FOR DISPOSAL: 10 M.cu.m. OF CALCIUM CARBONATE SLURRY

by

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Abstract

Construction of the Jebel Ali Port complex, 35 km southwest of Dubai, in the United Arab Emirates, has included the disposal of 110 Million cubic metres of excavated spoil.

Disposal of dredged carbonaceous breccia raised particular problems due to the high proportion of fines generated and which, unless properly controlled, could cause wide scale environmental damage in the coastal zone. At the same time it was necessary that acceptable reclamation should be created. An extensive data collection exercise was carried out in order to monitor the geotechnical, hydraulic, meteorological, marine climate and marine biology aspects of the operation.

Introduction

The new port of Jebel Ali, situated on the Emirates coast 35 km south west of Dubai, consists of two very large basins constructed inland of the line of coastal dunes. These basins are connected to deep water in the Arabian Gulf by a dredged navigation channel 17 km in length with a bottom width of 235 m at 16 m below LAT. The inner basin is 3750 m long and 420 m wide, excavated to a depth of 11.5 m below LAT. The outer basin is 2500 m long and 600 m wide, excavated to a depth of 14 m below LAT. The basic layout, shown in Figure 1, provides 17 berths approximately 300 m long and 49 berths approximately 200 m long. In addition the harbour entrance channel is flanked by a tanker berth, with 15 m of water depth, and 2200 m of wharfage dredged to 5.5 m below LAT.

The Excavations involved in construction of the port were:

Inner Basin	:	31 million cu.m. of dry excavation from which the spoil was used to raise ground levels in the proposed industrial area to the south of the port.
Outer Basin and Harbour Channel	:	58 million cu.m. of dredging, the spoil being used to raise the levels and reclaim a total area of 700 hectares as indicated on Figure 1.
Approach Channel	:	21 million cu.m. of dredging, the spoil being mostly conveyed in barges to an offshore dump area.

Ground Conditions and Excavation

Ground Conditions

At the beginning of the project soils investigations revealed the presence of a variety of carbonate breccias overlain by sand and sandstone across the entire site. Sand in dunes just behind the original shoreline was up to 10 m thick, but this reduced rapidly to a thin layer at two to three hundred metres offshore. Underlying this sand was a layer of caprock varying in thickness up to 2 m. The four basic material types can be described as follows:-

(i) Loose sand.
(ii) Caprock, described as bioclastic limestone, containing numerous small solution features up to gravel size.
(iii) Sandstone, fine to medium grained, occasionally laminated, with point load indeces averaging 2 MN/m^2.
(iv) Breccia, classified into five main types, the poorest of which consisted primarily of carbonate limestone containing attapulgate clay.

Samples taken from large diameter boreholes showed that, whilst the breccia would not present difficulties when excavated dry, when wetted a large portion tended to disintegrate into very finely divided material forming a soft slurry. This indicated that problems could arise in disposal of such material contained in a considerable volume of water after excavation by cutter suction dredgers. Even when cutting more uniform soils the process of disposal from a dredger pipeline inevitably involves fine material remaining in suspension when the excess water runs off.

With the exception of the Approach Channel and part of the Entrance Channel, the bulk of the excavation lay inland of the original shoreline and this presented the possibility of reducing the disposal problem by adopting dry excavation methods using conventional plant. The decision as to how much, if any, should be carried out in this way was dependent on a number of factors as follows:-

(i) The availability of different types of plant required to carry out excavations entirely in the wet or partly in the dry.

(ii) The method of construction of the blockwork quay walls.

(iii) The phasing requirements for utilisation of completed parts of the port at the earliest possible opportunity.

(iv) The suitability of the excavated material for backfilling, ground level raising and general reclamation.

(v) The extent of dewatering required for such large excavations in the dry.

(vi) The relative economics of each method of excavation.

(vii) The quality and quantity of material resulting from each type of excavation.

Considering all of these factors it was decided that the combination of both dry excavation and dredging in the proportions given in the Introduction would satisfy the majority of the requirements.

Dry Excavation

The material in the areas scheduled for dry excavation comprised primarily sand and breccia. Excavation of the former was carried out with scrapers whilst the breccia in its dry state was quite hard and required blasting for removal by hydraulic excavators.

Wet Excavation

In the Entrance Channel and Outer Basin all the major dredging was to be carried out using four large cutter suction dredgers (2000 h.p. at the cutter head) and two smaller dredgers (1200 h.p. at the cutter head) together with booster pumps as required. All of the spoil was to be used for reclamation or was to be pumped to stockpiles for use as fill behind quay walls etc.

In the Approach Channel material was initially dredged using one cutter suction dredger and two dipper dredgers. The fleet was later supplemented by the worlds first self elevating cutter suction dredger (2). The majority of this material was loaded directly into barges for disposal offshore.

