Appendix 26

Chatham Rise Rock Phosphates Project – 
Phase 2: Resuspension Study (Deltares 2014c)
Chatham Rise Rock Phosphates Project - Phase 2 Resuspension Study
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Chatham Rise Rock Phosphates Project - Phase 2 Resuspension Study

In the framework of the Chatham Rise Rock Phosphates (CRP) Project, Boskalis requested Deltares to investigate the dispersion behaviour of sediments released during the mining process on the Chatham Rise. This report focuses on the analysis of background turbidity in the study area as well as the analysis of bed properties collected from different sampling campaigns. The objectives are to investigate the resuspension of the bed at present, and how this will change after the mine tailings have been discharged. The results contribute to a detailed design study and an Environmental Impact Assessment for the Chatham Rock Phosphate Mining Project.

Important drivers of sediment transport on the Chatham rise are the residual currents and eddies, vertical mixing, tidally induced bottom shear stresses and the particle settling velocity. Sediments on the rise are a predominately glauconite, fine to medium sandy muds or muddy sands interspersed with phosphate nodules. Turbidity measured by instruments near the bed show that background concentrations are low and there is no clear relationship with residual flow patterns.

The cohesive nature of the sediment, density and shear strength measurements were used to estimate empirically the erosive nature of the bed. It was found that the critical shear stress for erosion required to erode the surficial sediments is higher than ambient modelled bed shear stresses. The critical erosion threshold for the mine tailings is lower due to a reduced bulk density and hence shear strength. However this range can vary considerably depending on the water content of the slurry. In addition, turbidity around the discharge area will be temporarily increased due to release of finer material from the slurry during the release. Extreme events, such as internal tides may play a role in increasing bed stresses and vertical mixing.

Note: this report has been updated to account for the changes made to the 2013 operational reports being re-issued as a single 2014 report (Deltares 2014a).
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1 Introduction

In the framework of the Chatham Rise Rock Phosphates (CRP) Mining Project, Boskalis (Royal Boskalis Westminster N.V.) requested Deltares to investigate the dispersion behaviour of sediments released during the mining process. The main interest is the turbidity generated in the water column and the deposition footprint on the seabed resulting from the mining discharge. Boskalis has requested that Deltares investigate the natural background turbidity in the water column and the resulting deposition footprint for several mining operation scenarios.

This particular study focuses on the analysis of background turbidity in the study area from Teledyne RD Instrument (RDI) Acoustic Doppler Current Profiler (ADCP) and AquaTec AquaLogger records, as well as the analysis of the bed properties collected from different sampling campaigns. The bed properties help determine the processes influencing resuspension of the bed at present and how this may change as a result of a) dredging of the coarser material from the seabed and b) the discharge of mine tailings onto the seabed.

This report is structured into the following sections

- The context and objectives of this study
- An introduction to the features of the study area and the characteristic bed properties, as determined from various cruise reports and Boskalis Offshore, (2012).
- Analysis of the background turbidity as recorded by the RDI ADCP and AquaLogger in relation to the Oceanographic Study (Deltares, 2014b).
- Analysis of the bed properties as derived from the different sampling campaigns to determine the erosive properties of the bed at present and how this may differ as a result of the discharge of the mining tailings.

The Chatham Rise is a submarine feature that is approximately 1000 km in length, extending east from the South Island of New Zealand (Figure 1.1). The rise has water depths that range from roughly 80 m to roughly 500 m, with the Chatham Islands near the eastern extent of the submarine feature. Just north and south of the Rise, water depths quickly approach 3000 m and more.

The Chatham Rise hosts economically significant amounts of rock phosphate captured in nodules lying on the seabed and in the top 30-40 cm of the seabed. Rock phosphate is a primary constituent of most fertilisers used in New Zealand, which is currently being imported from Morocco. Extraction of the Chatham Rise phosphate could provide a locally produced alternative for an estimated 100 year period and has a significant number of economic, environmental and market benefits.

The New Zealand Government awarded the joint venture Chatham Rock Phosphate Ltd (CRP) the prospecting license for two 2-year terms (2010-2014). CRP has the priority rights to either extend the prospecting permit or to apply for mining a license(s) after meeting all required obligations, including an Environmental Impact Assessment (EIA) study. In 2011, CPR exclusively selected Boskalis to undertake the detailed design of the offshore rock phosphate nodule project at Chatham Rise.
Figure 1.1 Map of New Zealand and the Chatham Rise (Wikipedia: Ngatimozart, 2010)
2 Objectives

2.1 Background and scope of this study

The dispersion and sedimentation behaviour of sediments released during the mining process is an important matter both in the EIA study and the detailed design study. On the request of Boskalis, Deltares conducted two exploratory studies on this topic in 2012 (see Deltares 2014a). The main interest of the first study was the turbidity generated in the water column and the deposition footprint on the seabed resulting from the mining discharge for several mining scenarios. The study involved indicative near-field computations of the dynamic plume with Jet3D and far-field computations of the passive plume (fine sediments only) with a Delft3D model. In the second study an initial validation of the modelled far-field (Delft3D) hydrodynamics was performed using measurement data from a moored RDI ADCP.

The present Phase 2 study is a follow-up of the Phase 1 studies and comprises 7 tasks clustered over three sub studies:

- **An Oceanographic study** (Deltares 2014b), focusing on assessing the representativeness of available and previously used oceanographic data of 2011 and the relative importance of various processes.
- **A Resuspension study** (this report), investigating how phosphate mining impacts the natural sediment dynamics and the resuspension of mine tailings in particular.
- **An Operational study** (Deltares 2014a), focusing on re-running the single-cycle, multiple cycles and incidents with a relocated local Delft3D model to the RDI mooring location.

The results of these studies feed into the on-going detailed design study undertaken by Boskalis and the Environmental Impact Assessment Study for the Chatham Rise Rock Phosphate carried out by Golder Associates.

2.2 Objectives of the Resuspension Study

The objective of the study reported here is to determine how the background turbidity, in particular the resuspension of bed material, and subsequent sedimentation as it presently is, will change due to the modification of bed surface material between pre- and post-mining. Through the mining process, the top 30 cm of the bed will be dredged, taken on-board and sorted. Anything larger than 2 mm will be removed and the remaining material, mixed with seawater, will be returned to the seabed using a tremie-like diffuser. The material will be discharged with a very low discharge velocity to minimize the area of the mine tailings footprint and turbid plume. The objective here is to investigate:

1. How the resuspension of the bed material after the mine tailings have been discharged will change under natural flow conditions, compared to the resuspension of the natural seabed material. It should be noted that consolidation of the deposited mine tailings will not be taken into account.
2. In-situ turbidity measurements (ADCP and AquaLogger) measurements will also be analysed to identify when, why and what turbidity events occur in the ‘natural’ system. Deltares will analyse the turbidity measurements, in combination with the findings of the Oceanographic Study results and previously run model scenarios around two potential mining sites on the Chatham rise (Figure 2.1).
Figure 2.1 Mine licensing areas on the Chatham Rise
3 Study Area

The currents on the Chatham Rise are driven by a combination of tides, wind, and buoyancy. Buoyancy effects (mainly temperature, to a lesser degree salinity) generate horizontal and vertical density gradients which, in combination with the topographic rise, drive up- and downwelling (vertical velocity circulation cells). In the case of vertical stratification, internal tides may be generated, characterised by opposing tidal current velocities below and above the density interface. Residual flow is mainly driven by large-scale wind patterns, generally in the eastward direction. Tides generate oscillations on semi-diurnal, diurnal, and fortnightly timescales. The combination of tides and residual flows drive large-scale horizontal circulation cells.

Important drivers of sediment dispersal on the Chatham rise are, 1) the role of mean flow and eddies in advecting and stirring suspended particles; 2) vertical mixing by wind driven shear near the surface or by internal tides (typically in the middle of the water column); 3) tidally induced bottom shear stresses and 4) the sediment settling velocity. A study by NIWA (Hadfield, 2011) found that near bottom, particles are not so widely dispersed.

