A SENSITIVITY ANALYSIS ON THE EFFECTS OF DIMENSIONS AND GEOMETRY OF TRAILING SUCTION HOPPER DREDGES

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ABSTRACT

In the past two decades the size of TSHD's has tripled and there are plans for TSHD's in the range of 50,000 m^3. When enlarging hoppers, there are some limitations like the draught of the vessel and the line velocity in the suction lines. It's interesting to compare the influences of length, width, height ratio's, flow capacity and some other parameters on the production and the overflow losses of TSHD's. To do so, mathematical models have been developed to simulate the sedimentation process in the hopper. Two models will be used and compared, first the model of Vlasblom/Miedema (1995) and Miedema/Vlasblom (1996) and second the more sophisticated 2DV model of van Rhee (2002) which is verified and validated with model and prototype tests. Both models are explained briefly. With the two models 3 cases are analyzed, a 2316 m^3, a 21579 m^3 and a 36842 m^3 hopper. The results of the case studies give the following conclusions and recommendations:

- The two models give the same magnitude for the overflow losses, but the shape of the curves is different due to the differences in the physical modeling of the processes.
- Due to the lower losses the computed optimal loading time will be shorter for the Vlasblom /Miedema approach.
- The strong point of the van Rhee model is the accurate physical modeling, giving the possibility to model the geometry of the hopper in great detail, but also describing the physical processes in more detail.
- The van Rhee model is verified and validated with model and prototype tests and can be considered a reference model for other models.
- The strong point of the Miedema/Vlasblom model is the simplicity, giving a transparent model where result and cause 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. One can think of:
    - 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.
    - Implementing a varying inflow and density of mixture.

Keywords: Trailing Suction Hopper Dredge, sedimentation, overflow losses

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. Groot (1981) added the effects of hindered settling. 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.

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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-ε turbulence model and includes suspended sediment transport for multiple fractions.

From a scientific point of view it is interesting to compare the sophisticated van Rhee model with the simplified models and to do so, the van Rhee (2002) model is compared with the Miedema & Vlasblom (1996) model. The comparison consists of a number of cases regarding real TSHD's. The following TSHD's will be compared:

Table 1. The data of the TSHDs used.

Hopper	Load	Volume	Length	Width	Empty height	Flow	Hopper load v_0	Mixture density
	ton	m^3	m	m	m	m^3/sec	m/sec	ton/m^3
Small	4400	2316	44.0	11.5	4.577	4	0.0079	1.3
Jumbo	41000	21579	79.2	22.4	12.163	14	0.0079	1.3
Mega	70000	36842	125.0	30.0	9.825	19	0.0051	1.3

Further it is assumed that all 3 TSHD's have a design density of 1.9 ton/m^3 and they operate according to the CVS system (no adjustable overflow). This gives a sand fraction of 0.54 and a porosity of 0.46. For the calculations a sand with a d_{50} of 0.4 mm is chosen, according to figure 1. The particle size distribution is chosen in such a way that there is a reasonable percentage of fines in order to have moderate overflow losses.