Disposal Methods

Disposal at Sea

The 21 million cubic metres of caprock and sandstone excavated from the Approach Channel was to be barge loaded and dumped offshore. Initially the disposal site was 21 km offshore in over 20 m depth of water. However, this was found to be unmanagable and the dump area was moved closer inshore, to an area in approximately 10 m of water as shown in Figure 2. This area is 5 km by 5 km so that the average depth of dumped material would be about one metre, although there were no rigorous controls on the dumping pattern. Barge loading was generally limited to between 50 and 75% of the theoretical full capacity in order to reduce overflow losses and re-sedimentation, while maintaining a high level of operational efficiency.

Disposal to raise existing land levels

Some areas of subkah flats around the port basins were low lying, much of it no higher than highest tide level. The area to the SE in particular required up to 4 m of fill to achieve an acceptable level for the proposed industrial development. This was achieved with spoil from dry excavations in the inner basin, and did not involve problems of fines disposal.

However, to the SW and NE of the port it was necessary to use considerable volumes of spoil arising from dredging the entrance channel and outer basin to fill the low areas (See Figure 1).

Discharge from the cutter suction dredger to be used would contain particles of all sizes from cobbles down to fine clays in view of the extent of breccia in these areas. A typical grading curve of actual discharge is given in Figure 3. This shows 30% silt and fines and immediately raised the questions, firstly, of how the fines were to be incorporated into the fill so as to provide land in an acceptable condition and secondly, how to control the flow into the sea of the calcareous fines suspended in the run-off water.

The initial wet filling was on the SW side of the port and it was anticipated that up to three of the large cutter suction dredgers could be discharging at any one time. Return of the potentially large quantity of water to the sea required a substantial channel excavated through the coastal dunes as shown on Figure 1.

In a second area to the north west of Quay 1 (See Figure 1) filling had to be done early in the Contract to provide areas for contractors depots and construction offices. Dry fill together with dredged sandstone was generally used for this. The eastern half of this area was also used for stockpiling dredged sandstone for re-use as selected fill behind quay walls etc.

Although not a serious problem, the run-off water from the area contained some calcareous fines arising from breakdown of the cementing material in the sandstone. The discharge was initially into the very large lagoon formed by the East Breakwater and the East Reclamation Bund shown in Figure 1.

A third area of land to be raised in level was to the east of Quay 2, and it was planned to fill this with spoil arising from dredging the east end of the outer basin. This was commenced late in the programme and the same procedure was adopted as that for the western area. In this case the water was returned to the sea via a long drainage channel down the east side of the site to discharge at the root of the East Breakwater.

Disposal to Reclamation

As originally planned in 1976 the east breakwater followed a conventional form on the lea side, being normal to the coast out to the harbour entrance. However, the problem of disposal of the carbonate breccias was appreciated immediately the results of the preliminary investigation began to come in. As a consequence, the breakwater was realigned to enclose together with the East Reclamation Bund a much larger area of approximately 320 hectares, so as to provide a disposal lagoon, as shown in Figure 1, in which the fines could be allowed to settle.

It was intended that this should be an area into which would be dumped material not suitable either for immediate use for raising land levels or stockpiling for use as backfill, and especially material in which the fines remaining in suspension would create environmental hazards if discharged directly into the sea. It was looked upon as a disposal area in which the ground conditions would improve over a long period and the land would be available for use in the later stages of port development. However, even before filling commenced proposals were being made for the land use for industry and consequently efforts had to be made to achieve the best ground conditions economically possible.

Disposal Problems

While it was anticipated that disposal from dry excavations would not present problems, the main conern in disposal of the breccias from wet excavations was the large amount of fines which were likely to remain in suspension. Little was known about the hydraulic disposal of carbonate breccia of the type to be encountered and literature on the subject, e.g. slurrying for the cement industry, was of little assistance. There were no fixed guidelines to the quantity of carrier water to be expected due to the number of variables involved in the dredging process, but the ratio of water to solid matter pumped was expected to be about 10:1.

Without special care it was obvious that environmental problems could arise if the large proportion of fines that was anticipated remained in suspension when the discharge water returned to the sea. To indicate the scale of the problem, the quantity of water to be returned would be of the order of 450 million cu.m. which could contain up to 3.6 million tonnes of carbonate fines (i.e. equivalent to 2.3 million cubic metres of in situ rock at a dry density of 1.54).

Following early field trials the major problems could be identified:

(i) It would be difficult to provide conditions in which an acceptable proportion of the fine material could settle out of suspension within a manageable retention period for the water. The bulking factors for breccia fines could remain very high for long periods of time before consolidation and meanwhile the fines would be sensitive to resuspension.

(ii) When settled in the reclamation areas the fine material could create poor ground conditions.

(iii) Disposal of the fines remaining in suspension in the vast quantities of overflow water which must eventually go into the Arabian Gulf, could damage the existing environment.

(iv) Evaporation rates were not high enough to consider pumping all the material inland. In any case the distances involved would incur unacceptable costs and still involve environmental problems.

