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Post-Disposal Behaviour of Sandy Dredged Material at an Open-Water, Inner Shelf Disposal Site

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ABSTRACT

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Geotechnical properties of dredged material placed in an open-water disposal site were monitored over a six-month period immediately following disposal to determine the consolidation behaviour of the spoil mound and the impact of dredged material on sediment transport behaviour.

The dredged material consisted largely ($>$ 90%) of fine to medium sand, with a significant proportion of gravel-sized pumice and shell fragments (1–10%), and minimal ($<$ 0.5%) mud. This distribution was compatible with the natural sediment at the dump ground.

Immediately after placement, mean grain size and settling velocity of surficial sediments increased compared with pre-disposal values, and sorting reduced. Dredged material bulk density and static friction angle were lower than those of pre-existing dump ground sediments, yet moisture content was comparable. These changes are attributed to the dredging and injection processes.

Due to the low mud content, the dredged material consolidated immediately upon deposition, attaining normal consolidation with respect to ambient stresses within a short period. Reduced static friction angles resulted in an enhancement of the potential for bedload transport relative to pre-disposal rates. Increased settling velocities resulted in decreased potential suspended sediment transport. Lower shear strength of the dredged material resulted in larger bedforms on the dump ground compared with surrounding areas.

With time, properties of the materials reverted towards pre-disposal conditions as a result of increased sorting and packing of grains. However, after six months, the properties had not completely returned to previous conditions.

ADDITIONAL INDEX WORDS: *Bedforms, consolidation, fate of dredged material, geomechanics, sediment texture, sediment transport, static friction angle.*

INTRODUCTION

Tauranga Harbour in the western Bay of Plenty (Figure 1) is the site of New Zealand's largest and busiest bulk export cargo port. Expansion of the port and maintenance of shipping channels requires periodic dredging of the harbour floor and ebb tidal delta. The 1990–1991 dredging programme involved the disposal of > 300,000 m^3 of harbour sediment on a 0.25 km^2 dump ground in 20–30 m of water on the inner shelf about 2 km northeast of Mount Maunganui (Figure 1).

This paper aims to investigate the geomechanical behaviour of the dredged material over time, to:

(1) better assess the rate of mound consolidation; and

(2) determine the sediment transport response to dredged material disposal, particularly bedform development, and likely changes in sediment transport rates near the dump ground.

To achieve this, the following studies were undertaken immediately before dredged material disposal and over the subsequent six-month period:

(1) determination of particle size and settling velocity distributions of surficial sediments in the area of the dump ground;

(2) measurement of a variety of geotechnical properties of the surficial dump ground sediments and consolidation parameters for the deposited dredged material;

(3) prediction of potential bedload and suspended load transport rates using published equations; and

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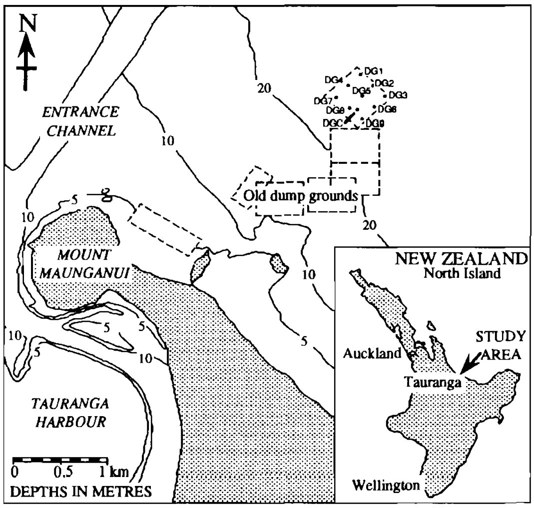

Figure 1. Location map of the study area and sea bed samples discussed in the text. Also marked are the positions of older dump grounds used at Tauranga.

(4) monitoring of bedforms by SCUBA, side-scan sonar and underwater video.

METHODS

Dredging Operations

Dredging and disposal occurred between 31 October 1990 and 9 January 1991. Dredging was carried out using a split-hopper suction-dredge. Disposal involved the hopper steaming at 1.0–2.5 m sec^{-1} (2–5 knots) across the dump ground as sediment was discharged; some 26–30 sec was required for complete emptying of the hopper. The water depth at the disposal site was approximately 25–27 m, and the sea floor was essentially flat.

Field Sampling

Samples were collected by SCUBA divers from ten sites over the dump ground (Figure 1) on 11 October and 22 November 1990 before and during disposal. The same sites were re-sampled on three occasions after disposal had ceased: 21–22 February, 8–10 April and 10 June 1991. Bulk samples for particle size analysis were collected by SCUBA divers; trowel loads of surficial sediment (from the top 25–50 mm) considered representative of the site were obtained. Similar bulk specimens were obtained from the surface of the dredged sediment in the hopper dredge.