The strongest flow is associated with the M2 barotropic tide and is consistent with a trapped wave rotating anti-clockwise around New Zealand (Heath et al., 1983; Nodder, 2012). However there are large gradients of water properties across the rise, associated with subtropical convergence (Heath et al., 1983). As with internal tides, currents associated with continental shelf waves are likely to influence sedimentation and mixing (Heath et al., 1985). Hadfield et al., (2011) and Nodder, (2012) found that the total horizontal particle mass fluxes increase with depth and there is a presence of a flux maximum around ~200m depth. They also found a high organic matter content in the suspended matter. Likely causes were lateral advection and/or resuspension of bottom sediments. Fluxes were found to be highest in spring, when organic carbon and biogenic silica fluxes are elevated (Hadfield et al., 2011).

Sediments in the area are mainly phosphorite bearing glauconite, fine to medium foraminiferal sandy muds or muddy sand, rock fragments, volcanic ash clay minerals and biogenic materials. The bed sediments often contain up to 30-40% calcium carbonate. Phosphorite nodules typically between 0.5 -1 mm, however, nodules up to 50 – 200 mm are found. The fact that the sediments have a high calcium carbonate content, resulting from broken down organic matter, suggests that there is a very slow natural rate of sedimentation. According to Nodder, (2012), bed sediments originate from remobilisation and redistribution of relic sediments and authigensis. The upper bed surface is relatively unconsolidated with no ripple features visible.

Bowen et al., 2012 found that there is little correspondence in time or magnitude between turbidity and the magnitude of the flows measured but that there are higher values of turbidity when flow directions are within +/- 45 degrees of north and south. A previous Deltares study found that the maximum horizontal velocities are of the order of 0.4 m/s, whereas the maximum vertical velocities are typically two orders of magnitude smaller, during the 2011 spring and winter (Deltares, 2014b). However, the 2011 summer has vertical velocities that are typically one order of magnitude smaller than horizontal velocities, with vertical velocities as large as 0.2 m/s (Deltares, 2014b).
3.1 Available Data

3.1.1 Turbidity Measurements

Within the Chatham Rise project, hydrodynamic and turbidity measurements on top of the Rise were conducted in 2011. The IX Survey Measurement data analysed in this report, consist of:

1. Turbidity and flow velocity over the vertical measured by an RDI ADCP
2. Turbidity measured by an Aquatec instrument, AquaLogger.

The ADCP measurement period ranged from May 21st to November 13th 2011 which was assumed to be representative for the flow conditions generally present near the ADCP mooring location specifically and in the mining area in general. The mooring was located at 43° 29.0030' S 179° 20.0990' E (Figure 3.1) on the Chatham Rise at a depth of 362.74 m. The RDI ADCP was fixed in a frame and located 17 m above the seabed. The centre of the first depth bin was located at 30.5 m above the bed. The water column was divided into bins with a height of 5 m. The top 10% of the data below the surface was removed, as they may be subjected to side-lobe interference. This leads to 64 valid cells with cell centres between 30.5 and 345.5 m above the bed. Every 30 minutes an ensemble averaged profile was recorded, consisting of 50 members spaced by 6 seconds, thus over a period of 5 minutes.

Nearby, 80 m from the ADCP frame, two turbidity sensors (AquaLogger) were mounted at 21 m and 7 m above the bottom. The AquaLogger measured for a slightly longer period than the ADCP: from May 21st to December 11th, 2011.

3.1.2 Cruise Overview

Field measurements from different sampling campaigns were summarised by Boskalis in, ‘Summary and Analysis of Site Investigation’ (Boskalis Offshore, 2012). This report compiled information from cruises from 1975 until 2012 (Figure 3.1-Figure 3.3). The main focus areas were the twelve proposed mining zones, the distribution of phosphate nodules and the chemistry therein. A brief summary of each cruise is provided below:

- The Valdivia Cruise (1978) surveyed the central part of Chatham Rise and found it to be covered by muddy, glauconite sand and silt, embedded with phosphorite nodules. The glauconite sand was bioturbated and had a widespread muddy surface layer without any stratifications or textures. Underlying this is a formaniferal ooze layer.
- The Sonne Cruise (1981) surveyed mainly the east of the mining areas and found that the phosphorite is a nodular gravel intermixed on the seabed with glauconite formaniferal muddy sand and overlying late Eocene to Middle Oligocene formaniferal nanno chalk. The overlying formaniferal glauconite sand is thoroughly mixed by bioturbation and has an average thickness of 20-50 cm. The phosphorite nodules usually occur as layers at the base of the glauconite sand and above the ooze. In general 2-70 cm or more of silt or sand are overlying this chalk or ooze layer. Different types of sediment were identified during this cruise; 1) very soft clayey fine sandy silt; 2) clayey silty fine sand and fine sandy clayey silt; 3) formaniferal ooze (stiff); 4) chalk, indurated and buried in the ooze and 5) hard rock like phosphorite nodules. In general the phosphorite bearing glauconite formaniferal sands are poorly to very poorly sorted, muddy and gravelly fine sands, with a mud percentage of 20-40% (with little clay), 30-60% fine and medium and a very little medium and coarse sand. The
surface sediments have low strengths but the underlying glauconite sand/silt material becomes stronger with increasing depth due to consolidation.

- The Dorado Cruise (2011-2012) took several samples surrounding the RDI location and found that most of the fine glauconite, silty sand behaves like well packed fine sand/coarse silt.
- The Tranquil Cruise took surficial sediment samples which were analysed with a focus on determining grain size characteristics, the trace element composition of the sand fraction, water absorption and the dry and saturated density of the phosphate nodules.

![Figure 3.1 Overview of sample locations from each sampling campaign](image-url)
Figure 3.2 Dorado Discovery cruise sample locations (2011-2012)

Figure 3.3. Tranquil cruise sample locations (2011)
4 In-situ turbidity analysis (ADCP and AquaLogger)

To determine the dominance of tidal and non-tidal phenomena, both the RDI ADCP current measurements and the Aquadopp current measurements were analysed in Deltares, (2014b). The RDI ADCP gives information over the full depth of the water column, except for the top 8% and the bottom 8% (30 m) close to the bed. This near-bed layer is covered by the Aquadopp, which has measured current speed and direction at a distance of 8 m from the bed. Nearby, 80 m from the ADCP/Aquadopp, two turbidity sensors (AquaLogger) were mounted at 21 m and 7 m above bottom. In this report, the results for the RDI ADCP are shown, complemented with the AquaLogger measurements.

It was concluded that the ADCP measurement period can be considered representative for the weakly stratified hydrodynamic conditions in the vicinity of the ADCP close to the bed (For more details see: Deltares, 2014b) and so we assume it is also representative for the turbidity signal.

4.1 AquaLogger

An AquaLogger turbidity sensor recorded background values of turbidity over a five-month period slightly different to the ADCP (Figure 4.1). The turbidity time series in general show sustained background values around 2 FTU (Formazin Turbidity Unit). Formazin Turbidity Units (FTU) is the unit applied when any angle is used when measuring light attenuation. Nephelometric Turbidity Units (NTU), as for the ADCP, requires for a 90° measurement technique and is more widely used. FTU and NTU units can be considered ~1:1. The increasing turbidity, and maintained high values above 4 FTU since October, is questionable (Deltares 2014b). An increasing trend in turbidity over time, without a known disturbance, is commonly linked to biofouling of the sensors. On the other hand, biofouling often leads to an exponentially increasing turbidity, and not to a new equilibrium at values ~5 FTU. Several short-term events with significantly higher values (> 10 FTU) were recorded during the deployment.