Of all the problems listed above the possibility of wide scale environmental damage was considered to be the most serious. If no special precautions were taken an average of 1500 cu.m. of soil would enter the sea in suspension each day for three years, with uncertain characteristics for settling in the turbulant open sea conditions. The cost of treating this amount of material, contained in about 100 times its volume of carrier water, was not economically feasible either by use of extracting equipment, such as cyclones or filters, or by floculation.

Early experiments indicated that initial settlement of sediment from a fully mixed column of water achieved 50% clear water in a 2 m column within 24 hours, while further settlement was very slow indeed. It was hoped that this initial rate of settlement could be utilised in the field in a series of settling lagoons, the capacity of each lagoon being sufficient to take the 24 hour discharge from one of the larger dredgers. For example, there was sufficient area to provide six rows of four lagoons and to allocate two rows to each of three dredgers. The head lagoon could be filled and drained into the second one and similarly into the third lagoon and so on. The initially decanted water could contain fairly high concentrations of sediment, but this would reduce as the discharge progressed down the lagoons before eventually being allowed to seep through the breakwater into the sea. As the head lagoon filled the bunds, could be raised until filling reached the final level plus an allowance for settlement and the second lagoon would become the head lagoon.

This appeared to be a very attractive solution, but a number of problems were foreseen:

(i) Bund building would have to be with dry material, otherwise material from a dredger discharge would flow out and considerably reduce the lagoon capacities. This would be an expensive operation and use material needed for fill elsewhere.

(ii) Wet bund building would also produce its own problems with fines disposal.

(iii) The fines might be so easily disturbed that is was quite possible that even the turbulance caused by bed shear as the flow crossed the lagoons to the decanting outlets would bring it back into suspension, especially as the discharge tends to form erosion channels through the fill.

(iv) The front of coarser fill materials, as it progressed over the settled fine material would push it forward and upward against the opposite bund, but it was not known whether it would then dry out sufficiently to be rehandled or to incorporate it in the bunds once it rose above water level. Rehandling could be very expensive.

It was decided to obtain further information on behaviour of the fines by forming experimental lagoons, firstly to the west of the port to determine the settling and drying characteristics of the fines and secondly, when construction had progressed sufficiently to achieve protection from the breakwaters, in the coastal disposal area. The results of these experiments are given later

Experimental Lagoons

Preliminary Lagoon Studies

Before the four specially built, large cutter suction dredgers arrived on the site, it was decided to do test dredging of breccia with the discharge into an experimental lagoon on the west side of the site, (See Figure 1), where future development had a low priority. The aims of these tests were to determine:

(i) The percentage of the breccia which would become fines in suspension when pumped through a representative length of pipe line.

(ii) The settling characteristics of the total solids discharged into the lagoon.

(iii) Quantities remaining in suspension when the carrier water was returned to the sea and diffusion characteristics of the suspended solids.

(iv) Guidance as to areas likely to be affected by abnormal settlement of fine material and how soon the concentration of solids would reach acceptable levels.

The lagoon was divided into three sections.

Section 1 into which the pump mixture was discharged.

Section 2 into which the carrier water would overflow and where settlement of some of the fine material would take place.

Section 3 to take the discharge of sandstone and gravel when the dredger encountered these as they represented better fill material outside interest in carbonate fines.

Excess water from the two latter sections discharged through water boxes into the main discharge channel leading to the beach.

The lagoon bunds were raised as necessary to maintain a 2 m depth of water, with overflow water box having an initial invert level of 3.5 m above LAT. At the discharge end of the lagoon the ground was brought up to + 6.5 m and allowed to advance at this level. Silt was carried away towards the water box. The settled silt was so soft that it appeared to be entirely moved forward by the advancing face. However,

the characteristics changed once it heaved above water level and the advancing fill spilled over it. When this happened a fairly well mixed material could be achieved.

Based on resources available to undertake data collection within the short time available, a testing programme was devised, aimed at determining the best method to utilise this ability to trap the breccia fines and the effect this would have on early ground conditions.

The programme included:

(a) Permeability tests on breccia fines situated above water level.

(b) Durability tests on samples of each type of in situ breccia by agitating them in vessels containing sea water so as to simulate pumping and pipeline conditions.

(c) Permeability tests on the rock fill breakwaters to determine their ability to filter out the fines from dredger discharge water.

(d) Flocculation tests using polymer flocculants.

(e) Analyses of particle size and shape of the material remaining in the lagoons.

(f) Degree of trapping of fines beneath advancing coarse material.

(g) Determination of bulking factors.

(h) Determination of bearing capacity and consolidation characteristics of reclamation.

A complete review was also made of the location of breccia deposits in the areas to be dredged and the most likely areas to which they would be pumped.

To increase the retention of fines, stub bunds were built within the lagoon in order to increase the path of the discharge water while still controlling the flow to a low velocity on its way to the water-box.

