

# **ENVIRONMENTAL PROTECTION IN MAINTENANCE DREDGING OF LAKES – RECENT PRACTICES IN CHINA**

Xiaojun Zhu

## **ABSTRACT**

This paper describes the engineering requirements for environmental protection associated with the dredging of lakes. Technical measures to reduce the negative impacts of maintenance dredging on aquatic ecosystems and on the surrounding general environment during maintenance dredging of lakes are also discussed. The selection of equipment, construction control, disposal programs for polluted sediment and the selection of areas for sediment placement are elaborated upon.

## **INTRODUCTION**

Non-draining lakes and reservoirs are relatively closed water areas with a small environment capacity. With the increase in human activities and industrialization, the amount of discharged waste water is also increasing, which deteriorates the water quality in the general environment. Environmental protection dredging is a recent emerging interdisciplinary area where environmental engineering and dredge engineering overlap. The goal of environmental protection dredging is to clear the polluted sediment in water, eliminate the contaminant source in a polluted water body, and reduce the amount of pollutant released from the bottom sediment to the water body. Maintenance dredging removes silts in a specific water area to maintain or restore original channel dimensions, which increases the capacity and maintains the depth and width of the lake or reservoir for sailing.

Conventional dredging results in mixing and diffusion of the polluted bottom sediment and non-polluted original silt layer move during the processes of dredging, transporting sediment, overflowing and reclamation. In the short term, dredging produces much more suspended particles in water, which further deteriorates the water quality. Lakes usually have functions of flood control, shipping, aquatics reproduction, irrigation, tourism, drinking water supply, among others. Maintenance dredging in lakes destroys the lake aquatic ecosystems, which causes negative impact to the tourism industry, aquatics reproduction, and drinking water supply.

This paper analyzes the characteristics of environmental protection dredging and discusses the technical measures to reduce the negative impact on a lake's ecosystem from the viewpoint of the equipment selection, construction control, disposal programs for polluted sediment, and the area selection for sediment placement.

## **INFLUENCE OF THE LAKE MAINTENANCE DREDGING ON SURROUNDING ECOSYSTEMS**

### **Agitation and Diffusion of Polluted Sediments**

The sediments in lakes and reservoir are an important carrier of nutrients and pollutants. Discharged water, dust from the air, surface water, and detritus from aquatic life usually lead to the accumulation of the nutrients and contaminants in sediments. Under certain circumstances such as high temperature and flood, the nutrients and pollutants that sink to the bottom of the lake release gradually. When the water decontamination ability is overwhelmed, eutrophication occurs, which could cause anoxia and the resulting death of aquatic life and/or odorous water. Directly dredging the polluted bottom without special treatment causes agitation and diffusion of polluted sediments, worsening the water quality. What is even worse is that it could affect the neighboring environments if the dredged mud is placed directly on land nearby.

### **Destruction of Aquatic Ecosystems by Non-Polluting Inorganic Suspension**

Non-contaminated inorganic suspended solids are the most universal pollutant present in conventional maintenance dredging. It affects the physiology, behavior, reproduction, growth of the aquatic life such as plankton. Suspended solids also impact benthic organisms by increasing the water turbidity and by burying after deposition, thus destroying the aquatic ecosystem. The closer the dredger is to the worksite, the denser the suspension is and the less transparent the water is. When some living creatures swallow the suspended solids, their metabolism becomes less efficient and they thus take up less energy and nourishment which is needed for their living, growing, and reproduction.

The deposition of the suspended sediment creatures causes the death of the benthic organisms. As a result the number of living creatures in the dredging area decreases sharply. Moreover, the suspended solids in areas of fish spawning greatly decrease the successful spawning rate. Furthermore, sinking sediments bury the gravels, crushed stones and other similar irregular object on the bottom of the lake, which destroys the natural shelter for young fishes thus lowering their survival.

### **Noise During Dredging**

To a certain degree the noises from the dredger in dredging and reclamation affect the ecosystem of the lake surroundings.

## **Pollution from Dredges**

Greasy dirty water from the bilges or holds of the vessels may leak into the lake while sailing or anchoring, which reduces the water quality. The disposal of sewage and other greasy dirty water generated in dredging can cause the same adverse impact on the water quality.

## **CHARACTERISTICS OF ENVIRONMENTAL PROTECTION DREDGING**

### **High Accuracies in Positioning and Digging**

The thickness of contaminated sediments is usually thin in water with a depth of 10~50 centimeters, less than 1 meter. The digging scope depends on the distribution of polluted sediment and the digging surface must match the distribution of polluted sediments. In order to avoid removing natural lake sediments, reducing the processing quantity, and to lower disposal expenses, one needs to not only remove the polluted sediments but also reduce an excess digging of non-polluted sediments as much as possible. Therefore the required accuracies of positioning and digging in environmental dredging are much higher than those in conventional dredging.

### **Controlling the Secondary Pollution in Dredging**

In conventional dredging the re-suspension of accumulated sediments is seldom taken into account. Leakage during transportation is usually neglected provided that the engineering quantity is not adversely affected. During dredging fine sediments increase rapidly in the water column in a short time. When the dredging is over, those suspending sediments sink quickly or are carried away to other areas. Thus in environmental dredging, prevention of the secondary pollution caused by suspended mud or sediments is of great importance. As a result, specific equipment and measures are necessary to assure good water quality.

### **Safe Processing of Polluted Sediments**

Appropriate techniques should be applied to the dredged sediments to prevent their potential hazard to the neighboring water or other environment elements. The resuspension of solids should be under a tight control in the reclamation area.

### **Professional Monitoring**

The dredging area, mud density, density of the dredging area water, and grain content of the suspended solids, etc all shall be closely monitored by environmental dredging professionals.

The differences between conventional dredging and environmental dredging are summerized in the following table:

**Table 1. Comparison of Conventional and Environmental Dredging**

	Conventional Dredging	Environmental Dredging
Objective	Increase water depth	Clear polluted sediment
Boundary requirement	Flat bottom, regular cross section	Determined by the polluted layer
Digging depth	Thick, > 1 meter	Thin, < 1 meter
Diffusion of thin grains	No limits	To avoid as much as possible
Overdepth	30~60 era	< 20 era
Equipment selection	Traditional equipment	Special equipment or modified traditional equipment
Disposal of polluted sediment	Conventional disposal	Special disposal according to the degree of pollution
Monitoring	Commonly	Strict, professional
Cost	Low	High

### **ENGINEERING MEASURES IN LAKE MAINTENANCE DREDGING**

Because the sediments may have pollutants, we suggest that the environmental dredging and conventional dredging be combined in a lake maintenance dredging.

#### **Survey of Sediments in the Dredging Area**

Before dredging, a precise measurement of alluvium shall be conducted, followed by an analysis of the slurry property and distribution. The total dredge amount and the amount of polluted slurry shall then be calculated in advance. If there is a polluted layer, then environmental dredging shall be used.

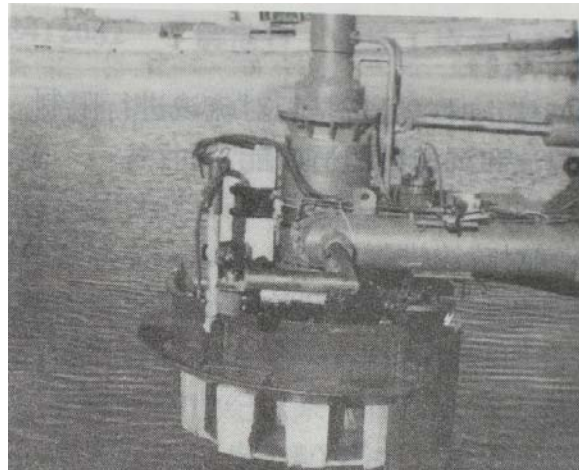
#### **Equipment Selection**

When choosing the dredger type and quantity as well as other related equipments, the following factors shall be taken into account: geographic environment, water characteristics, properties of the dredging soil, dredging scope and scale, quality requirements, and time constraints, etc.

We suggest that environmental dredgers shall be employed to remove the polluted sediments, because those dredgers cause relatively less negative impact on the environment and surrounding waters during dredging and transporting. Two typical approaches are: to use specialized environmental dredgers; or to use modified conventional dredgers. Equipment with a spiral digging device and hermetical revolve bucket wheel dredge invented in Japan for dealing with polluted sediments; a dredge with a pneumatic pump invented in Italy; and the beaver dredge by Holland are all specialized environmental dredges. The dredger called “water king” from Finland was used in the dredging project for the Donghu Cha Harbor and ShuiGuo Lake with the slurry

depth of 1 meter and slurry capacity of 20000 cubic meters under the water area of 7 hektare in Wuhan, China in 2004. The slurry and garbage were carried directly to a reclamation area by the spoil barge of 40 tons. The price of specialized environmental protection dredges is very high.

As an alternative, it is also popular in environment dredging to modify the cutter of a traditional dredge to reduce as much the diffusion and leakage of slurry as possible. For example, the cutter with an adjustable mantle whose bottom always joints the slurry surface in the course of operation from IHC Co. Holland prevents the bottom mud grains from diffusion caused by cutter agitation; the spiral cutter from DAMEN Co. Holland not only effectively prevents the release of contaminants but also ensures a high slurry concentration because the spiral cutter keeping level with the channel bottom, it disturbs the water little without skip. The adjustable cutter and screen invented in China to prevent diffusion of contaminants has a good adaptability to different types of sediments and prevents pollutant from diffusion. All those kinds of cutters have been installed and operated on different dredges for the purpose of environmental dredging. The following two figures are disc environmental cutter dredge and dipper suction environmental cutter dredge.



**Figure 1. Disc Environmental Cutter Dredge**



**Figure 2. Dipper Suction Environmental Cutter Dredge**

Modifications on monitoring, transport and drainage are still needed on these dredges, however. GPS, video display or ultrasonic system is added to monitor the dredging process, thus increasing the accuracy of digging, decreasing the skip or overdigging. The transport and drainage can be modified to decrease the leakage. The joint with slurry disposal equipment must be well designed to avoid secondary pollution. Such modified dredges were applied in the Caohai of Lake Dianchi in Kunming, Yunnan Province, China in 1998-1999. The environmental cutter was added to the dredge of 120 cubic meters per hour with DGPS, which worked very well.

Depending on the geographic environment, type of soil, quality requirements, and time constraints, different dredges should be chosen to dredge the common silt layer. The draft of the dredge must be less than the water depth before dredging. The least width and length of a dredger shall be considered, while the maximum depth that a dredger can reach shall meet the need. When the depth before dredging is not suitable for a single dredge, several dredges can be used in tandem. For example, a shallow-draft dredge can dig first to reach a certain depth; a deep-draft dredge can continue afterwards. When the dredging mud is transported by discharge pipes, the hydraulic capacity of the pipes shall be calculated whether using a cutter suction dredge, blow-off dredge, booster station, or trailing suction hopper dredge to shore discharge. In addition, the impact of wind and wave conditions in the work area shall be adequately assessed.

### **Dredging Control**

In the course of digging of polluted sediments, the following guidelines shall be followed closely:

- Reduce the disturbance to the polluted bottom slurry and take measures to prevent diffusion and leakage, which ensures a high concentration suction to avoid the pollution of the suspending pollutant to the surrounding water.
- Improve the accuracy of positioning and digging, remove the pollutant thoroughly, and minimize excessive digging. That is, reduce the project costs while meeting the objective of the environmental dredging. Methods such as DGPS or GPS-RTK can be used to increase the accuracy of dredging.
- Avoid the secondary pollution to the water column due to leakage during transportation. Lattice screen and geotextile are added before the spillway outlet to prevent the floating articles and thick grains from entering the waste channel. Steel surge basin is equipped on the mud stay of mud pipe to counteract some kinetic energy.
- Dispose of the polluted dredged slurry safely to prevent negative impacts to the surrounding water, groundwater or other elements of the environment.