Bowen (2012) and Bowen (2013) found no correspondence between turbidity and the magnitude of the flows measured at the current meter at 8 m above bottom at the mooring nearby, even when both records are averaged and time lags are applied to account for time taken for upward motion of suspended material. A correspondence would be expected if suspended material is dominated by material resuspended locally from the bed. Although the flow is being measured 80 m away, given the uniform bathymetry and the large scale of tidal flows, the currents at one mooring should be representative of the flows at the other. Local tidal resuspension is not clear at 7 m above bottom but may occur nearer bottom and contribute to the overall turbidity. This issue is addressed in the section Tidal Analysis below.
4.2 RDI ADCP

The Oceanographic Study (Deltanes, 2014b) found that the maximum tidal speed recorded by the ADCP is ~0.4 m/s near the surface and ~0.3 m/s near the seabed. The Aquadopp shows slightly larger values, which indicates that an under prediction of the near-bed ADCP velocities might occur. The flow velocity is composed of a tidal part (resulting in flow velocity periodicities from half a day to a fortnight) and a residual part (non-tidal part). Residual flows typically result in a residual advection of suspended sediments, whereas the tidal part of the flow is mainly important for resuspension and dispersion (vertically and horizontally) of sediment. In winter 2011, residual currents are largest near the surface, whereas in spring 2011 (~ September), largest residual currents occur near the bed. In the near-bed layer the residual has a northward to eastward and westward direction and magnitude of 2 to 7 cm/s (Figure 4.2 - Figure 4.3).

A signal emitted from an ADCP is scattered by suspended matter, including plankton, sediments, bubbles etc. (IX Survey, 2011). The backscatter coefficient (in dB) is calculated from the echo intensity corrected for water attenuation, power attenuation and properties of the transducer. The backscatter of the ADCP was converted to NTU values (a measure for turbidity) by IX Survey using a linear regression. However, it is important to realise that the sound absorption by seawater is computed with vertically uniform values for temperature and salinity (as recorded by the ADCP) whereas in reality the water column may be stratified (see Deltanes, 2014b). For a salinity of 30 ppt, the attenuation coefficient due to temperature may vertically change a factor 1.5 for stratified summer conditions (16°C near surface and 6°C near-bed). With a water depth of ~400 m, vertical variations in attenuation (while using a
constant attenuation coefficient) may lead to apparent concentration changes. However these measurements did not contain a period with strong stratification.

Figure 4.4 shows profiles of the mean, maximum and minimum turbidity values over the water column. These profiles show a reverse (convex) logarithmic profile for turbidity in the water column with lower values near the bottom ADCP bin. Such patterns are physically unrealistic: for conditions where the suspended sediment originates from the local bed, the sediment concentration is either vertically uniform or increasing towards the bed. Deltares, (2014b) showed that the measurement period, covering late autumn, winter and early spring, consistently represents the relatively weakly-stratified flow conditions. Therefore the reversed profiles seen here may also be the result of incorrectly applying linear calibration of the values through the whole water column. The reversed profiles may also be due to the greater advection of organic and inorganic particles mid-water column. The lack of a distinct logarithmic trend may also be explained by the overall low turbidity: maximum values throughout the whole measurement period do not exceed 3.5 NTU and no high turbidity events are captured therefore the measurements are very sensitive to errors in the calibration as the turbidity is so low.

Values from the AquaLogger turbidity measurements which are lower in the water column and closer to the bed are included (21 m and 7 m above bottom). The AquaLogger values have a slightly higher mean near bed value than the lowest ADCP bin in July, August and September and just over 1 NTU larger in October, but values remain low overall. Note that the spikes visible in Figure 4.1 were not removed and November values were ignored due to the unexplained shift in values near the bed.

In order to separate high-frequency tidal signals from long-term residuals the original turbidity signal (Figure 4.5) is low-pass filtered (using a Godin filter), see Figure 4.6. Again, the turbidity in the lower bins of the ADCP is low throughout the whole timeseries. The near-surface concentration is larger around mid-September. This may be related to the higher near-bed residual flows around this period. However, it is hard to determine if this is event-driven or as a result of ADCP calibration (especially considering that temperature-induced stratification will probably develop around October).

Like with the AquaLogger, there is no apparent link between current residual time-stacks and turbidity patterns. Northward residuals are more dominant near the bed in September/October and maybe linked with low turbidity as material is moved away from the area.
Figure 4.2 Residual flow (computed with tidal analysis using t-tide) based on RDI ADCP data (from Deltaires, 2014b)

Figure 4.3 Residual flow (computed with tidal analysis using t-tide) based on Aquadopp data. Direction in nautical convention.
Figure 4.4 Minimum, mean and maximum ADCP turbidity profiles per month with mean and maximum AquaLogger values plotted at two recorded depths.
Figure 4.5 Unfiltered time-stack of turbidity from the RDI ADCP

Figure 4.6 A Godin filtered time stack of turbidity from the RDI ADCP
4.3 Tidal Analysis

A tidal analysis on the turbidity signal from the RDI ADCP and the AquaLogger was performed using the T-tide toolbox for MatLab (Pawlowicz et al. 2002). Whether a constituent can be resolved and is significant depends on the measuring interval and duration. The Rayleigh criterion determines whether two tidal constituents with almost equal frequencies can be distinguished from each other. To be able to resolve the frequency pairs K1 and P1 and MSF and MF, the Rayleigh criterion is set to 0.9. This means that two waves with almost equal frequency need to differ by at least 0.9 wavelengths in the total length of the record in order to be resolved.

When tidal resuspension dominates the sediment concentration, a concentration peak should occur at both ebb and flood. Hence, the frequency of turbidity is twice the frequency of the water levels. The currents associated with the M2 tidal constituent are dominant in this region, and if this M2 tides result in tidally driven resuspension, the turbidity signal should show M4 dominance. However this is not the case in the ADCP measurements suggesting that the turbidity signal in the water column is (1) not supplied by resuspension from the bed (2) event-driven, or (3) dominated by noise.

A clear K1 (luni-solar diurnal) dominance is observed in the RDI amplitudes of turbidity (Figure 4.7-Figure 4.8) which is even more prominent in July and August. K1 has a period of 23.93 hours, and therefore this dominance could possibly be related to the day-night cycle (influencing biology-influenced scattering). The principal solar semi-diurnal S2 component is the next most dominant in the winter period (June, July and August) but decreases in the spring. It should be noted that the signal in Figure 4.7-Figure 4.8 could also include the effects of internal tides. There is a clear maximum turbidity range at a height between 200 and 300 m above the bed, corresponding to the location of maximum stratification (Deltares, 2014b). It could, therefore, be that the large turbidity in K1 is generated by day-night vertical motion of the interface.

Figure 4.9 and Figure 4.10 show tidal analysis of the AquaDopp current data and corresponding AquaLogger turbidity data, for the near-bed and upper sensor, respectively. A contribution of at most 0.1 FTU to the M4 signal in the turbidity data in the top AquaLogger (21 m above the bed) indicates that part of the signal near the bottom is due to resuspension from the bed. Between mid-October and mid-November, the bottom AquaLogger measures an M4 contribution to the turbidity of up to 0.35 FTU but this is expected to be associated with the unexplained shift in the data during this period (see Figure 4.1).

Note that the sharp rise in amplitudes in the near-bed signal from the start of November is associated with the unexplained shift in the data in this period (see Figure 4.1). However, the non-tidal residuals associated with the AquaLogger are approximately 10 times larger in magnitude than the associated M4 amplitude, suggesting that likely less than 10% of the turbidity signal is as a result of tidal resuspension of bed material (Figure 4.11).
Figure 4.7 Amplitudes of turbidity per tidal constituent for June to August
Figure 4.8 Amplitudes of turbidity per tidal constituent for September, October and the entire period.
Figure 4.9 Tidal constituents from the AquaDopp current velocities

Figure 4.10 Tidal analysis on AquaLogger turbidity data for the near-bed (upper panel) and upper sensor (bottom panel).
It is important to also note that from the measurements available, it is not clear as to what type of material(s) is (are) resuspending. It is quite likely that some of the resuspended material is detrital, which is typically light and would naturally be on the surface of the seabed. However, information on the properties of the surface detrital material is not available for consideration in this study nor has it been modelled.