Cores were collected using 100 mm diameter, 500 mm long, stainless steel, hand-hammered corers. Care was taken by the divers to ensure minimal disturbance and consolidation of the specimens during sampling. Where obvious consolidation of the cores had occurred, the material was discarded and the site resampled. The cores were sealed and packaged to maintain structural integrity and moisture content during retrieval, conveyance and storage.

On return to the laboratory, bulk density cores were sub-sampled from the upper 50–100 mm of the core samples, and moisture content specimens obtained from these small cores. These tests were thus undertaken on surficial sediment. Cores were sub-sampled from the remaining material of the large collection cores for consolidation and triaxial testing. Consolidation cores represent the deepest sediment (0.3–0.4 m), and triaxial cores were from higher in the profile (0.1–0.3 m).

Sample Analysis

Particle size distributions were determined using sieves with 150 to 500 g samples. Samples were wet sieved through a 4.0 ϕ sieve to determine the mud content and dry sieved through a stack of sieves from -1.0 to 4.0 ϕ at 0.5 ϕ intervals (Warren, 1992). The data were analysed by the Rapid Sediment Analyser program (Healy *et al.*, 1983), which uses both the graphical method and method of moments to determine textural parameters. Gravel and mud-sized sediment were lumped into coarser than -1.0 ϕ and finer than 4.0 ϕ, respectively, thereby biasing the higher moments; the results determined by the graphical method were used by this study.

Settling velocity distributions were determined using a settling tube (Healy *et al.*, 1983). Moisture content and bulk density of all specimens were determined following standard methods (Brown, 1981). Statistical analysis of the trends between samples was carried out using a Student's t-test with 95% confidence limits (Freund, 1974).

Consolidation

Consolidation of a soil or sediment refers strictly to the reduction in volume caused by the removal of pore or interstitial water under the influence of an applied stress. Upon initial application, much of the load is transmitted to the pore water creating a pore water pressure. Over time, this dissipates through the expulsion of pore water until the load is the total effective pressure, and the excess pore water pressure is zero (LAMBE and WHITMAN, 1979). This state is known as normal consolidation; under-consolidation exists before achievement of equilibrium, and a material is said to be over-consolidated when the pore water pressures are negative, such as following exposure after burial. The time taken to achieve normal consolidation is strongly dependent upon the permeability of the material as this controls the release of pore waters. Self-consolidation (under its own weight) has been found to be an important mechanism in the volume reduction and increased resistance to erosion of some dredge spoil mounds (BOKUNIEWICZ and GORDON, 1980; DEMARS *et al.*, 1984).

Consolidation parameters were measured using a hydraulic cell of the type described by ROWE and BARDEN (1966). A 100 mm diameter by 30 mm thick sample was sandwiched between porous discs and confined laterally. This sample was subjected to axial loading, which caused the pore water to drain through the porous discs. The load was increased at intervals, the sample allowed to attain equilibrium, and the rate of volume/height reduction of the sample noted (VICKERS, 1983).

Loads applied were calculated to span the range of total stresses resulting from the weight of the sediment in the mound and the column of water above the sampling site. The test was conducted using 50 kPa stress increments, up to a maximum total stress of 400 kPa. This considerably exceeds the effective stresses present *in situ*. Consolidation was read manually from a dial gauge.

Triaxial Testing

Triaxial testing is a method for determining the shear strength of a soil or sediment. Once extruded from the corer, a cylindrical specimen is jacketed in a rubber membrane, and water is used to apply a surrounding confining stress. An axial load is then applied, leading to failure of the specimen. Using data from several tests under different confining stresses, a plot of shear stress *versus* normal stress can be derived, commonly using a Mohr circle construction (LAMBE and WHITMAN, 1979). From this, a failure envelope describing the critical combinations of shear and normal stress leading to failure can be defined for which the simplest case is a straight-line relationship between shear stress and normal stress (a Mohr-Coulomb line). In such a straight-line relationship, the intercept is referred to as the cohesion, and the slope is the angle of internal friction or static friction angle (LAMBE and WHITMAN, 1979; NIELSEN, 1992).

Triaxial testing was undertaken using a cell of the BISHOP and WESLEY (1975) type, as described by MENZIES (1988). Cores of 50 mm diameter by 100 mm long were fully saturated after being confined within the rubber membrane. Confining stresses of between 215 and 275 kPa were applied; these were calculated to model the total *in situ* normal stresses. The specimens were allowed to fully consolidate under these stresses (all pore water pressures dissipated before application of the axial stress). Tests were run in the undrained condition to simulate rapid failure of the spoil mound.

Sample numbers were limited due to the difficulty in obtaining good, undisturbed cores of sufficient size for triaxial testing. Therefore, tests were undertaken using a minimum number of specimens, and a Mohr-Coulomb failure envelope was derived assuming no cohesion for these sandy sediments. The static fraction angles are, therefore, not totally reliable, but provide some information to quantify the effect of disposal on sediment transport rates.