Even so the discharge into the sea contained about 0.5% carbonate solids. It was of interest to note, however, that the flow, on entering the sea, hugged the coast towards the main west breakwater and most of the material in suspension was initially deposited near the beaches. Further, as sand was moved shorewards in calm to moderate seas, the beaches acquired a layered condition of silts and sand and, as this is an area of accretion, some of the fines were stabilised.

The deposition and accretion of the sediment in the lagoon was complex, but from the testing programme it appeared that the optimum settlement must be related not only to the percentage of clay size particles in the discharge, but also to time needed by the discharge to produce a suspended sediment concentration above an equilibrium value. The tests

using polymer flocculants which had indicated an initial improvement in settlement characteristics were not persued as after about two hours in still water this advantage was lost and no difference in rate of settlement could subsequently be detected.

It was soon established that fairly substantial quantities of fine carbonate cementing material was released when the sandstone was broken down by dredger cutting and pumping operations.

By the time the large cutter suction dredgers arrived on site, (late 1977 early 1978) the evidence collected tended to indicate that small lagoons were unlikely to be satisfactory and three further experimental lagoons were established in the coastal disposal area as shown in Figure 4.

Trial Area No 1

The first of the experimental lagoons had an area of only some $1\frac{3}{4}$ hectares, and pumping was continuous with height of fill carried up from a bed level of about 3 m above LAT to about 7.5 m above LAT in six days. This meant that as the front advanced, time for discharge water to reach the fixed overflow was reduced and the concentration of fines carried into the main lagoon gradually increased. Over 50% of the fines were lost in this way and the lagoon size and method of filling were obviously inadequate.

The volume of material dredged was 50,000 cu.m. comprising primarily breccia with appriximately 15% sandstone. The trial was monitored by sampling the dredger discharge and overflow water to determine quantities of fines entering and leaving the trial area. In addition pre and post fill surveys were carried out to determine the quantity of material retained in the area.

The scale of the trial was too small to create any significant pockets of silt, but it did enable sampling techniques to be tried out and confirmed the degree to which breccia would break down to form slurry.

Trial Area No.2.

The second experimental lagoon had a larger area and in this case pumping was intermittent over a period of six weeks. This produced a layered effect of coarser and finer fractions of the fines with a total thickness of about 3 to 4 m. and topped by 2 to 3 m of coarse material which had been dozed ahead over the finer material as filling proceeded. On completion of fill the lagoon contained entirely soft silty sand ahead of the final front of coarse material, overlying up to 1 m of very fine soft silt.

Float tracking showed that flow across a lagoon varies in a random manner, depending upon erosion channels leaving the point of discharge. However, loss of fines in the overflow water was found to be reasonably steady until the water in the lagoon was reduced to a critical depth.

From that point the velocity of flow was sufficient to carry most of the fines over the overflow and filling was stopped. It was possible to draw the immediate conclusions that:

(a) Even using intermittent discharge the larger the lagoon the greater percentage of fines would be retained;

(b) It would be possible to raise the overflow level by using course material to increase bund height and to have a water box in which the weir level could be raised to maintain sufficient depth of water for optimum settlement of fines in the lagoon;

(c) The original proposals to create twenty four small settling lagoons within the coastal reclamation area would not be very efficient in trapping the fines.

A final survey of the lagoon and the dredged areas indicated that 390,000 cu.m. of in-situ material had been pumped to the lagoon. The volume of bulked material retained was 278,000 cu.m. indicating a considerable loss of material from a lagoon with an area of only 50,000 sq.m.

On completion of filling trial pits were excavated and boreholes sunk to examine and collect samples of the various strata within the reclaimed ground. Settlement pads and piezometers were installed and surveys were carried out before, during and after the filling. Samples of slurry which had settled in the lagoon were collected and analysed for bulk density, moisture content, grading, Atterberg limits and specific gravity of solids.

As a result of these trials it was decided to use large settling lagoons by dividing the coastal reclamation area into four quadrants and a programme for monitoring these was established.

Trial Area No.3.

This consisted of monitoring the reclamation in the SW quadrant of the Coastal Reclamation Area from September 1978 to April 1979 and included a soils investigation of the completed reclamation as for Trial Area No.2. The results in general supported those from Trial Area No.2. and as anticipated, the percentage of fines deposited increased with size and depth of the lagoon.

A summary of silt losses for the three trial areas is given in Table 1.

Trial Area No	1	2	3
Area (m^2)	17,000	60,000	390,000
Av.Depth (m)	1.0	3.0	4.0
% Silt loss	60%	33%	18%

Table 1 Summary of Lagoon Disposal Trials

Study of Marine Conditions

Hydrographic studies

A parallel programme of studies being undertaken on the project was the comprehensive collection and analysis of data on the marine climate, in order to predict sediment transport and hence maintenance dredging potential, as well as local coastline disruption that may be caused by the port works. This included standard meteorological data, regular hydrographic and topographic surveys, two wave height recording instruments, two wave direction recording instruments, float tracking, five automatic recording current meters, and extensive water/sediment sampling. The location of these instruments and limits of surveys are shown in Figure 2. The data gave good coverage of long term trends with respect to waves, currents and existing background suspended sediment concentrations.

