THE USE OF ACOUSTIC DOPPLER CURRENT PROFILERS TO MEASURE SUSPENDED SEDIMENT

GEO REPORT No. 85

Dredging Research Ltd

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING DEPARTMENT
THE GOVERNMENT OF THE HONG KONG
SPECIAL ADMINISTRATIVE REGION

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This report was prepared by Dredging Research Ltd in March 1996 under Consultancy Agreement No. CE 2/93 for the sole and specific use of the Government of the Hong Kong Special Administrative Region

First published, January 1999

Prepared by:

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This publication is available from:

Government Publications Centre,
Ground Floor, Low Block,
Queensway Government Offices,
66 Queensway,
Hong Kong.

Overseas orders should be placed with:

Publications Sales Office,
Information Services Department,
4th Floor, Murray Building,
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Hong Kong.

Price in Hong Kong: HK$108
Price overseas: US$17 (including surface postage)

An additional bank charge of **HK$50** or **US$6.50** is required per cheque made in currencies other than Hong Kong dollars.

Cheques, bank drafts or money orders must be made payable to
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PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. A charge is made to cover the cost of printing.

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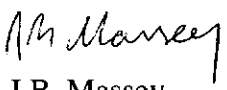

J.B. Massey
Ag. Principal Government Geotechnical Engineer
January 1999

FOREWORD

This report summarises the works of a study carried out to develop the Acoustic Doppler Current Profiler as a tool to measure the concentration of suspended solids in the water column, and field applications to establish the physical effects of sand dredging and mud disposal.

The report was prepared by Dredging Research Limited of the United Kingdom for Geotechnical Engineering Office (GEO) of the Civil Engineering Department under Agreement No. CE2/93. Mr P.G.D. Whiteside, Mr N.C. Evans and Dr K.C. Ng of GEO coordinated the study at various stages. Dr K.C. Ng reviewed the final report.

D.C.H. Chang
Chief Geotechnical Engineer/Fill Management (Ag)

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1. INTRODUCTION

1.1 This report summarises the work which has been undertaken during The Study and Measurement of Dredged Materials under Agreement CE 2/93. The Study commenced in February 1993 and was effectively completed in March 1996 when the draft report on the last field survey of the Study was submitted. The Study comprised two main elements:

1) the development of the Acoustic Doppler Current Profiler (ADCP) as a tool to measure suspended solids in the water column;

2) field measurements of suspended sediment intended to establish the effects on the sediment regime of the extensive dredging and dredged material disposal operations which were in progress throughout the Study.

1.2 The development of the ADCP under this Study followed from earlier experiments which had been undertaken in April 1992 during the Fill Management Study - Phase II (Binnie Consultants, 1993). The experiments showed that the ADCP had potential as a method of collecting vast amounts of suspended solids data throughout the water column and might therefore be used to monitor, on a large scale, the effects of dredging and dredged material disposal. However, at that stage, little was known of the acoustic theory which needed to be applied in order to derive reliable estimates of solids concentration and even less was known about the performance characteristics of the ADCP and how these might effect accuracy.

1.3 A limited amount of development work had been undertaken prior to the commencement of this Study, including the initial development of a data-processing software package. The first six months of the Study focused on more substantive development of the acoustic theory and the software, and included some preliminary field experiments and measurements. Some further development work was undertaken later as part of this Study, including additional field experiments. However, as is often the case with such innovative techniques, the development process has effectively been continuous and, even now, significant advances are being made and will likely continue to be made for several years in the future. This is partly due to the extensive practical experience gained during the work carried out in Hong Kong and partly because the technique is now being applied elsewhere, e.g. the UK and Germany, where field conditions are radically different to those in Hong Kong.

1.4 Although development continues, the work done during this Study has resulted in the establishment of the ADCP as a reliable tool for the measurement of suspended solids. In some situations, it has been shown to be more effective and more accurate than conventional methods such as silt metering and gravimetric analysis of water samples. Certainly, the capacity of the ADCP to collect suspended solids data throughout the water column from a moving vessel cannot be matched by any other technique and this capacity, irrespective of considerations of accuracy, makes the ADCP an invaluable tool with which to measure and understand sediment movement over large areas and in situations where conditions change very rapidly.

1.5 It is not the intention in this report to describe in detail the development of the ADCP; only the briefest summary is provided and the interested reader is referred to the more detailed reports submitted during this Study. The purpose of this report is to present in a summary form, the main findings of the field surveys which have been undertaken. These have provided valuable data on Hong Kong's natural suspended solids regime and its seasonal variation, on the magnitude of the effects of dredging and disposal generally and, in particular, on the formation and decay of the sediment plumes created by these activities.

1.6 A full list of the reports issued during this Study is presented in Appendix A, including those reports issued by the Term Geophysics Contractor (Electronic and Geophysical Services Ltd.) which relate to the experiments and surveys described here. Where these are referenced in the text, they are indicated by an asterisk, e.g. DRL, 1993A*. All other references are listed in Section 8.

2. THE SEDIVIEW METHOD

The Acoustic Doppler Current Profiler

2.1 The ADCP was developed as a means of measuring current velocity and direction in a non-intrusive manner throughout the water column. The principles of operation of the ADCP and the underlying acoustic theory relevant to the measurement of suspended sediment are set out in the Review Report (DRL, 1993-B*) and in the Draft ADCP Development Report (DRL, 1994-D*). In summary, the instrument comprises four acoustic transducers arranged in a 'Janus' configuration. It measures the doppler shift of an emitted acoustic pulse of known frequency which is reflected from particles in the water column. The doppler shift is used to calculate the velocity of the suspended particles in the direction of each of the four beams. Data from three beams are required to resolve the components of velocity, relative to the instrument, of the water containing the particles. The instrument has an internal compass and tracks its course over the seabed using a separate acoustic pulse. By combining these data, it is able to compute the current vectors relative to earth co-ordinates.

2.2 The present Study uses the intensity of the backscattered signal as a measure of the concentration of the suspended particles in the water column. These can be any particulate matter including sediment, plankton, algae, sewage or even fish and debris. The basic assumption adopted here is that the vast majority of the backscattering particles comprise suspended sediment. The method of data collection and processing which has been developed to establish reliable solids concentrations from acoustic backscatter data obtained using ADCPs has been named The Sediview Method.

Calibration and Data Processing

2.3 In theory, there is a linear relationship, with a slope of 1, between acoustic backscatter intensity (measured in dB) and sediment concentration up to concentrations of several thousand mg/l. However, as the acoustic pulse travels through the water column, it loses energy due to absorption by the seawater and due to scattering and absorption by the suspended sediment. The energy loss due to water absorption can be calculated if the temperature and salinity of the water are known and these are measured at regular intervals when the ADCP is used for the type of measurements described here.

2.4 The loss of acoustic energy due to the scattering and absorption by the sediment itself is small at low concentrations and over short ranges but rises rapidly as concentrations exceed 100 mg/l and as the measurement range increases. The mechanism by which energy is lost depends mainly on the particle size of the sediment; small particles tend to absorb acoustic energy whilst large particles scatter the energy. In Hong Kong waters, small particles predominate (except very close to overflowing trailer dredgers) and absorption is therefore the greatest cause of acoustic energy loss.

2.5 Each ADCP has a unique calibration arising from the performance characteristics of the instrument itself which varies according to the physical characteristics of the suspended sediment (size, shape, mineralogy etc.). It is thus necessary to collect calibration data (e.g. water samples) at frequent intervals during each deployment. Even after working with this technique for almost four years, we have to acknowledge the often extreme difficulty of establishing reliable calibrations. There are five calibration constants in all, relating to both instrument and sediment characteristics. The instrument-specific constants are difficult to establish initially but, once established, vary from time to time in a reasonably predictable manner. The sediment-specific constants may vary rapidly with both time and location and are far more difficult to establish.

2.6 The most extreme example of sediment variation which we have so far encountered (on the River Mersey in the UK) involved sediment which flocculated at slack water periods. The flocs broke apart again as the current speed (and turbulence) increased after slack water. The effect of this was to shift one of the calibration constants by 8 dB over a period of less than one hour. This, had it gone undetected, would have given rise to errors in the concentration estimates of more than 600% at some stages of the tidal cycle.

2.7 In order to convert the acoustic backscatter data into solids concentrations, complex data processing is required. The ADCP data is initially recorded using a software package called Transect which is supplied by the manufacturer of the ADCP. Transect is used to control the data gathering in the field and can be used for a variety of simple post-processing operations. The binary raw data recorded in the field is exported to DRL-Sediview®, a multi-tasking software package designed to convert backscatter data to sediment concentrations and to present the data in a variety of formats. Approximately 2,000 computations are required in order to convert the backscatter data obtained from one instrument 'ping' when working in water depths of 20 metres and with a vertical measurement interval of 1 metre.

Accuracy of Concentration Estimates

2.8 The accuracy of concentration estimates derived from ADCP backscatter data varies according to:

1) the type of instrument used and its unique performance characteristics;

2) the accuracy with which the five calibration constants have been established;

3) the extent to which the sediment characteristics vary during the deployment.

The theoretical accuracy of a single determination of concentration varies between about ±2% for the relatively new 'broadband' instruments and ±25% for the older 'narrowband' instruments when the concentration estimates are based on ensembles of data comprising four instrument 'pings'. One 4-ping ensemble is obtained every 2-4 seconds depending on instrument type and water depth. This is a truly random error and, as most data sets comprise many hundreds of pings, even along relatively short survey lines, the overall picture provided by the data can be considered extremely accurate.

2.9 However, quoting such figures as the accuracy of the concentration estimates implies that the calibration of the ADCP is perfect and that the particle size distribution of the suspended sediment does not change significantly during the course of the survey. Because there are deficiencies and inaccuracy inherent in all forms of suspended sediment measurement and because the ADCP can only be calibrated by comparison with one or more data sets obtained by such other methods, it is clearly difficult to guarantee that any calibration is 100% accurate. The potential errors which can arise from mis-calibration and variable particle size are well illustrated by the (somewhat extreme) example of the recent work on the River Mersey described in 2.6 above.

2.10 However, with care and when sufficient calibration data are obtained during the survey, systematic errors are unlikely to exceed about 10-20%. In this respect, it is worth noting that the calibration data should encompass the full range of concentrations and water depths encountered during the survey if absolute confidence is required.

2.11 It is also worth noting that when we have encountered real difficulties of calibration, it has almost invariably been shown to be due either to inaccuracies in the laboratory determinations of solids contents of water samples or siltmeter malfunction. One occasion, there was almost irrefutable evidence of systematic overestimates, of the order of 100%, in laboratory concentrations established on about one half of a batch of calibration water samples which were tested on one day. The other half of the batch were tested a few days later and appeared to match well with the ADCP and siltmeter data. In contrast, during a recent survey in Germany, almost 40% of the ADCP estimates were within 2 mg/L of the laboratory determinations and no systematic errors of any kind were apparent in the data.

Limitations of the Technique

2.12 The limitations of the Sediview Method have been described in reports issued during this Study. In summary, the main limitations are as follows:

1) due to the necessity to immerse the ADCP in the water and due to the form of the acoustic pulse and the manner in which it is processed, it is not possible to obtain data from the near-surface zone. The shallowest depth at which data can be obtained depends on the instrument specification and lies in the range 2-4 metres;

2) because the side lobes of the acoustic beam interfere with the seabed, the data obtained from the near-bed zone are unreliable. For the instruments used during this Study, the data from the lowest 6% of the water column (approximately) is corrupted in this manner and must be discarded;

3) the maximum concentration which can be measured is unknown; theoretical studies suggest that a limit of 30,000 mg/L applies for coarse sediment and it is likely that a lower concentration applies to fine sediment. However, the calibration is extremely sensitive at such high concentrations because of the corrections which are applied for attenuation due to the sediment; estimated concentrations in excess of about 3,000 mg/L cannot be considered to be accurate;

4) high concentrations (3-500 mg/L, depending on the particular instrument being used) within about 2 metres of the transducers may overload the ADCP's amplifiers and lead to erroneous estimates of concentration; high concentrations at greater ranges do not constitute a problem in this respect.

2.13 In addition, it must always be borne in mind that the acoustic pulse will reflect from any particulate matter, whatever its nature, and from air bubbles. The assumption that the backscatter is due to sediment alone may, on occasions, be far from the truth. However, it should be noted that the many siltmeters also suffer from this limitation, albeit to a much lesser extent.

