intersections of seismic lines is not likely to refine the understanding of the sand body. Rather, samples should be placed in geologically representative locations to assess the variability and limits of a resource.

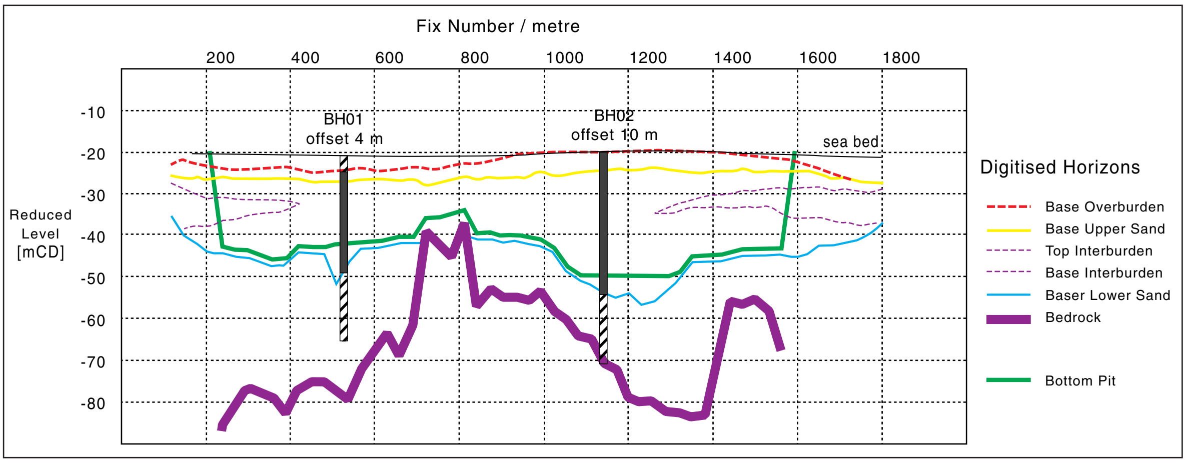
Although surveys should always begin with a seismic survey and an initial interpretation, further investigation should be designed to constrain the (i) quality and (ii) quantity of the reserve, as well as (iii) predicting the potential environmental impacts of dredging the reserve. Confident interpretation is reliant upon accurate positioning to define the limits of sand and gravel bodies offshore and it is assumed that all surveys and the majority of dredgers will utilise DGPS navigation systems offering positioning around +/-1 m. Site investigation methods are briefly reviewed below and are discussed further by Le Tirant (1979) and Spigolon (1995a).

Survey Strategy

If a survey is planned without consideration of geological structure, it is likely to prove expensive and unreliable in geologically complex areas. A phased approach guarantees cost effectiveness and achieves the level of detail required to plan a successful dredging strategy. Depending on the resource, it may only be necessary to complete part of the phases outlined below.

Phase I consists of seismic acquisition on a grid size depending on the size and origin of sand bodies. A line spacing of 250-750 m may be appropriate, with lines transverse to the trend and internal structure of sand bodies. The opportunity should be taken to acquire as

Figure 6. Cross-section of a proposed borrow pit based on horizons digitised from seismic data. The margins of the borrow pit are defined by the interburden and the base of the pit locally controlled by channeling in the base of the sand and an irregular bedrock surface. For modelling purposes 1m clearance is applied to the base of sand horizon and 2m to the top of bedrock. Operational dredging constraints are also taken into account together with overburden to sand ratios. A very misleading interpretation would arise if the resource assessment was based solely on boreholes as shown here.



much seabed and water column data as possible for use in forthcoming environmental studies and extraction plans. If possible, baseline suspended sediment concentrations should also be measured using siltmeters or water samples.
Phase II is composed of sampling and establishing cone penetration test correlation with existing seismic data. Additional seismic acquisition, at a line spacing of less than 250m and sampling is carried out with the objective of understanding the small-scale variability, defining overburden/interburden and the margins of the sand body.