Beyond the AquaLogger measurements, the lack of M4 amplitudes measured by the ADCP further up in the water column suggests that the extent of influence of tidally-induced resuspension remains in the lower water column.

In order to evaluate the relative importance of advection, the sediment flux is computed at several ADCP depth bins (Figure 4.12). The flux is approximated by multiplying the turbidity with velocity (since turbidity is not concentration, this is not formerly a sediment flux). There is no pronounced tidal asymmetry (only a minor flow asymmetry associated with the residual flow), so scatter plots of the fluxes could reveal if there is a preferential direction from which the sediment is coming from. The resulting plots show that there is no dominant flux direction associated with the turbidity values throughout the water column. In some bins the north-west quadrant is slightly prominent indicating that transport may originate from the opposite (south-easterly) direction. Bin 1 represents the ADCP bin closest to the bed (+30 m), where values are lowest with the least spread, and Bin 64 is that closest to the water surface with the largest spread of values.

4.4 Conclusions

The turbidity approximated by the ADCP and the AquaLogger sensors reveal that concentrations are quite low. It is likely that the sediment-induced signal is weaker than errors introduced by the measurement method. There is no clear relation with residual flow patterns or tidal resuspension, or tidal advection in the ADCP data. For the ADCP, the best correlation was obtained with the K1 tidal frequency. Since the frequency of this component is close to the day-night cycle, and the maximum turbidity is close to the (temperature-induced) density interface, this correlation may be influenced by solar radiation. The AquaLogger sensor shows a minor contribution by the M4 to the turbidity signal, likely less than 10%. This indicates that part of the signal is due to tidal resuspension, however, the influence of tidal resuspension remains limited to the lower water column and likely explains less than 10% of the total turbidity signal.
Figure 4.12 Direction dependent turbidity scatter plots for different ADCP bins over depth [NTU]
5 Resuspension analyses

The sediment bed on the Chatham Rise is composed of sand and (consolidated) mud. After mining, the majority of the sediment is placed back on the seabed. A major question is how erosion of this material by ambient currents may change due to mining. This question is addressed by (1) analysing the soil properties of the in situ bed material and translating this into erosion properties of the soil, (2) estimating changes in soil composition due to dredging and resulting change in erosion properties, and (3) comparing this to bed shear stresses exerted by ambient currents. The approach is as follows. First, the seabed sediments in the Chatham area are introduced (5.1), followed by a theoretical framework on erosion from a soil mechanical perspective (5.2). Then erosion of in situ sediment is estimated (5.3) erosion of mine tailings (5.4) by ambient currents, and finally a short analysis on possible occurrences of extreme erosion events is presented (5.5).

5.1 Bed composition and properties

The surface bed composition varies throughout the Chatham Rise from sandy silts, to muddy sands interspersed with phosphate nodules. Beneath is a combination of foraminiferal ooze and chalk layers (Boskalis Offshore, 2012). In this study only the properties of the surficial sediments (down to 20-30 cm depth) are analysed in terms of erosive properties. The Tranquil Image Cruise in 2011 sampled predominantly medium to fine grained sands, while the Dorado Discovery environmental cruise (2012) sampled predominately glauconite fine muddy sands with phosphate nodules dispersed through the upper sediment layers (Figure 5.1).

For the resuspension analysis, analyses were focussed on the area surrounding the RDI, within the CRP licence area (Figure 5.1) including Mining Areas 4 and 13, hence forth described as the study area. The geotechnical parameters (Atterberg limits, shear strengths) associated with the Sonne Cruise were not included in the analysis as they were not considered trustworthy (personal communication, (2013) and Boskalis Offshore, 2012) because the samples were too sandy. The parameters used in the analysis were therefore taken from the Dorado Discovery and Tranquil cruises (Figure 3.2 and Figure 3.3).

The variation in surface sediment properties over the Chatham Rise can be seen in Table 5.1. A larger range of shear strengths were measured from the Dorado Cruise samples, with the shear strength values for the Sonne cruise (1981) being at the lower end of this range. Unfortunately no shear strengths from the Tranquil Image cruise (2011) were available to validate the shear strengths from the Sonne Cruise samples east of the focus area.
Figure 5.1 Study area and highlight of samples used with mining areas outlined in dark blue

Table 5.1 Bulk density and undrained shear stress ranges per cruise

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Average Density [kg/m³]</th>
<th>Bulk Density Range [kg/m³]</th>
<th>Undrained Shear Strength [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonne Cruise: upper 10cm</td>
<td>1640</td>
<td>1510-1770</td>
<td>2-5</td>
</tr>
<tr>
<td>Sonne Cruise: from 10-50cm</td>
<td>1720</td>
<td>1590-1990</td>
<td>2-5</td>
</tr>
<tr>
<td>Tranquil Image Cruise (2012)</td>
<td>1800</td>
<td>1590-2090</td>
<td>n/a</td>
</tr>
<tr>
<td>Dorado Cruise (2012)</td>
<td>1705</td>
<td>1210-2160</td>
<td>4 - 20</td>
</tr>
</tbody>
</table>

The structure and packing of the sediment, reflected in the density, is important for its mechanical (erosional) behaviour. Boskalis Offshore, (2012) describes that the sediment in the area of interest here is well packed in some locations and looser in others. The density of the seabed is parameterised with the dry bed density \( \rho_{dry} = \frac{M_s}{V_t} \) and the bulk density \( \rho_{bulk} = \frac{M_s}{V_t} \), where \( M_t \) is the total mass of the sediment-water sample, \( M_s \) is the mass of the solids in the sediment-water sample, and \( V_t \) is the volume of the sediment-water sample.
The density of the sediment is influenced by:

- Cementation due to carbonates: the carbonate content in these samples is of the order of 30-40%.
- The sand-mud (and gravel) content: the percentage of gravel, sand and mud also varies throughout the study area with higher mean mud values for the Tranquil Image cruise shown in Table 5.2. The range of values for the Dorado Discovery Cruise samples is shown in Table 5.3.
- The uniformity of the sediment: the spreading of sediments over various size-classes can be expressed as a uniformity coefficient ($\sigma_d$). This is the ratio of $d_{60}/d_{10}$ with $d_{10}$ [m] and $d_{60}$ [m] the particle sizes for which 10% and 60% is finer by weight respectively. A uniform grain size distribution (i.e. a well sorted soil) occurs for $\sigma_d < 1.35$, for which the frequency distribution is narrow and the cumulative distribution rather steep. Poorly sorted samples with a wide frequency distribution curve ($\sigma_d > 1.35$) contain a variety of sizes (Jacobs, 2011). It can be seen that the samples from the Dorado cruises are very poorly sorted with a large variety of grain sizes (Table 5.4).

Table 5.2 Mean sediment composition

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mean % gravel</th>
<th>Mean %sand</th>
<th>Mean %mud</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorado Discovery Cruise</td>
<td>7.14</td>
<td>56.44</td>
<td>36.4</td>
</tr>
<tr>
<td>Tranquil Image Cruise</td>
<td>11.8</td>
<td>47.2</td>
<td>41.1</td>
</tr>
</tbody>
</table>