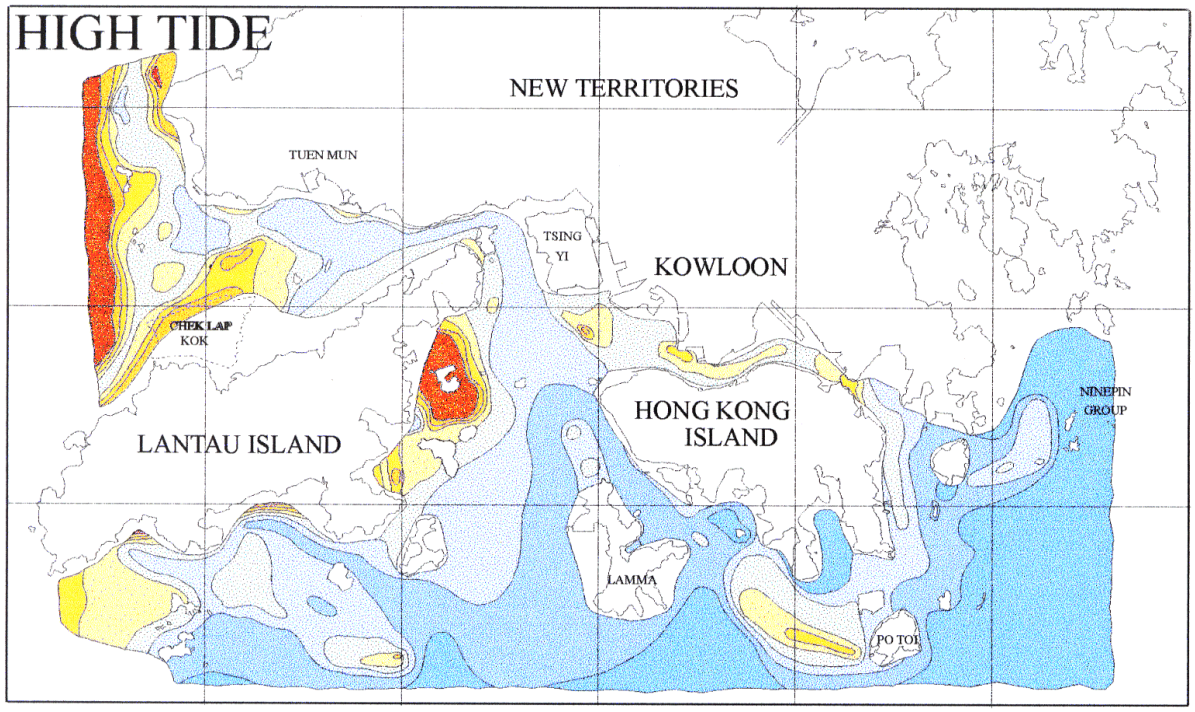
3. THE SUSPENDED SOLIDS REGIME IN HONG KONG

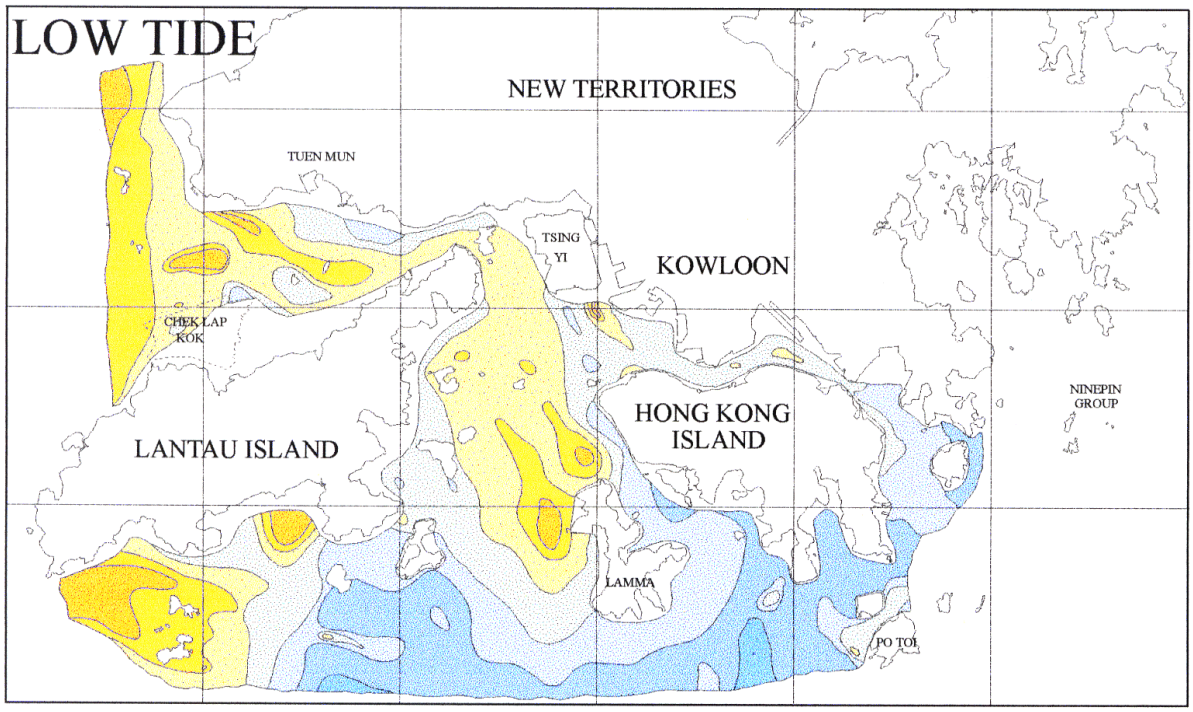
3.1 The general perception of the sediment regime in Hong Kong waters is one of marked and reliable seasonal variation controlled by the discharge of the Pearl River. During the wet season when river discharge is high, suspended solids in Hong Kong's north-western waters are high and, during the dry season, when river discharge is low, the suspended solids are also low. Southern and eastern waters are widely held to be relatively unaffected by the Pearl, exhibiting generally low concentrations throughout the year.

3.2 This scenario is an oversimplification. During this Study, data have been obtained which show that southern and eastern waters are probably significantly influenced by the Pearl River. In addition, the 'dry-season/low solids, wet season/high solids' rule is suspect; the situation is more complex.

3.3 The bulk of the data obtained during this study relevant to the general solids regime in Hong Kong was collected during the two Territorial Suspended Sediment Surveys. Inevitably, because so much dredging and disposal was in progress during the surveys, the overviews which have been derived include the effects of these activities (as was intended) but they nevertheless provide a valuable indication of natural conditions and processes.

3.4 The wet-season survey was carried out in August 1993 (DRL, 1994A*). Figure 1 shows the depth-averaged solids concentrations at high and low tide during the survey, which took four days to complete. The distribution of natural sediment is clear. At high tide, the concentrations in Hong Kong's southern and eastern waters are almost everywhere less than 2.5 mg/L and generally increase towards the north-west. In the Western Harbour and North of Lantau, they are in the range 5-25 mg/L and, at the edge of the Pearl, they rise very rapidly to more than 250 mg/L.





KEY

Depth-averaged solids concentrations:

< 2.5 mg/l	25 - 50 mg/l
2.5 - 5.0 mg/l	50 - 100 mg/l
5.0 - 10.0 mg/l	100 - 250 mg/l
10 - 25 mg/l	> 250 mg/l

FIGURE 1

WET-SEASON TERRITORIAL SUSPENDED SOLIDS SURVEY AUGUST 1993

PLAN OF DEPTH-AVERAGED SOLIDS CONCENTRATION

3.5 Areas of elevated concentration attributable to dredging and disposal activities can be seen at East Tung Lung Chau, West Po Toi, South Cheung Chau and around Chek Lap Kok. These are considered in more detail in Section 6. There are also some noticeable elevations which are not due to dredging activities. In Victoria Harbour, concentrations are typically in the range 10-25 mg/L which localised areas of up to 50-60 mg/L; this is almost certainly due to particulate effluent, rather than sediment. Marked elevations are also prominent in the shallow embayments on the southern and eastern coasts of Lantau Island. These are attributed to resuspension due to wave action in the generally poor sea conditions in which the survey was undertaken.

3.6 At low tide, there is a very prominent incursion of sediment-laden water into Hong Kong from the Pearl. A large tongue of water with concentrations of 100 mg/L and more extends from Ma Wan towards Lamma Island and similar high-concentration waters can be seen passing around the south-west tip of Lantau. The marked contrast between the solids distribution at high and low tides very clearly demonstrates the overwhelming influence of the Pearl River.

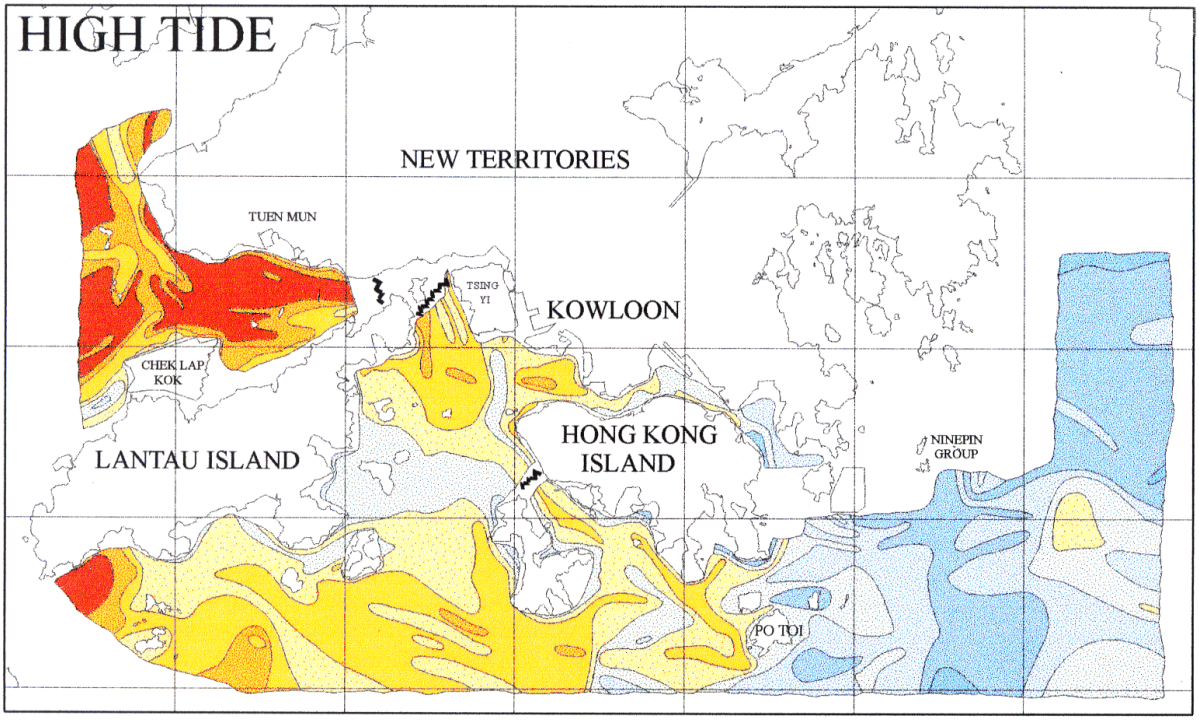
3.7 The dry-season survey was carried out in November 1994 (DRL, 1995D*) and the depth-averaged solids concentrations at high and low tides are shown in Figure 2. Surprisingly, whilst the differences between high and low tides reflect the observations made during the wet-season survey, the concentrations are everywhere substantially higher. There was much less dredging activity in progress than during the earlier wet-season survey so the general increase in solids concentrations cannot easily be attributed to such activity with the one exception of the area around the Brothers and East Sha Chau MBAs. Three large trailers were dredging mud with (permitted) overflow in this area and would undoubtedly have released very large amounts of sediment. At some points in this area, concentrations in excess of 1,000 mg/L were observed.