Before it became necessary for any outflow of dredge run-off water from the coastal reclamation area to be discharged into the sea, an uncontained breccia disposal trial was carried out. This involved discharging a limited quantity of dredged breccia directly into the sea over the outer arm of the East Breakwater. The progress of the plume so produced was monitored by float tracking and pumped suspended sediment sampling. Contrary to expectations the breccia laden plume displayed relatively little mixing and was observed to run close to the breakwater, in an easterly direction, until it reached the knuckle of the breakwater and there separated.

Aerial photographs were also taken during the exercise and on two occasions after completion. The latter covered a 60 km length of coastline during both rough and calm conditions and the photos were processed so as to enhance underwater features. The photographs taken under rough sea conditions enabled an assessment of the general levels of turbidity along the adjacent shorelines to be made and any increases in the Jebel Ali area noted. The photographs taken under calm sea conditions enabled the areas of deposition of breccia fines to be broadly indentified.

The photographic survey was intended also to monitor the behaviour of sediment already released into the sea from the offshore dredging in the Approach Channel and the first trial lagoon. The extent, nature and thickness of these, and subsequent, silt deposits were regularly estimated by diving surveys. Although a dual frequency echo sounder was used for the hydrographic survey work capable of giving broad indications of soft and hard deposits, it was found that there was no satisfactory way of calibrating the instrument to detect the interface between the original seabed and the overlying silt. However, successive silt surveys by diver, together with measurements of bulk densities allowed estimates to be made of volumes of material accumulating on the sea bed. Once all the dredger water discharge points were being monitored it was then possible to record concentrations of suspended material in the outflows and compare these with the volumes deposited in the survey areas.

Further records included regular chemical analyses of the dredge run-off water, the water in the lagoons and the sea water, close to and far from the port to determine whether there were any changes in the salinity levels or chemical changes in the sea due to disposal practices.

Marine Biology Study

The enclosed waters of the Arabian gulf are poor in marine organisms compared to the Red Sea and Indian Ocean. This is probably due to a combination of low nutrient levels, high salinities, (up to 40%) and high temperatures ($30^{\circ}C$). As a result there are fewer species of coral forming reefs and less associated marine life where these conditions approach the limits of their tolerance.

In the Jebel Ali area the most abundant of the corals is Acropora (Stagshorn coral) a genus with high salinity and temperature tolerance, but very sensitive to sediment in the water column. Other types of coral which are found to be less sensitive are Seriatopora (antler horn coral) Meandrina (Brain Coral), Goniopora and others. The approximate ratios by species are 50%, 10%, 20% and 20%. Acropora and Seriatopora, of all the corals, provide the biggest area of shelter with their flat table top and overhang effect. The largest of the fish associated with these corals were Groupers, Parrotfish, Perch, Angel Fish, Captain's Daughter, Sargeant Major, Clown Fish, Damsel Fish, Pampano, Saupe and Wrasse. These fish are not apparently seasonal. Demersal fish, however, appear to be seasonal and include Barracuda, Garfish, Spanish Mackeral, Yellow Tail Tuna, Yellow Jack and Sardines.

It is important to ascertain what damage the suspended fines might cause to various types of marine organisms. Marine life is dependent on the phytoplankton - microsoopic floating green plants - which is marginally seasonal in tropical waters.

Zooplankton consists of minute animals both mature and larval forms living directly off the phytoplankton and serving in their turn as food for larger predators. This continuous dependence forms the food chain of the marine ecosystem. Fisheries are an important local industry and are vulnerable to changes in the environment especially if they are persistent over a long period.

Early in 1977 a fisheries expert was engaged to study the effect of the breccia fines in the sea and advise on the possible consequences of pollution.

Laboratory tests were performed to assess the chemical and physical tolerance to the fines by a range of marine organisms. These included microscopic plankton and larger organisms representing stages in the interdependant food chains.

The conclusions were that toxicity of the fines in suspension was negligible. This was confirmed quite dramatically in Nov.1978 when the last lagoon of the series of 4 had been relatively undisturbed for about 4 months. The lagoon had about 1.5 metre depth of water over about 1 metre of settled sediment. At this period a survey was carried out and it was found that the lagoon had developed into a clearly balanced environment with fish and young fry evidently hatched there. The breccia had been flocculated by the combined activity of microorganisms, bacteria and algae and considerable invertebrate fauna was present.

The physical laboratory tests showed, however, that some zooplankton species were vulnerable to sediment concentrations of more than 500 ppm. This figure provided the key to the control needed at the sea outfalls and also to the consequent problem should the fines remain in suspension or become disturbed by storm waves. If a cloud of suspended material covered a large area of the Gulf, the reduction in zooplankton would cause extensive damage to the pelagic fishing industry.