Table 5.3 Values for the Dorado Discovery Cruise

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>% gravel</th>
<th>% sand</th>
<th>% mud</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD077</td>
<td>Surface</td>
<td>5.2</td>
<td>58.9</td>
<td>35.9</td>
</tr>
<tr>
<td>DD098</td>
<td>Surface</td>
<td>0.3</td>
<td>60.8</td>
<td>38.9</td>
</tr>
<tr>
<td>DD101</td>
<td>Surface</td>
<td>0</td>
<td>50.3</td>
<td>49.7</td>
</tr>
<tr>
<td>DD116</td>
<td>Surface</td>
<td>2.1</td>
<td>64.7</td>
<td>33.2</td>
</tr>
<tr>
<td>DD132</td>
<td>Surface</td>
<td>4.5</td>
<td>62.1</td>
<td>33.4</td>
</tr>
<tr>
<td>DD142</td>
<td>Surface</td>
<td>0</td>
<td>63.1</td>
<td>36.9</td>
</tr>
<tr>
<td>DD149</td>
<td>Surface</td>
<td>30.3</td>
<td>48.3</td>
<td>21.4</td>
</tr>
<tr>
<td>DD160</td>
<td>Surface</td>
<td>0.3</td>
<td>59.2</td>
<td>40.5</td>
</tr>
<tr>
<td>DD172</td>
<td>Surface</td>
<td>8.3</td>
<td>49.8</td>
<td>41.9</td>
</tr>
<tr>
<td>DD054</td>
<td>Surface</td>
<td>6.2</td>
<td>53.1</td>
<td>40.8</td>
</tr>
<tr>
<td>DD055</td>
<td>Surface</td>
<td>28.1</td>
<td>49.7</td>
<td>22.2</td>
</tr>
<tr>
<td>DD086</td>
<td>Surface</td>
<td>0.4</td>
<td>57.3</td>
<td>42.4</td>
</tr>
</tbody>
</table>
### Table 5.4 Uniformity coefficient (D60/D10) for the Dorado Discovery Cruise samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Uniformity Coefficient</th>
<th>Sample</th>
<th>Uniformity Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD4</td>
<td>5.4</td>
<td>DD207_6</td>
<td>5.2</td>
</tr>
<tr>
<td>DD8</td>
<td>8.7</td>
<td>DD213_2</td>
<td>8.4</td>
</tr>
<tr>
<td>DD12</td>
<td>15.9</td>
<td>DD212_2</td>
<td>5.2</td>
</tr>
<tr>
<td>DD19</td>
<td>6.0</td>
<td>DD212_4</td>
<td>7.4</td>
</tr>
<tr>
<td>DD23</td>
<td>24.4</td>
<td>DD192_1</td>
<td>13.5</td>
</tr>
<tr>
<td>DD29</td>
<td>8.8</td>
<td>DD192_4</td>
<td>4.2</td>
</tr>
<tr>
<td>DD33</td>
<td>7.6</td>
<td>DD190_2</td>
<td>8.7</td>
</tr>
<tr>
<td>DD38</td>
<td>9.9</td>
<td>DD195_1,2</td>
<td>6.5</td>
</tr>
<tr>
<td>DD43</td>
<td>4.3</td>
<td>DD195_3,4</td>
<td>5.9</td>
</tr>
<tr>
<td>DD45</td>
<td>4.7</td>
<td>DD195_5,6</td>
<td>6.3</td>
</tr>
<tr>
<td>DD47</td>
<td>11.0</td>
<td>DD200_1</td>
<td>11.0</td>
</tr>
<tr>
<td>DD50</td>
<td>6.8</td>
<td>DD200_3</td>
<td>11.3</td>
</tr>
<tr>
<td>DD186_1</td>
<td>5.7</td>
<td>DD203_1</td>
<td>6.8</td>
</tr>
<tr>
<td>DD186_3</td>
<td>2.3</td>
<td>DD202_4</td>
<td>11.5</td>
</tr>
<tr>
<td>DD186_4</td>
<td>9.6</td>
<td>DD205_1</td>
<td>6.4</td>
</tr>
<tr>
<td>DD198_3</td>
<td>3.1</td>
<td>DD205_3</td>
<td>2.3</td>
</tr>
<tr>
<td>DD207_1</td>
<td>4.0</td>
<td>DD206_3</td>
<td>9.2</td>
</tr>
<tr>
<td>DD207_4</td>
<td>22.3</td>
<td>DD206_4</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Ternary diagrams are often used to classify different bed types (Winterwerp and van Kesteren, 2004). As the exact clay content is unknown in these samples these diagrams are not used but rather the relationship between the proportion of sand and mud described in the next sections.

The bulk and dry densities describe the structure and packing of the sediment particles, however for fine cohesive sediments (showing plastic behaviour), the Atterberg limits are also important. These limits represent water contents defining the transition from liquid to plastic behaviour (Liquid Limit: LL [%]), and from plastic to solid behaviour (Plastic Limit: PL [%]). The difference between the liquid limit and the plastic limit is the Plasticity Index (PI [%]) (see e.g. Winterwerp and van Kesteren, 2004).

The undrained shear strength of sediments at the liquid limit is ~ 1 kPa and around 100 kPa at the PL. It depends on the clay content, the clay mineralogy and the chemical properties of the pore water. Samples are generally considered cohesive when the PI is > 7% (Winterwerp and van Kesteren, 2004). Numerous empirical relationships exist between the PI and sediment behaviour but due to a lack of reliable data and relevance to the study area in question, these relationships are not discussed further here. However these properties may be important for other areas in the Chatham Rise i.e. further east where cohesive sediment properties change. Two mud samples, from different locations and with different clay minerals may have the same densities but the undrained shear strength and therefore erodibility may be quite different (Winterwerp and van Kesteren, 2004).
5.2 Erosion mechanisms

This study investigates the erosion or resuspension of material from the seabed and so several erosion properties are considered. It is important to differentiate between erosion of cohesive and non-cohesive material. Non-cohesive material is sand, for which fairly predictive formulations for transport and erosion rates exist (see e.g. van Rijn, 1993). For sand, the critical erosion shear stress for erosion \( \tau_e \) typically increases with increasing grain size. Silt (grain size between 2 and 63 µm) shows pseudo-cohesive behaviour, with \( \tau_e \) increasing with decreasing grain size. The erosion of clay and very muddy sediment depends on soil properties and may strongly vary in time (with \( \tau_e \) increasing in time due to consolidation processes and therefore the stress history).

The transition between non-cohesive and cohesive erosion properties depends on the clay (or mud) content. Various authors suggest different critical mud contents, e.g. 3-15% (Mitchener and Torfs, 1996) or 20-30% (Houwing, 2000). There is a changing erosion behaviour at the transition from cohesive to non-cohesive due to a decreased internal friction of sediment grains for % mud (solids) >30%. Although non-cohesive sand-mud mixtures do not exhibit cohesive properties, their erosion behaviour is significantly influenced by even a small amount of mud.

Erosion of cohesive sediment is often described with an erosion threshold (\( \tau_e \) [Pa]) and an erosion flux (\( E \) [kg.m\(^{-2}\).s\(^{-1}\)]. The erosion threshold is determined by the bed shear stress (\( \tau_b \) [Pa]) at which particles begin to separate from the bed. The erosion flux is the amount of material that is lifted from the bed per unit area per unit of time. When there is an excess of bed shear stress relative to the critical shear stress for erosion (\( \tau_b > \tau_e \)), bed particles are eroded. Partheniades (1965) and Ariathurai (1974) parameterised bed stabilisation properties into an erosion parameter \( M \) [kg.m\(^{-2}\).s\(^{-1}\)] used in the formulation for erosion of cohesive sediments:

\[
E = M \left( \frac{\tau_b - \tau_e}{\tau_e} \right), \text{ for } \tau_b > \tau_e
\]

Equation 5.1

With \( M \) typically varying between 1 x 10\(^{-6}\) (consolidated sediment) and 1 x 10\(^{-1}\) (fluffy, unconsolidated fresh deposits).