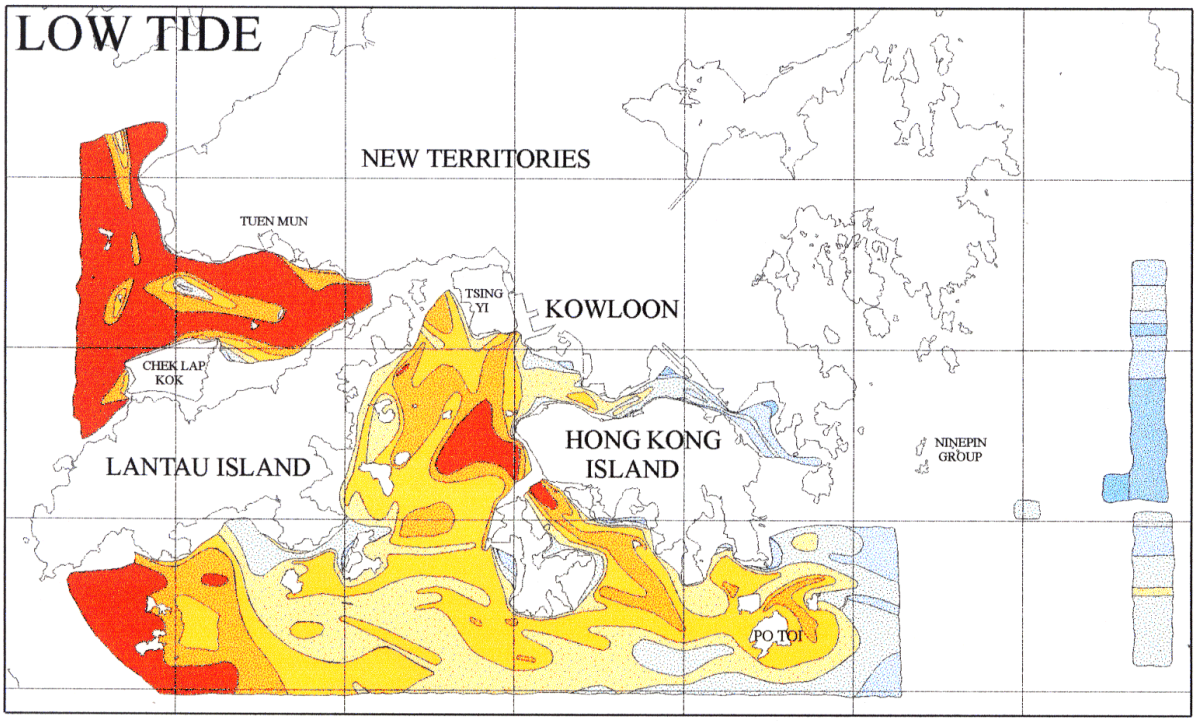
3.8 The cause of the Territory-wide increase of solids concentration is thought to be a combination of the greater tidal excursion during the dry season and the 1:100 year flood which occurred in the Pearl River during the '94 wet season. The flood would very likely have delivered a vastly greater amount of sediment to the Pearl Estuary than normal. It has been estimated that, during a normal year, the amount of mobile sediment within the estuary is several times the average annual input of around 80 M tonnes. The estuary thus acts as a sediment store or buffer zone, gradually releasing the sediment over an extended period of time.

3.9 The fact that the solids concentrations are elevated throughout Territorial waters, including those well beyond the Ninepins in the east, is consistent with this explanation and is supported by the fact that concentrations were elevated throughout the water column, suggestive of very fine sediment from a distant source. This contrasts with the known tendency for (relatively coarse) sediment plumes formed by dredging and disposal activities to quickly decay and subside towards the bed. Approximately contemporaneous satellite imagery obtained by the GEO supports (in an unquantified manner) the observations made during the dry-season survey and sediment-laden waters were clearly visible, extending even into the southern parts of Mirs Bay.

3.10 It is pertinent to note that, during a survey (unconnected with this Study) undertaken in the approach channel to Lamma Power Station in September 1995, one year after the dry-season survey, 72 water samples taken for ADCP calibration showed concentrations in the range 10-80 mg/L with the majority having concentrations of about 40 mg/L. There was no major dredging activity in progress in Hong Kong at that time.

3.11 It seems likely that during the dry season following a 'normal' wet season, solids concentrations in Hong Kong waters will be low compared with those of the wet season. This is generally confirmed by years of observation and is no doubt the rationale which underpins the general perception of the difference between the wet and dry season conditions. However, whilst the dry-season Territorial Survey followed an extreme event, it is quite reasonable to expect that Hong Kong's southern and eastern waters will be affected by concentration elevations during the dry season as a result of higher than average, but not necessarily extreme, rainfall in the Pearl catchment. The Pearl River flow and the amount of sediment delivered to the estuary during the wet season, to be released only gradually to surrounding areas, is likely to be sufficiently variable to make the 'dry-season/low concentration' rule anything but reliable.





KEY

Depth-averaged solids concentrations:

< 2.5 mg/l	25 - 50 mg/l
2.5 - 5.0 mg/l	50 - 100 mg/l
5.0 - 10.0 mg/l	100 - 250 mg/l
10 - 25 mg/l	> 250 mg/l

FIGURE 2

DRY-SEASON TERRITORIAL SUSPENDED SOLIDS SURVEY NOVEMBER 1994

PLAN OF DEPTH-AVERAGED SOLIDS CONCENTRATION

3.12 The influence of the Pearl River has also been observed during many of the focused surveys undertaken during this Study. Particularly, it has been observed that, in southern and eastern waters where concentrations are usually relatively low, solids concentrations in the near-surface waters are often higher than those at depth. These near-surface elevations were generally coincident with stratification of the water column and have been noted in the dry season as well as the wet season when they would be expected. The most recent example occurred during the measurements of trailer-dumping losses in the East Tung Lung Chau MBA (DRL, 1996*) in November 1995. Marked stratification was evident (Figure 3) throughout the survey. The near-surface waters were relatively warm and oxygen-rich when compared with the deeper waters and had a salinity of 2-4 ppt lower than the deep water. The near-surface solids concentrations were typically about 5 mg/L, occasionally rising to about 7 mg/L, whilst those in the lower part of the water column were of the order of 1 mg/L.

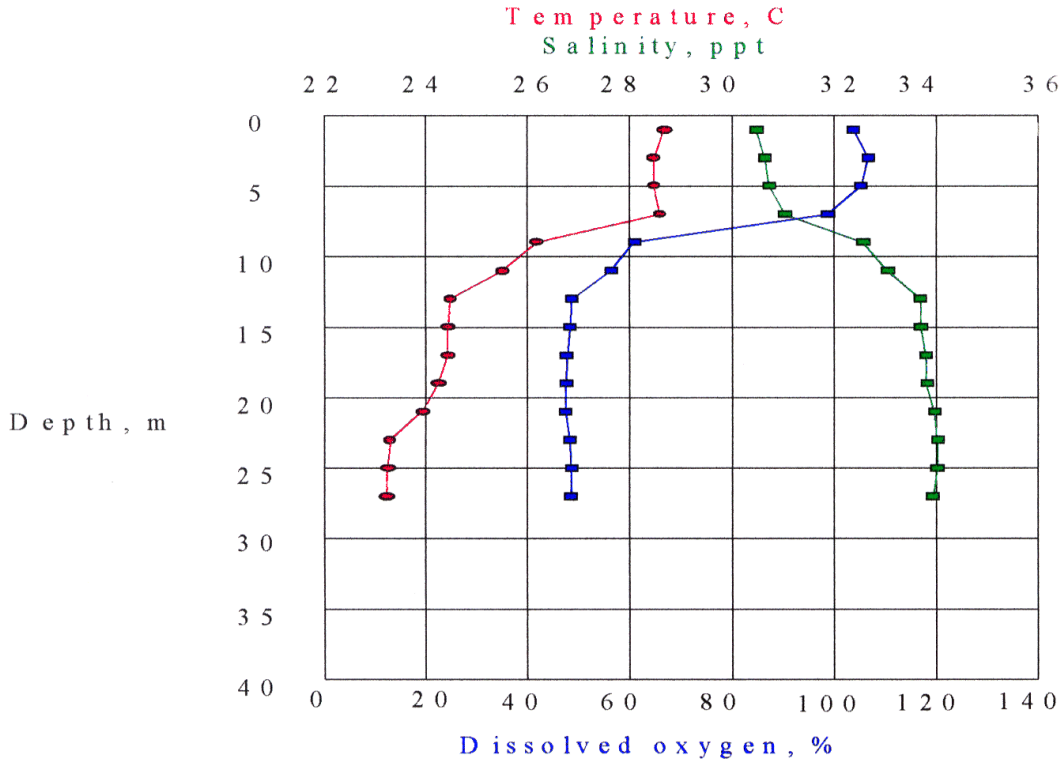


Figure 3. Stratification observed during the dry-season near the Ninepin Group.

3.13 In unstratified waters, turbulence tends to hinder the settling of sediment and is generally at a maximum at about 1/3 of the water depth. The effect of stratification is to dampen turbulence (Rodi, 1994). It might therefore be expected that when stratification is absent, 'hanging layers' of suspended sediment might be seen in the water column (whether the sediment is natural or released by dredging and disposal activities matters not) and these have been noticed on two occasions. On the first occasion, during a survey at the East of Ninepins disposal site (DRL, 1995B*), a very distinct thin layer of sediment was noted at a depth of about 10 metres at the end of the fieldwork period. On the second occasion, during the trailer-dumping measurements at East Tung Lung Chau, similar layers were noted in which solids concentrations were of the order of 5-10 mg/L above background. These were seen before, during and after the dumping measurements and were interpreted to be both natural sediment and sediment from the dumping operations.

3.14 Although the water was stratified during the East Tung Lung Chau survey, the fact that hanging layers were observed indicates that it was not sufficiently well developed to fully dampen turbulence. This is important as it suggests that sediment can be carried over large distances from the Pearl. It also has implications with respect to the decay of plumes formed during dredging and dredged material disposal operations (see Section 5 below).

4. DECAY OF SEDIMENT PLUMES CREATED BY OVERFLOW FROM TRAILER DREDGERS

4.1 When this study commenced, the main concern with respect to water quality and the effects of the major reclamation projects was loss of material during disposal at the South Cheung Chau and East of Ninepins sites. However, theoretical studies during numerous EIAs, supported by field measurements, have shown that the dredging of sand releases a substantially greater amount of sediment than any of the disposal operations. Whilst the immediate loss during dumping from trailer dredgers and barges is generally accepted to be in the range 1-5%, perhaps slightly more on some occasions, the losses through overflowing whilst dredging sand with trailer dredgers may be as much as 50% or more in fine, silty materials.

4.2 Most of the focused surveys in and around MBAs which were carried out during this Study were mainly directed towards establishing the extent of plumes caused by dredging operations, i.e. where did the plumes go and what were the concentrations? However, some have also provided coherent data sets which can be used to asses the rate of decay of such plumes.

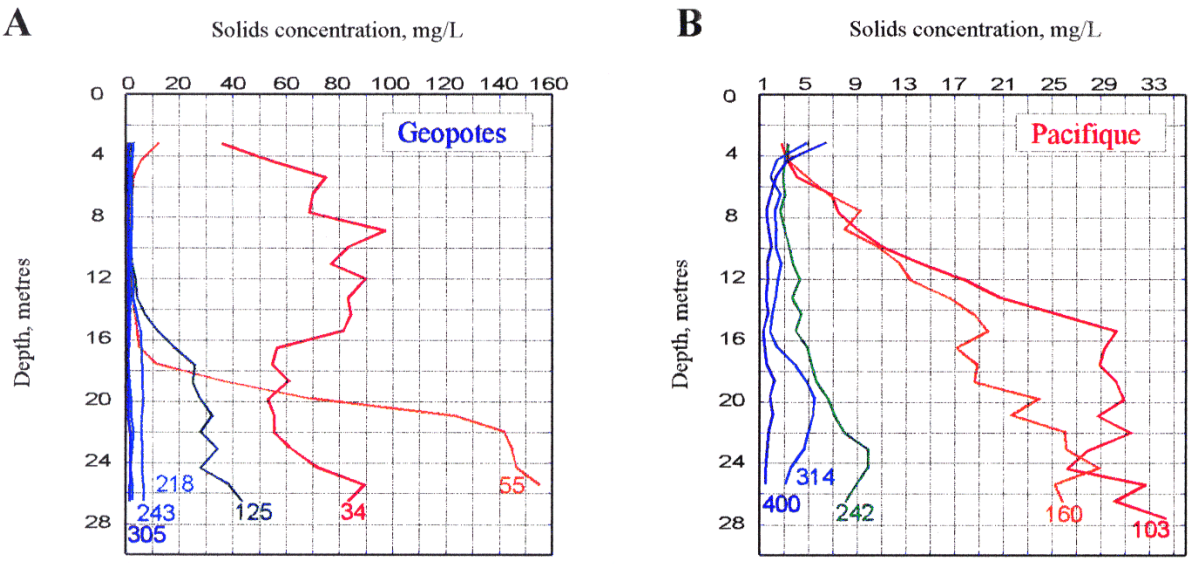
4.3 The survey carried out in the West of Ninepins MBA (also known as the eastern part of the East Tung Lung Chau MBA) provided two sets of data (DRL, 1994E*). The first relates to a plume created by the Geopotes XV which has a hopper capacity of 11,160 m^3 and is equipped with two suction pipes. The second relates to a plume created by the Pacifique which has a hopper capacity of 9,260m^3. She is also equipped with two suction pipes but, due to mechanical problems, she was working with only one pipe when the plume data were obtained.