The two limiting factors then were the effect of concentration of suspended breccia on the microscopic fauna and the direct effect of settled sediment on the major coral species Acropora. Both of these could affect the fishing, the former especially the pelagic and the latter especially the coral fish, the former being the most important commercially.

The control of the outfall was established and continuous monitoring was maintained at fixed points on the coral reefs. Regular sampling of the plankton also was carried out.

Results

Offshore Reclamation Area

It is not the intention of this paper to rigourously discuss the geotechnical aspects of the completed reclamation. The proportions of fines trapped for different lagoon sizes are given in Table 1 and a typical grading envelope for spoil at the discharge point is shown in Figure 3. Figures 5, 6 and 7 show typical grading envelopes for material sampled as trapped fines, untrapped slurry in the lagoon and that material which found its way onto the sea bed. It can be seen that as the material progressed and was deposited through the system the proportion of very fine material increased, the coarser end of the grading having been retained.

Comparison of grading of the dredge discharge, concentration of suspended sediment in the lagoon, and the lagoon water level showed that the correlation between these three aspects was generally weak. There was a notable drop in concentrations when the lagoon water level was raised, but generally peak concentration levels appeared to correspond more with strong winds which maintained the material in suspension by way of the turbulence generated. It was also found that once the material had a chance to settle and form attractive bonds during a cessation in the dredge discharge it took a considerable flow to resuspend material below the water level. Table 3 gives a chronological account of the values of

material dredged, volumes lost in suspension, volumes of trapped fines and respective bulking factors. All volumes are expressed in millions of cubic metres and the volumes of discharge water include run-off from stockpiles of sandstone provided outside the reclamation area.

Date	Vol. of dredging to date	Vol. of discharge water direct to sea	Vol. of reclamation to date	Vol. of soil lost in suspension	Vol. of un-trapped slurry	Average bulking factor of slurry	Vol. of trapped fines	Average bulking factor
Nov 78	11	20	15.4	0.07	5.2	3.1	Small	-
Feb 79	13	20	17.8	0.20	5.9	3.1	Small	1.35
May 79	16	58	21.7	0.28	7.7	3.0	0.9	1.35
Sept 79	20	108	25.1	0.46	6.8	2.9	2.7	1.34
Jan 80	21	147	27.4	0.66	8.9	2.6	2.9	1.33
July 80*	26	187	29.9	1.32	3.5	2.3	8.0	1.3
Sept 80*	27	200	30.7	1.54	nil	-	10.2	1.3

*These quantities are predicted

Table 2: Chronological Summary of Dredged and Trapped Fines

The surveys of the offshore reclamation area showed that actual quantities compared well with predicted quantities as shown typically in Table 3. The predictions for Feb.1979 were based on borehole data from the early experimental lagoons, whereas the Jan.1980 predictions were based on all the information available in March 1979.

	Predicted		Actual from survey	
	Feb 79	Jan 80	Feb 79	Jan 80
Total volume dredged soil	12.5	21.3	13.2	21.3
Total volume of fill	18.4	28.6	17.8	27.4
Overall bulking factor	1.47	1.38	1.35	1.33
Volume of coarse fill	11.2	16.7	11.9	15.5
Volume of soft slurry	7.2	11.8	5.7	11.9
Percentage of soil as coarse fill	75	85	86	82
Percentage of soil as slurry	25	11	14	14
Percentage silt lost (Balance)	Trace	4	Trace	4

Table 3. Comparison between Predicted and Measured Quantities.

It can be seen that the actual volumes compare very well with the predicted volumes particularly with respect to silt losses.

Seabed Deposits

The unconfined breccia disposal trial did not lead to any firm conclusions with respect to levels of fines remaining in suspension near the discharge point. It did lead to the general conclusion that the plume of heavily concentrated sediment was very localised indicating that the majority of material found its way rapidly to the sea bed in the form of a density current. However, as a result of this trial it was decided that the reclamation area outfall should be a little way inshore of the knuckle on the East Breakwater as shown in Figure 1. on the grounds that the majority of the material would tend to deposit in this relatively sheltered area.

The development of the silt bank each side of the port was monitored as previously described. Figure 8 shows the extent of the area over which 100% coverage by silt occured at various stages in time. It would appear that on the east side of the port the silt bank reached a sensibly stable limit beyond which further migration was extremely slow. On the west side of the port the silt bank was very much more spread out and was relatively more mobile. In fact, after an initial period of discharge from the western drainage outfall there was a long period over which there was no discharge. During this period it was noted that large areas of seabed naturally cleared and benthic communities began to re-establish themselves.