High Resolution Profiling and the Seabed
High resolution shallow seismic profiling forms the basis of a variety of offshore site investigations. Interpretation of the data reveals the configuration, relationships and a guide to the composition of sedimentary units lying below the seabed (Figure 4).
The standard profiler used in sand and gravel assessment is the surface-tow boomer system (Sylwester 1983). The boomer provides a balance of penetration, (up to 80 m) and resolution (around 0.5 m), in a wide range of sediments including gravels and can be processed if required. Pinger and existing chirp acoustic profiling systems often do not penetrate sands and gravels. A bathymetry survey should be carried out concurrently with the profiling using a multibeam system if required. Interpretation of side scan sonar data reveals the configuration and composition of the seabed sediments and provides baseline evidence for the pre-dredging condition of the seabed. The identification of obstacles, including debris and bedrock exposures which could result in serious damage to dragheads and suction pipes, allows a dredging plan to be formulated. At a later stage interpretation problems may arise as a result of the susceptibility of acoustic systems to gas blanking in overlying muds. Geoelectric systems offer an alternative, if lower resolution, system to profile sub-seabed successions.

Sampling
Coarse-grained clastic seabed sediments are successfully sampled using hydraulic grabs (up to 0.5 m^3 bucket) to ensure cargo quality for aggregates (coal is occasionally a deleterious contaminant) and provide baseline data for an environmental assessment and ensuing monitoring. Undisturbed sampling of the sedimentary succession underlying the seabed is achieved by a variation on a vibrated tube, for example a vibrocorer, or a pushed/driven tube of varying length, for example a U76. The vibrocore consists of a frame with a sliding, vibrating pod and barrel which is lowered from an anchored or dynamically positioned ship to rest on the seabed. Vibrocotre samples are generally up to 6 m long (occasionally up to 9 m), recovered in a 70 mm diameter plastic liner, quick and relatively cheap. However, vibrocore samples are compromised by variable recoveries. Vibrocoring to a greater depth using casing requires stable mooring. Boreholes may be drilled to depths >-60 m for investigations of fill resources from rigs, barges or drillships. The borehole is formed using a bit and is cleaned using a bailer, pumped water or mud. Typically, 70 mm diameter samples are recovered: 1m long, thin walled piston samples in soft silt/clays and sands, and pushed, driven, hammered or Mazier samples in loose sands and gravels. A variety of other methods have been developed, including airlift and reverse circulation (Browne 1994), for specialised sampling requirements. To complement the sampling programme, the relative density of the cohesionless sedimentary succession should also be assessed by the Standard Penetration Test (SPT) N value, whilst drilling the borehole.

Accurate compositional assessment of the sand body demands that the sampling is continuous, at least in the target sand body. Although disturbance of the samples should be kept to a minimum, two common problems often arise: the coarse gravel component of a deposit (>25 mm clast diameter) is difficult to establish due to the diameter of the sampling tube or vibrocore; and poor recoveries are typical with clean, medium to coarse-grained sands and gravels.

Cone Penetration Testing
The in situ physical properties of the sedimentary succession are commonly measured by the Cone Penetration Test (CPT) as outlined by Meigh (1987). Although of limited use within seabed marine sand sheets, within complex channel infills and superimposed resources, the test provides additional information on consistency, type, relative density and strength of the sediment, together with refining the correlation and interpretation of seismic data. The CPT consists of a rod pushed into the sediment column, whilst measurements of cone resistance are recorded, together with the sleave friction and pore pressure. Interpretation of CPT data to provide lithological data is site-specific and it is essential that the CPT is correlated with an adjacent borehole to establish the local relationship.

Testing and Reporting
Site investigation reporting should be to established standards (see discussion in Spigolon 1995b), for example BSI (1981), BSI (1990) or PIANC (1984), adapted to the requirement of each project. Representative subsampling of cores for testing following extraction establishes several dredging characteristics of the deposits based on particle size distributions (PSDs) and geotechnical parameters. PSD testing should include sieves of particular importance to the project, for example the sand fraction retained on the 106Ám sieve provides additional resolution when calculating TSHD overflow.
A tendency exists to concentrate subsampling in potential problem zones and this skews the data if combined PSD plots are used to define the sorting within sand units. Geotechnical parameters to be test-

ed that may affect dredging production rates include moisture content, undrained shear strength, bulk density, compaction, index properties and carbonate content. Petrological analyses are required to assess compositional suitability of the aggregate for concrete mixtures (Gutt and Collins 1987) and predict wear rates of dredging pumps and pipes. Grain sphericity and angularity also influence wear rates of dredge pumps and pipes. Finally, it should be recognised that the unconsidered application of standards may not always provide the information required to make decisions regarding production rates, quality and potential environmental impacts.