Potential Sediment Transport

Many methods for predicting sediment transport rates make implicit assumptions about the geotechnical properties of the sediment. In particular, it is generally assumed that spherical quartz sediment with a static friction angle of ~32° is involved, so that the friction angle can be treated as a constant (FREDSØE and DEIGAARD, 1992; NIELSEN, 1992). Alternatively, the ratio of static friction angle to the drag coefficient is taken to be constant so that both can be ignored (FREDSØE and DEIGAARD, 1992). The Tauranga dredged material varies widely from this ideal in terms of grain shape, grain density, and static friction angle. In this paper, we will consider mainly the influence of static friction angle.

The immersed weight sediment transport rate may be calculated for both bedload and suspended load using equations explicitly incorporating the static friction angle, such as those derived by BAGNOLD (1963). The bedload transport rate may be expressed as:

$$q_b = \frac{e_b C_D \rho u^3}{\tan \phi - \tan \beta} \tag{1}$$

where

q_b = bedload transport rate,
e_b = efficiency of bedload transport,
C_D = drag coefficient,
ρ = fluid density,
u = wave orbital velocity,
ϕ = static friction angle, and
β = the local sea-floor slope.

Given this relationship, the ratio of the potential bedload transport after disposal to the pre-disposal rate can be expressed as:

$$\frac{q_{b_{new}}}{q_{b_{old}}} = \frac{\tan \phi_{old} - \tan \beta_{old}}{\tan \phi_{new} - \tan \beta_{new}} \tag{2}$$

where:

old = pre-disposal conditions, and
new = post-disposal conditions.

Hence for the same wave conditions (u constant), the change in potential bedload transport is only a function of the changes in static friction angle and local bed slope. A decrease in static friction angle and/or an increase in local bed slope will result in an increase in bedload transport rates relative to pre-disposal conditions.

The suspended load transport rate may be expressed as (BAGNOLD, 1963):

$$q_s = \frac{e_s C_D \rho u^3}{\dfrac{w}{u} - \tan \beta} \tag{3}$$

where:

q_s = suspended load transport rate,
e_s = efficiency of suspended load transport,
w = settling velocity of the sediment.

Therefore, the ratio of potential suspended sediment transport after disposal to the pre-disposal rate can be expressed as:

$$\frac{q_{s_{new}}}{q_{s_{old}}} = \frac{w_{old} - u \tan \beta_{old}}{w_{new} - u \tan \beta_{new}}. \tag{4}$$

Hence, assuming no change in wave conditions, the change in suspended sediment transport rate is a function of the change in sediment settling velocity and local bed slope. A decrease in sediment settling velocity and/or an increase in local bed slope will result in an increase in suspended load transport rates relative to pre-disposal conditions.

Bedform Monitoring

The characteristics of the bedforms near the sampling sites were determined by SCUBA divers during the various sampling dives. The observations consisted of measurements of bedform dimensions and general descriptions of the seabed. Due to the limited visibility (< 1–2 m) during most sampling dives, measurements were normally limited to ripple-sized ($\lambda < 0.6$ m) bedforms (FOSTER, 1992; WARREN, 1992). Additional data on bedforms were obtained by:

1) extra SCUBA observations at various localities over the dump ground and the surroundings;
2) SCUBA observations from Manta Board transects across the dump ground;
3) underwater video, taken by a Remote Operated Vehicle with SCUBA assistance along transects across the dump ground; and
4) repeated side-scan sonar surveys of the dump ground and surroundings.

Theoretical bedform dimensions were also predicted using empirical methods. NIELSEN (1981) defined relationships between ripple dimensions and the wave orbital semi-excursion distance and mobility number, as given by:

$$\eta = \begin{cases} \xi(0.275 - 0.022\sqrt{\psi}) & \psi \le 10 \\ \xi 21 \psi^{\;1.85} & \psi > 10 \end{cases} \tag{5}$$

$$\lambda = \begin{cases} \xi(2.2 - 0.345\psi^{-0.34}) & \psi \le 10 \\ \xi \exp\left(\frac{693 \quad 0.37 \ln^8 \psi}{1000 + 0.75 \ln^7 \psi}\right) & \psi > 10 \end{cases} \tag{6}$$

where

η = ripple height,
λ = ripple wavelength,
ξ = wave orbital semi-excursion distance, and
ψ = mobility number, given by:

$$\psi = \frac{(\xi\omega)^2}{(s - 1)gD} \tag{7}$$

where

ω = wave radian frequency,
g = gravitational acceleration,
D = grain diameter, and
s = relative sediment density, given by:

$$s = \frac{\rho_s}{\rho} \tag{8}$$

where

ρ_s = sediment density.