Dredging of the common alluvium shall be controlled according to its technical specifications. Before dredging, double check the flat surface control point, benchmark, and water gauge to ensure their accuracy. When the leading marks are used in dredging, the milestone, fringe digging marks, and stripe dredging marks can be made when necessary. The layout of discharge pipes shall be based on dredging site conditions. When the width of dredge-cut is bigger than the maximum width that a cutter suction dredger digs once, dredging in stripes shall be followed. When the length of dredge-cut is longer than the effective extension length of the dredger's water pipes, dredging in sections shall be considered. When the slurry layer is very thick or the demand to the

fringe is high, dredging in layers shall be arranged. In summery, dredge-cut setting out, dredging commencement, digging, mobilization of dredger, reclamation, and quality shall be controlled and monitored strictly to assure the project progress, quality and safety. Improving the digging device should be an ongoing effort to decrease the slurry diffusion caused by the slurry cutting.

The noises during dredging are mainly from the diesel engines of the dredges and hydraulic booster stations. The way to control and reduce those noises is to close the cabin door during dredging or install noise-absorbing devices.

The direct discharge of sewage and rubbish shall be forbidden. The water quality in sensitive areas shall be real-time monitored. Containers to collect oily waste water shall be installed in the lower part of small dredgers and oil-water separation devices shall be installed in large dredgers. Sewage collectors, muck boxes, and garbage containers shall be shipped to designated sites and be disposed when the dredges are back in shore.

### **Disposal of Polluted Bottom Mud**

The polluted bottom mud may contain heavy metals, organic pollutants and nutrients such as nitrogen, phosphorus, etc., which may spread. Thus the contaminated sediments must be disposed appropriately. Selection of a reclamation area, design of a reclamation dike, and disposal techniques for polluted bottom mud must be professionally designed and monitored. The following items shall be considered:

- Choose the place for reclamation where the ground water level is low, the soil layer has a good adsorption, and it is suitable to install linking pipelines. The dimension of the settlement pond shall be estimated properly.
- Preventive leakage measures shall be adopted in the reclamation area. Internal geotextile shall be used in the reclamation dike. The reclamation area for contaminated sediments with high pollutant and heavy metals levels shall be far away from the lake.
- Pour the dredged mud into pipe bags made from special and high strength geotextile to form the reclamation dike as the bags drain without leaking mud. Using the lake bottom mud as filler makes the long-distance transport of clay borrow unnecessary, which minimizes damage to the ecosystem environment and lowers the project cost. It percolates the pollutants inside the bottom mud, which plays the role of dredging, enclosure, and clearance at the same time. Such reclamation dike was successfully used in the dredging project of Caohai of lake Dianchi in Yunan, China.
- Periodically analyze and appropriately dispose the remaining water. Whether the slurry remaining water needs a special treatment or not and how to treat it is determined by the makeup and content of pollutants in the remaining water, and the property, function, and comprehensive analysis result of the water that receives the remaining water.
- Dry the dredged mud. The polluted bottom mud is silty dirt with high organic compounds, which dries very slowly in the natural environment. It can be dehydrated using the methods like vacuum press, load press, deposition with chemical addition, physical dehydration, and active reclamation draining etc.
- Post processing of reclamation area. Clean soil can be overlaid on the silt after the silt is dried by air. Grass can then be planted on top of it, which absorbs the organic materials like phosphorus, nitrogen etc in the silt.

## **Selection of Reclamation Areas and Utilization of Dredged Sediment**

The selection of reclamation areas for sediments dredged from the non-polluted layer is important in dredging, and it shall prevent dredged sediments from eroding back to their original areas with storm water. Under such condition, the distance between reclamation and dredge area should be as short as possible. The disposal and utilizations of dredged sediment should be considered together while selecting reclamation area. The capacity, location, and boundaries of reclamation areas shall be decided according to the quantity of dredged material. If the dredged sediment is used for reclamation, to constrain its pollution within a limited scope, the boundaries of reclamation areas shall be controlled strictly and the rest water shall not be allowed to overspread everywhere. Reclamation area should be outside the main current or peak flow and should be marked. It should not interfere with the depth of channel, basin or anchorage. The selection of reclamation area should meet the related international agreements and the regulations of local environment protection department.

Dredged sediment, as a resource, can be handled properly to minimize the land needed for placement and reduce the expenses related to land takeover. Generally, a few methods can be used:

- Non-polluted dredged silt is directly filled into trenches and gulleys around the lake, and leveled off, which comprehensively utilizes the land resources and effectively protects the good farmland.
- The slurry can be applied to farmland to enrich farmlands. Non-polluted sediment from the bottom of lakes is a kind of good organic fertilizer since it has nitrogen, phosphorus, potassium chemical element, and other various minerals that are scarce in common mineral fertilizers. After dilution and filtering, slurry is transported to farmlands with a slurry pump, which effectively settles lots of abandoned fields, reduces dredging cost, and enriches farmlands. This method can be applied wherever the contaminant levels in the slurry are low and its transportation is convenient. The thickness of placed slurry layer shall be well controlled, however.
- The dredged sediment can be used for making and beautifying green belts alongside lakes, reinforcing dikes by resisting wind, and retaining water.

## **CONCLUSIONS**

In lake maintenance dredging, combining environmental and conventional dredging, along with the proper utilization of removed sediment can effectively reduce the adverse impact to ecosystems and the general surrounding environment.

## REFERENCES

Bai, X.M and Xu, Z.L (2000). “*The Effects of Suspended Sediment on Aquatic Organisms*”. The Editorial Board for Journal of Shanghai Fisheries University, Vol.9, No.1, pp.65-68.

Jin, X.C. and Liu, W.S. (1999). “*Engineering Techniques for Polluted Sediment Dredging of Lakes: Caohai of Lake Dianchi*”. Research of Environmental Sciences, Vol.12, No.5, pp.9-12.

Zhang, F.X. (2004). “*Foreground of Environmental Dredging in our Country*”, <http://www.cws.net.cn/Journal/cwr/200411/09.htm>, accessed in Nov. 2006.

# **THE EFFECT OF THE BED RISE VELOCITY ON THE SEDIMENTATION PROCESS IN HOPPER DREDGES**

S.A. Miedema

## **ABSTRACT**

In the last decennia there has been a strong development in the enlargement of TSHD's (Trailing Suction Hopper Dredges) from roughly 10,000 m<sup>3</sup> in the early 90's up to 50,000 m<sup>3</sup> expected loading capacity in 2010. Because of the economy of the loading process, but also environmental regulations, it is important to predict the overflow losses that are occurring. Van Rhee (2002) developed a sophisticated model, but this model is not easy to reproduce. The strong point of the Miedema & Vlasblom (1996) model is the simplicity, giving a transparent model where cause and result are easily related. The Miedema & Vlasblom model can be extended with a number of features that do not really influence the simplicity of the model. These include: implementing the layer thickness of the layer of water above overflow level; implementing a horizontal velocity distribution in the hopper that will result in a more gradual influence of the scour effect during the loading process; implementing a storage effect; implementing a starting volume of water when the loading process starts, and implementing a varying inflow and density of mixture. As a first attempt an analytical model has been developed to predict the overflow losses with a single equation. This model has been verified with test data of van Rhee (2002) and Ooijens (2001). Other papers will follow describing the other effects as mentioned above.

## **INTRODUCTION**

For the estimation of the sedimentation process in TSHD's a number of models have been developed. The oldest model used is the Camp (1946) model which was developed for sewage and water treatment tanks. Camp and Dobbins added the influence of turbulence based on the two-dimensional advection-diffusion equation, resulting in rather complicated equations. Miedema (1981) used the Camp approach with some modifications to predict the settling efficiency and the overflow losses. Miedema & Vlasblom (1996) simplified the Camp equations by means of regression and included a rising sediment zone, as well as hindered settling and erosion and an adjustable overflow. Van Rhee (2001) modified the implementation of erosion in the Camp model, but concluded that the influence is small due to the characteristics of the model. Ooijens added the time effect, since the previous models assume an instantaneous response of the settling efficiency on the inflow of mixture. Yagi (1970) developed a new model based on the concentration distribution in open channel flow.

---

Associate Professor in Dredging Engineering, Delft University of Technology, Mekelweg 2, 2628CD Delft, the Netherlands. Email: [s.a.miedema@tudelft.nl](mailto:s.a.miedema@tudelft.nl)

The models mentioned above are all black box approaches assuming simplified velocity distributions and an ideal basin. Van Rhee (2002) developed a sophisticated model, the 2DV model. This model is based on the 2D (horizontal and vertical) Reynolds Averaged Navier Stokes equations with a  $k-\epsilon$  turbulence model and includes suspended sediment transport for multiple fractions. The software developed by van Rhee however is not free available and is not easy to reproduce.

An attempt has been made to improve the model of Miedema & Vlasblom, to match the results of measurements and computations made by van Rhee (2002) and Ooijens (2001).

### THE BED RISE OR SEDIMENTATION VELOCITY

Suppose a vertical element of the hopper with length and width equal to 1m consists of 3 layers. At the top a layer of water with a concentration of particles equal to zero, in the middle a layer of mixture with an average concentration ( $c_b$ ) and at the bottom a layer of sediment with a concentration ( $c_{bed}$ ). All the particles in the mixture layer have a vertical settling velocity ( $v_c$ ), (including the hindered settling effect), while the sediment is moving up with a velocity ( $v_{sed}$ ), the so-called sedimentation or bed rise velocity because of the sedimentation of the particles. Now the question is, what is the value of this sedimentation velocity if  $c_b$ ,  $c_{bed}$  and  $v_c$  are known and constant during a certain time interval.

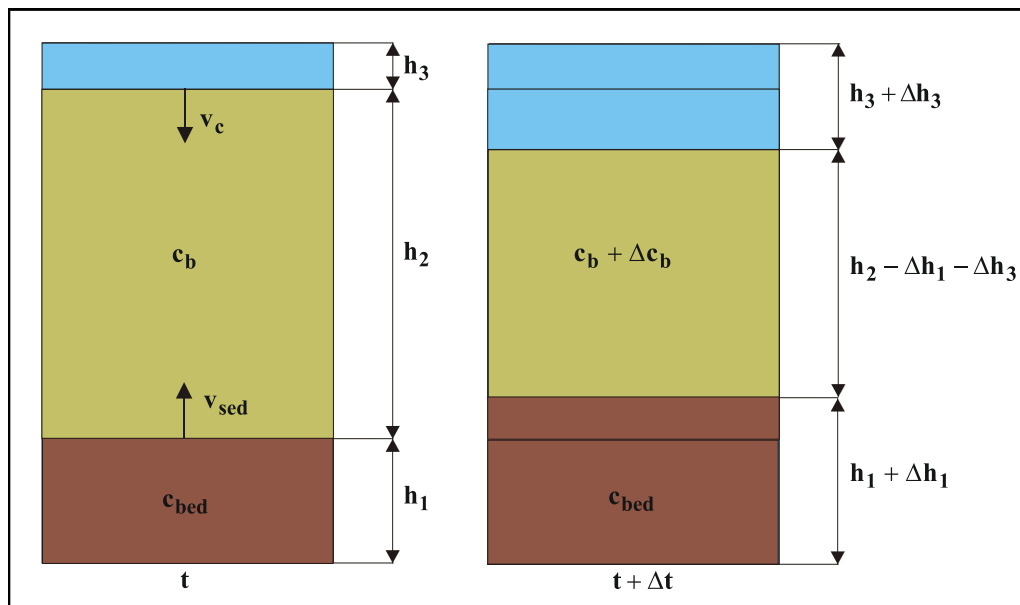


Figure 1. Segment of a Hopper at 2 Subsequent Time Steps

Figure 1 shows the hopper at 2 subsequent time steps. During one time step, the mixture moves down with the settling velocity ( $v_c$ ), causing the sediment to rise with the bed rise velocity ( $v_{sed}$ ). There is no mass added during the time step, so the sum of the mixture mass and the sediment mass remains constant. At time  $t$  (left figure) the total mass in TDS (Tonnes Dry Solids) in the hopper is:

$$TDS = (h_1 \cdot c_{bed} + h_2 \cdot c_b) \cdot L \cdot W \cdot \rho_q \quad (1)$$