Data Interpretation

Seismic interpretation is based on the establishment of a seismic stratigraphy, defining units which are characterised by their geometries, external relationships and the internal configuration of reflectors (Mitchum *et al.* 1977). The application of sequence stratigraphic concepts, based on sediment supply and sea level change (Posamentier et al. 1993; Swift *et al.* 1991), assists in placing units in their depositional context. Most importantly for the resource assessment, the interpretation of seismic units allows predictions of lithology and lithological variation within target sand and gravel bodies. Although minor modifications may arise following analysis of sample data, the geometry of the resource is delimited entirely by seismic data. It is clearly essential that the type of deposit constituting the target resource should be defined. As previously stated, for some projects the minimum acceptable sand content for fill may be as low as 60%, whereas aggregates for concrete may require as low a sand content as possible. In addition, the accurate identification of overburden and interburden forms an important component of the interpretation. Typically overburden forms sheets and interburden forms lenses.

Interpretation problems arise where gradual compositional changes occur within successions which are unlikely to result in the generation of a reflector on seismic records, but are clearly defined as resource horizons on the basis of sampling and testing. These horizons would not be picked in a geological assessment and indeed need not be reflectors, but are compositional and may cross-cut seismic units and geological structure. For the final interpretation horizons are marked on the seismic profiles. The records are digitised at every fix (assuming a velocity of sound in sediment of around 1600m/s) and input files produced for use in the resource modelling (Figure 8). The confidence of interpretation and assessment of risk associated with the geological aspects of dredging productivity, is therefore controlled by the geometry and composition of the resource and the quality of the site investigation data. It is clear from this analysis that the detailed understanding of the resources based on seismic interpretation and the recognition of critical horizons cannot be matched by the traditional, unrealistic method of assessment, joining levels of similar lithologies in boreholes and assuming geological units occur as flat layers.

Resource and Reserve Modelling

As outlined in the Introduction, it is the specification of the required sands and gravels that broadly defines the resource and reserve. Once the specification has been established, the *resource* is the volume of that grade of sediment lying within the offshore investigation area. Commonly, resources cannot be fully utilised due to constraints imposed by economics, extraction methodology, legal obstacles or the location of utilities (Figure 5). The resource volumes are further reduced by pit slopes, interburden lenses and losses during the dredging process. Following deduction of all non-recoverable volumes from the resource, the *reserve* may be calculated.

Assessments of resources and reserves in potential dredging areas appear similar to assessments for mining and quarrying. However, there are major differences in the approach of each assessment. Developers of mines or quarries often carry out their own site investigation or hire specialist site investigation contractors to carry out a geological survey aimed at the delineation of the target resources. In-house knowledge of the developer guarantees that the survey is tailored to the mining practices to extract the target resources. This is not the case with the site investigations for dredging and reclamation works (BSI 1991). Proponents typically do not have in-house capability to develop a project and seek consultants to carry out feasibility and detailed design studies. The consultants design the project according to the proponent’s objective, for which the dredging or reclamation is often just a minor, although expensive detail. Therefore site investigations for dredging projects should assist the contractor to locate and quantify the resource, and establish the parameters which are relevant to assessment of settlement of sediment in the hopper and disintegration and transport of sediment as slurries through pipelines .

Use of a Database

Depending on the scale of the planned marine dredging programme, individual site investigations may be considered, or the results of several investigations may have to be analysed to assess the resources. In both cases a database may be used to structure the data collected during the site investigation and the laboratory testing. The collected data should be tailored to suit easy input, output and use. The stored data could be used to assess and manage the resources; assign dredging areas; provide contractors with the information collected during site investigations; study the production from dredging areas to reclamation or disposal sites; study the recovery factors and production efficiency for differing sediment types and working conditions.