Table 1. *The mean gravel, sand and mud content, textural description, and mean grain size, sorting and settling velocity of the sediments sampled from the dredge hopper, pre- and post disposal inner shelf sediments. Pre-disposal samples were collected on 11 October and 22 November 1990, and post-disposal samples were collected on 21-22 February, 8-10 April and 10 June 1991.*

	Hopper (n = 4)	Pre-disposal (n = 16)	Post-disposal February (n = 9)	Post-disposal April (n = 9)	Post-disposal June (n = 5)
Gravel (%)	3.1	3.8	9.5	6.0	8.1
Sand (%)	96.6	95.5	89.9	93.6	91.4
Mud (%)	0.3	0.7	0.6	0.4	0.5
Textural description	slightly gravelly sand	slightly gravelly sand	gravelly sand	slightly gravelly sand	slightly gravelly sand
Grain size (ϕ)	1.41	1.71	1.20	1.40	1.30
(mm)	0.38	0.31	0.44	0.38	0.41
Sorting (ϕ)	0.77	0.76	0.91	0.75	0.77
Settling velocity (x)	4.14	4.43	3.88	3.97	3.90
(cm sec^{-1})	5.67	4.65	6.78	6.37	6.68

For the Tauranga inner shelf dump ground, wave periods typically range from 7–11 sec (DE LANGE, 1991), corresponding to transitional Linear Theory conditions. Hence, the wave orbital semi-excursion distance at the seabed can be found from:

$$\xi = \frac{H}{2 \sinh(kh)} \quad (9)$$

where

H = wave height,
k = wave number, and
h = water depth.

The relationships between ripple dimensions and wave mobility number (Equations 5 and 6) are very sensitive to sediment density and are strictly valid only for quartz density sediments (NIELSEN, 1992). There is considerable variation in the density of sediments at Tauranga due to the presence of pumice, shell fragments and heavy minerals (DE LANGE *et al.*, 1991). Hence, the NIELSEN (1981) approach may not provide satisfactory results. An alternative method is that of KOS'YAN (1988) who presented relationships for bedform dimensions based solely on sediment texture, as given by:

$$\eta = 17.3D^{1.22} \quad (10)$$

and

$$\lambda = 83.5D^{1.08} \quad (11)$$

where

η, λ = ripple height and wavelength (cm), and
D = grain diameter (mm).

RESULTS

Particle Size Analysis

Table 1 summarises the particle size characteristics of the sediments near the dump ground and in the hopper immediately before disposal. Before disposal, the surficial sediment of the dump ground was generally a moderately sorted, slightly gravelly, fine to medium sand. It had a very low mud content (< 1%) with a low to moderate gravel content (Figure 2). A very similar grain size distribution existed in the hopper sediments (Figure 3).

Immediately post-disposal, the surface of the dump ground shows a considerable coarsening, reflected in a higher mean gravel content of the post-disposal sediments (Table 1) and a reduction in the amount of fine sand (Figure 2), resulting in a slightly increased mean grain size. The mean mud content remains the same at ~0.6%, so the coarsening mainly occurs by altering the relative proportions of sand and gravel in the material (Figure 3). This coarsening is also associated with a reduction in the degree of sorting of the sediments (Table 1).

The coarse gravel-sized sediment consisted of low density wood, pumice and shell fragments. Initially this material appeared to be randomly scattered over the surface of the dump ground. However, the coarse material quickly became concentrated in the troughs of bedforms; and by the February sampling, most gravel-sized sediment occurred within troughs.

Over time, the surficial dump ground sediment tends to revert towards the grain-size distribution