A time step ( $\Delta t$ ) later (right figure), if the total mass in TDS in the hopper is assumed to be constant:

$$TDS = ((h_1 + \Delta h_1) \cdot c_{bed} + (h_2 - \Delta h_1 - \Delta h_3) \cdot (c_b + \Delta c_b)) \cdot L \cdot W \cdot \rho_q \quad (2)$$

This gives:

$$\Delta h_1 \cdot c_{bed} + (-\Delta h_1 - \Delta h_3) \cdot c_b + (h_2 - \Delta h_1 - \Delta h_3) \cdot \Delta c_b = 0 \quad (3)$$

Neglecting the double derivatives this gives:

$$\Delta h_1 \cdot (c_{bed} - c_b) = \Delta h_3 \cdot c_b - h_2 \cdot \Delta c_b \quad (4)$$

If the particles in the mixture layer all move downwards with the same settling velocity ( $v_c$ ), then the increment of the concentration ( $\Delta c_b$ ) in the second term on the right hand side equals zero, resulting in the following relation for the sedimentation or bed rise velocity:

$$v_{sed} = v_c \cdot \frac{c_b}{c_{bed} - c_b} \quad \text{with : } v_c = v_s \cdot (1 - C_v)^\beta \quad (5)$$

$$\begin{aligned} \text{With : } \Delta h_1 &= v_{sed} \cdot \Delta t \\ \Delta h_3 &= v_c \cdot \Delta t \end{aligned} \quad (6)$$

Van Rhee (2002) already derived equation 5 based on a finite element near the bed surface. If this equation is derived for a small element near the surface of the sediment, the concentration near the bed (the near bed concentration) does not have to be equal to the average concentration as used in the derivation above. Other researchers, Ooijens (2001) and Braaksmā (2007), used this equation for determining the global overflow losses and just like van Rhee use the concentration of the dredged mixture ( $c_{in}$ ) as a first approximation for the near bed concentration ( $c_b$ ). This may lead however to results which are physically impossible.

## THE DIMENSIONLESS OVERFLOW RATE

Based on the conservation of mass it can be proven that in general the near bed concentration ( $c_b$ ) and the mixture concentration ( $c_{in}$ ) are not equal.

If the increase of the sand mass in the sediment (bed) is considered as:

$$Q_{m_{bed}} = v_{sed} \cdot c_{bed} \cdot W \cdot L \quad (7)$$

Then the total sand mass in the hopper at the end of the loading process, assuming a constant sedimentation velocity, after a time  $T$  equals to:

$$TDS_{bed} = Q_{m_{bed}} \cdot T = v_{sed} \cdot c_{bed} \cdot W \cdot L \cdot T \cdot \rho_q \quad (8)$$

The total mass of TDS that has entered the hopper during this time equals to:

$$TDS_{in} = Q_{m_{in}} \cdot T = Q_{in} \cdot c_{in} \cdot T \cdot \rho_q \quad (9)$$

The cumulative overflow losses are equal to the amount of mass that entered the hopper, minus the amount that has settled, divided by the amount that has entered the hopper, according to:

$$ov_{cum} = 1 - \eta_{cum} = \frac{TDS_{in} - TDS_{bed}}{TDS_{in}} = \frac{Q_{in} \cdot c_{in} \cdot T - v_{sed} \cdot c_{bed} \cdot W \cdot L \cdot T}{Q_{in} \cdot c_{in} \cdot T} = 1 - \frac{W \cdot L}{Q_{in}} \cdot v_{sed} \cdot \frac{c_{bed}}{c_{in}} \quad (10)$$

Using the unmodified hopper load parameter  $v_o = Q_{in}/W \cdot L$  and equation 5 for the sedimentation velocity, this gives:

$$ov_{cum} = 1 - \eta_{cum} = 1 - \frac{W \cdot L}{Q_{in}} \cdot v_c \cdot \frac{c_b}{c_{bed} - c_b} \cdot \frac{c_{bed}}{c_{in}} = 1 - \frac{v_c}{v_o} \cdot \frac{c_b}{c_{in}} \cdot \frac{c_{bed}}{c_{bed} - c_b} \quad (11)$$

Ooijens (2001) uses equation 11 for determining the cumulative overflow losses. Van Rhee (2002) defined a dimensionless overflow rate ( $S^*$ ), based on the sedimentation velocity according to equation 5:

$$S^* = \frac{v_o}{v_c} \cdot \frac{c_{in}}{c_b} \cdot \frac{c_{bed} - c_b}{c_{bed}} = H^* \cdot \frac{c_{in}}{c_b} \cdot \frac{c_{bed} - c_b}{c_{bed}}, \text{ where } H^* = \frac{v_o}{v_c} \quad (12)$$

Substituting equation 12 in equation 11 gives a relation between the cumulative overflow losses ( $ov_{cum}$ ), the cumulative settling efficiency ( $\eta_{cum}$ ) and the dimensionless overflow rate ( $S^*$ ):

$$\text{ov}_{\text{cum}} = 1 - \frac{1}{S^*} \quad \text{or} \quad \eta_{\text{cum}} = \frac{1}{S^*} \quad (13)$$

Since the overall settling efficiency can never be greater than 1, this means that  $S^*$  should always be greater or equal to 1. Besides, the name dimensionless overflow rate does not seem to be appropriate, because  $S^*$  equals to the reciprocal of the cumulative settling efficiency and not to the cumulative overflow losses.

## THE NEAR BED CONCENTRATION

Both van Rhee (2002) and Ooijens (2001) state that making the near bed concentration ( $c_b$ ) equal to the mixture concentration ( $c_{in}$ ), is a good first approximation. For coarse particles with a settling velocity ( $v_c$ ) higher than the unmodified hopper load parameter ( $v_o$ ), equation 11 leads to negative overflow losses and equation 12 will give an  $S^*$  smaller than 1. This leads to the conclusion that for an overall approach, the near bed concentration should not be chosen equal to the mixture concentration. From equation 11, the following equation can be derived for the overall settling efficiency:

$$\eta_{\text{cum}} = \frac{v_c \cdot c_b}{v_o \cdot c_{in}} \cdot \frac{c_{\text{bed}}}{c_{\text{bed}} - c_b} \quad (14)$$

From this equation, an equation for the near bed concentration ( $c_b$ ) can be derived:

$$c_b = \frac{\eta_{\text{cum}} \cdot c_{\text{bed}}}{\left( \eta_{\text{cum}} + \frac{v_c}{v_o} \cdot \frac{c_{\text{bed}}}{c_{in}} \right)} = \frac{\eta_{\text{cum}} \cdot c_{\text{bed}} \cdot c_{in}}{\left( \eta_{\text{cum}} \cdot c_{in} + \frac{v_c}{v_o} \cdot c_{\text{bed}} \right)} = c_{\text{bed}} \cdot \frac{\eta_{\text{cum}} \cdot \frac{c_{in}}{c_{\text{bed}}}}{\left( \eta_{\text{cum}} \cdot \frac{c_{in}}{c_{\text{bed}}} + \frac{v_c}{v_o} \right)} \quad (15)$$

Thus:

$$\frac{c_b}{c_{\text{bed}}} = \frac{\eta_{\text{cum}} \cdot \frac{c_{in}}{c_{\text{bed}}}}{\left( \eta_{\text{cum}} \cdot \frac{c_{in}}{c_{\text{bed}}} + \frac{v_c}{v_o} \right)} = \frac{\eta_{\text{cum}} \cdot \kappa}{\left( \eta_{\text{cum}} \cdot \kappa + \frac{v_c}{v_o} \right)} \quad \text{With :} \quad \kappa = \frac{c_{in}}{c_{\text{bed}}} \quad (16)$$

Now, two cases can be considered:

1. There are hardly any overflow losses, which means that the particle settling velocity is much higher than the hopper load parameter, giving a cumulative efficiency almost equal to 1.
2. The particle settling velocity is smaller than the hopper load parameter, giving a particle settling efficiency smaller than 1.

In both cases it is assumed that the loading process starts with a hopper full of water, otherwise the filling of the hopper up to overflow level is part of the cumulative settling efficiency, while there are no overflow losses during this phase, so a too high settling efficiency is found. If the loading process starts with an empty hopper or a partially filled hopper, this part of the filling process should not be considered when determining the cumulative settling efficiency, for the purpose of determining the correct near bed concentration.

Case 1:  $\eta_{cum} \approx 1$

$$\frac{c_b}{c_{bed}} = \frac{\kappa}{\left(\kappa + \frac{v_c}{v_o}\right)} \quad (17)$$

Since in this case the velocity ratio ( $v_c/v_o$ ) is always greater than 1, the near bed concentration ( $c_b$ ) will always be smaller than the mixture concentration ( $c_{in}$ ). The greater the settling velocity of the particle, the smaller the near bed concentration. In other words, the ratio  $c_b/c_{bed}$  will always be smaller than the ratio  $c_{in}/c_{bed}$ . Physically this means that the particles settle faster than they are supplied by the inflow of mixture.

Case 2:  $\eta_p = \frac{v_c}{v_o} < 1$

$$\frac{c_b}{c_{bed}} = \frac{\eta_{cum} \cdot \kappa}{\left(\eta_{cum} \cdot \kappa + \eta_p\right)} \quad (18)$$

If the PSD is very narrow graded, the cumulative settling efficiency ( $\eta_{cum}$ ) is equal to the settling efficiency ( $\eta_p$ ) of the particle considered, leading to the following equation:

$$\frac{c_b}{c_{bed}} = \frac{\kappa}{\left(\kappa + 1\right)} \quad (19)$$

The near bed concentration ( $c_b$ ) in this case is always smaller than the mixture concentration ( $c_{in}$ ). Physically this is caused by the overflow losses.

If the PSD is not narrow graded, the cumulative settling efficiency ( $\eta_{cum}$ , the settling efficiency of all the particles in the PSD) can be smaller or greater than the particle settling efficiency ( $\eta_p$ , the settling efficiency of an individual particle), where it is assumed that for the particle efficiency the settling efficiency of the  $d_{50}$  is chosen. If the PSD is steep for the grains smaller than the  $d_{50}$  and well graded for the grains larger than the  $d_{50}$ , the cumulative settling efficiency  $\eta_{cum}$  will be greater than the particle settling efficiency  $\eta_p$ . Figure 2 shows that in this case the near bed concentration ( $c_b$ ) is greater than the mixture concentration ( $c_{in}$ ) for small mixture concentrations and smaller than the mixture concentration for high mixture concentrations. Physically this is caused by the fact that the larger particles dominate the settling efficiency. For

example, the cumulative settling efficiency in Figure 2 is chosen 0.8. For a particle settling efficiency  $\eta_p$  of 0.6, the ratio  $\lambda$  is greater than 1 for a value of  $\kappa$  smaller than 0.25. The ratio  $\lambda$  between the near bed concentration ( $c_b$ ) and the mixture concentration ( $c_{in}$ ) is:

$$\lambda = \frac{c_b}{c_{bed} \cdot \kappa} = \frac{c_b}{c_{in}} = \left( \frac{\eta_{cum}}{\eta_{cum} \cdot \kappa + \eta_p} \right) \quad (20)$$

If the PSD is steep for the grains larger than the  $d_{50}$  and well graded for the grains smaller than the  $d_{50}$ , the cumulative settling efficiency ( $\eta_{cum}$ ) will be smaller than the particle settling efficiency ( $\eta_p$ ) for the  $d_{50}$  resulting in a ratio  $\lambda$  that is always smaller than 1, so the near bed concentration ( $c_b$ ) is always smaller than the mixture concentration ( $c_{in}$ ). Physically this is caused by the fact that the smaller particles dominate the cumulative settling efficiency.