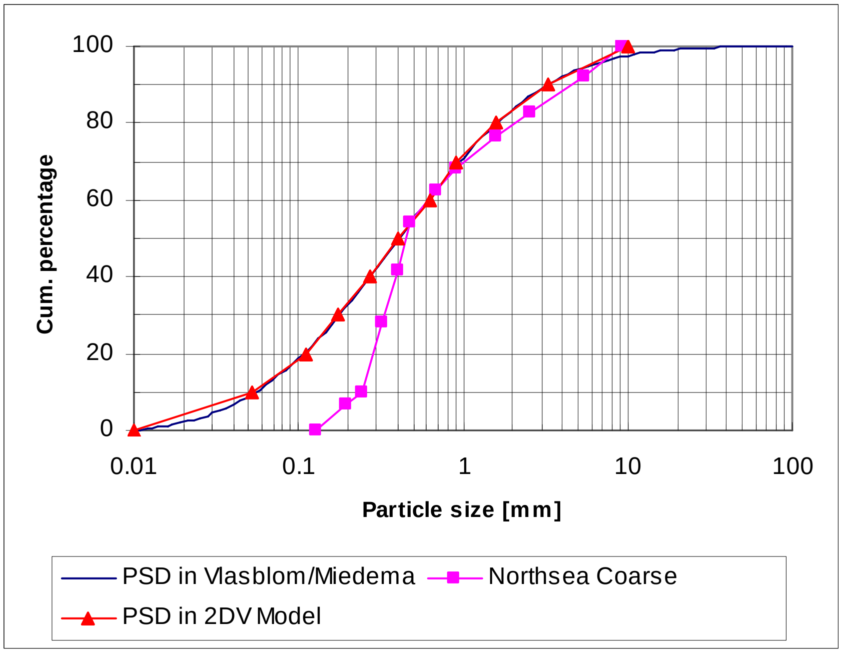

Figure 1. The 0.4 mm grain distribution.

THE CAMP MODEL

The ideal settlement basin consists of an entrance zone where the solid/fluid mixture enters the basin and where the grain distribution is uniform over the cross-section of the basin, a settlement zone where the grains settle into a sediment zone and a zone where the cleared water leaves the basin, the overflow zone. It is assumed that the grains are distributed uniformly and are extracted from the flow when the sediment zone is reached. Each particle stays in the basin for a fixed time and moves from the position at the entrance zone, where it enters the basin towards the sediment zone, following a straight line. The slope of this line depends on the settling velocity v and the flow velocity above the sediment $\mathbf{s_0}$. Figure 1 shows a top view of the ideal settlement basin. Figure 2 shows the side view and figure 3 the path of individual grains. All particles with a diameter $\mathbf{d_0}$ and a settling velocity $\mathbf{v_0}$ will settle, if a particle with this diameter, entering the basin at the top, reaches the end of the sediment zone. Particles with a larger diameter will all settle, particles with a smaller diameter will partially settle. Miedema & Vlasblom (1996) adapted the Camp model to be used for hopper sedimentation. The biggest difference between the original Camp (1936, 1946, 1953) model and the Miedema & Vlasblom model is the height H above the sediment zone. In the Camp model this is a fixed height, in the Miedema & Vlasblom model this height decreases during the loading process.

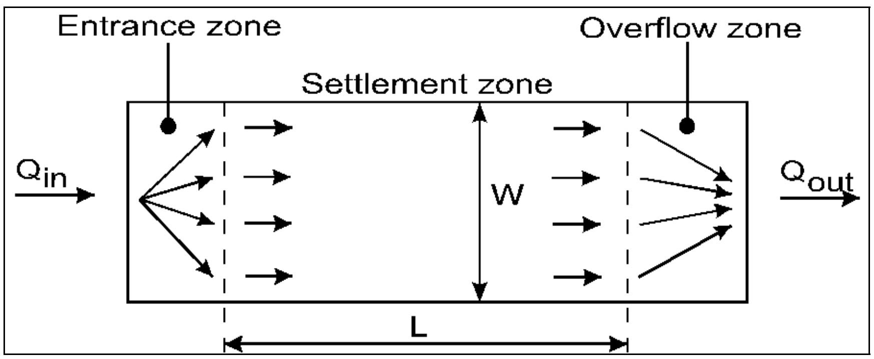

Figure 2. The top view of the ideal basin.

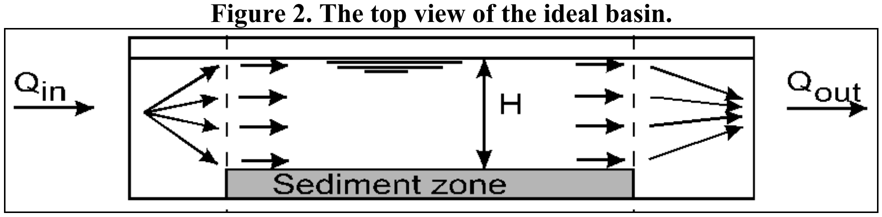

Figure 3. The side view of the ideal basin.

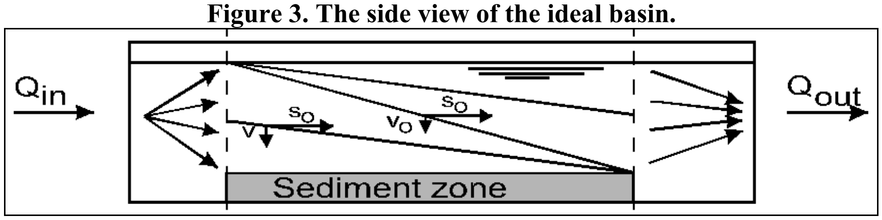

Figure 4. The path of a settling grain.