4.4 Figures 4A and B show vertical profiles of solids concentration obtained in the middle of the two plumes formed by the Geopotes and the Pacifique respectively. In the case of the plume formed by the Geopotes, the first profile was obtained about 34 minutes after formation of the plume when most, if not all, of the entrained air bubbles should have dissipated. With the exception of the near-surface zone where solids concentrations appear to be low, concentrations are fairly uniform throughout the water column, lying in the range 50-100 mg/L. The plume had rapidly subsided towards the bed after about 55 minutes; concentrations in the upper part of the water column were near-background whilst those below about 20 metres water depth had increased to about 150 mg/L. Thereafter, the plume decayed throughout the water column and concentrations had reduced to near-background after four hours. A broadly similar picture is revealed by the data from the Pacifique.

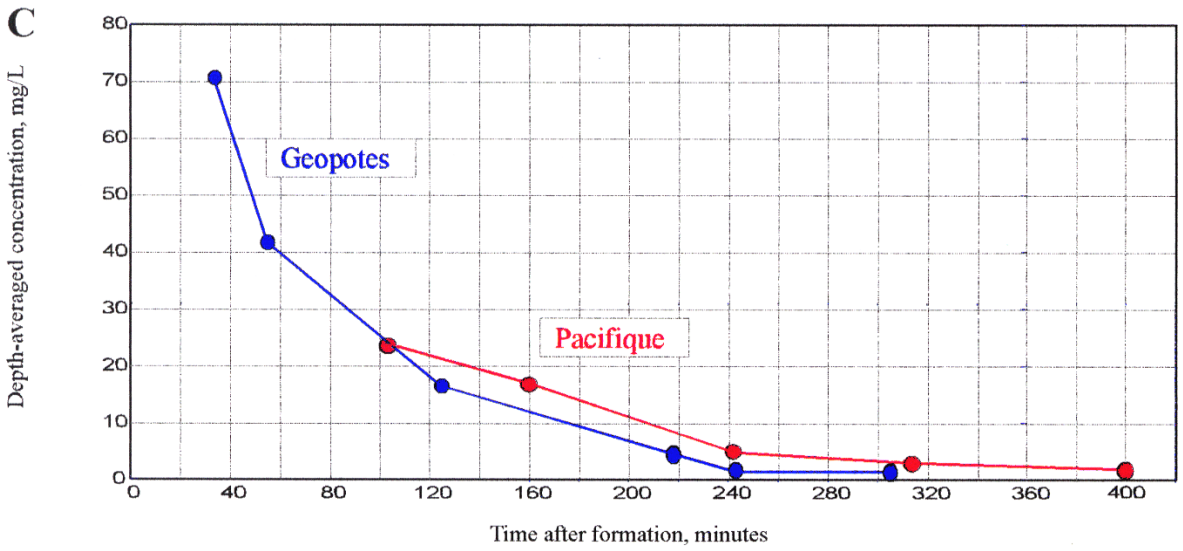
4.5 Figure 4B shows the decay of the depth-averaged (throughout the full water column) concentration with time for both plumes. The initial concentrations are unknown but are likely to have been of the order of 500 mg/L. These data were analysed in an informal report to GEO (uncirculated) in which it was concluded that the particle settling velocities which would have been required to cause such rapid plume decay were substantially greater than those characteristic of the sizes of particles involved. In addition, the rapid increase of plume width (measured near the bed, see Figure 4D) was greater than could be explained by diffusion.

4.6 The evidence indicates that the rapid decay and spread is caused by the plume acting as a density current, driven by only very small excess solids concentrations. It has long been appreciated that a large proportion of the sediment in overflow plumes descends very rapidly to the bed as a density current during the first few minutes after formation. However, it is believed that this is the first time that observational data have demonstrated that density currents persist for periods of 2 hours or more after plume formation and serve to accelerate the decay of the 'residual' plume which remains after most of the sediment has reached the bed during the first few minutes.

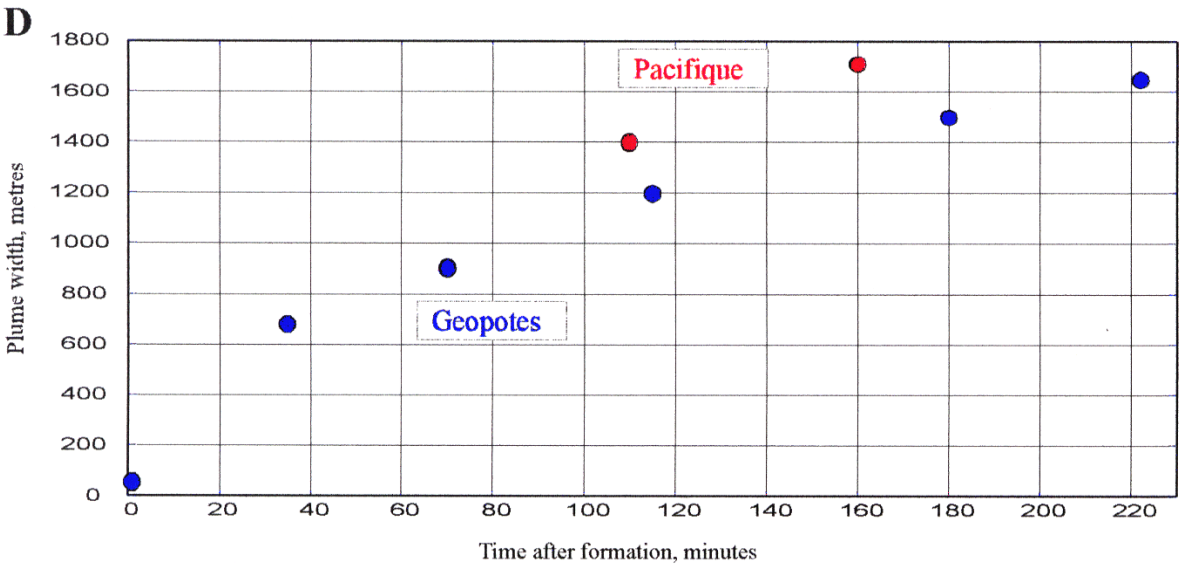
4.7 On the basis of these observations, and those during other surveys including work undertaken at the West Po Toi MBA by GEO and their dredging consultants DEMAS, it was proposed to define three phase of plume development which are summarised in Table 1.



Vertical concentration profiles in plumes showing rapid concentration decay with time
(Numbers indicate time after plume formation in minutes)



Decay of depth-average concentration with time



Increase of plume width with time

Figure 4. Summary of overflow plume decay data obtained in the West of Ninepins MBA, April 1994

Phase	Typical time after formation	Characteristics
Active	0 - 15 minutes	• rapid descent towards the seabed as a very turbulent jet • release of entrained air • stripping of sediment from the descending jet to form a (relatively) low-concentration plume
Quasi-passive	15 minutes to 2 hours	• density currents are more important than diffusion in the lateral spreading of the plume • density currents are more important than particle settling velocity in the top-down decay of the plumes
Passive	> about 2 hours	• particle settling and diffusion are the dominant process in the further decay/development of the plume.

Table 1. Suggested definition of the phases of overflow plume decay.

5. SEDIMENT LOSS AND DECAY OF PLUMES DURING DUMPING FROM BARGES AND TRAILER DREDGERS

5.1 Until the development of the Sediview Method, measurements of the loss of sediment to suspension during dumping operations relied on the use of siltmeters and conventional current meters and were thus subject to severe limitations with respect to the amount of data which could be obtained. Several accounts of such measurements are available in the literature (e.g. Sustar and Wakeman, 1977; Tavolaro, 1982: Gordon, 1974; Bokuniewicz et al., 1978), all of which suggest that losses are generally of the order of 5% or less of the total dry solids which are discharged. This Study provided an almost unique opportunity to measure, in far more detail than has hitherto been possible, the loss of sediment during dumping from both barges and trailer dredgers and to study the decay of the plumes during the first few hours after formation.

South Cheung Chau

5.2 The first attempt to measure dump-plume decay was made during the second survey at the South Cheung Chau MDS in 1993 (DRL, 1995A*). The main objective of the survey was to define the suspended solids regime in the general area of the MDS but the opportunity was taken to measure the decay of a single plume formed by the dumping of marine mud from a 1,000 m^3 barge.

5.3 Figure 5 shows the depth-averaged solids concentration observed in the plume. The initial concentration is unknown but it can be seen that the concentration decays rapidly. After 40 minutes, it is less than 20 mg/L and has reached near-background after about 100 minutes.

East Sha Chau

5.4 In early 1995, concern over the uncertainty surrounding estimates of amount of material lost during dumping at the East Sha Chau contaminated mud pits prompted two series of loss measurements which were undertaken in January and March 1995 (DRL, 1995E*). A total of nine dump events were monitored. No attempt was made to study plume decay on this occasion; the overriding objective was to establish the losses. This was achieved by sailing repeated lines along the margin of the pit, down-current of the dumping position, until the plume had passed out of the pit. Loss estimates were established for six of the nine events. The remaining three events took place at approximately slack water and no sediment was observed to pass out of the pits. The results of the loss measurements are summarised in Table 2.

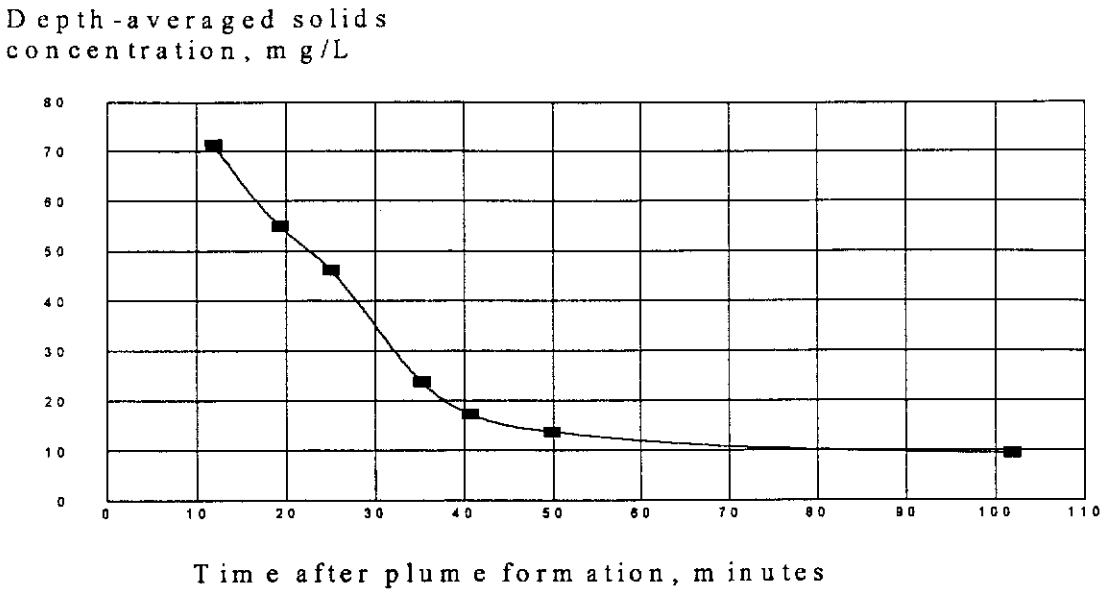


Figure 5. Observed depth-averaged solids concentrations in a plume formed by dumping mud from a barge at South Cheung Chau MDS.