Equation 5.1 applies to well-consolidated (\( \rho_{bulk} \sim 1400-1800 \) kg.m\(^{-3}\)) sediments that are homogeneously mixed beds, which is not the case here, and assumes that \( \tau_e \) and M are constant over the upper few mm's of the bed. A modified erosion formula was proposed by Winterwerp and van Kesteren (2004)

\[
E = M_e \left( \tau_b - \tau_e \right), \text{ for } \tau_b > \tau_e
\]

Equation 5.2

In which, the erosion parameter is:
\[ M_E = \frac{c_v \phi_s \rho_{dry}}{10D_{50}^c u} \]

*Equation 5.3*

Where \( \phi_s \) is the mass concentration, \( c_v \) the consolidation coefficient, \( c_u \) the undrained shear strength, and \( D_{50} \) the median grain size of the sediment. The undrained shear strength \( c_u \) increases, whereas \( c_v \) decreases with the bulk density (see Winterwerp et al., 2012). Therefore, \( M_E \) decreases non-linearly with increasing density, although in Eq. 5.3, \( M_E \) appears to increase with \( \rho_{dry} \). This is because the volumetric erosion rate (which decreases with decreasing \( c_v \) and increasing \( c_u \), therefore increasing \( \rho_{dry} \)), is converted to erosion rate by weight using \( \rho_{dry} \). Most parameters on the right hand side of Eq. 5.3 are indirectly related to \( \rho_{dry} \), therefore the erosion parameter also decreases with \( \rho_{dry} \).

\[ \hat{\tau}_b < \tau_d \rightarrow \text{Stable bed} \]
\[ \hat{\tau}_b > c_d \rightarrow \text{Floc erosion} \]
\[ c_d < \hat{\tau}_b < c_u \rightarrow \text{Surface erosion} \]
\[ \hat{\tau}_b > c_u \rightarrow \text{Mass erosion} \]

*Figure 5.2 Classification scheme for erosion modes based on erosion thresholds, reflected by the drained and undrained strength of the bed, in relation to the mean and turbulent component of the deviatoric stress (from Jacobs, 2011). Mass erosion is not considered here.*

5.3 *In-situ material resuspension*

At present, the sediment bed in the study area has been described as glauconite, muddy, fine sands present in a loosely-to-well packed layer of ~ 10-30 cm’s. These formaniferal sands are indicative of a very slow rate of deposition. Additionally, bed morphology (flat bed) does not indicate a bed load-transport dominated system. This indicates that the bed at present appears quite stable with little resuspension under average flow conditions. A lack of bed resuspension is also indicated in the RDI ADCP and AquaLogger measurements which show very low-to-no turbidity near the bed (Section 4). Scatter diagrams (Figure 4.12) also suggest that there is little to no flux of suspended matter.
For resuspension, it is important to establish whether the bed sediment is cohesive or non-cohesive. The majority of samples analysed in the study area are considered to behave in a cohesive fashion due to the percentage of mud present (Figure 5.3), although many are close to the limits of cohesiveness. Therefore, the erosion of the bed is mainly evaluated for cohesive sediment, although, at the end of this section, erosion of non-cohesive sediment is also discussed.

![Figure 5.3 Percentage of sand versus percentage of mud for samples in the study area](image)

### 5.3.1 Cohesive sediment resuspension

Several highly empirical correlations between the critical (threshold) shear stress for erosion ($\tau_c$) and the bulk density of the cohesive sediment bed exist (e.g. Winterwerp and van Kesteren, 2004). One of these relationships (given in Equation 5.4) was derived by Whitehouse et al., (2000) for a wide range of cohesive beds from a series of laboratory experiments with clay in the same range of undrained shear strength as the Dorado Cruise samples in the study area ($C_u = 0.1$ kPa to 10 kPa).

$$\tau_c = 0.015\left(\rho_{\text{bulk}} - 1000\right)^{0.73}$$

*Equation 5.4*

Converting the observed bulk densities of the bed to critical shear stresses for erosion (using Equation 5.4, see Table 5.5) yield values for $\tau_c$ between 1 and 3 Pa. Bed shear stresses computed with the numerical model (Deltares, 2014a) show that at the ADCP location in the study area are 0.3 Pa at most. This demonstrates that the bed shear stresses under normal
conditions, even in winter, are not sufficient to erode the bed. The modelling was performed with Delft3D to assess far field plume dispersal. The simulations were set-up using a Regional model (40 Z layers), to include the large-scale oceanic flow effects, as well as a Local model (horizontal grid resolution of 30 x 30 m) which was nested in the Regional model to have sufficient resolution to model the dredge plume dispersion. The model was run under seasonal forcing for spring, summer and winter (Deltaires, 2014a).

Table 5.5 Critical shear stresses for a range of samples from the Dorado Discovery Cruise

<table>
<thead>
<tr>
<th>SAMPLE ID</th>
<th>$\tau_c$ (Pa)</th>
<th>$\rho_{bulk}$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD2</td>
<td>1.9</td>
<td>1800</td>
</tr>
<tr>
<td>DD5</td>
<td>1.9</td>
<td>1760</td>
</tr>
<tr>
<td>DD6</td>
<td>2.0</td>
<td>1840</td>
</tr>
<tr>
<td>DD7</td>
<td>1.9</td>
<td>1760</td>
</tr>
<tr>
<td>DD8</td>
<td>0.7</td>
<td>1210</td>
</tr>
<tr>
<td>DD9</td>
<td>1.7</td>
<td>1690</td>
</tr>
<tr>
<td>DD12</td>
<td>1.4</td>
<td>1500</td>
</tr>
<tr>
<td>DD14</td>
<td>1.7</td>
<td>1650</td>
</tr>
<tr>
<td>DD15</td>
<td>1.6</td>
<td>1600</td>
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<tr>
<td>DD16</td>
<td>1.8</td>
<td>1690</td>
</tr>
<tr>
<td>DD17</td>
<td>2.6</td>
<td>2160</td>
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<td>DD18</td>
<td>1.9</td>
<td>1810</td>
</tr>
<tr>
<td>DD19</td>
<td>1.7</td>
<td>1670</td>
</tr>
<tr>
<td>DD23</td>
<td>1.9</td>
<td>1740</td>
</tr>
<tr>
<td>DD25</td>
<td>1.3</td>
<td>1455</td>
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<td>1720</td>
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<td>1620</td>
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<td>DD29</td>
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<td>1515</td>
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<tr>
<td>DD31</td>
<td>1.4</td>
<td>1520</td>
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<td>DD32</td>
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<td>DD41</td>
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<td>1710</td>
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<tr>
<td>DD44</td>
<td>1.9</td>
<td>1750</td>
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<td>DD186</td>
<td>1.7</td>
<td>1670</td>
</tr>
<tr>
<td>DD196</td>
<td>1.9</td>
<td>1780</td>
</tr>
<tr>
<td>DD207(surface)</td>
<td>2.0</td>
<td>1840</td>
</tr>
<tr>
<td>DD207 (0.2-0.45 m depth)</td>
<td>2.0</td>
<td>1850</td>
</tr>
<tr>
<td>DD192a</td>
<td>2.0</td>
<td>1830</td>
</tr>
<tr>
<td>DD195</td>
<td>1.6</td>
<td>1610</td>
</tr>
</tbody>
</table>
Table 5.6 Maximum, Minimum and mean shear stress over the range of samples

<table>
<thead>
<tr>
<th>Shear Stress Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum shear stress (hardest to erode substrate)</td>
<td>2.7 Pa</td>
</tr>
<tr>
<td>Minimum shear stress (most easy to erode substrate)</td>
<td>0.7 Pa</td>
</tr>
<tr>
<td>Mean shear stress (average)</td>
<td>1.7 Pa</td>
</tr>
</tbody>
</table>

Figure 5.4 Model bed shear stresses (Pa) at the RDI location in spring with the horizontal velocities in the near-bed model layer.

Figure 5.5 Model bed shear stresses in red (Pa) at the RDI location in summer with the horizontal velocities in the near-bed model layer (blue).
As can be seen from Figure 5.6 the maximum bed shear stress at the RDI location in the model does not reach the critical erosion shear stress for the weakest sample (Table 5.6). Figure 5.7 show the spatial distribution of bed shear stress in winter are less than 0.3 Pa, far less than the computed critical erosion shear stress of the samples analysed from the in situ bed. This concurs with the measurements of turbidity and that fact that until now, the thin, fine, sandy bed remains in place.