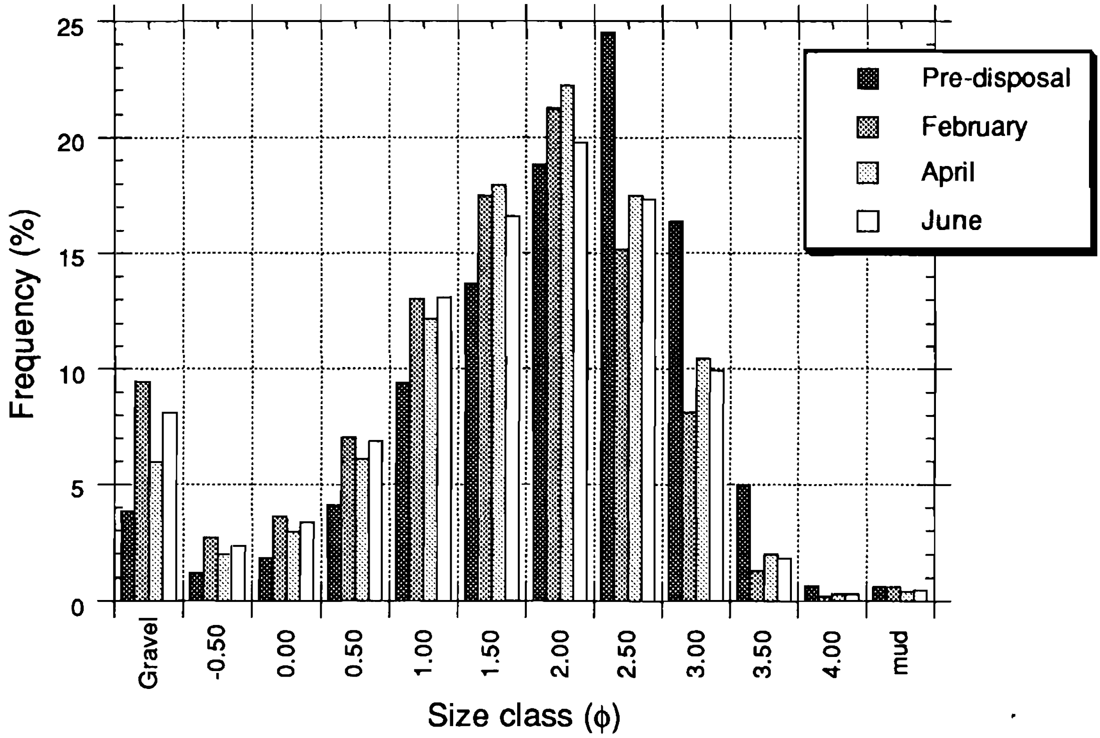

Figure 2. Composite grain size distributions for pre-disposal, February, April and June surficial sediment samples summaries in Table 1.

present immediately before dredge material placement. In particular, the material fines again, largely as a result of the proportion of gravel reducing. However, the fining is also in response to an increasing proportion of fine sand associated with the crests of bedforms. However, at the June sampling, the sediment is still appreciably coarser than the pre-disposal materials, and the trend is not monotonic. More marked is a return to pre-disposal sorting values, especially between the February and April sampling periods (Table 1).

These results are also reflected in the settling velocity data (Table 1) which show a marked increase in mean settling velocity following disposal. The increased mean settling velocity remains relatively constant throughout the monitoring period.

Moisture Content and Bulk Density

Table 2 summarises the sediment moisture content from samples collected from the dump ground before and after the placement of dredged material. No statistically significant changes in moisture content are apparent in these data.

The oven dry bulk densities of the samples are also summarised in Table 2. A statistically significant ($\alpha = 0.05$) reduction in bulk density can be seen in the surficial dump ground sediments immediately following disposal. Following this initial reduction in bulk density, there is an increase (significant at $\alpha = 0.05$) in the dry bulk density at all sites over time, though pre-disposal bulk densities are not re-established within the time-frame of this experiment.

Consolidation Testing

Consolidation tests performed on the post-disposal samples show no change in sample height (settlement) with the loads applied. The test was repeated on laboratory-remoulded specimens of the same material to ensure that the lack of measurable settlement is not an artifact of machine or operator error; these remoulded specimens show settlement of up to 3 mm (10% strain) at total stresses of < 400 kPa. The zero consolidation

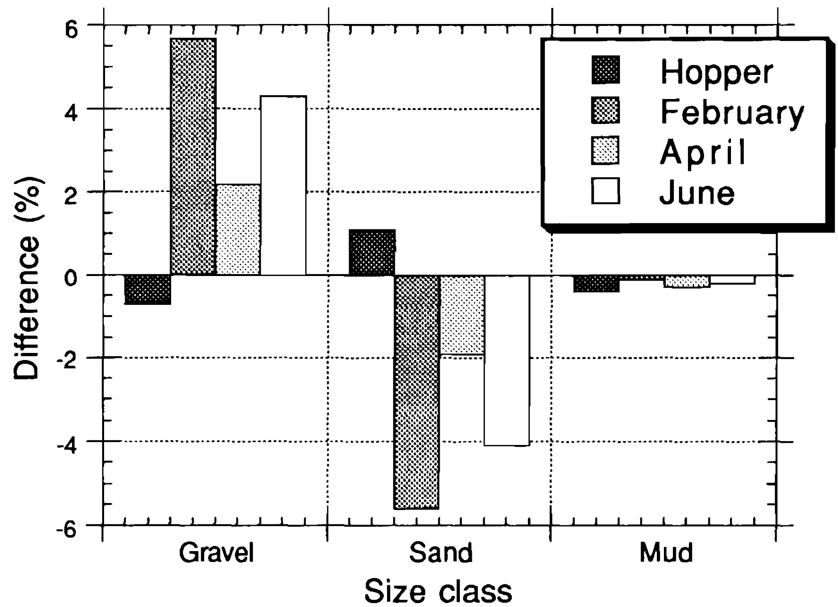

Figure 3. Difference in sediment texture relative to the pre-disposal conditions by textural size class. The difference is defined as (class %) − (pre-disposal class %).

measured for the field samples is thus believed to be a valid result.

Triaxial Testing

Table 3 presents the static friction angles determined for the pre- and post-disposal sediment cores. It is notable that none of the measured angles match the ~32° angle commonly assumed for sediment transport calculations (FREDSØE and DEIGAARD, 1992; NIELSEN, 1992). It is also evident that there is considerable temporal and spatial variation in these data, which may partly result from experimental technique, but which probably represents natural strength variability in the sediments.