Based on the average horizontal velocity $\mathbf{s_0}$ in the basin:

$$\mathbf{s_0 = \frac{Q}{W \cdot H}} \tag{1}$$

The hopper load parameter $\mathbf{v_0}$ can be determined according to:

$$\mathbf{\frac{v_0}{s_0} = \frac{H}{L}} \quad \text{thus:} \quad \mathbf{v_0 = s_0 \cdot \frac{H}{L} = \frac{Q}{W \cdot L}} \tag{2}$$

The settling velocity $\mathbf{v_0}$ is often referred to as the hopper load parameter. A smaller hopper load parameter means that smaller grains will settle easier. From figure 3 the conclusion can be drawn that grains with a settling velocity greater then $\mathbf{v_0}$ will all reach the sediment layer and thus have a settling efficiency $\boldsymbol{\eta_g}$ of 1. Grains with a settling velocity smaller then $\mathbf{v_0}$ will only settle in the sedimentation zone, if they enter the basin below a specified level. This gives for the settling efficiency of the individual grain:

$$\eta_g = \left(\frac{v}{v_0}\right) \tag{3}$$

If the fraction of grains with a settling velocity greater then $\mathbf{v_0}$ equals $\mathbf{p_0}$, then the settling efficiency for a grain distribution $\boldsymbol{\eta_b}$ can be determined by integrating the grain settling efficiency for the whole grain distribution curve.

$$\eta_b = (1 - p_0) + \int_0^{p_0} \eta_g \cdot dp \tag{4}$$

When the sediment level in the hopper is rising, the horizontal velocity increases and there will be a point where grains of a certain diameter will not settle anymore due to scour. First the small grains will not settle or erode and when the level increases more, also the bigger grains will stop settling, resulting in a smaller settling efficiency. The effect of scour is taken into account by integrating with the lower boundary $\mathbf{p_s}$. The fraction $\mathbf{p_s}$ is the fraction of the grains smaller then $\mathbf{d_s}$, matching a horizontal velocity in the hopper of $\mathbf{s_s}$. The scour velocity for a specific grain with diameter $\mathbf{d_s}$ is:

$$s_s = \sqrt{\frac{8 \cdot (1 - n) \cdot \mu \cdot (\rho_q - \rho_w) \cdot g \cdot d_s}{\lambda \cdot \rho_w}} \tag{5}$$

This gives for the settling efficiency $\boldsymbol{\eta_g}$:

$$\eta_b = (1 - p_0) + \int_{p_s}^{p_0} \eta_g \cdot dp \tag{6}$$

$$\eta_b = (1 - p_s) \tag{7}$$

The effect turbulence is taken into account by multiplying the settling efficiency with the turbulence efficiency $\boldsymbol{\eta_t}$ according to Miedema & Vlasblom (1996). Since the turbulence efficiency is smaller then 1 for all grains according to the equations 8 and 9, the basin settling efficiency can be determined with equation 10, where $\mathbf{p_s}$ equals 0 as long as scour does not occur..

$$\eta_t = \eta_g^0 \cdot \left(1 - 0.184 \cdot \eta_g^{+.885 - .20 \cdot \eta_g} \cdot \left(1 - \mathrm{TanH}\left(\eta_g^{-.13 - .80 \cdot \eta_g} \cdot \left(\mathrm{Log}\left(\frac{v}{s_o}\right) - .2614 - .5 \cdot \mathrm{Log}(\lambda) + \eta_g^{-.33 - .94 \cdot \eta_g}\right)\right)\right)\right) \tag{8}$$

$$\eta_t = \eta_g^{-1} \cdot \left(1 - 0.184 \cdot \eta_g^{-.69 - .38 \cdot \eta_g} \cdot \left(1 - \mathrm{TanH}\left(\eta_g^{+.77 - .08 \cdot \eta_g} \cdot \left(\mathrm{Log}\left(\frac{v}{s_o}\right) - .2614 - .5 \cdot \mathrm{Log}(\lambda) + \eta_g^{+1.01 - .18 \cdot \eta_g}\right)\right)\right)\right) \tag{9}$$

$$\eta_b = \int_{p_s}^{1} \eta_g \cdot \eta_t \cdot dp \tag{10}$$

CASE STUDIES WITH THE CAMP MODEL

The calculations according to the modified Camp model as developed by Miedema (1991) and published by Vlasblom & Miedema (1995) and Miedema & Vlasblom (1996) are carried out with the program TSHD (Miedema 1991). The effects of hindered settling, turbulence and scour and an adjustable overflow are implemented in this program as described previously.

