Accuracy in Spill Monitoring
Turbidity Distribution and Conversion Factors

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The present paper is based upon work carried out at the Spill Monitoring Department within Öresund Marine Joint Venture (ÖMJV)[3].

Abstract

In connection with the dredging and reclamation works at the Öresund Link Project between Denmark and Sweden carried out by the Contractor, Öresund Marine Joint Venture (ÖMJV), an intensive spill monitoring campaign has been performed in order to fulfil the environmental requirements set by the Danish and Swedish Authorities.

Spill in this context is defined as the overall amount of suspended sediment originating from dredging and reclamation activities leaving the working zone.

The maximum spill limit is set to 5% of the dredged material, which has to be monitored, analysed and calculated within 25% accuracy.

Velocity data are measured by means of a broad band ADCP and turbidity data by four OBS probes (output in FTU). The FTU's are converted into sediment content in mg/l by water samples.

The analyses carried out, results in high acceptance levels for the conversion to be implemented as a linear relation which can be forced through the origin.

Furthermore analyses verifies that the applied setup with a 4-point turbidity profile is a reasonable approximation to the true turbidity profile. Finally the maximum turbidity is on average located at a distance 30-40% from the seabed.

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Nomenclature

P : production [T]
τ : turbidity [FTU], ([Formazin Turbidity Unit])
C : concentration [g/m^3]
V : current velocity [m/s]
I : flux intensity [g/m^2/s]
F : flux [g/s]
Q : discharge [m^3/s]
S : spill [g]

a_0 : conversion factor (with zero intercept) [g/m^3/FTU]
a_1 : conversion factor (free intercept) [g/m^3/FTU]
b_1 : conversion offset [g/m^3]

T : production period [s]
Γ : surface [m^2]
$\vec{\Gamma}$: surface normal unit vector
A : plane [m^2]

x : current perpendicular coordinate [m]
y : current parallel coordinate [m]
z : depth coordinate [m]
t : time coordinate [s]

μ : standard mean
σ : standard deviation
Δ : difference
d : distance from sea bed to maximum turbidity [m]
D : water depth [m]
∂ : normalised distance from sea bed to maximum turbidity

Area ID's:

TT : Tunnel Trench, sections A, B and C
CD : Compensation Dredging, sections 1 and 3
DCC : Drogden Construction Channel
FL : Flinte Channel, sections A, B2 and C1
EP : East Pylons
WP : West Pylons
LN : Lernacken
WB : Outlet from Sedimentation Basins

Introduction

In connection with the construction works at the Öresund Fixed Link Project connecting Denmark and Sweden, the potential environmental effects of the associated construction works were of great political interest.

For the dredging and reclamation works this meant strict environmental requirements regarding the allowable amount of spill caused by these activities. A large scale Spill Monitoring Programme as prescribed by the owner was put in action by the Contractor. The Spill Monitoring System was ship and land based, and monitoring of the spill causing activities was performed on a 24 hour basis as dredging was not permitted after 6 hours lack of spill monitoring.

In general the overall spill limit is set at 5% by weight of the design quantity to be dredged (some 7 million m^3) and has to be determined with a 25% accuracy with a 75% probability. Also seasonal variations in daily and weekly spill limits are to be followed in order to protect the biological life on a short term basis.

As spill monitoring in this intensive way with such strict specific requirements has never been carried out before, the system was (and still is) under continuous discussion and verification. The intention of this paper is to clarify some of the more serious discussions related to accuracy in spill monitoring that have been raised, based on the very large amount of data which are available after almost 3 years of spill monitoring.

Spill in this context is defined in the contract as the portion of dredged or excavated material brought into suspension during dredging, transport or filling and leaves the work zone or land reclamation areas as follows:

1. *Suspended and resuspended materials originating from the dredging activities leaving the work zone.*

2. *Suspended materials leaving the reclamation or backfilling areas.*

3. *Materials lost during transport from dredging to reclamation areas or from reclamation areas to backfilling areas.*

Spill at any time is the sum of 1. to 3. and is measured by dry weight of suspended material.

The work zone is defined as the area to be dredged plus a surrounding 200 metre zone.

Basic theory

The governing equations for the spill calculations are derived by considering a balance (continuity equation) of suspended material through an enclosed box as shown in Fig. 1.