A subset of these data comprising the sites with a continuous time series of measurements (DG2,

Table 2. *The range, mean and standard deviation of the moisture contents and oven dry bulk densities from sediments sampled from the dredge hopper, and pre-disposal and post-disposal inner shelf sediments.*

	Number of Samples	Range	Mean	Standard Deviation
Moisture content (%)				
Pre-disposal	6	28–34	31	1.9
February	9	16–37	27	6.9
April	9	17–38	27	6.0
Bulk density (kg m^{-3})				
Pre-disposal	6	1041–1448	1298	126
February	9	1052–1284	1135	68
April	9	1105–1345	1188	73

Table 3. *Static friction angles (φ) derived from the triaxial strength testing of sediment collected from the inner shelf dump ground pre- and post disposal, for all sites from which reliable data were obtained. The mean represents the average for the three sites that have a continuous record (DG2, DG3 and DG9). DG denotes dump ground site numbers (Figure 1).*

	Friction Angle (°)		
Sample Site	Pre-disposal	February	April
DG1			22
DG2	29	22	26
DG3	44	21	20
DG5	26		15
DG6			18
DG7		22	
DG8	27		
DG9	27	17	28
DGC	15		15
Mean (DG2, 3 & 9)	33	20	25

Table 4. *Summary of the percentage ratios of post-disposal potential bedload and suspended load immersed weight sediment transport rates to pre-disposal rates. Bedload ratios could not be calculated for June due to the absence of static friction angle measurements.*

Site	Bedload Ratio (%) February	Bedload Ratio (%) April	Suspended Load Ratio (%) February	Suspended Load Ratio (%) April	Suspended Load Ratio (%) June
DG1			66	86	70
DG2	139	116	61	50	
DG3	268	264	80	56	32
DG4			79	72	
DG5		189	66	71	56
DG6			53	66	
DG7			95	97	
DG8			58		88
DG9	173	99	54	99	
DGC		93		81	128
Mean	193	152	68	75	75

DG3 and DG9) was used to statistically analyse trends over time. The immediately post-disposal sediments show a dramatic and statistically significant ($\alpha = 0.10$) decrease in static friction angle compared with the pre-disposal shelf sediments. After two months, the static friction angles show a significant ($\alpha = 0.20$) increase over the immediate post-disposal values, although they are still lower than pre-disposal angles.

Predicted Potential Sediment Transport

The ratios between the post-disposal and pre-disposal sediment transport rates as determined by Equations 2 and 4 are summarised in Table 4. Calculations were only performed when the necessary data were available for pre- and post-disposal conditions.

Evidently there is a markedly increased potential for bedload sediment transport following disposal. The data also suggest that this decreases with time, but the differences between the February and April data are not statistically significant ($\alpha = 0.05$–0.20). The increase in bedload transport is primarily due to a decrease in the static friction angle, and only to a minor extent (2–5%) on an increase in local bed slopes. This is demonstrated by the data for site DG3 where a 1° change in the static friction angle is associated with an increase of 13% in the bedload transport rate ratio.

The potential suspended sediment transport rates decrease markedly after disposal. This is primarily due to an increase in the mean settling velocity of the surficial sediments. The rates appear to increase with time, but the changes are not statistically significant ($\alpha = 0.05$–0.20).

Bedform Monitoring

Prior to disposal, the seabed consisted of predominantly flat, featureless regions, with occasional patches of rippled to megarippled sand. The bedformed regions consisted of medium to coarse surficial sediment (mean grain size of 1.17 ϕ to -0.13 ϕ, 0.44 mm to 1.09 mm), whereas the flat regions were associated with fine to medium sand (2.15 ϕ to 1.40 ϕ, 0.23 mm to 0.38 mm). There was a positive correlation between grain size and bedform dimension, as noted previously for this area (HEALY *et al.*, 1991). Both the NIELSEN (1981) and KOS'YAN (1988) methods were good predictors of the pre-disposal bedform dimensions (FOSTER, 1992).

Following placement, the entire dump ground was characterized by patchy sonagraphs as noted previously in similar studies (HANDS and DELOACH, 1984). The seabed within the dump ground consisted of degraded mounds, corresponding to individual hopper loads of dredged material, with superimposed sand-waves and megaripples. Some of the patchiness of the sonagraphs was due to the presence of pumice and fragments of wood incorporated into the dredged material. The dredge spoil mounds were also covered with a higher proportion of large shell fragments than the surrounding regions, these being concentrated in the troughs of bedforms. Side-scan sonar, Manta Board, and underwater video indicated bedforms were more common within the dump ground than surrounding regions, and that the bedforms were consistently larger (FOSTER, 1992; WARREN, 1992).