Tests on undisturbed core samples from the silt bank next to the East Breakwater revealed a sensibly linear relationship between bulk density and depth below surface, at least for the upper layers. It appeared that at the early stages of deposition bulking factors can be as high as 5 or more. Continual sampling of sediment concentrations and the dimensions of the silt bank enabled estimates of volume of fines which remained on the seabed in the immediate vicinity of the port and that which dispersed elsewhere to be made. This confirmed that most of the fines carried into the sea in suspension remained in the silt bank. Also the deposits on the east side were relatively stable, whilst those on the west side had a greater tendency to migrate, due to the higher degree of turbulance on the weather side of the port entrance breakwater. Without carrying out tracer studies it is difficult to be definitive as to the exact patterns of sediment movement. However, the extensive current measurements from the self recording current meters and float tracking enabled qualitative estimates of general movement to be made. From these it was evident that the material from the west silt bank migrated both to the west and around the breakwaters to the east to supplement the east silt bank. Migration from the east silt bank was limited and predominantly in a northerly direction.

Marine Life

The Plankton samples were collected for more than a year on a fortnightly basis. These did not reveal any particular seasonal trends and hence did not indicate that dredge run-off should be curtailed during any potentially sensitive periods.

Careful long term observations of specific monitoring areas close to and remote from the run-off discharge points were made. It was found that the sea bed in the immediate vicinity of the outfalls and over which there was complete coverage by silt, became completely sterile as predicted. The bank on the east side were more stable than anticipated partly due to the formation of an algae carpet over the surface of the bank. This helped to prevent the movement of the upper layers of fluid mud which might otherwise have occurred.

In January 1980 the situation was as shown in Figure 8. This shows an area outside the silt banks in which there was up to 10% mortality of Goniopora and Meandrina type corals. Further out as shown pollution resulted in 1% mortality of Acropora type corals, but no deterioration of the hardier species. These zones were not extensive and the area was soon reached where young corals were found re-colonising where the silt lay only sparsely in troughs and deterioration of coral was reduced to background levels in response to normal prevailing conditions.

Conclusions

The problems involved in dredged spoil disposal have attracted an increasing amount of attention during recent years particularly with respect to achieving acceptable reclamation with difficult spoil[3], optimising disposal area dimensions and outfall arrangements [4,5] and avoiding environmental problems [6,7]. In the situation described in this paper the disposal area was under water so that assisted drainage techniques such as trenching etc, could not be employed. Pumping distances were too great to contemplate drying by evaporation and in any case the quantities involved were too large.

An ongoing monitoring and testing programme enabled timely measures to be taken so that silt losses to the sea were reduced to a minimum and an acceptable reclamation area was created within the economic constraints of the project. It was estimated that if no measures had been taken between 10 and 15% of the fines would have entered the marine environment. By optimising lagoon size, bund levels and water box controls it is predicted that this will be reduced to between 2 and 5%, a quantity that could be and was retained within an acceptably small area adjacent to the breakwater.

It appears that the major bank of silt created in the port area will remain quite stable due to the combination of shadow effects of the breakwater, high cohesion and consolidation of the sediment, the intermittent formation of an algal carpet and the damping effects on waves passing over a fluid mud bottom. Further the concentrations of suspended sediments measured in the sea never seriously exceeded the harmful levels established from laboratory experiments.

It was found that the corals, especially the more sensitive species, were excellent monitoring agents. Deterioration, initially identifiable by the bleached appearance at the centre of the branches was not a rapid process. Since Acropora are already living outside their temperature and salinity optima, further stress due to siltation of the fine coral polyps,

removal of adequate substrate for larval settlement and higher light attenuation due to silt turbidity could be readily dedected.

In order to replace the reefs, in the immediate area of the port that have been unavoidably destroyed an experimental programme of installing artificial tyre reefs has been initiated. Several different pilot schemes have been implemented according to past practices. but it is too early to report whether these will be effective.

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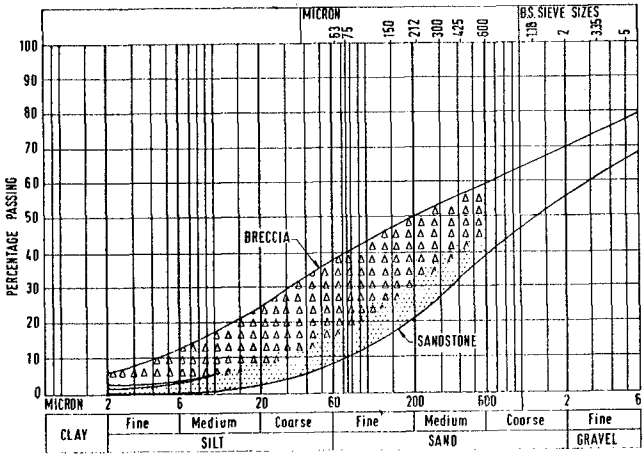