In order to make data input flexible, it should be possible to enter data from a keyboard, a data disk in a selected format, or by digitising a graph or map. The output data should be available in any selected format and scaled to either a screen, a plotter (up to A0 size), a printer or disk. Data formats should be selectable to suit the importation of the information into other data processing application, for example spreadsheets, CAD and survey programs and other databases.

Preparation of the Data

It is necessary to store all of the information used during the assessment to quantify the reserve. This would normally consist of bathymetric, seismic, borehole, CPT, SPT, PSD and other geotechnical data. Other useful information includes the position of utilities, coastlines of local islands, navigation channels and marine traffic constraints. This data should be stored in a separate database. A record of all the changes that have been made to the original data during the assessment permits back analysis following exhaustion of the dredging area, if disputes arise about the volume and accessibility of the reserves.

Validation of the Data

The raw data in a database is often unsuitable for the direct calculation of volumes of sand bodies, overburden and interburden. All data should be checked for its validity and compared with other sources of information before it is entered into the database. Interpreted seismic data and borehole logs form the basis of the geological assessment of the area, together with CPT, SPT, PSD and other data. As previously outlined, the data should be interpreted to suit the requirements of the dredging assessment. Resolution to 0.50 m is acceptable, as thinner layers generally can not be worked independently by a dredger.

Although costs may be saved on site investigations if the collection of information from areas close to known features, such as rock outcrops, is avoided, this additional data should be entered into the database for the preparation of the ground model by a computer. In many site investigations the boundaries of a resource have been poorly investigated with boreholes or CPTs, although the seismic survey may be extended beyond the boundary of the target area. This seismic information then forms the basis of the ground model. PSDs, SPTs and CPTs are used to check that the borehole descriptions match with the laboratory results. If these indicate a relationship between the layer description and the values derived from the samples the system should be able to calculate an average and standard deviation of the respective values in that particular layer.

Ground Model

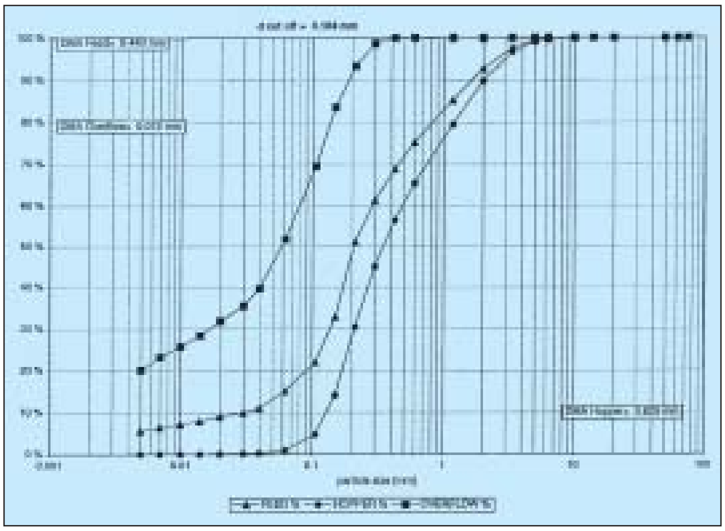
Following the selection, addition and modification to the original data undertaken during the interpretation, the data is ready to build the ground model. To build a good ground model it is necessary to extend interpretation to areas where information is not available from the site investigation. The ground model may be generated by calculation of all relevant information on the basis of Thiessen polygons or a selected square grid. However, as soon as a connection to other systems is necessary it is advisable to have all information for the nodes or centres of a square grid.