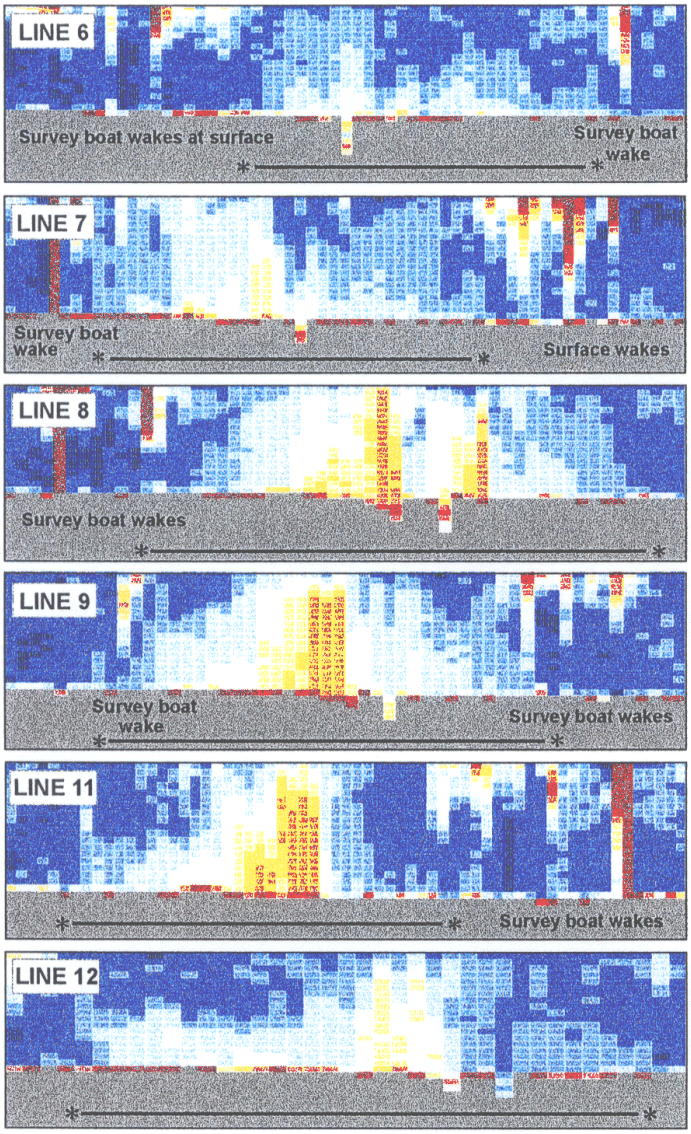
Event	Barge volume	Material characteristics		Current	Estimated loss,
	m^3	% fines(<63μ)	Dry density	speed, ms^{-1}	% dry solids
2.1	600	90	? 0.751	0.13 - 0.30	3.112
1.4	600	68	0.718	0.07 - 0.14	2.806
1.1	400	40	1.235	0.07 - 0.14	2.218
2.3	400	? 40	? 1.235	0.45 - 0.25	2.176
2.2	968	? 90	? 0.751	0.35 - 0.50	1.421
1.2	1,000	55	1.039	0.20 - 0.30	1.193

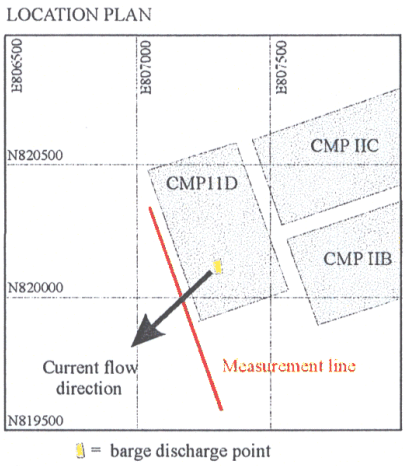
Table 2. Summary of losses measured during barge-dumping at East Sha Chau CMPs.

5.5 Figure 6 shows some of the results of the measurement which gave the highest loss (Event 2.1). Selected ADCP profiles illustrate the solids concentrations during the passage of the plumes. These are sometimes 'contaminated' by air bubbles where the survey boat sailed through the wake it had formed on the previous lines, but the plume formed by the dumping operation is clearly discernible. The contaminated data were replaced with 'clean' data from adjacent parts of the record in order to derive the estimates of sediment flux. These showed the plume to have a well-defined core in which the flux peaked at about 9 kg/sec.

5.6 The sediment flux curves for all six measured events are shown in Figure 7. The flux curves include an allowance for the near-bed transport, based on analysis of vertical siltmeter profiles. The highest measured fluxes were 14 and 20 kg/sec during the last two quantified dump events when the fastest currents were also observed. The main core of the plume passed through the survey line in about 10-12 minutes during these events. In contrast, for example, during dump 1.4, there was a weak current of about 0.14 m/sec and the flux curve is very broad with a poorly-defined peak at about 7.5 kg/sec.

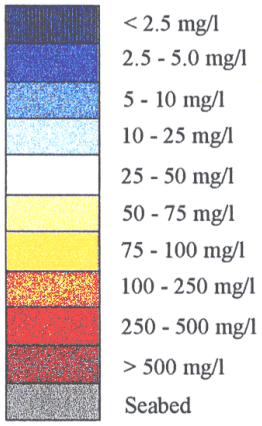
5.7 Analysis of the loss measurements suggested, albeit on the basis of limited data, that current speed had little influence on the magnitude of the losses. This was attributed to the fact that the sediment is put into suspension by 'stripping' from the rapidly-descending jet of dumped material which travels at up to 6 metres/sec, much faster than the current speed. The amount of material which is stripped is influenced most by the nature of the dumped material and the size of the barge, which determines the area ratio of the jet. The effect of the current speed was limited to influencing the duration of the passage of the plume through the measurement line and the magnitude of the peak sediment flux. The data suggest that a high fines content and a low material density give rise to the greatest losses.





KEY TO ADCP CONCENTRATION PROFILES

* = Plume from dumping operation



NOTES:
Water depth along surveyed lines approx. 7.5m.
Profiles are plotted South (left) to North (right).
Air-contaminated (wakes) data were substituted for 'clean' adjacent data when estimating solids flux.

12 Flux estimate and record No.

Estimated total sediment flux = 14,021 kg

Estimated loss of sediment = 3.112% of total dry solids discharged

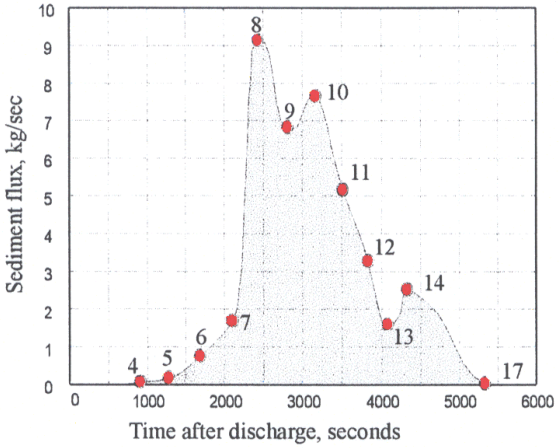


Figure 6. Measurements of Barge-dumping losses at East Sha Chau CMP IID - Summary of data obtained from Dump 2.1

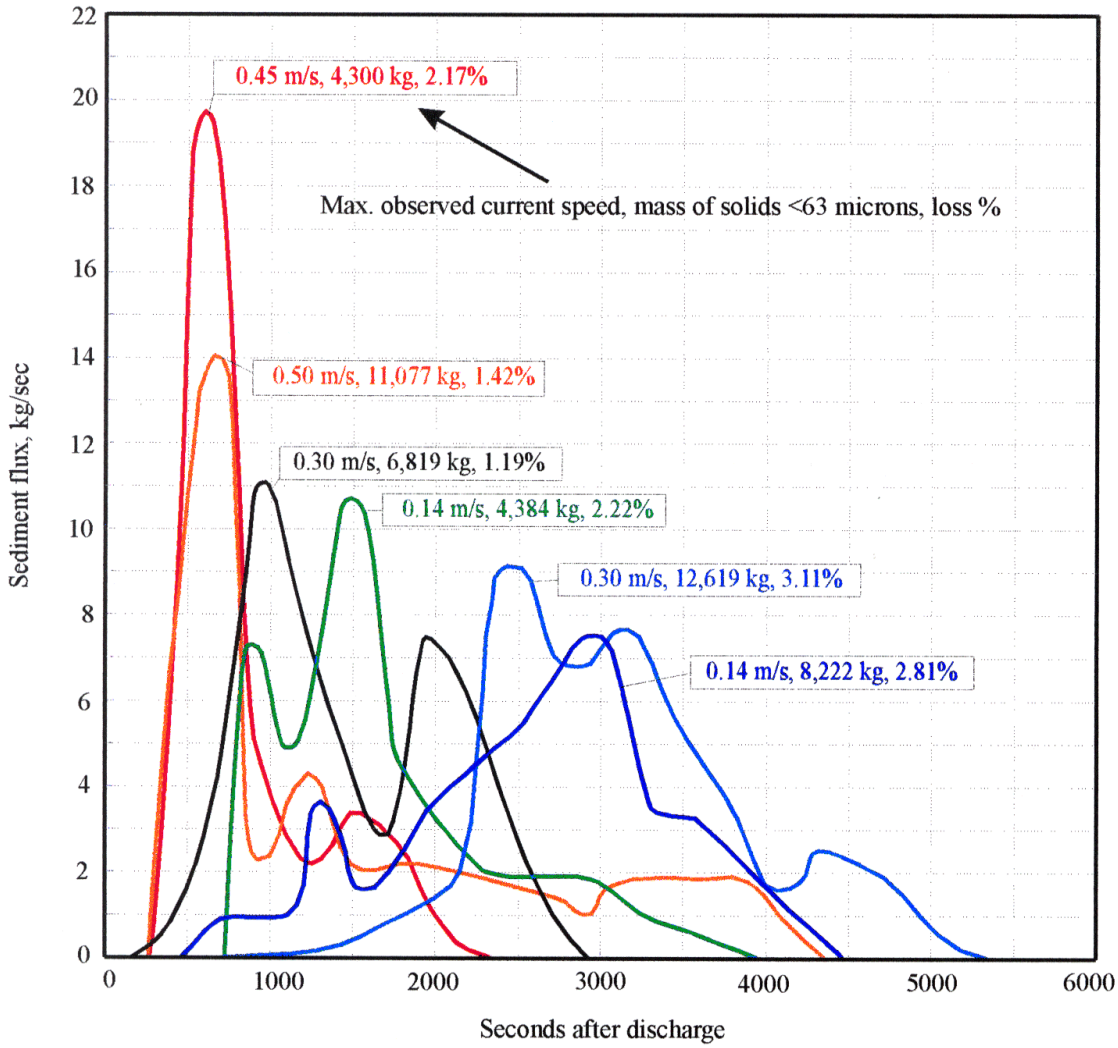


Figure 7. Sediment flux curves observed during barge-dumping loss measurements at East Sha Chau MBA, 1995.

East Tung Lung Chau

5.8 In September 1995, a series of measurements were undertaken in the East Tung Lung Chau MBA in order to quantify the loss of sediment during dumping from trailer dredgers and to monitor the decay of the resulting plumes (DRL, 1996*). The measurements were intended to provide data which could be used to assess the potential effects of backfilling the seabed depression which remained after the area had been worked for fill materials, principally for the west Kowloon Reclamation. A total of six dump events were monitored. Two dredgers were used. The Krankeloon, a split-hull vessel with a hopper capacity of 2,803 m^3, was used for the first two events. The last four events utilised the Pacifique, a twin-hopper vessel with a total capacity of 9,208 m^3 which discharges through bottom-valves. Measurements were made at two locations, in the deep pit (-46 mPD) immediately west of the Ninepins and in an area midway between the Ninepins and Po Toi where dredging had removed only about 5 metres of material.

5.9 The loss of sediment was measured across a survey line located approximately 300 metres down-current of the dumping point. The dredgers discharged whilst still underway (as is usually the case when no restrictions are in force) and turning through a wide arc at the dump site. Unfortunately, this, combined with the fact that the Pacifique flushed its hoppers after discharge, led to air-contamination of some of the data and the estimated losses are thus somewhat uncertain, probably tending towards overestimates. The loss measurements are summarised in Table 3.

Event	Dredger	Location	Mass of dry solids discharged	Hopper density	Estimated loss, % dry solids
1	Krankeloon	A	1,830	1.425	0.86
2	Krankeloon	B	1,753	1.409	2.09
3	Pacifique	A	2,282	1.200	8.42
4	Pacifique	B	1,970	1.167	6.87
5	Pacifique	B	1,380	1.121	5.33
6	Pacifique	A	1,986	1.168	8.74

Location A is the deep pit, Location B is the shallow area between Ninepins and Po Toi.

Table 3. Summary of results of loss measurements during dumping from trailer dredgers at East Tung Lung Chau MBA.