Table 5 compares predicted ripple bedform dimensions following disposal, as determined by Equations 5–11 assuming quartz density sediment, with those measured by SCUBA divers. The NIELSEN (1981) method was applied to the range of wave heights and periods observed near the dump ground (DE LANGE, 1991). A total of 1,640 combinations of wave heights from 0.1 to 4.0 m (at 0.1 m increments), and wave periods from 5.0 to 15.0 sec (at 0.25 sec increments) were simulated for each dump ground site. The two examples presented in Table 5 represent the mean annual wave climate (Nielsen 1) and typical storm values (Nielsen 2).

A comparison between bedform dimensions predicted by the NIELSEN (1981) method for all

Table 5. *Ripple bedform height (η) and length (λ) in centimetres observed within the dump ground shortly after disposal and predicted by the methods of Nielsen (1981) and Kos'yan (1988). The first Nielsen case corresponds to the mean annual significant wave height (0.5 m) and peak period (10.6 sec), and the second to typical storm values (H_s = 2.0 m, T_p = 8 sec). Also included are the mean values, and the Pearson-Product moment correlation coefficients (r) between the various predictions and the measured bedform dimensions.*

	Measured		Nielsen 1 (mean annual)		Nielsen 2 (storm)		Kos'yan	
Site	η	λ	η	λ	η	λ	η	λ
Dump ground								
DG1	12	70	4.5	35.4	7.4	44.1	6.1	33.0
DG2	4	20	4.4	35.8	6.9	38.7	4.3	24.3
DG3	15	75	4.5	35.7	7.1	39.6	4.6	26.0
DG4	10	50	4.6	34.5	8.1	78.2	10.6	54.1
DG5	6	35	4.6	35.1	7.7	48.6	7.3	38.9
DG6	8	45	4.5	35.2	7.5	46.0	6.6	35.6
DG7	10	65	4.5	35.5	7.3	42.8	5.7	31.1
DG9	8	45	4.5	35.4	7.4	43.8	6.0	32.5
DGC	5	30	4.5	35.5	7.3	42.3	5.5	30.4
Mean	8.7	48.3	4.5	35.3	7.4	47.1	6.3	34.0
Correlation coefficient			0.198	−0.006	0.076	0.020	0.060	0.019

the combinations of wave height and period considered and those observed shows that < 5% of the predicted bedforms had a similar height or length to those measured. No storms matching or exceeding the conditions required to produce predicted bedforms similar to those observed occurred between the cessation of disposal and the measurement of the bedforms. These conditions correspond to moderate storms with wave heights of 1.7 to 2.5 m, and periods of 7 to 9 sec. Most of the remaining combinations of wave height and period under-predicted both bedform height and length.

The correlation coefficients between the measured values and the predictions by the NIELSEN (1981) method are very low (Table 5). The KOS'YAN (1988) predictions based solely on sediment grain diameter do not provide a significantly better estimate of bedform dimensions for the dump ground. This is due to both methods being based on parameters that do not vary greatly from site to site over the dump ground, whereas the actual measured bedforms show considerable variability.

DISCUSSION

Consolidation of Spoil Mound

The lack of measurable consolidation in the consolidation tests suggests that the sediments making up the spoil mound are normally consolidated with respect to the ambient stresses, or even over-consolidated such as has been reported by RICHARDS (1984) for marine sediments. It is thus apparent that primary consolidation of the dredged material occurred before the sediment sampling in February 1991.

This is confirmed by the moisture content data which show no significant increase over pre-disposal values. It is commonly reported that the moisture content of the post-disposal sediment is higher than the pre-disposal moisture content owing to the entrainment of site water during descent (BOKUNIEWICZ *et al.*, 1978; TRUITT, 1988). However, consolidation involves the expulsion of pore waters, so the attainment of normal consolidation will mean the establishment of an equilibrium moisture content similar to that existing before disposal.

Consolidation in these sediments is, therefore, believed to be extremely rapid. This is consistent with the sandy nature of the material which allows free and rapid drainage of pore water and release of pore water pressures and, hence, very rapid consolidation (CHANEY, 1984). Such behaviour is characteristic of sandy materials; sediments containing clays will take a much longer time to consolidate due to the reduced permeability of the material (LAMBE and WHITMAN, 1979). Thus, self-consolidation over time may be an important factor in the deflation of other spoil mounds if they contain appreciable quantities of cohesive clay minerals, but it is not significant for materials such as these which have insignificant mud contents.

From the data in this study, clearly the consolidation phase was completed within a month of the final sediment placement. However, it is believed that normal consolidation was probably achieved well before the February sampling time and most likely occurred contemporaneously with deposition, such as described by PANE and SCHIFFMAN (1985). Indeed, observations of the spoil mounds by diver and echo sounder records suggest that consolidation is complete within minutes to hours of the release of the dredged material (FOSTER, 1992; WARREN, 1992).