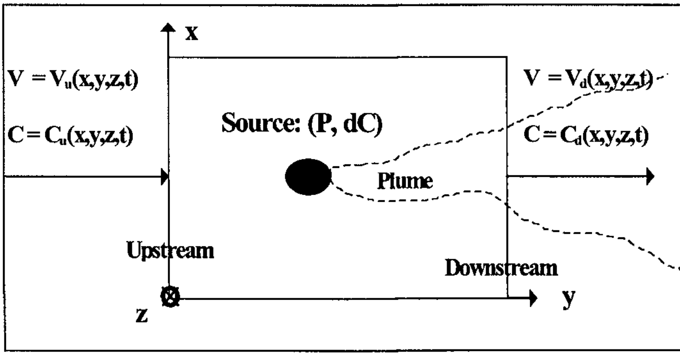

Figure 1. Spill Calculation Box.

The flux intensity of suspended material at a given coordinate in time is given by

$$\vec{I}(x,y,z,t) = C(x,y,z,t) \cdot \vec{V}(x,y,z,t) \tag{1}$$

and the net flux through the box at time (t) is calculated by integration along the vertical surface (Γ) of the box

$$F(t) = \int_{\Gamma} \vec{I}(x,y,z,t) d\vec{\Gamma} \tag{2}$$

This way the spill (S) related to the production (P) during a dredging period of duration (T) will equal

$$S = \int_{T} F(t) dt \tag{3}$$

which is the basic formula used for calculation of spill from dredges.

The most common situation is a one-directional current with a clear and well defined plume and in this case the spill calculation can be expressed as the difference between downstream and upstream values

$$S = \int_{T} (F_d(t) - F_u(t)) dt \tag{4}$$

Data Collection

Considering eq. (1)-(4) the necessary data needed for the spill calculations are current velocity and concentration of suspended material.

Current data are gathered by a broad band Acoustic Doppler Current Profiler (ADCP) mounted at the hull of the vessel. Data are hereby obtained from 0.7 m below the vessel at intervals of 0.5 m (centre of each bin cell) until 1 m above sea bed. Output from the ADCP in [m/s].

Concentration data are gathered by four Optical Back Scatter (OBS) sensors with one mounted on a pole at a fixed depth and the remaining three mounted at 2 m intervals on a winch controlled streamer. Output from these sensors is Formazin Turbidity Unit [FTU] which is converted into sediment content by means of water samples.

Since the turbidity sensors work by light reflection, the magnitude of the output depends upon several material parameters such as colour, shape and grain size distribution. This means that water samples have to be gathered at regular intervals in order to reflect the geological changes in the dredged material. How the conversion process should be implemented will be discussed further in this paper.

Considering the gathered current and turbidity data approximated velocity and turbidity profiles are produced as described in the following. The velocity profile is constructed by vertical extrapolation of the top measurement to the water surface, straight line interpolation in between all points and a power fit from the lowest point towards sea bed. The turbidity profile is made by linear interpolation in between points and vertical extrapolation of top and bottom sensor registration. Examples of both profiles are shown in Fig. 2, and it is clear that the velocity profile is relatively well described due to the more measuring points. However the turbidity profile may stand as a weak part with its 4-point approximation when compared with the velocity profile. Furthermore the lowest measurement will always be located around 1-2 m away from the sea bed due to equipment safety.

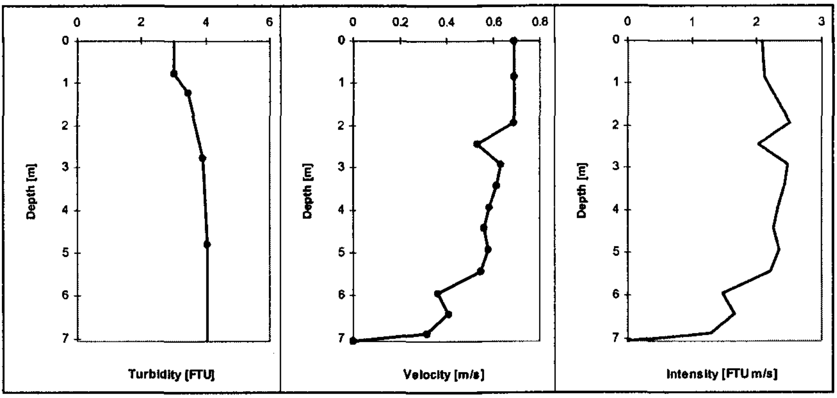

Figure 2. Approximated Profiles.

The turbidity intensity profile is obtained by multiplication of the two approximated profiles, and can be seen in Fig. 2. Current and turbidity data are logged continuously (10 per second) and average values are stored at regular intervals (e.g. every 6 s which corresponds to a registration at distances of average 10 m).