The program assumes that first the hopper is filled with mixture up to the overflow level and all the grains entering the hopper during this phase will stay in the hopper, so the overflow losses are 0 during this phase. The table below shows the filling time, the total load and the TDS at the end of this phase.

Table 2. The hopper content after the filling phase.

Hopper	Load	Volume	Flow	Filling time	Total load	TDS	Overflow losses	Mixture density
	ton	m^3	m^3/sec	min	ton	ton	%	ton/m^3
Small	4400	2316	4	9.65	3011	1039	20.0	1.3
Jumbo	41000	21579	14	25.69	28053	9678	20.0	1.3
Mega	70000	36842	19	32.32	47895	16523	16.6	1.3

After this phase the program will determine the total settling efficiency and based on this the increase of the sediment and the overflow losses in time steps of 1 minute. Each time step the program checks whether or not scour occurs and if so which fraction of the PSD will not settle due to scour. Usually first there is a phase where scour does not occur. The overflow losses are determined by the settling efficiency according to equation 10. If the hopper has a CTS system, each time the necessary overflow level is calculated and the overflow level is adjusted. In the cases considered a CVS system is assumed, so the overflow level is fixed. When the sediment level is so high that the velocity above the bed is very high, scour starts. This will happen at the end of the loading process. In the calculations the loading process is continued for a while, so the effect of scour is clearly visible.

The results of the calculations are show in figures 5, 6 and 7 for the small, Jumbo and Mega hopper. The initial overflow losses of 20, 20 and 16.6% match the values of the hopper load parameter as mentioned in Table 1. The Mega hopper has a smaller hopper load parameter and thus also smaller initial overflow losses (without scour).