Alteration in Packing Characteristics

Data from the bulk density determinations on surficial sediment samples show a significant drop in bulk density following dredged material disposal with an increase with time after disposal. Since consolidation is not occurring over this time scale, these changes in bulk density are attributed to variations in the density of packing of sediment grains. This repacking does not occur in response to vertical stresses (consolidation), but is due to the formation and migration of bedforms through the dredged material. Therefore the repacking is limited to the depth of sediment disturbed by the bedforms which appears to be ~0.5 m for this study.

The dredging and depositional processes severely disrupt the original structure of the sediment (TRUITT, 1988). This results in a poorly sorted, loosely packed sediment compared with that existing before disposal, and, hence, a reduced bulk density. With time, mobilisation of the upper layers of the spoil mound results in improved sorting characteristics and an increase in the degree of grain packing. This is reflected by the increased bulk density; and it is anticipated that over a longer time interval, there may be a further increase in bulk density up to a pre-disposal level.

Intuitively, a change in bulk density due to repacking in saturated sediments should be associated with a change in moisture content. Unfortunately, the observed variability of moisture contents for the dredged sediment was too great to provide any statistically meaningful trends. However, the interpreted changes in grain packing are supported by the measured static friction angles. The static friction angle of a sandy sediment is primarily controlled by the void ratio of the material and degree of interlocking of the grains. These, in turn, are functions of the packing, grain size, grain shape, and sorting of the sediments (LAMBE and WHITMAN, 1979); closely packed, well-sorted materials have high static friction angles due to a large number of grain-to-grain contacts. Marine sands typically have static friction angles of 26° to 34° (NIELSEN, 1992); however, the data from this study indicate that the variability may be much greater than this range.

The observed initial dramatic reduction in static friction angle can thus be explained in terms of the reduced density of packing of the grains and is enhanced by the sediment being less well sorted after disposal. Over time, we infer that closer packing developed, which, together with improved sorting, resulted in an increase in the frictional resistance of the sediment. As the shear strength (represented directly by static friction angle in this case as the materials are believed to be cohesionless) of the material is critical for determining the capacity for bedload transport, these temporal alterations in the packing arrangements have important ramifications when considering the migration of sediment away from the disposal site.

Mobilisation of Dump Ground Sediment

The dump ground after dredged material disposal exhibits an increased potential for bedload transport and a decreased potential for suspended load transport. This is attributed to decreased static friction angles, increased local bed slopes, and increased mean settling velocities of surficial sediments. There is also an increase in the development of bedforms within the dump ground compared with the surrounding sea bed.

The surficial sediment observed over the dump ground consisted mainly of quartzo-felspathic sand, with coarser sediment within the troughs of bedforms composed mainly of shell and wood fragments and pumice (WARREN, 1992). An influx of sediment matching the coarse trough materials was observed on beaches inshore of the dump ground immediately following disposal. Although previous dredging operations have deposited similar materials on the inner shelf landward of the dump ground examined here (HEALY *et al.*, 1991), it is probable that the influx of sediment originated primarily from the dump ground studied given the timing of the event. This observation is consistent with the predicted increase in potential bedload transport immediately following disposal.

The results of this study indicate that the increase in bedload transport is likely to be short-lived, but the study does not cover a sufficient time span to quantify the total duration involved. Previous studies of similar dredge grounds nearby concluded that spoil mounds became static within two years of dredged material placement (HEALY *et al.*, 1991).

Large bedforms within the dump ground may be a consequence of the increased mean grain diameter of the surficial sediments as indicated by the relationships of KOS'YAN (1988). However, the bedforms within the dump ground were consistently larger than predicted by either of the empirical methods used and representative of a higher flow regime than accounted for by the observed conditions.

Except for extreme storm conditions, suspended sediment transport rates near the dump ground were found to be negligible; as calculated by Equation 3 and determined from turbidity measurements (FOSTER, 1992). During extreme storm conditions, suspended transport rates were still at least an order of magnitude smaller than bedload transport rates.

CONCLUSIONS

The dredged material considered here underwent very rapid consolidation, the bulk of which occurred contemporaneously with deposition. This result is in keeping with the very coarse, sandy nature of the dredged material for which rapid consolidation is the norm.

Immediately after deposition, the static friction angle (shear strength) decreased markedly and then increased slowly with time. Bulk density displayed a similar trend of an initial decrease followed by a gradual increase over time. The reduction in shear strength and bulk density reflects a disordering of the structure of the material during the dredging and disposal process. Re-packing of the surficial sediments over time was responsible for the subsequent increases measured.

As a result of reduced static friction angles following deposition, potential bedload sediment transport rates increased dramatically over pre-disposal conditions. The potential bedload transport rates decreased with time following placement as static friction angles increased. It is considered likely that static friction angles and bedload transport rates will return to near pre-disposal values, but this study was not long enough to observe this. Bedforms within the dump ground reflected a higher energy regime than would normally be expected, being consistently larger than predicted because of the decreased shear strength of the dredged material.

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