When enclosing a spill source with the survey vessel a discrete 3D picture of the intensity is derived and the net flux of suspended material through the box can be calculated numerically based upon eq. (2). Numerically integration in time is then obtained by sailing enclosed boxes continuously around the spill source and use of eq. (3).

Problems

The summary of the problems introduced in the previous section is:

I) What is the relation between turbidity and sediment content?

II) The 4-point approximated turbidity profile is coarse compared to the velocity profile. Does this lead to large deviations from the true turbidity profile?

III) Where is the maximum turbidity located? Does the lack of turbidity information close to the sea bed lead to any systematic error in the 4-point profile?

Conversion Factors - ad I)

An example of a water sample session can be seen in Fig. 3. It is important to cover as wide a turbidity range as possible during the water sampling process to obtain a satisfactory picture of the conversion relation. In Fig. 3 the best line fit is included and it seems evident that a linear relation exists.

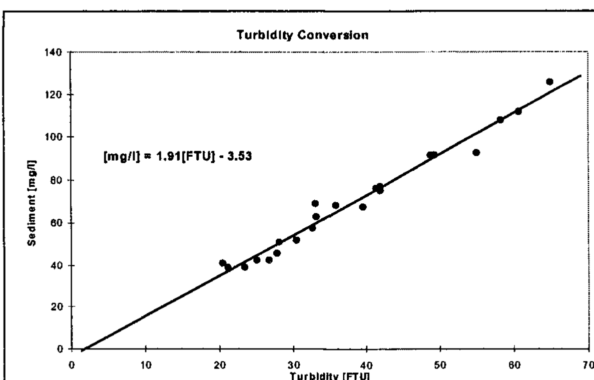

Figure 3. Ideal Water Sample Session Result.

When performing a water sample session it can be difficult to obtain a wide range of turbidity registrations due to the nature of the sediment plumes, which can lead to results as seen in Fig. 4. This water sample session does not indicate any linear relation. However a linear relation through the origin has proven to give reasonable values for the conversion factor when comparing with results obtained from more ideal water sample sessions.

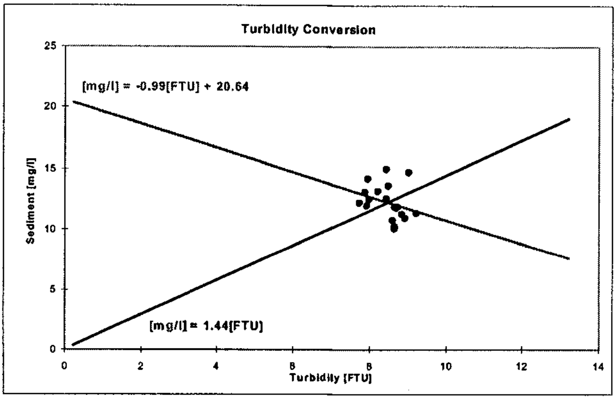

Figure 4. Forced and Non-Forced Line Fit.

In order to verify an existing linear relation a large amount of water samples have been analysed.

As mentioned previously the conversion factors are strongly dependent upon the type of suspended material. Therefore the dredging areas have been divided into subareas within each a high degree of geological homogeneity can be assumed. For each of these subareas all water samples have been plotted in one graph as shown in Fig. 5 and the linear relation becomes obvious.

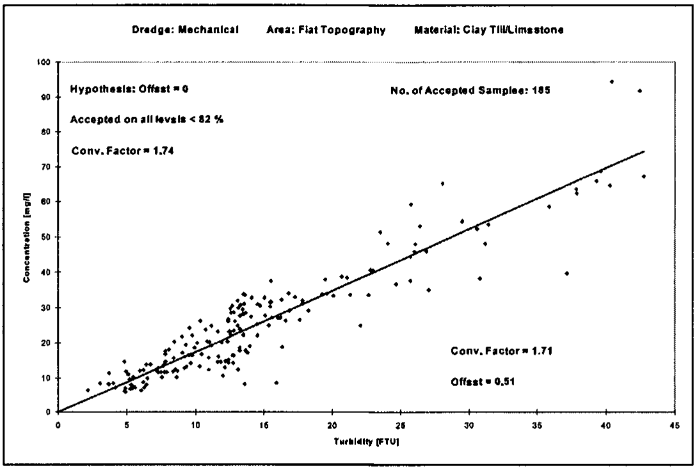

Figure 5. Conversion Graph for an Area of 50/50 Clay Till/Limestone.