Figure 5.6 Model bed shear stresses in red (Pa) at the RDI location in winter versus the horizontal velocities in the near-bed model layer (blue)

Figure 5.7 Maximum bed shear stresses for the winter scenario showing location of RDI
It should be noted that the bed shear stress computed in the model (Deltares, 2014a) uses a roughness length (Ks) of 0.02 m in order to represent the coarser nature of the phosphate nodules. The roughness length will affect the bed shear stresses being computed in the model. According to the Soulsby formulation (Soulsby et al. 1993), a larger roughness length will result in a smaller friction factor and, therefore, a higher bed shear stress. Therefore, the bed shear stresses generated in the model are the upper bound of shear stresses compared with if a shorter roughness length, representing skin friction was applied. In areas with a lower distribution of surface phosphate nodules, the bed shear stresses are expected to be lower.

Figure 5.8 Measured values of yield and Bingham strength for a variety of mud samples from the Netherlands compared to samples from the Chatham Rise (original plot from Winterwerp et al., 2012).

The bulk density can also be related to the shear strength, as in Figure 5.8, which shows that the surface samples analysed from the study area have a high bulk density and a high strength. The other points on the graph represent data from Dutch estuarine systems. Only a few samples from the Dorado Cruise existed for which bulk density and shear strength measurements were derived simultaneously. These samples were soft, greenish, silty clay and firm, greenish, clayey silt and so may have a higher strength than many of the other samples. The Chatham samples seem to fall in the same bandwith of bed sediments as the Dutch estuaries, and therefore the envelope of the relation in Figure 5.8 is assumed to apply for the Chatham bed sediments as well. This extrapolation approach, assumes that the activity of the different samples are comparable based on similar clay properties (Winterwerp and van Kesteren, 2004), for which insufficient information is available. Nevertheless, this graph can be used, as a first assessment, to extrapolate how the strength of the sediment surface may change as a result of the decreased density associated with the mining tailing discharge. This will be elaborated in the next chapter.
5.3.2 Non-cohesive resuspension

In areas of the study area where the fine sediments are not in the cohesive range, a Shields curve will apply (Figure 5.9). The mine tailing d50s range from 75-140 μm (Boskalis, 2012) and so the finer particles, once settled, may be resuspended again at shear stresses of ~ 0.1 Pa - which is in exceeded in the spring and winter modelled scenarios. The original bed properties include a larger d50 range from 72-360 μm (excluding a very gravelly sample) (Boskalis, 2012) and so critical bed shear stresses will range from 0.1 – 0.2 Pa.

![Figure 5.9 Effect of cohesive forces on critical bed-shear stress of fine sediments (submerged, weakly consolidated beds for particles < 62 μm). (Taken from van Rijn et al., 2007)](image)

Non-cohesive material that is eroded from the bed can be transported as suspended load or as bed load material. Fine material is transported in suspension and larger/denser fractions may be entrained along the bed. If bed transport is common, bed forms such as ripples, will exist. No such bed forms are visible in the images (Figure 5.10-Figure 5.11) nor descriptions of the Chatham rise sea bottom. This indicates that bed transport is not an important process over the study area.

![Figure 5.10 Mud ooze with sparse phosphate nodules](image)  ![Figure 5.11 Relatively flat mud/ooze](image)
5.4 Resuspension of mine tailing deposit

The *in situ* bed as it is now, undergoes very little resuspension as described in the previous section. This is evident from the RDI ADCP data and the AquaLogger data, the nature of the bed sediments and from the empirical estimations of critical shear stress for erosion. One of the objectives of this study is to see how resuspension from the bed may change as a result of dredging, subsequent removal of the coarser material and the release of the fine tailings onto the dredged bed. The mine tailings differ in three ways from the *in situ* bed, being:

- The grain size distribution: all sediment larger than 2 mm remains in the hopper whereas finer sediment is placed back on the bed
- The water content will initially be significantly larger
- The bed may become segregated

From the dredging procedure, it is known that the mixture intake occurs at a rate of 1.84 m$^3$/s and the sediment intake is at a rate of 0.31 m$^3$/s (of solids). Therefore the density of this mining slurry being discharged onto the bed can be computed according to Equation 5.5:

$$\rho_{\text{slurry}} = \left( \rho_{\text{solids}} \times V_{\text{solids}} \right) + \left( \rho_{\text{w}} \times V_{\text{w}} \right) \div \left( V_{\text{w}} + V_{\text{solids}} \right)$$

*Equation 5.5*

Using the mean specific density of sediments from the study area (2675 kg/m$^3$) and a $\rho_{\text{w}}$ of 1020 kg/m$^3$, a slurry density of 1234 kg/m$^3$ is estimated. It must be noted that the slurry density calculated is the slurry density just before release (Boskalis, 2013). The mean specific density of the sediments was provided by Boskalis. Extrapolating the envelope in Figure 5.8, a $\rho_{\text{bulk}}$ of 1234 kg/m$^3$ results in a shear strength of 5 - 10 Pa. However, whether sediment is eroded depends on the critical bed shear stress. Using Equation 5.4 for $\rho_{\text{bulk}} = 1234$ kg/m$^3$, would result in reduced critical shear stress of erosion in the order of ~ 0.8 Pa. This critical erosion shear stress remains larger than the estimated bed shear stresses calculated by the model (Figure 5.12).

A sensitivity assessment by Boskalis on the slurry density gave a range from 1211 kg/m$^3$ to 1260 kg/m$^3$. This assumes that the tailings develop strength as they settle. If the tailings initially deposit at the bed in a very fluffy state, the eroding forces might immediately pick-up this material and, the clay fraction in particular, might be washed out. This can never be fully prevented. However, once the tailings settle into a slightly coherent mode, they will be harder to erode (Boskalis, 2013).

Extrapolating the relationship in Equation 5.4 and plotting in Figure 5.12 shows that only mixtures with a very low density or lacking in cohesion would be eroded at the bed shear stresses simulated in the model scenarios. However, the critical bed shear stress of the mine tailings range as plotting in Figure 5.12 may be exceeded during events such as the passing of an eddy or stronger internal tides or if the bulk density of the mine tailings becomes lower as indicated by the range.
Whether or not erosion will take place is further influenced by 3 considerations:

- The probabilistic nature of (critical) bed shear stress
- The vertical structure of the mine tailings
- The exact formulation used to compute the bed shear stress in the model (Deltares, 2014a)

The effect of the bed shear stress formulation was described previously; below we will explain the probabilistic nature of bed erosion, and the vertical structure of the deposits.

Erosion of sediments follows a probabilistic erosion curve as the shear stresses vary both in time and in space due to turbulent forces and changes in bed roughness (Winterwerp et al., 2012, see also Figure 5.13). Because of turbulent fluctuations around the mean bed shear stress, and the natural variations in critical bed shear stress, erosion may occur even though \( \tau_b < \tau_c \).

The vertical structure of the mine tailing deposits is determined by the degree of segregation. The degree of segregation will be influenced by the level above the bed at which the mine tailings are discharged. Different scenarios were explored in the Jet3D simulations described in Deltares, (2014a). Depending on details of the tailings deposition process, it is expected that the sediment is not entirely segregated. As a result all sand particles and clay aggregates will probably remain, which settle rapidly towards the bed (Figure 5.14), particularly when discharge is very near the bed. Near the sediment-water interface, the bed density will therefore be lower than the average (estimated at \( \rho_{\text{bulk}} = 1234 \text{ kg/m}^3 \)). If pronounced segregation occurs, the bulk density of the mixture may become so low that mixing of bed sediment with water is determined by entrainment processes rather than by erosion.
processes. Mixing of sediment by entrainment may occur at very low shear stresses, even at shear stresses as low as predicted by the model.