The model should be able to generate depths to digitised horizons, isopachs for all layers and calculate the stripping ratio (the ratio of overburden over sand) for the base of each sand layer. The system should be able to present the contoured isopachs and ratios at a selected scale. Cross-sections through the multi-layered model are generated at selected lines and scales to compare the result of the modelling with the interpreted seismic lines. The grid size of the model may alter during the course of the assessment and for a feasibility study the model must be able to provide a quick estimate, although at a lower resolution. However, when detailed designs of pits need to be prepared, the model grid size has to be reduced, for example to 20 m. The larger the grid size, the greater the effect of smoothing the data, whilst computer running time will increase if the grid size is reduced. A reduced grid does not neccessarily contribute to a greater accuracy in the assessment if the density of the data collected during the site investigation is spaced at greater intervals than the grid size. A grid spacing equal to, or half of, the average separation of the seismic lines is usually sufficient to build a reliable ground model. As SI information is typically much denser along seismic lines, the standard deviation of the horizons is smaller along the lines than between the lines, and depends on the horizon variability, for example a highly irregular bedrock compared with an even channel base.

Volume Calculation

The ground model allows volumes of layers to be calculated as a resource in a block with the outer boundary of the dredging area as a limit. In situ volumes should be calculated without considering limitations caused by a maximum dredging depth or loss of material due to overburden and interburden. A second step is the calculation of volumes where a maximum dredging depth is imposed on the model. All resources below this depth should then be discarded in the volume calculation. Furthermore, a minimum layer thickness may be selected for exploitation, and thinner layers should not be considered. It is also important to

Figure 7. In situ PSD compared with the predicted hopper and overflow PSDs following dredging of a moderately well-sorted, medium-grained sand with a typical 8000 m^3 TSHD. The predicted hopper PSD indicates that a significant proportion of the sub-100Ám sediment present in the reserve is lost to the overflow and over 60% of the sediment in the overflow is coarser than 30Ám. The medium to coarse silt and very fine sand will form a density current which flows down onto the seabed close to the dredging area. In this type of sand reserve, overall dredging losses are estimated at 25%.



recognise that utilities not only sterilise the underlying resource, but a large volume associated with a safety zone and stable slopes.

When calculating the reserves, the reliability and resolution of the data should be considered. TSHDs work to tolerances of several metres horizontally and a metre vertically. A sub-seabed layer less than 2 m thick should not be considered, as the horizons are defined to an accuracy of 1 m and the dredger requires a layer thickness of at least 2 m to make dredging worthwhile. Irregularities in the horizons also results in the dredging of unsuitable sediment before the reserve is exhausted. For the estimates, rock outcrops must be avoided with a 2 m safety margin due to the risk of damage to the draghead and the suction pipe.

Cross-sections through the Area

In order to validate and to improve the model, it should be possible to generate cross-sections along selected lines through the area which show all relevant information (Figure 6). The offset of all boreholes and other data points selected should be given, along with the SI data. It is necessary to have the choice to change the maximum offset of the data points to be taken into account for each line. The effect of smoothing the data can be checked in this stage. PSD data and other soil properties should be correlated with the units defined in the assessment.

Slopes

In view of the fact that, especially in deep deposits, slopes cover a high percentage of the MBA, it is advisable to quantify the volumes that are found within the slopes. Therefore the system should be able to generate a borrow pit layout, to a chosen depth, with selected barter slopes for each soil type, for example 1 in 3 for sand and 1 in 5 for soft muds. Finally, the volumes for each of the selected layers within the boundaries of the selected borrow pit are calculated.

Overflow Losses and Assessment of Environmental Impacts

The environmental impacts associated with dredging form an important component of an increasing number of dredging projects and many are now subject to some form of Environmental Impact Assessment. Impacts from dredging arise from the physical disruption of the seabed, which occurs over relatively small areas, and from sediments within the overflow mixture entering the water column. Overflowing occurs from the keel or over spillways of a TSHD (Figure 1) and has been briefly considered by Pennekamp and Quaak (1990). As a result of dredging trials Whiteside *et al*. (1995) estimated that 80% of sediment contained in the overflow is transported to the seabed within a density flow and around 20% of the sediment forms a plume which becomes established around 250 m behind the dredger. Therefore high dredging production rates commonly lead to the rapid, proximal deposition of fine sands and silts on the seabed from density flows close to the dredger, and fine silts and clays settling from suspension distally, perhaps up to several kilometres downstream of the dredger. Consequently both proximal and distal sedimentation rates are likely to increase above background levels. Sensitive receivers around the dredging area may include corals, intertidal and seabed communities, which may be often susceptible to increased sedimentation rates (Hodgson 1994), whereas fisheries are often considered to be more sensitive to variation in suspended sediment levels. Realistic prediction of overflow rates is therefore of critical importance when predicting environmental impacts. Site investigation provides the required data for; (i) assessing baseline conditions in and around the dredging area, and (ii) input into a dredging model.