In Fig. 5 all water samples for an area 900 metres long and 400 metres wide (FL A) are plotted in one graph. The dredged material is here a mix of approximately 50% Clay Till (or Moraine) and 50% Limestone.

Implementing the linear conversion

$$C(\tau) = a_l \tau + b_l, \text{ with } \tau = \tau(x,y,z,t) \tag{5}$$

in the spill equations (1)-(2) yields

$$F(t) = a_l \int_\Gamma \tau(x,y,z,t)\vec{V}(x,y,z,t)d\vec{\Gamma} + b_l Q_{net}(t) \tag{6}$$

and in the ideal case, that is if the time used to box in the source is small compared to the current velocity, the net discharge through the box will equal zero which reduces eq. (6) to

$$F(t) = a_l \int_\Gamma \tau(x,y,z,t)\vec{V}(x,y,z,t)d\vec{\Gamma} \tag{7}$$

So in the case of a one directional current spill can be calculated as

$$S = a_l \int_T \int_A (\tau_d V_d - \tau_u V_u) d\vec{A} dt \tag{8}$$

Eq. (8) shows that the spill calculation is independent upon the conversion offset (b_l) and depends upon the conversion factor (a_l) only.

With the result from Fig. 4 in mind and the fact that the origin is the natural zero (since clear water has zero turbidity) the conversion results are tested (T-test) for the hypothesis H_0: Offset = 0 against H_1: Offset $\neq$ 0 on a 95% significance level.

In the analysis related to Fig. 5 the best line fit has been determined with one (zero intercept) and two (free fit) degrees of freedom respectively by use of least squares method. With two degrees of freedom the conversion factor yields a_l = 1.71 [g/m^3/FTU] with an offset b_l = 0.51 [g/m^3]. The conversion factor with zero intercept becomes a_0 = 1.74 [g/m^3/FTU] corresponding to an increase Δa = 2% compared to the free fit. Finally the outcome of the T-test shows a minimum of 82% probability of rejecting a true hypothesis, if H_0 is rejected.

A summary of the results from all investigated sub areas can be seen in Table 1, where CS indicates a Cutter Suction dredge and M indicates a Mechanical dredge. The material is described by the relative amount of Clay Till (CT) and Lime Stone (LS).

In Table 1 the uppermost results originate from dredging activities whereas the last three results represent samples taken inside the pipelines used for pumping out of excess surface water from the reclamation basins. The suspended material inside these basins is very homogeneous and varies slowly with time. Only areas where more than hundred accepted samples were available have been included in the analyses.

Area ID	Dredge CS/M	Material CT/LS [%]	Number of Samples	a_1 [mg/l/FTU]	b_1 [mg/l]	a_0 [mg/l/FTU]	Δa [%]	Accept Level [%]
CD#3	CS	100/0	396	1.80	-1.81	1.76	-2	49
LN	M	90/10	644	1.61	-0.36	1.60	-1	84
FL A	M	50/50	185	1.71	0.51	1.74	2	82
EP	M	40/60	359	1.48	2.08	1.57	6	24
WP	M	40/60	442	1.63	-0.26	1.62	-1	87
TT A	CS	15/85	123	1.73	-0.28	1.72	-1	96
TT B	CS	15/85	622	1.69	-0.05	1.69	0	98
TT C	CS	15/85	688	1.71	0.18	1.71	0	93
DCC	CS	0/100	162	1.71	4.89	1.80	5	47
FL B2	M	0/100	510	1.92	-1.97	1.82	-5	18
FL C1	M	0/100	412	1.55	-0.13	1.54	-1	89
WB 1			*126*	*1.03*	*0.95*	*1.03*	*0*	*92*
WB 2			*124*	*1.17*	*-3.66*	*1.16*	*-1*	*87*
WB 3			*333*	*1.03*	*0.48*	*1.03*	*0*	*93*

Table 1. Water Sample Results for Subareas.

The areas named WP and EP consist of several small pits dredged over a long distance with an uncertain degree of homogeneity. This may explain the large offset and low acceptance level for EP.

From all these results it can be concluded that a linear relation exists between turbidity and sediment concentration. Furthermore the generally high acceptance levels imply that the conversion line can be forced through zero, indicating that a_0 can be assumed equal to a_1 (the difference Δa between a_0 and a_1 is within ± 5%).