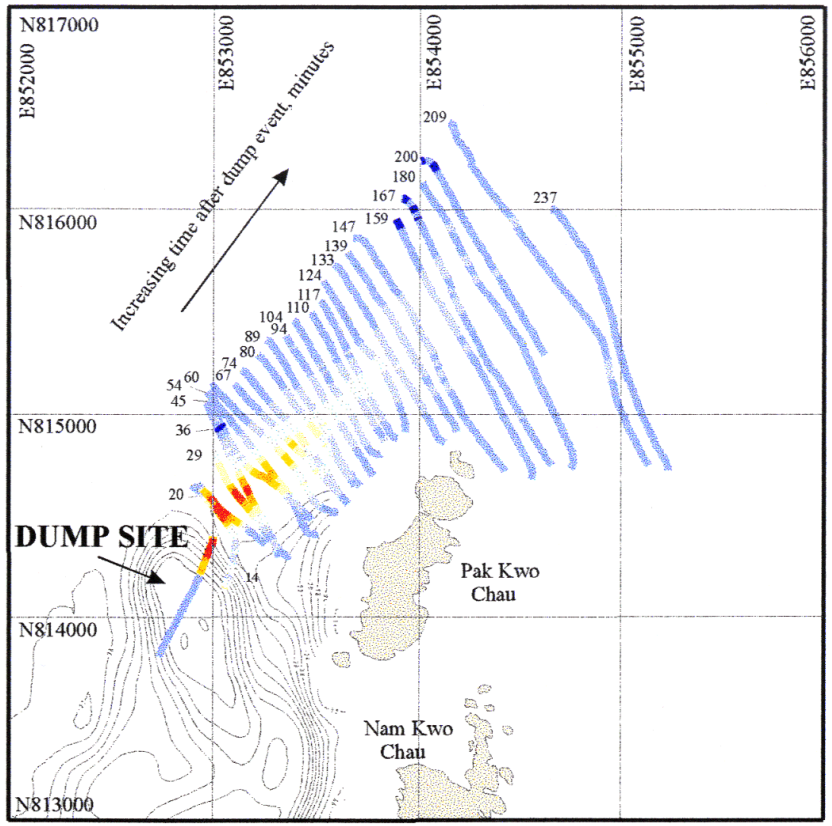
5.10 There is a clear difference between the small losses incurred by the Krankeloon and the much higher losses incurred by the Pacifique. This was attributed to the fact that the Krankeloon discharges through its split hull much faster than the Pacifique and to the much higher density of the Krankeloon's hopper contents compared with those of the Pacifique. There were no significant differences between the particle size distributions of the materials discharged during the six events; all were marine mud with very similar gradings which averaged 12% sand and small shell fragments, 53% silt and 35% clay.

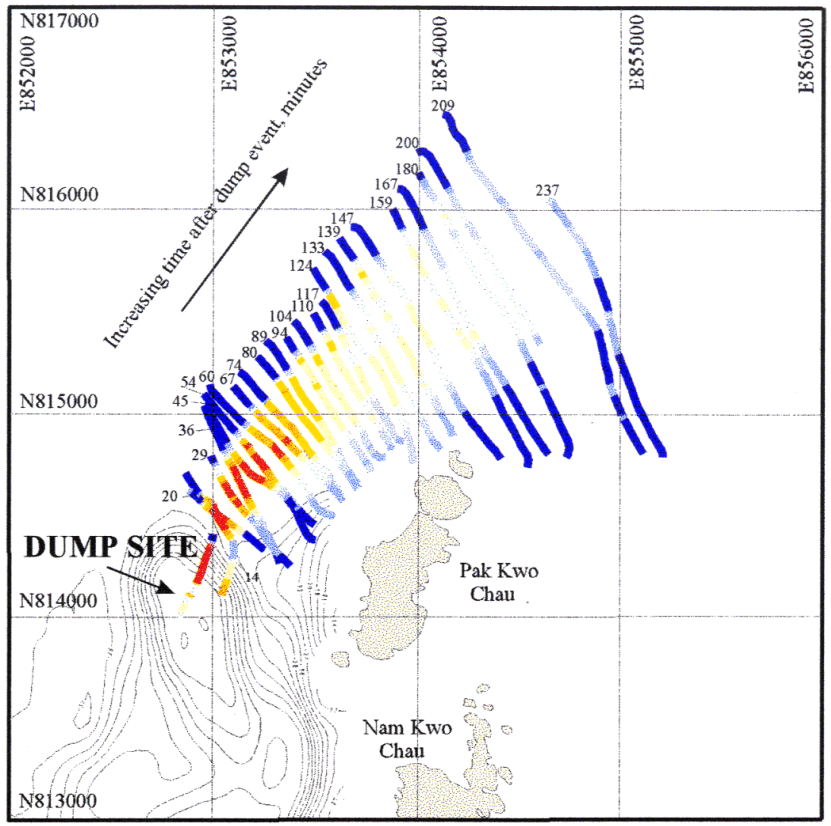
5.11 Neither of the two dredgers can be considered typical of the trailers which have worked in Hong Kong. The Krankeloon is one of few medium trailers which has a split hull and it is capable of dredging mud at a very high density; loss might therefore be expected to be lower than the average trailer. In contrast, the Pacifique has, unusually, two hoppers and discharges slowly; it dredges mud relatively inefficiently at low density and losses might therefore be expected to be higher than average. After analysis of the measurement data, it was concluded that a figure of about 4.5% would be a reasonable approximation of the dumping losses from an 'average' trailer. This compares favourably with the 5% loss which is generally assumed for the purposes of modelling the environmental effects of dumping in Hong Kong.

5.12 There was no apparent correlation between the magnitude of the losses and the characteristics of the two sites where the measurements were made. This tends to confirm that the losses are principally governed by the nature of the material and the extent to which is stripped from the descending jet of material during the first few minutes after dumping (in addition to the characteristics of the dredger itself).

5.13 The decay of the plumes formed during dumping was closely monitored by tracking two drogues which were released at the dump site as the dredgers discharged. Figure 8 shows the results of one of the tracking exercises. The depth-averaged solids concentrations in the upper and lower parts of the water column are shown as colour-coded ribbons along successive tracks of the survey boat. The dredger discharged in the deep pit adjacent to the Ninepins and the plume migrated towards the north-east. It was tracked for approximately four hours by which time solids concentrations in the upper water column had been observed to be at or near background levels (about 4-5 mg/L) for about 1 hour. Concentrations in the lower water column were observed to be in the range 5-10 mg/L above background (about 1 mg/L).

5.14 Figure 9 summarises the plume decay data for all six dump events. The difference between the Krankeloon and the Pacifique is readily apparent and the concentrations observed the plumes formed by the Pacifique are markedly higher than those formed by the Krankeloon. Solids concentrations in the upper water column decayed to near-background levels after about 2 hours in the case of the Krankeloon and 3 hours in the case of the Pacifique. The period of observation was insufficient to determine the full decay time of the plumes in the lower water column but the data indicate that near-background concentrations would have been attained after about 2-3 hours in the case of the Krankeloon and about 4-5 hours in the case of the Pacifique.





Solids concentration, mg/L

Less than 2.5	25 - 50
2.5 - 5.0	50 - 100
5.0 - 10	100 - 250
10 - 25	More than 250

IMPORTANT NOTE:

This plan shows concentrations observed along survey lines which were sailed in sequence. The plan is therefore a time-series plot and does NOT represent the extent of the plume at any given time. The plot indicates only the area affected by the plume during the survey period and, approximately, the maximum transient solids concentrations.

MEASUREMENT OF TRAILER-DUMPING LOSSES AT EAST TUNG LUNG CHAU MBA

DEPTH-AVERAGED SOLIDS CONCENTRATIONS OBSERVED ABOVE AND BELOW 15 METRES WATER DEPTH

FIGURE 8

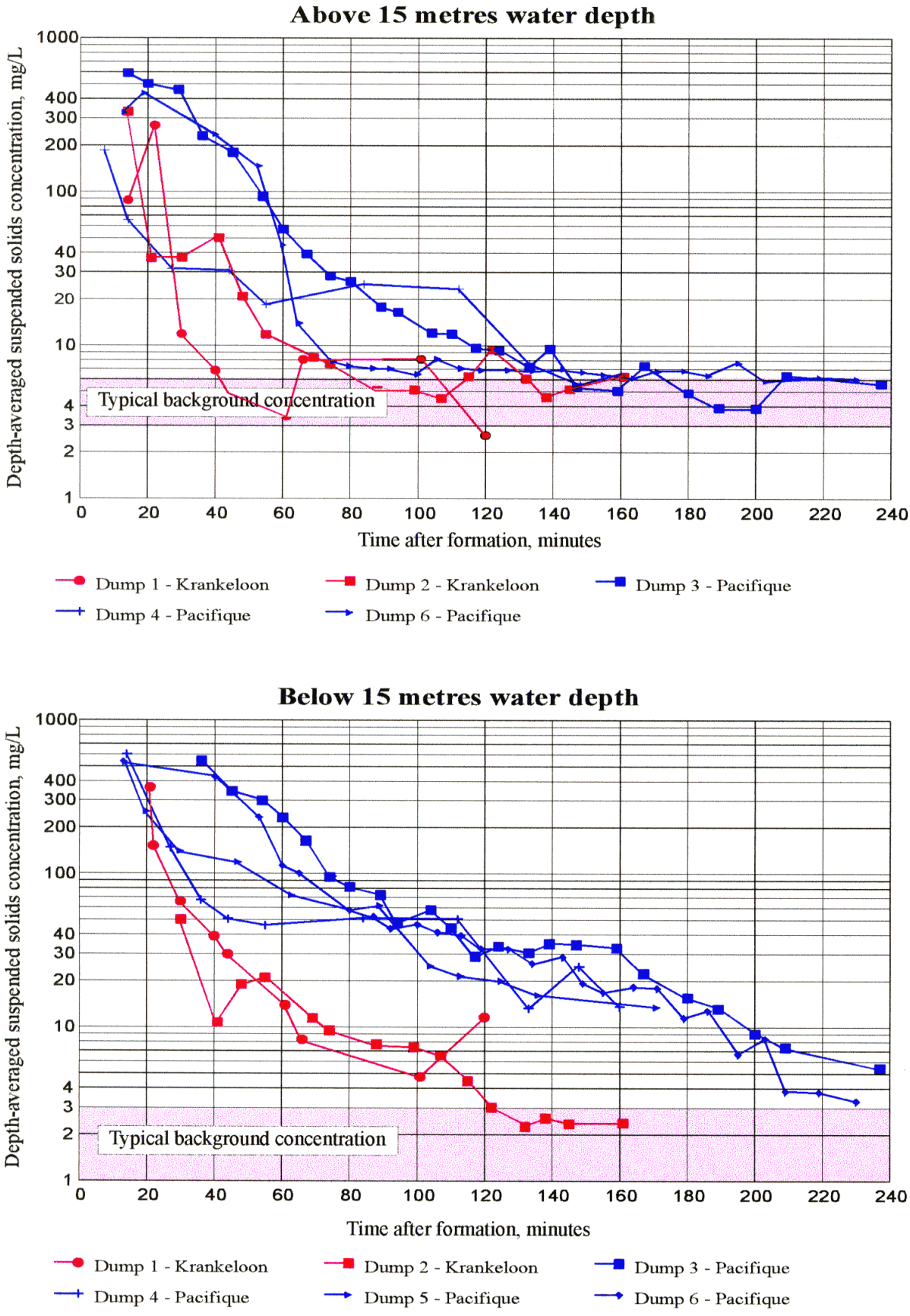
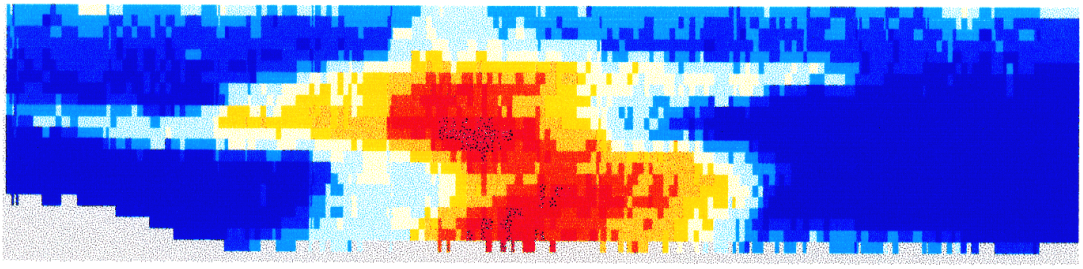
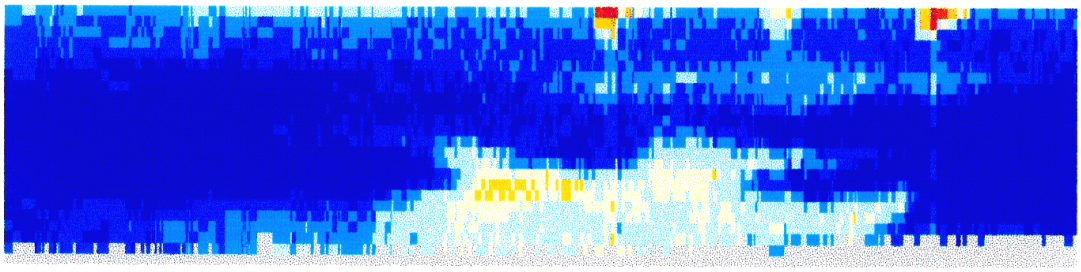


Figure 9. Summary of trailer-dumping plume decay data obtained in the East Tung Lung Chau MBA in September 1995.

5.15 The hindering of the settlement of suspended solids caused by turbulence which is typically at a maximum at about 1/3 of the water depth (see 3.13 above) was clearly seen in some of the data obtained during this survey. Figure 10 shows two ADCP transects through a plume approximately 36 and 167 minutes after it was formed. After 36 minutes, the plume can clearly be seen to be spreading out at one third to mid-depth where turbulence is interpreted to be at its maximum. After 167 minutes, although the main body of the plume has settled into the lower part of the water column, there remains a distinct relict plume 'hanging' at about 1/3 the depth of the water.