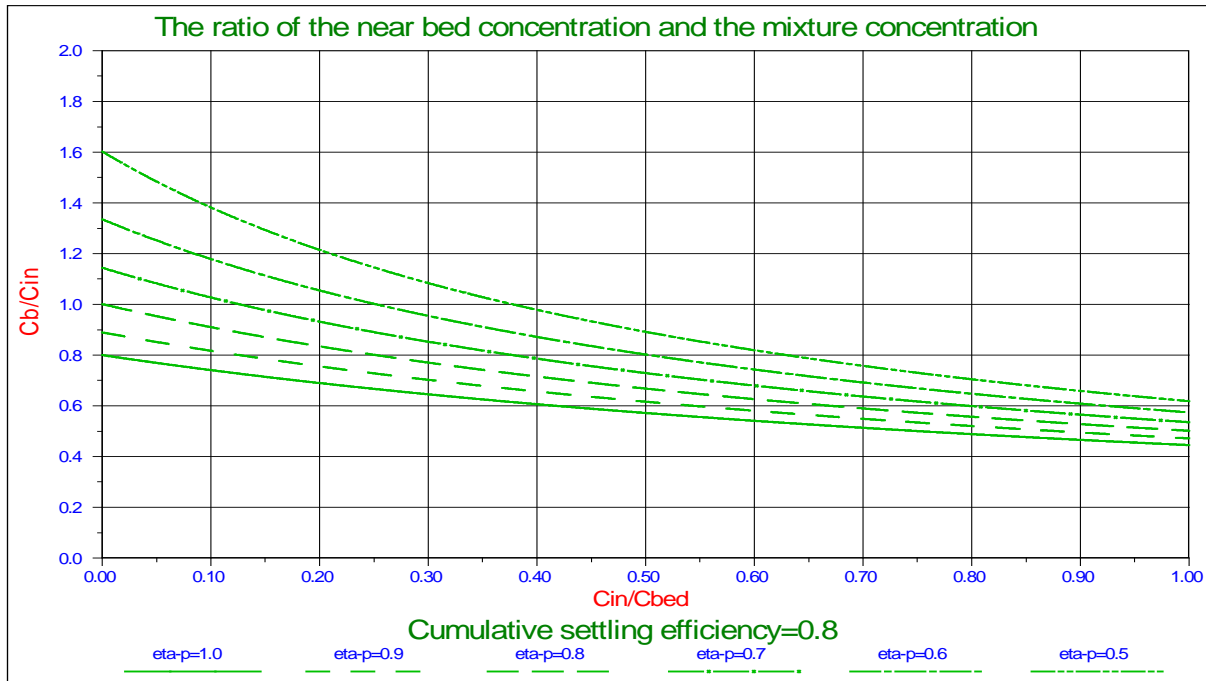


Figure 2. The Ratio between  $c_b$  and  $c_{in}$

## THE OVERALL BED RISE OR SEDIMENTATION VELOCITY

Based on the conservation of mass, it has been proven that the near bed concentration ( $c_b$ ) should not be chosen equal to the mixture concentration. In fact the near bed concentration ( $c_b$ ) can be smaller or greater than the mixture concentration ( $c_{in}$ ), depending on the PSD of the sand. The loading process considered, should start at the moment the overflow level is reached, otherwise a too high cumulative settling efficiency is chosen. If equation 16 is substituted in equation 5, the following equation for the sedimentation or bed rise velocity is found:

$$v_{sed} = v_c \cdot \frac{c_b}{c_{bed} - c_b} = v_c \cdot \frac{c_{in} \cdot \frac{\eta_{cum}}{\eta_{cum} \cdot \kappa + \frac{v_c}{v_o}}}{c_{bed} - c_{in} \cdot \frac{\eta_{cum}}{\eta_{cum} \cdot \kappa + \frac{v_c}{v_o}}} = v_o \cdot \eta_{cum} \cdot \kappa \quad (21)$$

In other words:

$$L \cdot W \cdot v_{sed} \cdot c_{bed} = Q \cdot c_{in} \cdot \eta_{cum} \quad \text{With : } v_o = \frac{Q}{L \cdot W} \quad (22)$$

From the point of view of conservation of mass this is logic, so the circle is round again. The derivation is for the whole loading cycle, from the moment the overflow level is reached to the moment the hopper is economically full. Some aspects of the loading process however are not taken into account:

1. The filling of the hopper up to the overflow level. Since it is assumed that there are no overflow losses during this phase, this will increase the cumulative settling efficiency and thus the bed rise velocity. This also gives a higher near bed concentration, which is valid for the whole loading cycle, but not realistic for the loading after the overflow level has been reached.
2. The occurrence of scour at the end of the loading cycle. This will decrease the average sedimentation velocity resulting in a lower cumulative settling efficiency. The calculated near bed concentration will also decrease, which is not representative for the main part of the loading cycle. Fortunately the scour does not occur very long if the loading stops at the most economical point, so this influence is not very important.

Equation 13 implies that the factor  $S^*$  should always be greater than 1. Van Rhee (2002, page 72 and page 205) however found values for  $S^*$  between 0.5 and 1 with the approximation that the near bed concentration ( $c_b$ ) equals the mixture concentration ( $c_{in}$ ). For this case he found the following empirical relation between the cumulative overflow losses and the dimensionless overflow rate:

$$ov_{cum} = 0.39 \cdot (S^* - 0.43) \quad (23)$$

To explain this, the example from chapter 8 of van Rhee (2002) will be reproduced. Van Rhee used the TSHD Cornelia, a hopper with  $L=52m$ ,  $W=11.5m$ ,  $H=8.36m$ ,  $Q=5.75m^3/sec$  and  $c_{bed}=0.54$ ,  $c_{in}=0.15$ ,  $\eta_{cum}=0.92$  and  $d_{50}=0.235mm$ . This gives  $v_c=14.8mm/sec$  including the hindered settling effect,  $v_o=9.6mm/sec$ ,  $\kappa=0.278$ ,  $H^*=0.648$ ,  $S^*=0.47$  and  $ov_{cum}=0.015$  if  $c_b=c_{in}$ . From equation 16 it can be seen however that  $c_b=0.513 \cdot c_{in}$ . This gives  $S^*=1.09$  according to equation 12 and 13, which in fact is a self fulfilling prophecy and  $ov_{cum}=0.259$  according to equation 23 using  $S^*=1.09$ . The real cumulative overflow losses were 0.08, so the empirical equation 23 for the overflow losses is not very accurate. In fact using the approximation of  $c_b=c_{in}$

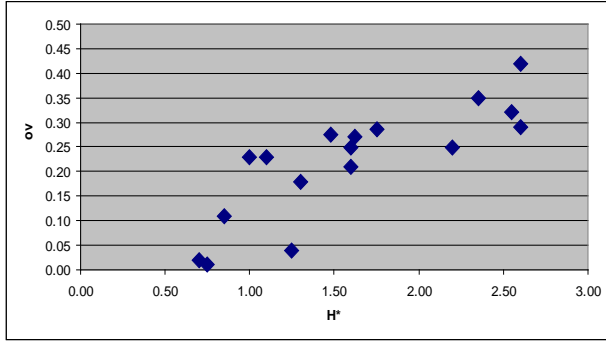
does not match the conservation of mass principle and should only be applied as a first approximation.

Equation 23 has been derived by van Rhee (2002, page 72) based on a set of model tests, see Table 1. Recalculating the values for  $c_b$  with equation 16 and  $S^*$  with equation 12 gives a new relation between the cumulative overflow losses  $ov_{cum}$  and  $S^*$ . This gives a 100% correlation matching equation 12, but this is a self fulfilling prophecy, since the near bed concentration has been derived from the cumulative overflow losses. Table 1, Figure 3 and Figure 4 show the original data from van Rhee (2002), while Figure 5 shows the results of the recalculation.

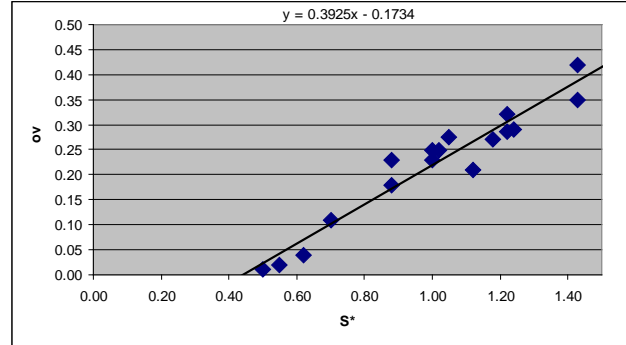
The original equation 5 for the bed rise velocity, however is still valid for a small element of sediment and mixture at a certain moment of the loading process if the correct near bed concentration  $c_b$  is used. For the overall approach equation 21 should be used to calculate the average bed rise velocity.

**Table 1. Model Tests by van Rhee (2002)**

Test	$\rho_{in}$	$c_{in}$	Q	$v_o$	$d_{50}$	$ov_{cum}$	$H^*$	$S^*$ ( $c_b=c_{in}$ )	$c_b$	$S^*$ ( $c_b \neq c_{in}$ )
1	1310	0.18	0.099	2.75	0.140	0.01	0.75	0.50	0.105	1.01
2	1210	0.11	0.139	3.86	0.146	0.02	0.70	0.55	0.068	1.02
4	1460	0.27	0.100	2.78	0.147	0.04	1.25	0.62	0.201	1.04
5	1350	0.20	0.100	2.78	0.102	0.25	1.60	1.00	0.165	1.33
6	1420	0.24	0.137	3.81	0.107	0.42	2.60	1.43	0.218	1.72
7	1100	0.05	0.140	3.89	0.089	0.23	1.10	1.00	0.037	1.30
8	1500	0.29	0.075	2.08	0.103	0.25	2.20	1.02	0.255	1.33
9	1260	0.14	0.138	3.83	0.096	0.27	1.62	1.18	0.130	1.37
10	1310	0.18	0.101	2.81	0.105	0.18	1.30	0.88	0.139	1.22
11	1290	0.16	0.137	3.81	0.106	0.21	1.60	1.12	0.149	1.27
12	1480	0.28	0.101	2.81	0.105	0.32	2.55	1.22	0.255	1.47
13	1480	0.28	0.102	2.83	0.104	0.29	2.60	1.24	0.264	1.41
15	1370	0.21	0.138	3.83	0.101	0.35	2.35	1.43	0.203	1.54
16	1130	0.06	0.141	3.92	0.103	0.23	1.00	0.88	0.046	1.30
17	1290	0.16	0.142	3.94	0.104	0.29	1.75	1.22	0.148	1.40
18	1280	0.16	0.140	3.89	0.111	0.28	1.48	1.05	0.128	1.38
19	1180	0.10	0.100	2.78	0.100	0.11	0.85	0.70	0.063	1.12