Turbidity Profiles - ad II)-III)

Regarding the uncertainty that may be related to the turbidity profile a large series of spot checks have been carried out. A spot check was performed by logging the turbidity approximately each 4 cm from sea bed to water level. Hereby a very accurate turbidity profile was obtained, hereafter denoted "the true profile". In each of these spot checks the "would have been" survey positions of the four sensors are marked. The corresponding approximated 4-point turbidity profile can then be compared with the true profile, see Fig. 6 and Fig. 7.

As it can be expected that different dredging methods create different turbidity patterns, the analysis is divided into profiles originating from cutter suction, Fig. 6, and mechanical dredge, Fig. 7. Furthermore the cutter suction analysis has been subdivided based upon topography, as flat cut (data from two different areas available) or trench.

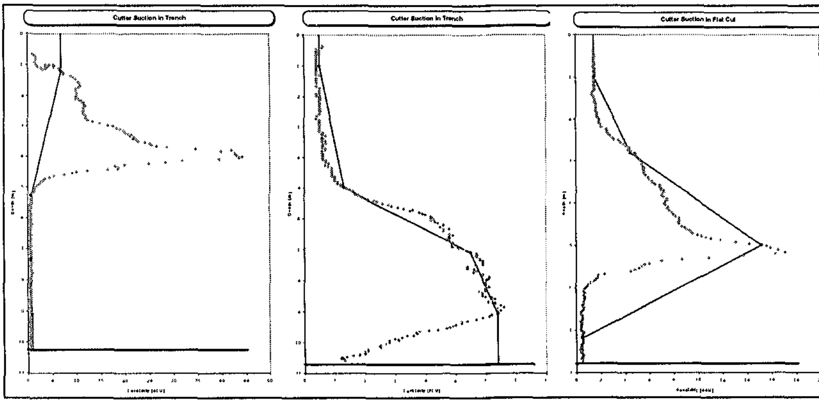

Figure 6. Examples of Turbidity Profiles for a Cutter Suction Dredge.

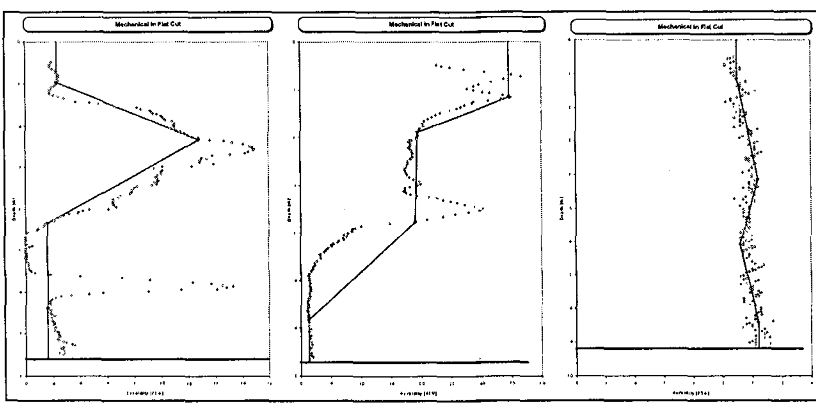

Figure 7. Examples of Turbidity Profiles for a Mechanical Dredge.

In order to compare the 4-point profile with the true profile, the depth averaged turbidity is calculated by

$$\mu(SC) = \frac{1}{2}\frac{1}{D}\sum_{i=1}^{5}(d_i - d_{i-1})(\tau_i - \tau_{i-1}) \tag{10}$$

$$\mu(WS) = \frac{1}{n}\sum_{j=1}^{n}\tau_j \tag{11}$$

SC indicating the 4-point approximation and WS indicating the true profile.

The depth averaged deviation from the true profile can then be directly calculated as

$$\Delta = \mu(SC) - \mu(WS) \tag{12}$$

Fig. 8 shows a frequency plot of Δ for 133 spot checks for a cutter suction dredge working on a flat topography.

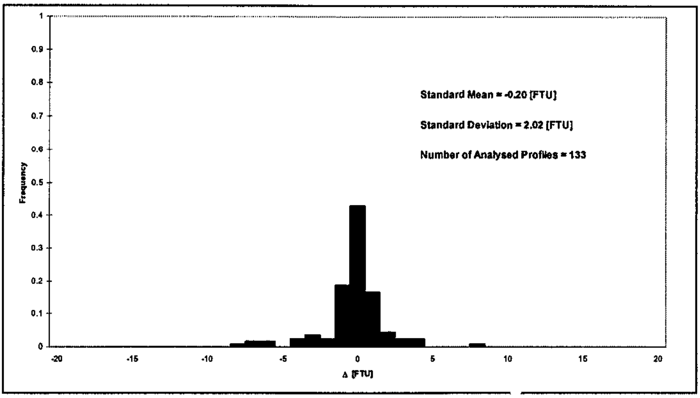

Figure 8. Frequency Plot of Δ.