Length of transect = 800 metres, water depth approx. 30 metres



Length of transect = 1,100 metres, water depth approx. 30 metres

Figure 10. Profiles through a dump plume, 36 minutes (top) and 167 minutes (bottom) formation illustrating the hindering effects of turbulence on settlement.

6. OVERVIEW OF THE EFFECTS OF DREDGING AND DREDGED MATERIAL DISPOSAL ON THE SEDIMENT REGIME

6.1 In addition to providing valuable data on the natural suspended solids regime in Hong Kong (and the manner in which exceptional events can reverse the usual trend of wet season/ high concentration, dry season/low concentration), the two Territorial Surveys showed very clearly the extent of measurable concentration increases which are attributable to dredging and dredged material disposal activities. A number of focused surveys carried out in and around MBAs and MDSs provided further useful data.

South Cheung Chau MDS

6.2 Figure 1 (wet-season Territorial Survey) clearly shows sediment plumes attributable to the disposal operations at South Cheung Chau in August 1993 when approximately 1 Mm^3 of dredged mud was being delivered each week. At high tide, a large plume extended towards the west and north-west covering an area of about 50 km^2 but only a very small area of approximately 1 km^2 was affected by depth-averaged concentrations in excess of 25 mg/L. The vast majority of the plume area exhibited concentrations of less than 10 mg/L. At low tide, a small elongated plume was observed, extending over a distance of approximately 5 km towards the east.

6.3 The dry-season Territorial Survey in November 1994, when the disposal rate had fallen to a fraction of that in 1993, failed to reveal any indications of plumes which could be attributable to the disposal operations. However, as the background concentrations were between 25 and 100 mg/L at the time of the survey, is not surprising than nothing was detected.

6.4 The South Cheung Chau MDS was also the subject of two focused surveys carried out in June 1993 and August 1994 (DRL, 1993C* and 1995A* respectively). During the June '93 survey, when disposal operations were close to their peak, maximum depth-averaged concentrations in the immediate areas of active dumping were observed to be about 150 mg/L but they very rapidly diminished away from the dump sites. However, large areas of seabed, within the gazetted boundaries, showed concentrations in the subsiding plumes of typically 10-50 mg/L.

6.5 During the August '94 survey, the dumping rate was tentatively estimated to be of the order 110,000 m^3/week. During two days of fieldwork which included three complete surveys of the site, the largest area affected by depth-averaged concentrations in excess of 10 mg/L was observed to be about 70 hectares. Vertical profiling with a siltmeter indicated that a large proportion of the seabed was mantled by a thin (1-3 metres) mobile suspension with concentrations typically in the range 400 - 1,000 mg/L. These data suggested that, of the total mass of sediment in suspension in the MDS (including natural sediment), 90% was restricted to the near-bed zone beyond the reach of the ADCP. The near-bed suspensions may not, however, have been entirely due to the disposal of dredged material as similar observations were made at the East of Ninepins MDS during a period when dumping activity was negligible.

East of Ninepins MDS

6.6 The East of Ninepins MDS was surveyed twice, in June 1993 (DRL, 1994C*) and August 1994 (DRL, 1994E*). During both surveys, dumping activity was minimal (a few barges per day). Depth-averaged concentration elevations were restricted to the immediate area of dumping and did not exceed 10 mg/L. Maximum concentrations of the order of 25 mg/L were observed in the lower part of the water column. During the second survey, vertical profiling with a siltmeter showed that the seabed within the MDS and a over a large area (at least 12 km^2) to the east were covered with a thin suspension between 0.5 and 2.1 m thick with concentrations in the range 100 - 2,500 mg/L. The disposition of this sediment relative to the dumping site and the current flow direction at the time strongly suggested that the suspension was in large part natural although the duration of the survey prevented sufficient data being obtained to draw any positive conclusions in this respect.

West Po Toi MBA

6.7 During the wet-season Territorial Survey, the West Po Toi MBA was being intensively worked by several large trailer dredgers for fill material for the new airport and for West Kowloon Reclamation (Yau Ma Tei). Figure 1 shows a distinct plume at high tide, extending WNW and curving towards the East Lamma Channel. The overall area affected by concentration elevations clearly attributable to the dredging activity is about 50 km^2 although about half of this area was subject to relatively minor elevations of less than 10 mg/L. The maximum observed depth-averaged concentration, within the MBA and directly adjacent to a working dredger, was 100 mg/L extending over a sailed distance of about 100 metres. The plume observed during this survey was by far the most prominent, in terms of combined concentration and area affected, of all of the plumes which have been mapped during this study. In view of the fact that at least four very large trailers were working the area at the time, this might be assumed to approximate the likely worst-case scenario for sand dredging activities in Hong Kong subject to the acknowledgement that the sand at West Po Toi had a lower fines contents than some of the other MBAs.

6.8 The West Po Toi MBA was also the subject of a focused survey in December 1993 (DRL, 1994B*) when dredging activity was at a similar level of intensity as that during the wet-season territorial survey four months earlier. Unfortunately, the survey was severely disrupted by poor sea conditions but, at one stage, the survey boat sailed between the world's four largest (at that time) trailer dredgers working in close proximity. The maximum observed depth-averaged concentration, excluding those times when the survey boat was directly in the wake of a dredger and the ADCP data were corrupted by air, was a little over 100 mg/L.

6.9 It was evident, however, that a large area was affected by the intense dredging activity but it was not possible either to establish the extent of the affected area or whether the concentration elevations were entirely due to the dredging activity. It is almost certain that some of the elevated concentrations in the lower part of the water column were caused by resuspension due to the sea conditions. However, one plume with depth-averaged concentrations in excess of 25 mg/L, created by four vessels working simultaneously, was fully-mapped and extended over an area of about 3 km^2. Within this area, four distinct patches were observed to have concentrations in excess of 50 mg/L, each of which had an area of 7-10 ha.

East Tung Lung Chau MBA

6.10 The wet-season Territorial Survey (Figure 1, high tide) revealed a large, low-concentration plume extending from the Ninepins to the southern tip of Tung Lung Chau while the area was being worked for fill material for West Kowloon Reclamation. The plume displayed depth-averaged concentrations typically in the range 5-10 mg/L reaching a maximum of about 25 mg/L. The area of the plume with concentrations in excess of 10 mg/L was about 12 km^2.

6.11 The trailer dumping measurements undertaken in late-1995 in this area, in connection with the evaluation of the potential effects of backfilling the pit, showed that the plumes formed by the dumping were relatively small features. Figure 11 shows the approximate extent of the areas affected by detectable concentration increases during the migration of the six plumes which were monitored.

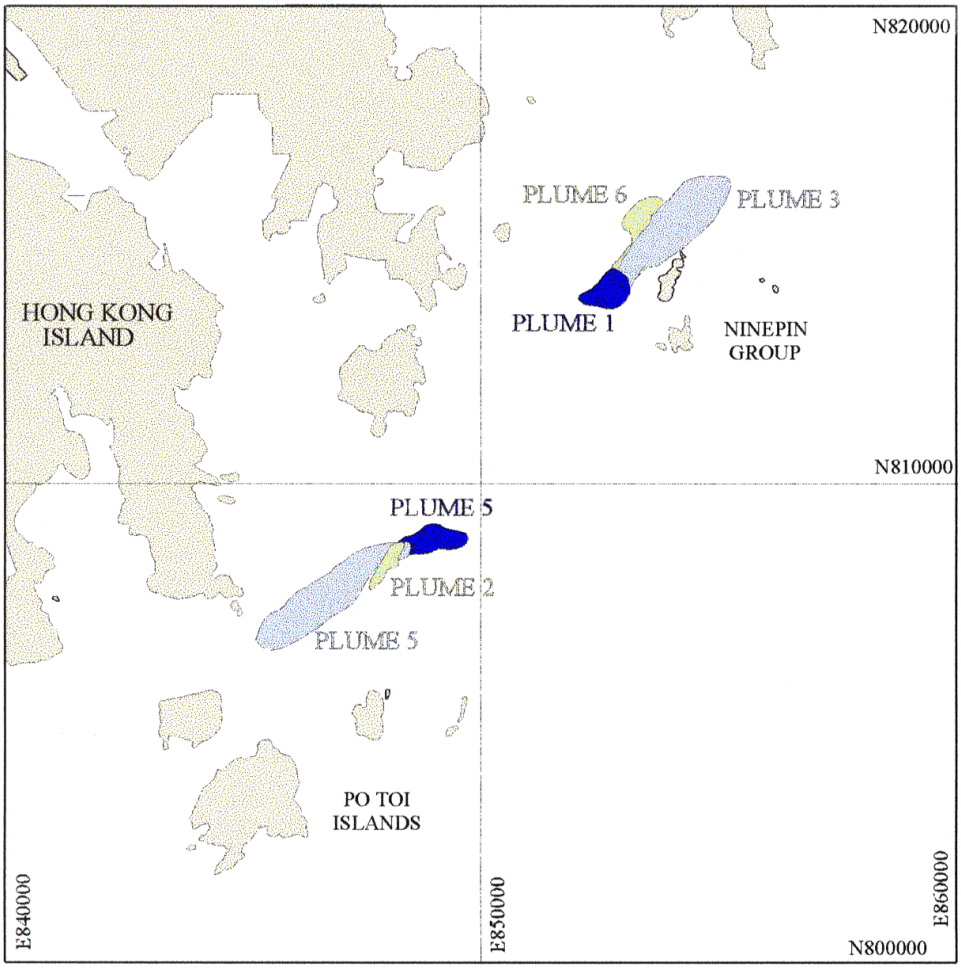


Figure 11. Approximate extent of plumes monitored during the dumping measurements at East Tung Lung Chau MBA.

6.12 During the focused survey in the area in April 1994 (DRL, 1994E*), overflow plumes formed by two trailers were tracked north-east from the pit adjacent to the Ninepins for a distance of more than 10 km. In the near-bed zone they had concentrations of about 5 mg/L above background. The near-surface plumes had concentrations of only 1-2 mg/L above background. It seems likely that the surface plumes comprise the finest of the overflowed particles (or possibly organic matter) and that the particles tend to remain in suspension near the surface due to turbulence. The main part of the water column was not subject to any concentration elevations at these distances.

The Tuen Mun Channel and Chek Lap Kok

6.13 It is difficult to assess the effects of the very concentrated dredging activity which was in progress in this area during this Study, largely because of its proximity to the Pearl which tends to mask, or at least make indistinct, the plumes created by dredging. However, it is not unreasonable to assume that, at times during the construction of the airport platform and the reclamation for the North Lantau Expressway, a large part of this area was subject to substantial elevations of solids concentration. No focused surveys were carried out in this area with the exception of the barge-dumping loss measurements at East Sha Chau which were, on one occasion, suspended for three hours due to a massive influx of sediment (1,000 mg/L) caused by a trailer dredger overflowing whilst dredging mud in an adjacent area.

6.14 The dry-season Territorial survey was carried out when three large trailers were working in mud with permitted overflow and one large trailer was working in silty sand. Locally, solids concentrations were observed to exceed 1,000 mg/L but the extent to which this can be attributed to the activities of the dredgers is unclear because of the general increase of solids concentration which was observed during this survey.

East Po Toi MBA/Fury Rocks

6.15 Two ADCP surveys were undertaken in 1994 in and around the Fury Rocks MBA (part of the East Po Toi MBA). The first survey (not undertaken directly for this Study) obtained current data over complete spring and neap tide cycles which were used to devise a system of dredging the area which minimised the risk of damaging the coral communities on the Rocks. The approach which was adopted involved initial loading the dredger almost to the point of overflow in an area adjacent to the Rocks and completing the loading, with overflow, in a more distant part of the MBA from where it was estimated that sediment plumes would not impinge on the Rocks.

6.16 The second survey was undertaken during the dredging (DRL, 1994F*) in order to establish whether or not the system of working the MBA was achieving the objective of protecting the corals. The dredging was carried out using the Krankeloon, the same 2,803 m^3 split-hull trailer which was used during the later measurements of dumping losses in the East Tung Lung Chau MBA. The survey showed that, during the early stages of the initial loading close to Fury Rocks, there was slight leakage from the hopper. This was attributed to the design of the hopper which requires an initial load before the seals fully close. The concentration elevation which resulted from this very short-duration leakage was of the order of 5-10 mg/L but there was no evidence that this sediment was carried onto the Rocks.