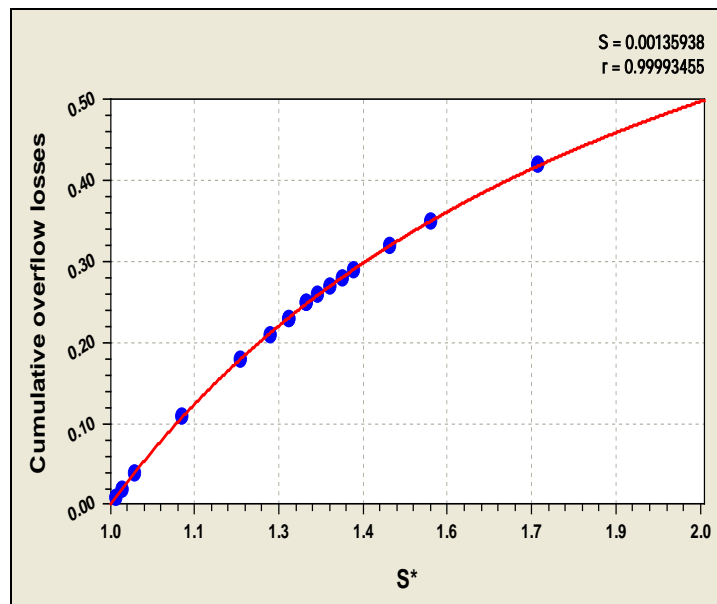


**Figure 3. Overflow Losses vs H\***

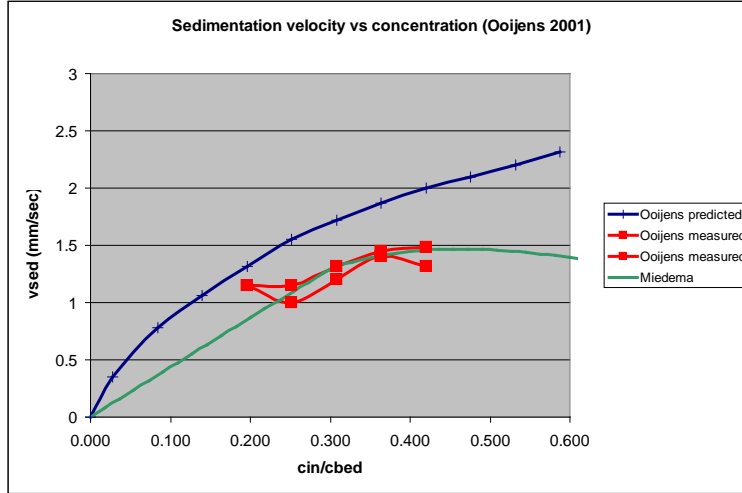


**Figure 4. Overflow Losses vs S\***

Ooijens (2001) also published data of research carried out to validate the model of the sedimentation velocity. He used equation 5 with  $c_b=c_{in}$ . Figure 6 shows the measurements and prediction of Ooijens (2001) and the prediction using the near bed concentration according to equation 16. The cumulative efficiency  $\eta_{cum}$ , required in equation 16 has been calculated using the modified Camp model of Miedema and Vlasblom (1996). It is obvious that using the near bed concentration according to equation 16 results in a better match with the measured data. Ooijens (2001) used a hopper with  $L=11.34m$ ,  $W=2.0m$ ,  $H=1.4-2.4m$ ,  $Q=0.1m^3/sec$ ,  $d_{50}=0.1mm$  and densities up to  $1.6 ton/m^3$ . For the calculations a bed concentration  $c_{bed}$  of  $0.55$  has been used.



**Figure 5. Cumulative Overflow Losses vs S\* ( $c_b$  re-calculated)**



**Figure 6. Sedimentation Velocity Measured by Ooijens (2001)**

### THE CONCENTRATIONS DURING THE LOADING CYCLE

Equation 16 gives the average near bed concentration, averaged during the total loading process, the momentary near bed concentration however may differ from the average. If a hopper with a height  $H$  and a sediment level  $h$  is considered, the following equation can be derived based on the conservation of mass principle, starting with a hopper full of water at  $t=0$ , and assuming a uniform concentration distribution with concentration  $c_b(t)$  above the sediment level and a concentration  $c_{bed}$  in the sediment. Assuming a width and a length of 1 m, the total mass TDS in the hopper at any moment of time equals the amount of TDS that has entered the hopper during this time:

$$h \cdot c_{bed} + (H-h) \cdot c_b = \eta \cdot v_o \cdot c_{in} \cdot t \quad (24)$$

The left hand side shows the amount of mass in the sediment ( $h \cdot c_{bed}$ ) and above the sediment ( $(H-h) \cdot c_b$ ), while the right hand side shows the amount off mass that has entered the hopper ( $\eta \cdot v_o \cdot c_{in} \cdot t$ ) at a time  $t$  after the loading has started. This can be rewritten as:

$$h \cdot (c_{bed} - c_b) + H \cdot c_b = \eta \cdot v_o \cdot c_{in} \cdot t \quad (25)$$

Taking the derivative with respect to time gives:

$$(c_{bed} - c_b) \cdot \frac{dh}{dt} + (H-h) \cdot \frac{dc_b}{dt} = \eta \cdot v_o \cdot c_{in} \quad (26)$$

With the sedimentation velocity according to equation 5:

$$\frac{dh}{dt} = v_{sed} = v_c \cdot \frac{c_b}{c_{bed} - c_b} \quad (27)$$

This gives for the derivative of the near bed concentration:

$$\frac{dc_b}{dt} = \frac{\eta \cdot v_o \cdot c_{in} - v_c \cdot c_b}{H - h} \quad (28)$$

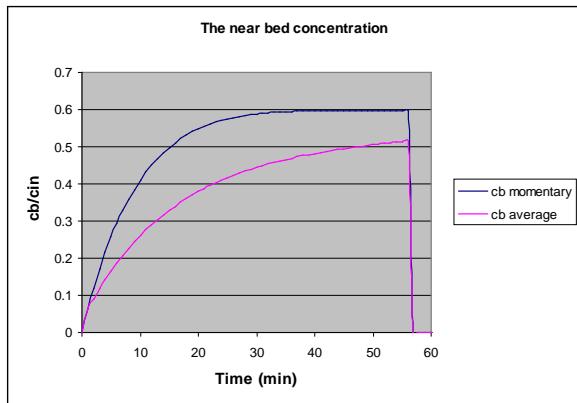
Or:

$$(H - h) \cdot \frac{dc_b}{dt} + v_c \cdot c_b - \eta \cdot v_o \cdot c_{in} = 0 \quad (29)$$

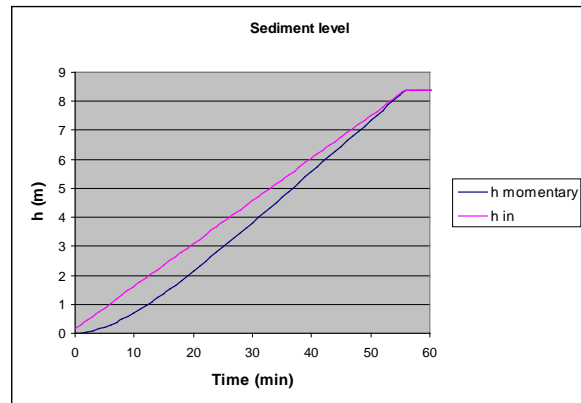
Solving equation 29 for a constant sediment level h gives:

$$\frac{c_b}{c_{in}} = \eta \cdot \frac{v_o}{v_c} \cdot \left( 1 - e^{-\frac{v_c}{H-h} t} \right) \quad (30)$$

Now an expression has been found for the average near bed concentration (equation 16) and an expression for the momentary near bed concentration (equation 30). For the case of the Cornelia, as discussed before, equations 27 and 28 have been solved numerically. The results are shown in Figure 7 and Figure 8. It is obvious that the near bed concentration has to build up, causing a time delay in the momentary sediment level, with respect to the sediment entered in the hopper. The vertical distance between the momentary sediment level and the level of the sediment in, is the amount of sediment still in suspension. It should be noted here that the near bed concentration is assumed to be the concentration of all the mixture above the sediment. Although this is not in accordance with the definition of van Rhee (2002), it gives more insight in the loading process.

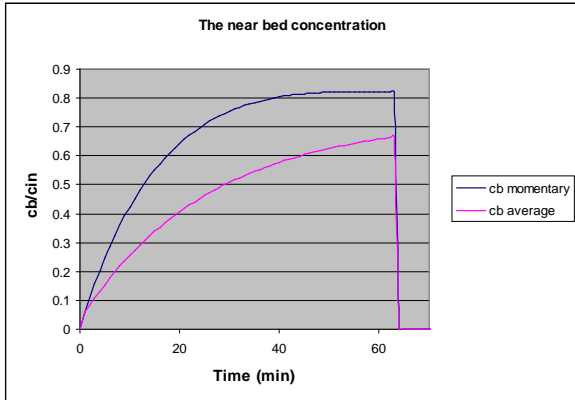


**Figure 7. Near Bed Concentration,**  
 $v_c=14.8$  mm/sec

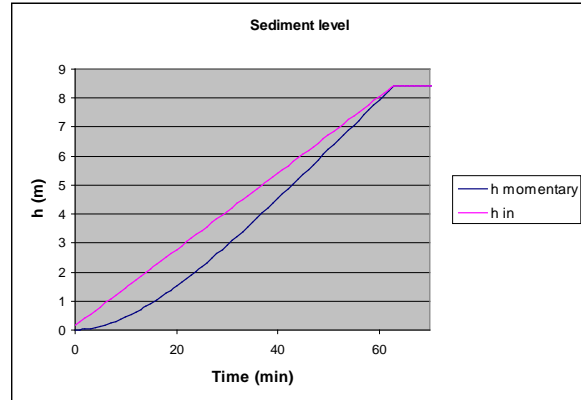


**Figure 8. Sediment Level,**  
 $v_c=14.8$  mm/sec

The case considered in Figure 7 and Figure 8, has a sand with a settling velocity of 14.8 mm/sec, so a rather coarse sand. It is interesting to see what these figures would look like for finer sands. If two other cases are considered, a sand with a settling velocity of 9.6 mm/sec (equal to the hopper load parameter) and a sand with 50% of this settling velocity, 4.8 mm/sec, including the hindered settling effect. This gives values for the  $S^*$  of 0.72 and 1.44 (assuming  $c_b=c_{in}$ ). The estimated overflow losses according to equation 23 are now 11.31% and 39.39%, but since the estimation was 6.5% to low for the sand with a settling velocity of 14.8 mm/sec, as discussed before, this 6.5% is added to the estimation, giving 17.8% and 45.9%. So the settling efficiencies are estimated to 0.822 and 0.541.