Baseline Conditions

Site investigation provides baseline suspended sediment and seabed sediment data associated with the natural sediment regime. In areas where benthic communities are adapted to high sedimentation rates, for example in deltas and estuaries, or disturbance of the seabed, for example stormy or intensely trawled seas, it is possible that the impacts of overflowing will be

Table I. Overflow rates from a typical TSHD with an inboard pump loading in about 1.5 hours, dredging a moderately well-sorted sand containing 20% fines (Figure 7) from a depth of 40m and a cycle time of around 5 hours. The sorting and concentration of sediment in the overflow does not remain constant throughout loading. The sediment concentration increases and becomes increasingly poorly sorted as the hopper fills.

Payload per trip (net sand reserve m^3)	Sand production per week (net sand reserve, m^3)	Overflow losses per trip (Mg)	Overflow losses per week (Mg)
6,500	200,000	5,000	150,000

insignificant. However in areas of low suspended sediment levels and depositional rates, mitigation measures should be taken.

Dredging Model

The dredging process can be simulated using a dredging model. The dredging model developed by DEMAS takes into account all dredging parameters, eg. pumping rates, mixture densities, loading level, hopper configuration and location of overflow, in combination with the characteristics of the dredged sediments, i.e. the reserves. The model predicts overflow rates and overflow PSDs (Figure 7) for the average or the range of deposits forming the reserves throughout the loading time. As an example, the sediment losses associated with the overflow occurring during loading of a typical 8000 m^3 TSHD, are shown in Table I.

The information obtained from the dredging model may be combined with a hydrodynamic model and used in environmental impact studies to ensure that the potential impacts associated with dredging are assessed and mitigated through operational restrictions prior to the beginning of operations. Once a realistic input has been defined by the dredging model, the plume model predicts compliance with Target/Action/Trigger (TAT) levels established for environmental monitoring and audit. Alternatively, the contractor may propose and develop mitigation measures throughout the course of the dredging operation. Mitigation measures must accommodate all the factors described above and include working in conjunction with currents (tidal, oceanic and seasonal), controlling the dredging method (e.g. minimise overflowing) and restricting the dredging area. In conclusion, an unrepresentative site investigation can lead to unexpectedly high overflow losses, increased depositional rates and elevated suspended sediment levels. This may result in unacceptable environmental impacts and culminate in a restriction of production rates.

Conclusions

Offshore sands and gravels are finite resources and have been deposited in fluvial and marine environments. The sand and gravel bodies are often complex, superimposed and combine to form resources characterised externally by irregular geometries and internally by abrupt vertical and lateral compositional variation.

To assess and understand the variabilty of these resources and ensure efficient production of high quality cargoes, a dedicated site investigation should be designed. An effective investigation will consist of high resolution seismic profiling, sampling and CPTs, and designed to define the resource and its limits, together with the identification of overburden/interburden.

Following interpretation and the establishment of a database, the resource and reserve assessment based on digitised horizons defines the dredging area, volumes and predicts losses. A dredging strategy based on this data is formulated and, if necessary, an environmental mitigation plan proposed.

Consequently a well-planned site investigation benefits both the contractor and the client through the development of an efficient and effective dredging programme. Compared to the cost of developing dredging technology, a site investigation is a cheap and cost-effective investment; it increases confidence in estimation of production rates, identifies possible sources of delay, permits dredging of marginal resources and ensures the quality of the dredged cargo. A thorough, integrated site investigation will enhance efficiency and hence profitability, as well as giving the opportunity to effectively mitigate against unacceptable environmental impacts. For these reasons the benefits of site investigation must become the focus of increased scrutiny within the dredging industry in the future.

A complete list of references is available from the authors upon request.