Figure 3. Particle Size Grading Envelope for Dredger Discharge

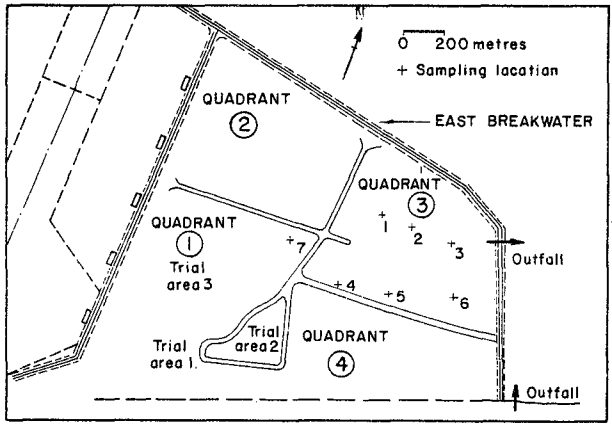

Figure 4. Location of Trial Areas

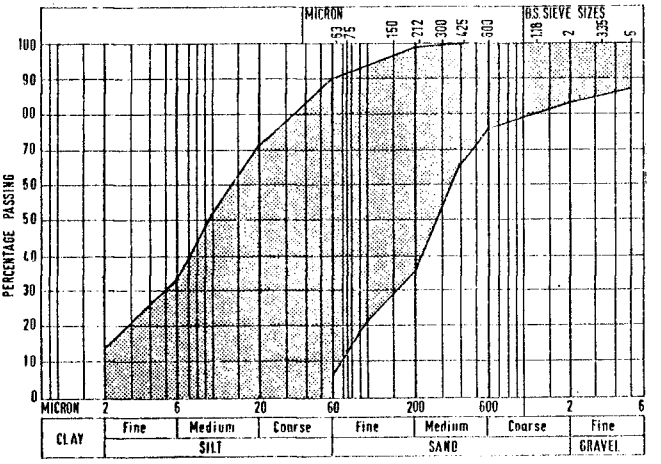

Figure 5. Particle Size Grading Envelope for Trapped Fines

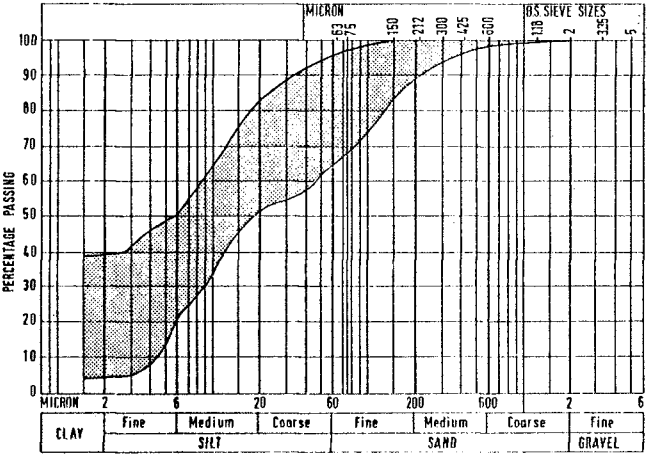

Figure 6. Particle Size Grading Envelope for Untrapped Fines

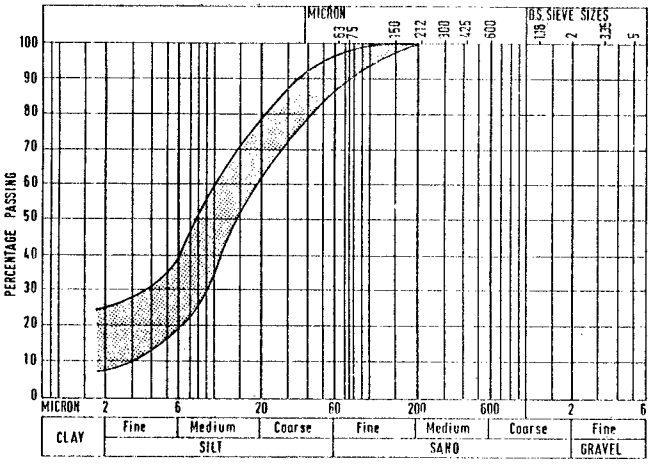

Figure 7. Particle Size Grading Envelope for Seabed Deposits

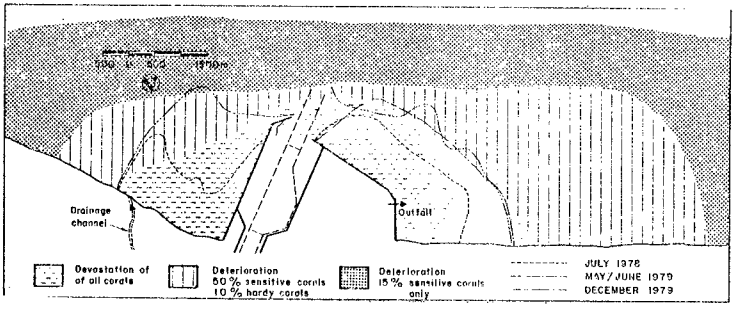

Figure 8. Development of Silt Bank and Areas of Coral Deterioration