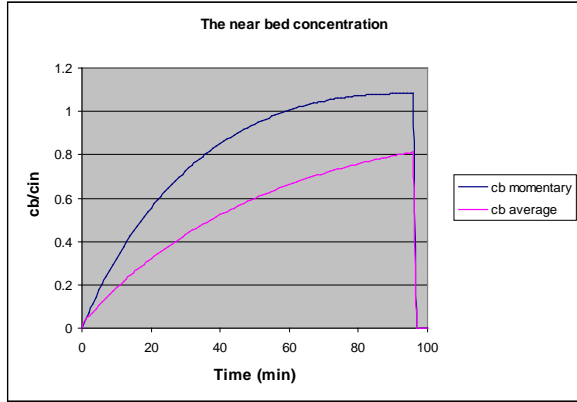


**Figure 9. Near Bed Concentration,**  
 **$v_c=9.6$  mm/sec**

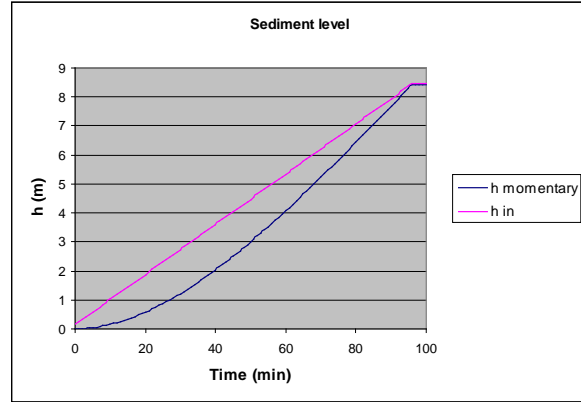


**Figure 10. Sediment Level,**  
 **$v_c=9.6$  mm/sec**

From these figures it can be seen that a smaller grain with a smaller settling velocity will result in a higher near bed concentration as also was concluded from Figure 2 and equation 20. The smallest grain gives a momentary near bed concentration which is higher than the incoming mixture concentration at the end of the loading process, while the average near bed concentration is still below the incoming mixture concentration. Another conclusion that can be drawn and also makes sense, is that the time required for the mixture to settle increases when the settling velocity decreases. This is in accordance with equation 30.



**Figure 11. Near Bed Concentration,**  
 $v_c=4.8$  mm/sec



**Figure 12. Sediment Level,**  
 $v_c=4.8$  mm/sec

The fact that the near bed concentration (here it is the average concentration in the hopper above the bed) is different from the incoming mixture concentration also implies that this near bed concentration should be used for determining the hindered settling effect. In most cases this will result in a near bed concentration smaller than the incoming mixture concentration, but in specific cases the near bed concentration is higher.

### ANALYTICAL MODEL TO PREDICT THE OVERFLOW LOSSES

After discussing the empirical equation 23 of van Rhee (2002), it is interesting to see if there is a more theoretical background behind this equation. Of course equation 13 has been found, but using it in combination with the near bed concentration according to equation 16, is a self fulfilling prophecy. Equation 23 at least gives a first estimate of the overflow losses, although some questions can be asked about the validity as already mentioned by van Rhee (2002) himself. One of the omissions of equation 23 is, that it is based on tests with a certain grading of the sand, so the question would be, how accurate is this equation if a sand with another grading is used. To investigate this, an old analytical model of Miedema (1981) is used. The model is based on the Camp (1946) approach and published by Miedema and Vlasblom (1996). The settling efficiency  $\eta_b$  at a certain moment of the hopper loading process is defined as:

$$\eta_b = (1 - p_o) + \int_{p_{fs}}^{p_o} \frac{v_c}{v_o} \cdot dp \quad (31)$$

One should read Miedema & Vlasblom (1996) for the derivation of this equation. Basically, there are 3 area's in this equation. The area from 0 to  $p_{fs}$  are the particles that will not settle due to scour, or because they are too small (fines), the area from  $p_{fs}$  to  $p_o$ , which are the particles that settle partially, some reach the sediment but some don't and leave the hopper through the overflow, and last but not least the area above  $p_o$  which are the particles that settle 100%. To find

an analytical solution for this equation, the PSD should be approximated by a straight line according to:

$$\log(d) = a \cdot p - b \quad (32)$$

A number of examples of PSD's according to equation 32 are shown in Figure 13. Equation 32 can also be written as:

$$p = \frac{\log(d) + b}{a} \quad (33)$$

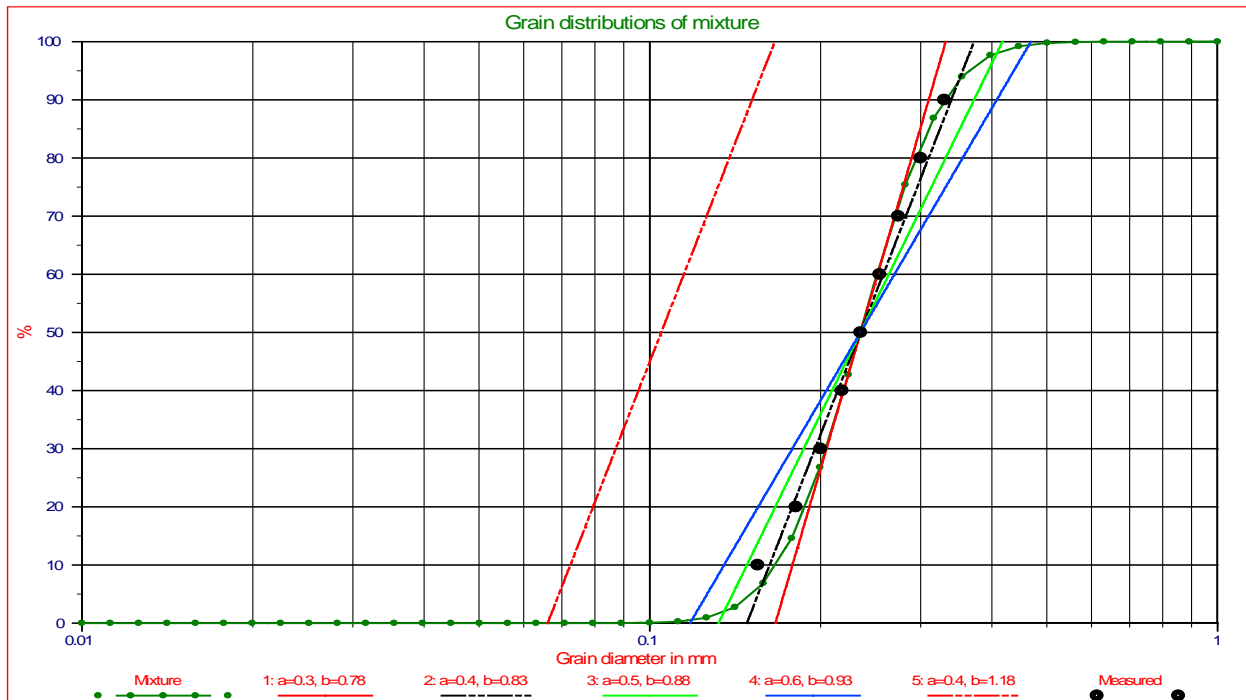


Figure 13. The PSD's as used in the Examples

Now the grains that cause overflow losses, are usually grains that settle in the Stokes region, according to:

$$v_s = 424 \cdot R_d \cdot \mu \cdot d^2 \quad (34)$$

Hindered settling can be taken into account with the well known Richardson and Zaki equation:

$$v_c = 424 \cdot R_d \cdot \mu \cdot d^2 \cdot (1 - C_v)^\beta \quad (35)$$

This can be rewritten as equation 36 to show the grain diameter as a function of the settling velocity.

$$d = \left( \frac{v_c}{424 \cdot R_d \cdot \mu \cdot (1 - C_v)^\beta} \right)^{1/2} \quad (36)$$

The number 424 is based on the original Stokes equation but can be changed using the variable  $\mu$ . The particle diameter that matches the hopper load parameter  $v_o$ , the particle that will just settle 100% is now:

$$d_o = \left( \frac{v_o}{424 \cdot R_d \cdot \mu \cdot (1 - C_v)^\beta} \right)^{1/2} \quad (37)$$

This gives for the fraction of the particles that will settle 100%,  $p_o$ :

$$p_o = \frac{\log(d_o) + b}{a} \quad (38)$$

For the particles that settle partially the second term on the right hand side of equation 31 has to be solved according to:

$$p_1 = \int_{p_{fs}}^{p_o} \frac{v_c}{v_o} \cdot dp = \int_{p_{fs}}^{p_o} \frac{424 \cdot R_d \cdot \mu \cdot d^2 \cdot (1 - C_v)^\beta}{v_o} \cdot dp = \int_{p_{fs}}^{p_o} \frac{424 \cdot R_d \cdot \mu \cdot (1 - C_v)^\beta \cdot e^{2 \cdot (a \cdot p - b) \cdot \ln(10)}}{v_o} \cdot dp \quad (39)$$

$$p_1 = \frac{1}{2 \cdot a \cdot \ln(10)} \cdot \frac{424 \cdot R_d \cdot \mu \cdot (1 - C_v)^\beta}{v_o} \cdot e^{-2 \cdot b \cdot \ln(10)} \cdot \left( e^{2 \cdot a \cdot p_o \cdot \ln(10)} - e^{2 \cdot a \cdot p_{fs} \cdot \ln(10)} \right) \quad (40)$$

This gives for the settling efficiency of the whole PSD:

$$\eta = (1 - p_o) + p_1 \quad (41)$$

Equation 41 does not include the turbulence effect as described by Miedema & Vlasblom (1996), because here it is the aim to find a simple equation to predict overflow losses. Of course this will give an error, but the magnitude of the settling efficiency found will be correct. The derivation until now assumes that the loading process starts with a hopper full of water, so from the beginning of the loading process the settling efficiency is active. In reality, though it is possible that the loading process starts with an empty hopper or a partially filled hopper. When the hopper at the start of the loading process has to be partially filled with mixture for a fraction  $\alpha$ , and it is assumed that all the particles that enter the hopper before the overflow level has been reached will settle, then the sediment level will already reach a fraction  $\varepsilon$  of the height of the hopper when the overflow level has been reached. This fraction  $\varepsilon$  can be calculated with:

$$\varepsilon = \alpha \cdot \left( \frac{\rho_{in} - \rho_w}{\rho_{bed} - \rho_w} \right) \quad (42)$$

Since this has an effect on the cumulative settling efficiency  $\eta_{cum}$ , the settling efficiency has to be corrected by:

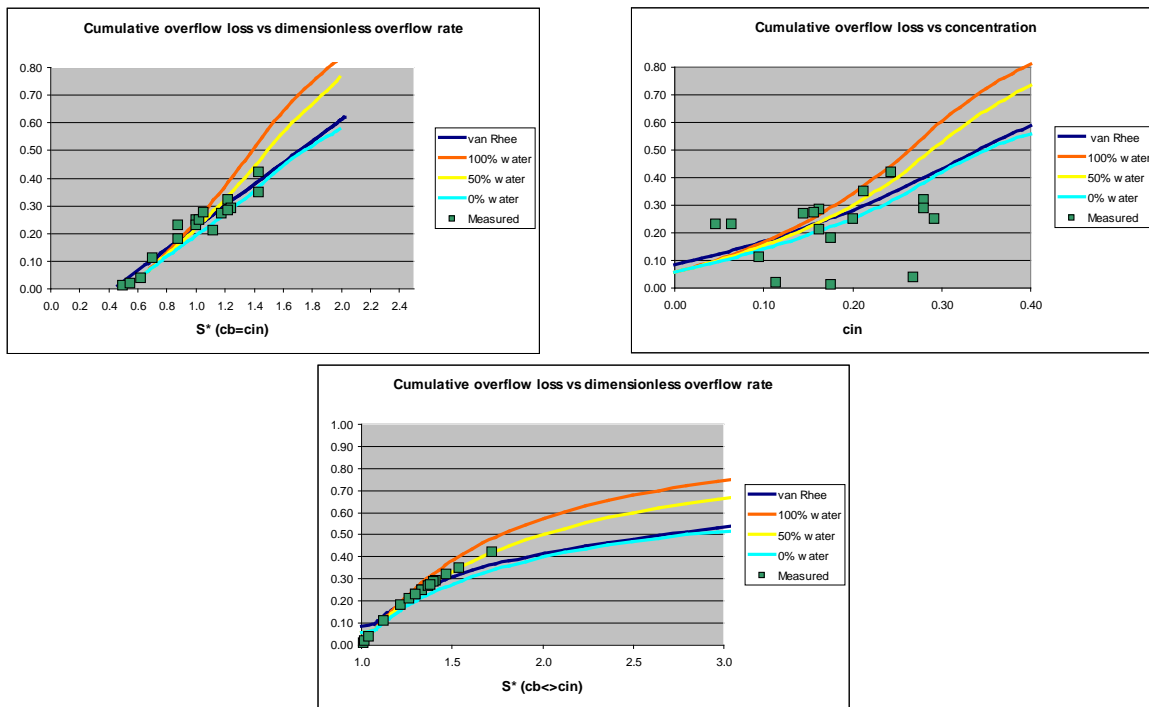
$$\eta_{cum} = \frac{\eta \cdot (1 - \varepsilon)}{1 - \varepsilon \cdot \eta} \quad (43)$$