The symmetrical shape of the frequency plot together with an average difference close to zero (which means that the error introduced because of the difference is nonbiased) is also recognised for the other analysed areas, se Table 2.

For all four areas an average value of Δ between ± 0.2 FTU has been found, thus indicating that the 4-point approximated profile on average describes the true profile satisfactory. The standard deviation on Δ seems to decrease with increasing number of spot checks.

Another important result from the spot checks is the distance, $d(\tau_{max})$, from the sea bed to the location of the maximum turbidity. This distance is normalised by the water depth.

$$\partial = \frac{d(\tau_{max})}{D} \tag{13}$$

Examples of frequency plots for ∂ are shown in Fig. 9 for a cutter suction dredge working respectively on a flat bed and in a trench, and for a mechanical dredge working on a flat bed.

Fig. 9 shows that the maximum turbidity most often occurs in the middle third of the water column for a cutter suction dredge working on a flat bed. This may be due to the rotation of the cutter head which whirls the sediment upwards. When the cutter suction is dredging in a trench the maximum turbidity most often is located in the lowest third of the water column, because the sediment has to be dragged over the edge of the trench. For the mechanical dredge on a flat cut the maximum turbidity occurs most often in the lowest third. Considering only the lowest 10% of the water column it seems that the maximum turbidity occurs at a rate of respectively 15%, 30% and 30% in the three different situations.

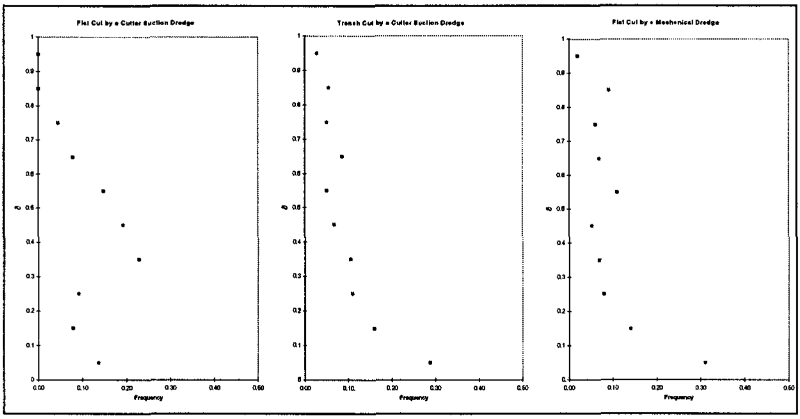

Figure 9. Frequency Plots for ∂.

Table 2 presents the average position of the maximum turbidity and related parameters.

Topography/ Area ID	Dredge CS/M	Spot Checks	$\mu(\Delta)$ [FTU]	$\sigma(\Delta)$ [FTU]	$\mu(\partial)$	$\mu(\tau_{min}/\tau_{max})$	$\mu(\tau_{mean}/\tau_{max})$
Flat/CD#1	CS	88	0.0	4.8	0.37	0.06	0.40
Flat/CD#3	CS	133	-0.2	2.0	0.29	0.36	0.63
Trench/TT	CS	167	0.1	2.9	0.32	0.29	0.57
Flat/FL	M	264	-0.1	0.9	0.35	0.29	0.54

Table 2. Results From Turbidity profile Spot Checks.

On average it has been found that the maximum turbidity is located 30% - 40% away from the sea bed for all areas. Based on this information it must be important to cover this depth region in order to avoid any systematic error in the turbidity measurements.

Furthermore the results indicate that the minimum turbidity amounts to some 30%-35% of the maximum turbidity and the mean turbidity is between 40%-60% of the maximum turbidity. This implies that the typical turbidity profile only varies over a limited turbidity range.

Conclusion

Based on the results from the analyses carried out on a large amount of data, the following can be concluded:

I) It has been validated that the conversion from turbidity into sediment concentration can be expressed by a linear relation. Furthermore the statistical T-test resulted in high acceptance levels for the offset = 0, implying that the conversion line can be forced through the origin.

II) The analysis of the applied 4-point approximation of the turbidity profile leads to results which on average comply with the true profile.

III) It is verified that the location of the maximum turbidity on average is located 30% - 40% away from the sea bed. Hence it can be concluded that the lack of turbidity information close to the sea bed does not lead to any systematic error in the 4-point profile.

References

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