6.17 During the second stage of the loading cycle, which was carried out with overflow close to the eastern shore of Po Toi, it was noted that during the ebb tide, some sediment was carried towards the Rocks by an eddy which forms as the tidal current passes eastwards out of Lo Chau Mun (the Beaufort Channel). The vast majority of the sediment was carried south-east, passing south of Sung Kong and well away from Fury Rocks. During the flood tide, all of the sediment released during overflow appeared to be carried west through Lo Chau Mun, away from the Rocks. The concentration elevations at the Rocks during the ebb tide, caused by the sediment transport from the northern part of the eddy, were up to about 10 mg/L. However, they were concentrated in the upper part of the water column and appeared unlikely to affect the coral communities.

6.18 It is understood that frequent diving inspections of the corals during the dredging operations showed that little no sediment had accumulated and that the coral communities appeared not to have suffered any damage as a result of the dredging.

7. SUMMARY OF CONCLUSIONS

7.1 This Study has lasted for 39 months, during which time a powerful method of suspended solids data collection has been developed and numerous surveys have been undertaken. These have provided useful data on the natural suspended solids regime in Hong Kong and on the effects of the extensive dredging and dredged material disposal operations which were in progress for much of the Study period. The main conclusions which can be drawn from the Study are summarised below.

Use of the ADCP to Measure Suspended Solids

7.2 With respect to the measurement technique, the following conclusions can be drawn from this Study and from approximately contemporaneous work undertaken in the UK and Germany:

1) the ADCP is the probably the most powerful available technique for the rapid collection of detailed suspended solids data in large areas or in very dynamic situations, e.g. work in fast currents or the study of rapid development of sediment plumes;

2) when working within the limitations imposed by acoustic theory and the performance characteristics of the instrument, the accuracy of the technique can be summarised as follows:

   - subject to accurate calibration, the absolute accuracy of a single measurement of acoustic backscatter intensity (and the consequent error in the concentration estimate) varies between about ±2% and ±25% for broadband and narrowband instruments respectively; this is a random/short-term error which is substantially eliminated, in practical terms, by the large amount of data which is collected;
   - systematic errors arising from mis-calibration are most unlikely to exceed 10-20% without being noticed;
   - substantial errors could occur if the nature of the sediment changes during the deployment; these can be avoided if calibration and verification data are collected at frequent intervals during the deployment.

3) the method is subject to a number of limitations, some of which are instrument-dependent and some of which are related to the underlying acoustic theory, including:-

   - the near-surface and near-bed zones cannot be observed (varies according to instrument specification and water depth);
   - estimates of concentrations in excess of about 3,000 mg/L must be regarded as approximations due to the extreme sensitivity of the calibration and the corrections for attenuation due to the sediment;
   - high concentrations (>about 3-500 mg/L) very close to the transducers cause amplifier overload;
   - the acoustic pulse will reflect from any particulate matter and from air bubbles leading to the possibility of misinterpretation of data.

The Natural Suspended Solids Regime

7.3 The overwhelming influence exerted on Hong Kong's suspended solids regime by the Pearl River has been confirmed. The influence can be seen over both the tidal and seasonal cycles. However, yearly variation of the Pearl River wet-season flow, and thus the amount of sediment which is delivered into

the estuary, is likely to have a significant effect on the extent to which dry-season solids concentrations in Hong Kong differ from those during the wet season. The dry-season Territorial Survey was undertaken after a quite exceptional Pearl River flood (1:100 years), the effects of which seem to have lasted a year or more. Solids concentrations in Territorial waters were everywhere significantly higher than those observed during the earlier wet-season survey. It is surmised that lesser flood events will also have an effect and that the general assumption that dry season concentrations are consistently lower than those in the wet season is unreliable.

7.4 In addition, there is clear evidence that stratification extends into eastern waters even, on occasions, during the dry season. Whilst solids concentrations in that area are usually very low, relative to the rest of Hong Kong, significant natural elevations do occur. Depth-averaged solids concentrations in excess of 25 mg/L have been observed in eastern waters which cannot be attributed to dredging or dredged material disposal and which, we conclude, must be natural.

Decay of Sediment Plumes Formed by Overflowing Trailer Dredgers and by Dumping Operations

7.5 Three phases of plume decay have been observed:

- an *Active Phase* which lasts for a period of minutes during which much of the dumped or overflowed sediment descends to the bed as a coherent but very turbulent jet of material, accompanied by release of entrained air (this phase cannot be observed in a quantitative manner using the ADCP);
- a *Quasi-passive Phase* which lasts for 1-2 hours during which the remnant plume of sediment, stripped from the descending jet in the Active Phase, decays rapidly; the decay is 'driven' mainly by density currents caused by the small excess density of the plume leading to a general lowering of the plume through the water column accompanied by rapid spreading; particle settling and diffusion are subsidiary process during this phase of development;
- a *Passive Phase* during which the plume decays slowly and where particle settling and diffusion are the dominant processes.

7.6 The initial decay of sediment plumes created during dredging and dredged material disposal has been confirmed to be rapid. Data from South Cheung Chau MDS, East Sha Chau CMPs, East Tung Lung Chau MBA, East and West Po Toi MBAs and the East of Ninepins MDS were obtained during the Study. These showed that solids concentrations in the upper part of the water column typically return to near background levels about 1-2 hours after formation whilst those in the lower part of the water column reduce to near-background levels after about 3 - 4 hours. However, there is evidence that minor concentration elevations of 1-2 mg/L (up to about 5 mg/L very close to the bed) can persist for a much greater length of time.

Loss of Sediment During Dumping Operations

7.7 Detailed measurements of the immediate loss of sediment during barge- and trailer-dumping operations have been made:

1) the loss of sediment when dumping from stationary barges into the pits at East Sha Chau was measured for six events and found to lie between 1.2 and 3.1% when the tide was running. No immediate losses were observed during a further three events that took place in slack-water conditions;

2) the immediate loss of sediment (at a range of 300 metres) when dumping from slowly-moving trailer dredgers was found to be between 0.9 and 8.7%:

    - the smaller losses (1-2%) were observed when dumping dredged mud with a hopper density of about 1.4 t/m^3 from a medium split-hull trailer;

- the larger losses were observed when dumping mud with a hopper density of 1.1 - 1.2 t/m^3 from a large, twin-hopper vessel which needed to flush its hoppers after discharge.

3) the limited evidence suggests that, in addition to the speed of discharge (a function of vessel design), the magnitude of the losses are most influenced by the nature of the materials (i.e. density and particle size distribution). Low hopper densities and fine materials are likely to result in the greatest losses. Current speed appears to have a relatively minor effect on immediate losses when the loss is measured over short ranges (with the obvious exception that no losses will be incurred if there is no current);

4) there is no doubt that the losses observed during the trailer-dumping measurements would have been smaller had the vessels been stationary when dumping;

5) the common assumption of a 5% loss for the purposes of modelling water quality impacts arising from (slowly-moving) trailer-dumping operations appears to be sustainable, a loss of 3% or less might be more appropriate in the case of barges loaded with grab-dredged materials.

The Overall Effects of Dredging and Dredged Material Disposal on the Suspended Solids Regime

7.8 The extent of the areas which are affected by concentration increases due to dredging and dredged material disposal is inevitably strongly dependent on the current speed in the area. In general however, it has been shown that the overall effects on the suspended solids regime are limited in extent in addition, of course, to being transient.

7.9 It is certain that the worst-effected area was north of Lantau during the construction of the airport platform and the reclamation for the North Lantau Expressway. Although focused surveys were not undertaken in this area, data from the Territorial Surveys suggests that a large area was affected and that, at times, very substantial concentration elevations occurred. These would have been carried into the Western Harbour at low tide.

7.10 Elsewhere, the most significant effects were observed at West Po Toi during a period when the area was being worked by several very large trailer dredgers. Plumes extending over 50 km^2 were observed although concentration elevations were 10 mg/L or less over much of this area.

7.11 In the other MBAs and disposal sites, the effects have been less marked. High concentrations have been observed only in the immediate vicinity of active dredging and disposal sites. Based on a combination of ADCP and water sample data, it is estimated that concentrations immediately after overflow plume formation are of the order of 500 mg/L and that they diminish very rapidly (within a few minutes) to 100 mg/L or less. Initial concentrations in dump plumes are likely to be slightly lower. Very few of the focused surveys showed concentration elevations in excess of about 25 mg/L extending beyond the limits of the dredging or disposal sites.

7.12 Very low-concentration plumes have been tracked for distances of 10 km or more from an active dredging site; these were separated near-surface and near-bed plumes with concentration elevations of about 1-2 mg/L and up to 5 mg/L respectively.

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ACKNOWLEDGEMENT

This Study has provided us with a unique opportunity to develop a powerful measurement technique which will be of use for many years to come, and to collect valuable data on the natural suspended solids regime in Hong Kong and the effects on that regime of dredging and dredged material disposal activities. It has been an interesting, challenging and rewarding study. We are grateful to the Geotechnical Engineering Office for instigating this innovative work. We thank those GEO staff who supervised the Study for their consideration and patience, particularly during those periods when development difficulties delayed reporting activities.

We also gratefully acknowledge the staff of the Term Geophysical Contractor, Electronic and Geophysical Services Ltd., who first suggested to us that ADCPs might be used for this type of measurement and for their efforts during the surveys which have been undertaken as part of this Study.

APPENDIX A

LIST OF REPORTS ISSUED DURING THIS STUDY

Dredging Research Limited

1993A. *Inception Report.* February 1993.

1993B. *The use of Acoustic Doppler Current Profilers to Measure Suspended Sediment: Review Report.* March 1993.

1993C. *The use of Acoustic Doppler Current Profilers to Measure Suspended Sediment: Initial Report on ADCP Field Experiments.* August 1993.

1993C. *Suspended Sediment Data Collection: Draft Report on the Initial Survey at South Cheung Chau (June 1993).* November 1993.

1994A. *Suspended Sediment Data Collection: Draft Report on the First Territorial Suspended Sediment Survey (August 1993).* February 1994.

1994B. *Suspended Sediment Data Collection: Draft report on the Focused Survey at West Po Toi (December 1993).* March 1994.

1994C. *Draft Report on the Initial Survey at East of Ninepins disposal site (June 1993).* May 1994.

1994D. *The Use of Acoustic Doppler Current Profilers to Measure Suspended Sediment: Draft Final Report.* June 1994.

1994E. *Focused Survey at West of Ninepins Marine Borrow Area.* August 1994.

1994F *Report on the ADCP Surveys at Fury Rocks (April and June 1994).* August 1994.

1995A. *Report on the Focused ADCP Survey at the South of Cheung Chau Marine Disposal Site (August 1994).* February 1995.

1995B. *Report on the Focused ADCP Survey at the East of Ninepins Marine Disposal Site (August 1994).* February 1995.

1995C. *Second Territorial Suspended Sediment Survey (Dry Season), November 1994: Draft Report on Results of the Survey in Eastern Waters.* April 1995.

1995D. *Second Territorial Suspended Sediment Survey (Dry Season) November 1994.* August 1995.

1995E. *Measurements of Sediment Losses During Dumping from Barges at the East Sha Chau Contaminated Mud Disposal Pits.* August 1995.

1996 *Measurements of Sediment Transport after Dumping from Trailing Suction Hopper Dredgers in the East Tung Lung Chau Marine Borrow Area.* February 1996.

Electronic and Geophysical Services Limited

1993A. *Fill Management Study - Phase III: Mud Management, Siltmeter profiling and other measurements: Task 1 - ADCP Experiments.*

1993B. *Rapid drop and towed sediment profiling system: Initial trials and observations of sediment transport processes at South Cheung Chau Disposal Area.*

1993C. *Fill Management Study - Phase III: Mud Management Study and Measurement of Dredged materials: Task 2 - Observations of suspended sediment, currents and dissolved oxygen in the whole of Hong Kong Territorial waters.*

1993D. *Detailed observations of suspended sediment in and around the West Po Toi Marine Borrow Area - Dry season field data acquisition.*

1994A. *ADCP surveying in the sea around the Ninepins Island group.*

1994B. *Report on the Fury Rocks ADCP survey.*

1994C. *Surveying with GEO siltmeter array, ADCP, conventional siltmeters and collecting water samples - South Cheung Chau and Ninepins Dumping Grounds.*

1994D. *Dry-season territorial survey, November 1994. Measurement of current velocities and silt concentrations in the Territorial waters of Hong Kong.*

1995A. *East Sha Chau Dumping Trial; surveying with ADCP, conventional siltmeter, collecting water samples and related measurements.*

1995B. *Surveying with ADCPs, conventional siltmeters, collecting water samples and related measurements: East Sha Chau Contaminated Mud Pits (II).*

1995C. *Surveying with ADCPs, conventional siltmeters, collecting water samples and related measurements: East Tung Lung Chau Borrow Pits.*