The cumulative overflow losses are now:

$$ov_{cum} = 1 - \eta_{cum} \quad (44)$$

### VERIFICATION OF THE ANALYTICAL MODEL

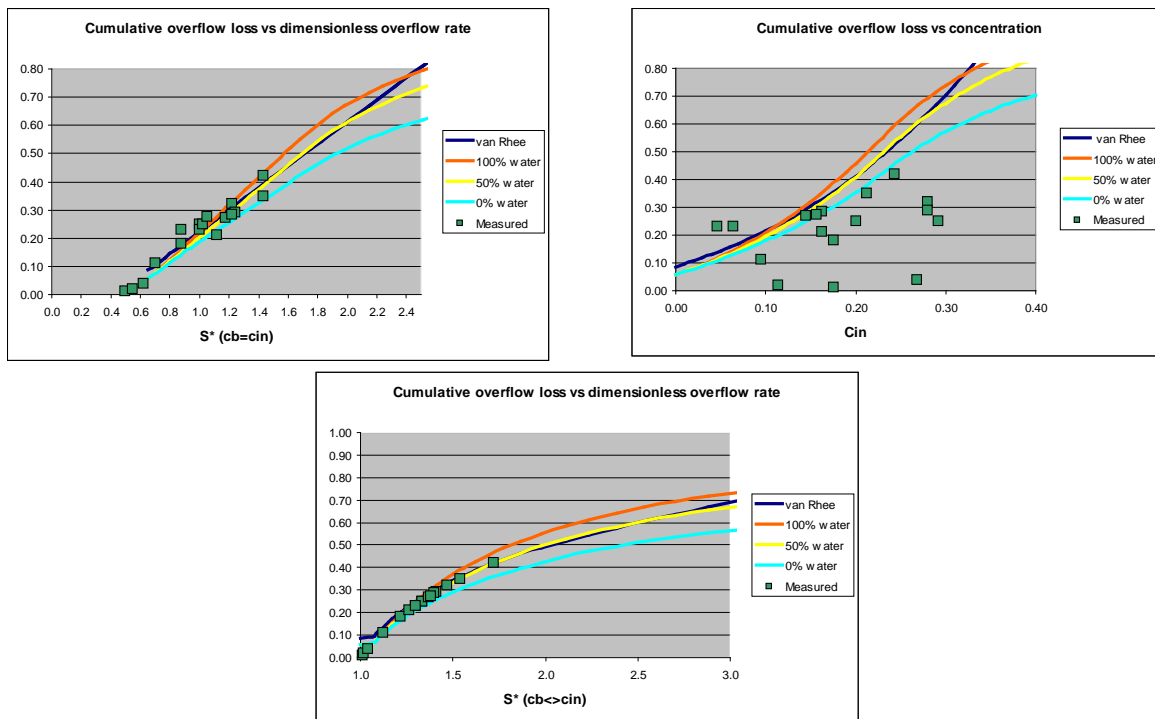
The analytical model found has been verified using the data from van Rhee (2002), as given in table 1. Figure 1 shows the cumulative overflow losses of the analytical model, the empirical equation 23 and the measured data of table 1, as a function of the dimensionless overflow rate  $S^*$  assuming  $c_b=c_{in}$ , as a function of the concentration and as a function of the dimensionless overflow rate  $S^*$  with  $c_b$  calculated according to equation 16.



**Figure 14. Comparing van Rhee (Chapter 4) with the Analytical Model**  
 (Q=0.125, L=12, W=3, H=2,  $d_{50}$ =0.105, a=0.4, b=1.18,  $\beta$ =4.47, n=0.4,  $\mu$ =1)

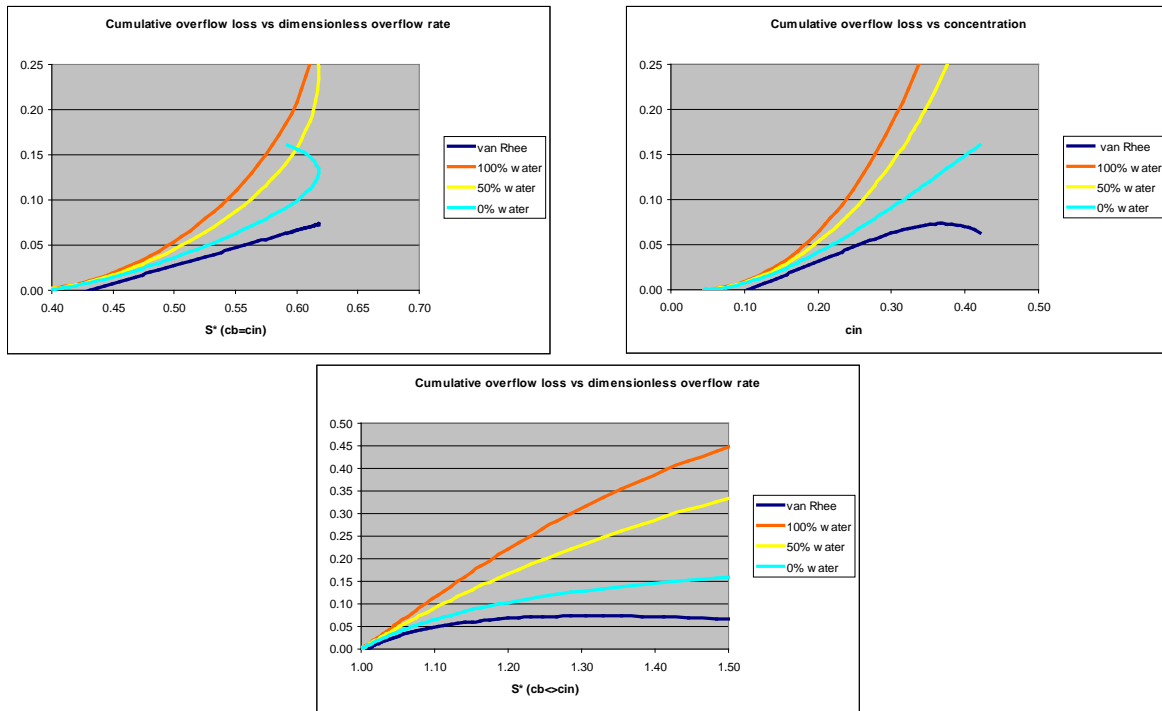
The analytical model has been computed for a hopper filled with 0%, 50% and 100% water at the start of the loading process. It should be noted that the measurements of van Rhee (2002) from table 1 are carried out with a hopper with about 50% of water at the start of the loading process. So the analytical model for 50% initial hopper filling should be compared with the empirical equation 23. It is obvious that the analytical model matches the empirical equation 23 up to a value of  $S^*$  of 1.2 in the top left graph, up to a concentration  $c_{in}$  of 0.2 in the top right graph and up to a value of  $S^*$  of 1.5 in the bottom graph. For these computations, the settling velocity has been calculated using the iterative method based on the drag coefficient and using the Richardson and Zaki equation for hindered settling. Van Rhee (2002) however states that the hindered settling process is more complicated for a well graded sand. In the experiments a sand according to Figure 13 sand number 5 has been used. In such a sand there is interaction between smaller and larger particles regarding the hindered settling effect. If this is taken into account by the principle of hindered density, which means, that the larger particles settle in a heavier mixture of the smaller particles according to:

$$\rho_f = \frac{C_v}{2} \cdot \rho_q + \left(1 - \frac{C_v}{2}\right) \cdot \rho_w \text{ with: } R_d = \frac{\rho_q - \rho_f}{\rho_f} \quad (45)$$



**Figure 15: Comparing van Rhee (Chapter 4) with the Analytical Model, including the Hindered Density Effect**  
 (Q=0.125, L=12, W=3, H=2,  $d_{50}$ =0.105, a=0.4, b=1.18,  $\beta$ =4.47, n=0.4,  $\mu$ =1)

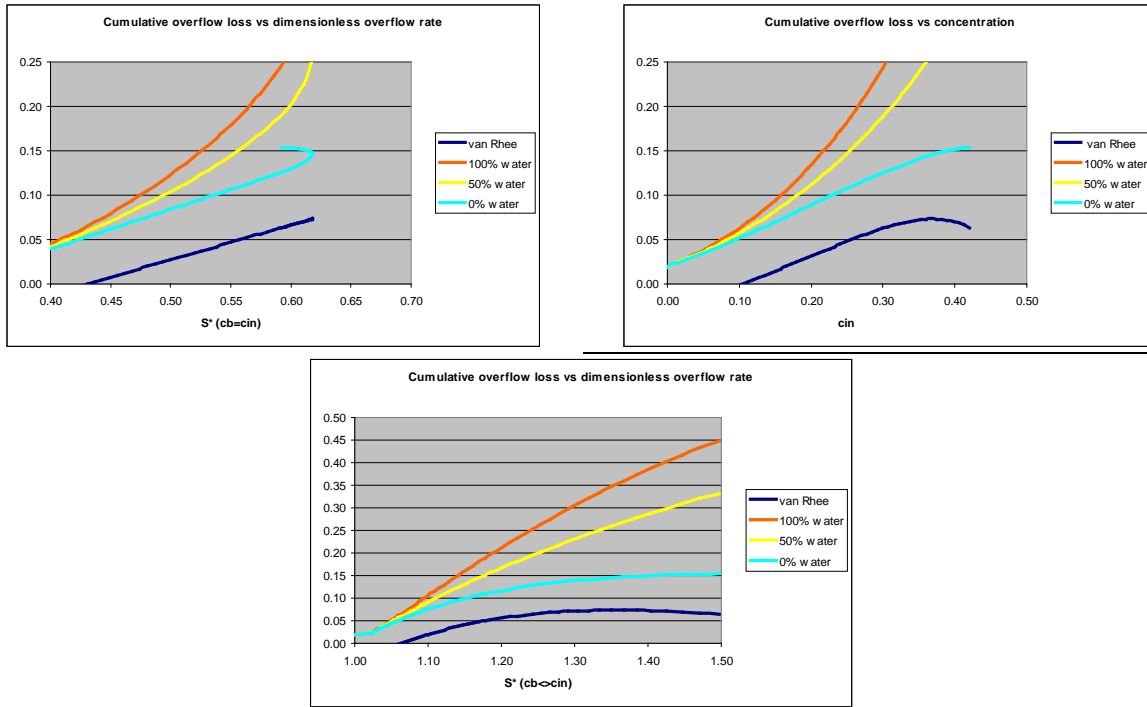
Using equation 46 in the equations 37 and 40, gives an improved result according to Figure 15. It is obvious from this figure that the analytical model with 50% filling at the start of the loading process matches the empirical equation perfectly. This proves the validity of the analytical model derived and gives amore physical background to the empirical equation of van Rhee (2002). Now the question is, does the analytical model give good predictions in other cases. Van Rhee (2002) tested equation 23 on the measurements of the Cornelia as mentioned before and found cumulative overflow losses of 1.5%, while the measurements gave cumulative overflow losses of 8%. One of the reasons for this might be that the model tests on which equation 23 is based are carried out with a sand with a certain grading, see Figure 13 sand number 5. The tests with the Cornelia used a sand with another grading. First the overflow losses are computed with the same grading as in the model tests which is sand number 2 in Figure 13. The results of this computation are shown in Figure 16. The top left figure shows the results according to equation 23 with  $c_b=c_{in}$ . Now cumulative overflow losses are found of about 2% at  $S^*=0.47$ , similar to the 1.5% of van Rhee (2002). In these calculations, the hindered density effect has not been used because of the narrow grading of the PSD.