Figure 5.13 Sketch of spatial distribution in critical shear stress and temporal distribution in bed shear stress at a location (x,y). The shaded area depicts the distribution of erosion events (taken from Winterwerp et al., 2012).
5.5 Dynamics of the outflow plume

A number of uncertainties are related to the dynamics of the slurry release. The material will be discharged with a very low discharge velocity to minimize the area of the mine tailings footprint and turbid plume. The majority will settle towards the bed as a sediment-induced density current. However, some of this material will be entrained by the surrounding water masses. The amount of material entrained depends on the height of the discharge and the settling velocity. This sediment has a much lower settling velocity, and may be advected over long distances before settling on the bed. This mechanism is likely the dominant source of sediment dispersal, and was evaluated in the modelling study along with different scenarios showing the plume dispersion depending on whether the mine tailings were released at or above the bed (Deltaires, 2014a). This study showed that sedimentation mainly occurs along the mining track. During active mining, high sediment concentrations occur along the mining track but most of these sediments directly deposit along the track line. A minor part is picked up by the flow and transported throughout the model domain. Sediment concentration at the mining location is two orders of magnitudes higher than concentrations outside the mining area. Both inside and outside the mining area, suspended sediment concentrations decay rapidly to values below 0.1 mg/l once mining stops and this study shows that limited resuspension of deposited sediment occurs over the course of one mining cycle (Deltaires, 2014a).

Secondly, depending on details of the release of the mine tailings, the released plume may settle on the bed at considerable (density-driven) flow velocities. When sufficiently large, these flow velocities may be able to erode bed sediment. Assessing the erosion rate by these
sediment-density driven currents requires detailed laboratory testing, which is beyond the scope of the current study.

Thirdly, after deposition the mine tailings spread out radially over the bed as a density current. During this process, the bed sediment may significantly mix with ambient water masses, leading to further entrainment of sediment.

5.6 Resuspension by extreme events

Barotropic surface tides in combination with stratified flow may result in the generation of internal tides and waves. Internal tides are internal waves with the frequency of tides; internal waves have higher frequencies (with periods between minutes to hours). Due to the small difference in density between stratified layers compared to the large density difference between air and water, internal waves/tides have much larger elevation of internal surfaces than surface waves/tides. The degree of stratification determines the presence and magnitude of internal waves as well as the propagation. The ADCP measurements show clearly that internal tides are present in this area and that their magnitudes reach up to 20 cm/s. As such, they may increase the bed shear stress, thereby increasing the erosion rate of mine tailings. Furthermore, the vertical velocities associated with these internal tides typically are 1/10 of the magnitude of horizontal velocities. In this case that would imply vertical velocities in the order of 2 cm/s significant which is large compared to estimated settling velocities of sediment. Hence, internal tides can be important for maintaining material from the mining location in suspension (Deltres, 2014b).

Other extreme events include tropical cyclones and tsunamis. Cyclones may generate strong winds and large waves but near the study area on the Chatham Rise, in depths of about 350 m; such short waves do not impact the bed. For typical tsunami waves with amplitudes between 0.5 and 1.5 m, a period of about 1000 s at a depth of 350 m, the flow velocity amplitude lies in the range of 0.08 to 0.25 m/s (uniform over depth). The magnitude of the wave-averaged bed shear stress due to waves alone equals half the water density times the wave friction factor times the near bed velocity amplitude squared. The wave friction factor can be computed using de Swart, (1974). The typical tsunami waves specified above thus result in bed shear stresses of 0.04 to 0.3 Pa, using an equivalent geometrical roughness of 0.02 m, which is well below the critical shear stress of the mine tailings.

5.7 Conclusions

One of the main questions addressed in this analysis was how erosion of the seabed, under normal conditions, may change as a result of mining the upper surface of the sediment bed and subsequently discharging the mine tailings to the bed. The surface bed composition varies throughout the area of interest from sandy silts to muddy sands and only the surficial sediments, in the area surrounding the ADCP, were considered. The cohesive nature of the sediment, density and shear strength measurements, when available, were used to estimate empirically the critical erosion threshold of the sediment bed at present and after the mine tailings are discharged. These characteristics of the sediment will not change if discharge occurs at 10 m above the bed.
It was found that the critical erosion shear stress required to erode the cohesive surface sediments (clay and silt fractions) is higher than the bed shear stresses under ambient conditions. This concurs with findings from the turbidity measurements that show low turbidity values both near the bed and throughout the water column. Tidal analysis of near-bed values indicate minor, tidally-induced resuspension of bed material occurs, however, it is in the order of 10 times less than the background values of 1 FTU. Fine, non-cohesive sediments will be eroded more easily, but the critical shear stress is only exceeded at times in winter.

The critical erosion threshold for erosion of the mine tailings (after settling) is lower, as a result of a lower density mixture, but still remains greater than the expected ambient bed shear stress. However, because of uncertainties in the bed shear stress as well as the critical bed shear stress, erosion of mine tailings may occur (especially during winter, when bed shear stresses are larger) as well as variation in the density of the mixture.

Cyclones and storms do not increase the bed shear stresses dramatically at the depths considered, however internal tides over the Chatham Rise may generate larger shear stresses and vertical mixing throughout the water column.
6 Discussion

In the framework of the Chatham Rise Rock Phosphates Project, Boskalis requested Deltares to investigate the dispersion behaviour of sediments released during the mining process. This study investigated the background turbidity of the study area using in-situ measurements, as well as the determination of the erosive properties of the bed material, both before dredging and for the mine tailings after disposal. Sediment in the area is mainly phosphorite bearing glauconite, fine to medium foraminiferal sandy muds or muddy sands mixed with fragments of rock and biogenic minerals.

Important drivers of sediment transport on the Chatham rise are, 1) the role of mean flow, the strongest flow associated with the M2 barotropic tide, and eddies in advecting and stirring suspended particles; 2) vertical mixing by wind-driven shear near the surface or by internal tides; 3) tidally induced bottom shear stresses and 4) the sediment settling velocity.

The turbidity approximated with an RDI ADCP (May 21st to November 13th 2011) and AquaLogger (May 21st to December 11th) at depths of approximately 360 m on the Chatham Rise, reveal that concentrations are fairly low during the weakly stratified measurement period.

- It is likely that the sediment-induced signal is weaker than errors introduced by the measurement method.
- There is no clear relation with residual flow patterns or tidal resuspension, or tidal advection in the ADCP data. The best correlation was obtained with the K1 tidal frequency. Since the frequency of the latter is close to the day-night cycle, and the maximum turbidity is close to the (temperature-induced) density interface, this correlation may be influenced by solar radiation.
- The AquaLogger sensor shows a minor contribution of M4 signal to turbidity, indicating that part of the signal is due to tidal resuspension, but only in the order of 0.1 FTU.

One of the main questions addressed in this analysis was how erosion of the seabed, under normal conditions, may change as a result of mining the upper surface of the sediment bed and subsequently discharging the mine tailings to the bed. The surface bed composition varies throughout the area of interest from sandy silts to muddy sands, and only the surficial sediments in the area surrounding the ADCP were considered. The cohesive nature of the sediment, density and shear strength measurements, when available, were used to estimate empirically the critical erosion threshold of the sediment bed at present and after the mine tailings are discharged. These sediment characteristics remain the same even if sediment release is at 10 m above the bed so long as the density of the released sediments remains the same. These field measurements came from several sampling campaigns throughout the Chatham Rise and focussed on those from the Tranquil Image Cruise (2011) and the Dorado Discovery cruises (2011-2012).

- It was found that the critical erosion shear stress required to erode the cohesive surface sediments is higher than the modelled bed shear stresses under modelled ambient conditions. This concurs with findings from the turbidity measurements that show low turbidity values both near the bed and throughout the water column, indicating little resuspension of bed material occurs. The minor part of the signal associated with tidally-induced resuspension may be associated with easily-eroded, surface organic material (detritus) which is not represented in the model.
• Non-cohesive sediments will be eroded more easily, but the critical shear stress is only exceeded at times in winter.
• The critical erosion threshold for the mine tailings (after settling) is lower than the in-situ sediment as a result of a less dense mixture. However, the critical shear stress for erosion still remains greater than the ambient bed shear stress. This may vary due to variations in the density of the discharge.
• Cyclones and storms do not increase the bed shear stresses dramatically at the depths considered, however, internal tides over the Chatham Rise may generate larger shear stresses and vertical mixing throughout the water column.
7 References


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