**Figure 16: Comparing van Rhee (Chapter 8) with the Analytical Model**  
 ( $Q=6, L=52, W=11.5, H=8.36, d_{50}=0.235, a=0.4, b=0.829, \beta=3.7, n=0.46, \mu=0.725$ )

From Figure 13 it can be seen however that the fines are not taken into account properly and it is the fines that cause the higher cumulative overflow losses. If sand number 4 is used however, taking into account the fines, Figure 17 is the result giving cumulative overflow losses of about 8% for  $S^*=0.47$  in the top left graph. It is clear that finding the right model PSD is difficult and

sand number 4 is a little bit jumping to conclusions, but it is also clear that using a PSD that matches the real sand closer will result in a better prediction of the overflow losses.



**Figure 17. Comparing van Rhee (Chapter 8) with the Analytical Model**  
 ( $Q=6$ ,  $L=52$ ,  $W=11.5$ ,  $H=8.36$ ,  $d_{50}=0.235$ ,  $a=0.6$ ,  $b=0.929$ ,  $\beta=3.7$ ,  $n=0.46$ ,  $\mu=0.725$ )

## CONCLUSIONS

Using the equations to determine the near bed concentration as derived here are based on known cumulative overflow losses and should thus not be used to predict overflow losses because that is a self fulfilling prophecy. The modeling should be used to verify experiments where the near bed concentration is measured.

The use of the sedimentation or bed rise velocity to determine the sedimentation process when loading a TSHD with sand can only give good predictions if the correct near bed concentration is used and measured. Using the assumption that the near bed concentration equals the inflowing mixture concentration may lead to results that do not obey the conservation of mass principle.

Using the empirical equation 23 of van Rhee (2002) to predict the overflow losses with the assumption that  $c_b=c_{in}$  is a good first approximation, but with some restrictions. It should be noted that van Rhee used the assumption of  $c_b=c_{in}$  to find this equation by curve fitting. The dimensionless overflow rate  $S^*$  in this equation has to be considered to be the reciprocal of the settling efficiency, that is the correct physical meaning.

The analytical model derived in this paper matches this empirical equation, but has the advantage that sands with different gradings can be taken into account. The model derived for the sedimentation velocity, the near bed concentration and the overflow losses matches both the experiments as carried out by van Rhee (2002) and Ooijens (2001). The model however is very sensitive for the values of the parameters  $a$  and  $b$  describing the PSD in equation 32, but with correct values, the model gives a very good prediction of the cumulative overflow losses.

### LIST OF ACCRONYMS AND SYMBOLS

$a$	Steepness of the PSD	mm
$b$	Offset of the PSD	mm
$c_b$	Near bed concentration	-
$c_{bed}$	Bed/sediment concentration	-
$c_{in}$	Volume concentration	-
$c_v$	Volumetric concentration	-
$d$	Grain diameter	mm
$d_o$	Grain diameter matching the hopper load parameter	mm
$d_{50}$	Grain diameter at 50% of PSD	Mm
$g$	Gravitational constant (9.81)	m/sec <sup>2</sup>
$h$	Height	m
$H$	Height of hopper	m
$H^*$	Dimensionless hopper load parameter	-
$L$	Length of basin	m
$ov$	Overflow losses	-
$ov_{cum}$	Cumulative overflow losses	-
$p$	Fraction of grains	-
$p_o$	Fraction of grains that settle partially (excluding turbulence)	-
$p_{fs}$	Fraction of grains that do not settle due to scour or fines	-
$Q$	Mixture flow (volumetric)	m <sup>3</sup> /sec
$Q_m$	Mixture flow (mass)	ton/sec
$R_d$	Relative density	-
$S^*$	Dimensionless overflow rate	-
$t, T$	Time	sec
$TDS$	Tonnes dry solid	ton
$v_c$	Settling velocity including hindered settling	m/sec
$v_o$	Hopper load parameter	m/sec
$v_s$	Settling velocity of individual particle	m/sec
$v_{sed}$	Sedimentation/bed rise velocity	m/sec
$W$	Width of basin	m
$\alpha$	Fraction of hopper to be filled with mixture at start of loading process	-
$\beta$	Power for hindered settling	-
$\varepsilon$	Fraction of hopper filled with sediment when reaching the overflow	-

$\rho_f$	Density of fluid	ton/m <sup>3</sup>
$\rho_q$	Density of particles (quarts=2.65)	ton/m <sup>3</sup>
$\rho_w$	Density of water (1.025)	ton/m <sup>3</sup>
$\eta$	Settling efficiency	-
$\eta_{cum}$	Cumulative settling efficiency	-
$\eta_p$	Settling efficiency individual particle	-
$\lambda$	Concentration ratio $c_b/c_{in}$	-
$\kappa$	Concentration ratio $c_{in}/c_{bed}$	-
$\mu$	Settling velocity factor	-

## REFERENCES

Miedema, S.A. (1981). *"The Flow of Dredged Slurry in and out of Hoppers and the Settlement Process in Hoppers"* ScO/81/105, Delft University of Technology, 1981, 147 pages.

Miedema, S.A. and Vlasblom, W.J. (1996). *"Theory for Hopper Sedimentation"*. 29th Annual Texas A&M Dredging Seminar. New Orleans, June 1996.

Ooijens, S. (1999). *"Adding Dynamics to the Camp Model for the Calculation of Overflow Losses"*. Terra et Aqua (76), 12-21.

Ooijens, S., de Gruijter, A., Nieuwenhuijzen, A. and Vandycke, S. (2001). *"Research on Hopper Settlement Using Large-Scale Modeling"*. Proceedings CEDA Dredging Days 2001, pp. 1-11.

van Rhee, C. (2002). *"On the Sedimentation Process in a Trailing Suction Hopper Dredger"*. PhD thesis, TU Delft, the Netherlands.

Richardson, J. and Zaki, W. (1954). *"Sedimentation and Fluidisation: Part I"*. Transactions of the Institution of Chemical Engineers 32, 35-53.

Yagi, T. (1970). *"Sedimentation Effects of Soil in Hopper"*. Proceedings of WODCON 1970.

Camp, T. (1946). *"Sedimentation and the Design of Settling Tanks"*. Trans. ASCE, 895-936.

# NOTES FOR CONTRIBUTORS

## GENERAL

The Journal of Dredging Engineering is a peer-reviewed practice periodical on dredging engineering topics. Prospective authors should **email an MS word version** of their manuscript to the following address: Dr. Ram K. Mohan, Anchor QEA LLC, 12 Penns Trail, Suite 135, Newtown, PA 18940, USA; Phone: 267-756-7165; Fax: 267-756-7166; email: [rmohan@anchorqea.com](mailto:rmohan@anchorqea.com)

Authors should obtain all necessary approvals for publication from employers or others involved, before submission of the paper. Submission of a manuscript implies that it is not under consideration for publication elsewhere and that original, previously unpublished work is being presented. **The paper should be free from evident commercialism or private interest** Copyright will be the property of the Western Dredging Association, but the author will be granted permission to reprint the paper and third party requests will be passed on to the authors. **Papers should be concisely written and not exceed 20 total printed pages including figures.** The papers will be reproduced directly from the camera-ready manuscripts provided by the authors and bound into a volume. Please give the manuscript preparation instructions to the person responsible for the preparation of the text.

### Keywords

Please provide 5 keywords that are not already contained in the title, on a separate sheet of paper.

## MANUSCRIPT PREPARATION

### Order of contents

Title, author(s), affiliations, addresses, countries

Abstract (not to exceed 300 words).

Introduction, main body, and following text, conclusions, nomenclature (if necessary), and references.

5 keywords that are not already contained in the title (on a separate sheet of paper).

**Refer to a previous issue of the journal for general guidelines on format.**

### Preparation of the text

The text should be submitted on unlined white 8½ x 11 inch paper with **single line spacing**, and top and side margins of 1 inch. Use full justification. **The image area or block of text will then be 6.5 x 9.0 inch.** The bottom margin should be 1½ inch. Page numbers should be marked in pencil and placed at the bottom center of each page. **Do not leave additional margins. Do not use company letterhead paper.**

### Fonts

If possible please use proportional, serif font such as Times New Roman 12 point. If such fonts are not available, use a 12 pitch typeface and work to the margins indicated above. Do not use headers or footers or draw a frame around your text. Use a letter quality or laser printer. **Do not use a dot matrix printer.** It may be possible for us to print your text directly from your disc. In this case we shall still require hard copies of your text. The preferred word processing program is Microsoft Word 6.0 or Word 97. If using other programs please also save your text as ASCII files. Discs should be labeled with the file name in both word processed and ASCII forms, the word processing package used, and the operating system.

### Headings

Headings should be typed in bold capital letters centered and followed by a double space. Bold capitals and lower case letters should be used for subheadings, which should be preceded and followed by a double space as illustrated by these instructions. Sub-subheadings should use bold capitals and lower case letters and placed at the start of the paragraph.

## Equations

All symbols must be defined in the nomenclature section that follows the conclusions. The SI system of units should be used. If units other than SI units are included, they should be given in parenthesis after the relevant SI unit. Equations should be successively numbered (in parenthesis) flush with the right-hand margin (see example below).

$$y = a + b + cx^2 \tag{1}$$

## References

References in the text should be given as: Smith (1988), (Smith, 1988) or (Jones et al., 1986). References should be listed alphabetically in the References section at the end of the paper. Give the names and initials of all authors, followed by the title of the article and publication, the publisher and the year of publication. References to conference papers or proceedings should include the name of the organizers. References to articles published in journals should also include the name of the journal, the number of the issue and page numbers (see example below). References to publications in a foreign language should give all details in the original language followed by a translation of the title.

Hunt, J.B. (1995). "*Environmental Dredging*". Smith & Son, Inc., New York, NY.

Donegan, T.M., and Dinicola, W.J. (1986). "*Turbidity Associated With Dredging Operations*". Technical Report, XYZ Consultants, Inc., Baltimore, MD., 60 p.

Jones, F., Doe, A., Hart, E.J.E., and Next, J.P.J. (1986). "*The Design of Dredged Material Disposal Sites.*" Proceedings XIVth World Dredging Congress, CEDA, Amsterdam, The Netherlands, pp. 350-368.

White, F.K. and Jones, J.M. (1991). "*The Analysis of Flow Fields Around Dragheads.*" Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol. 121, No. 5, pp. 1-16.

## Page numbers

Page numbers should be marked in pencil and placed at the bottom center of each page.

## Figures and Tables

High quality figures and tables should be incorporated into the body of the text. Figures must not be placed at the end of the paper. Leave spaces for photographs. Figure captions should be below the figure; table captions should be above the table.

## Line drawings

The lines and lettering on the figures should be clearly legible. If originals cannot be supplied, ONLY BLACK AND WHITE COPIES OF VERY HIGH QUALITY are suitable for reproduction. PENCIL AND PHOTOCOPIES OR COPIES WITH A BACKGROUND COLOR ARE NOT SUITABLE.

## Photographs

Photographs must be sharp, high contrast, glossy prints. Please use a pencil to indicate the title of the paper, figure number and title and top edge on the back of each photograph. Paste in the photographs where they should appear in the final manuscript. Place captions under the photograph as part of the text.