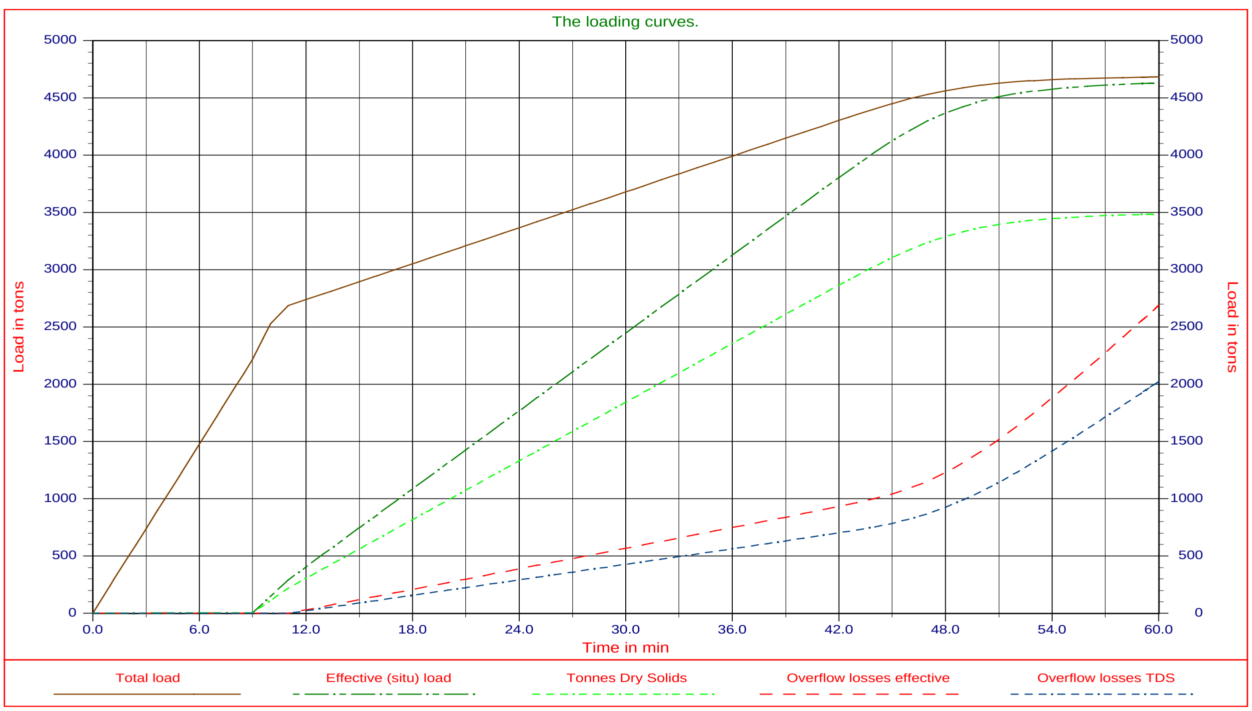

Figure 5. The loading curves of the small TSHD.

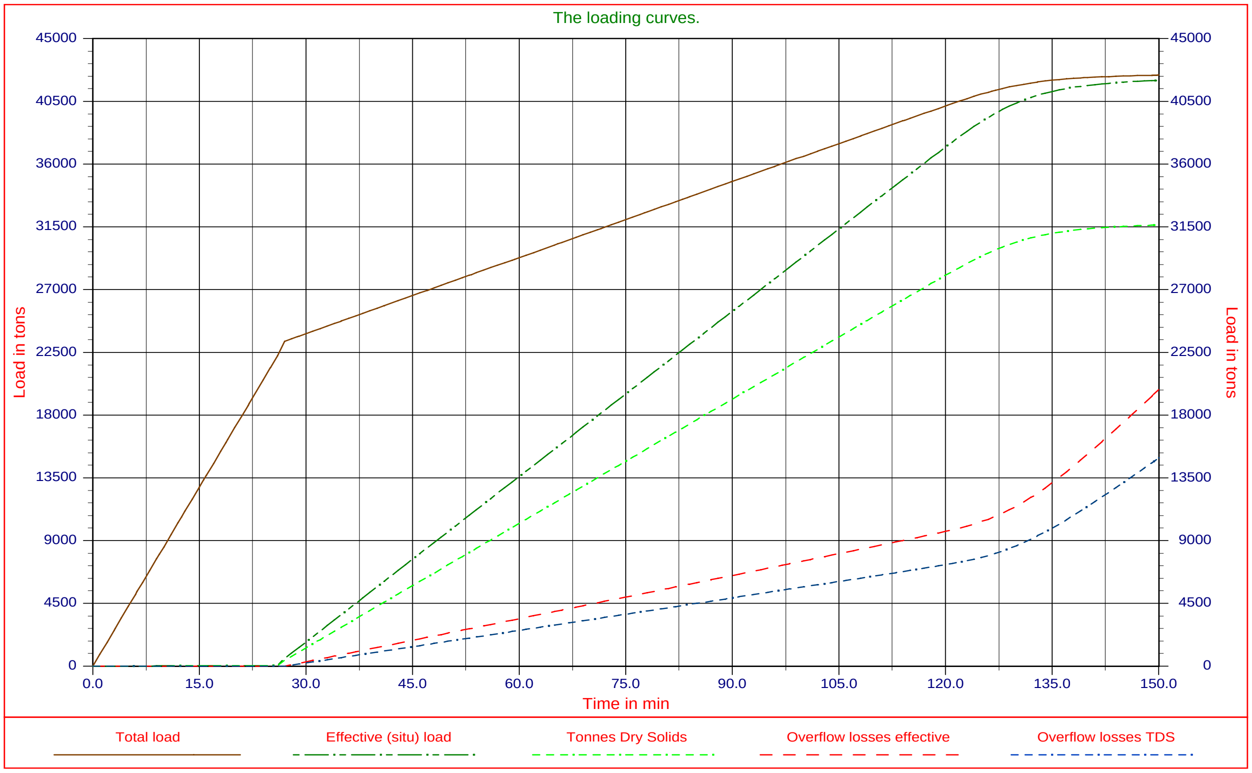

Figure 6. The loading curves of the jumbo TSHD.

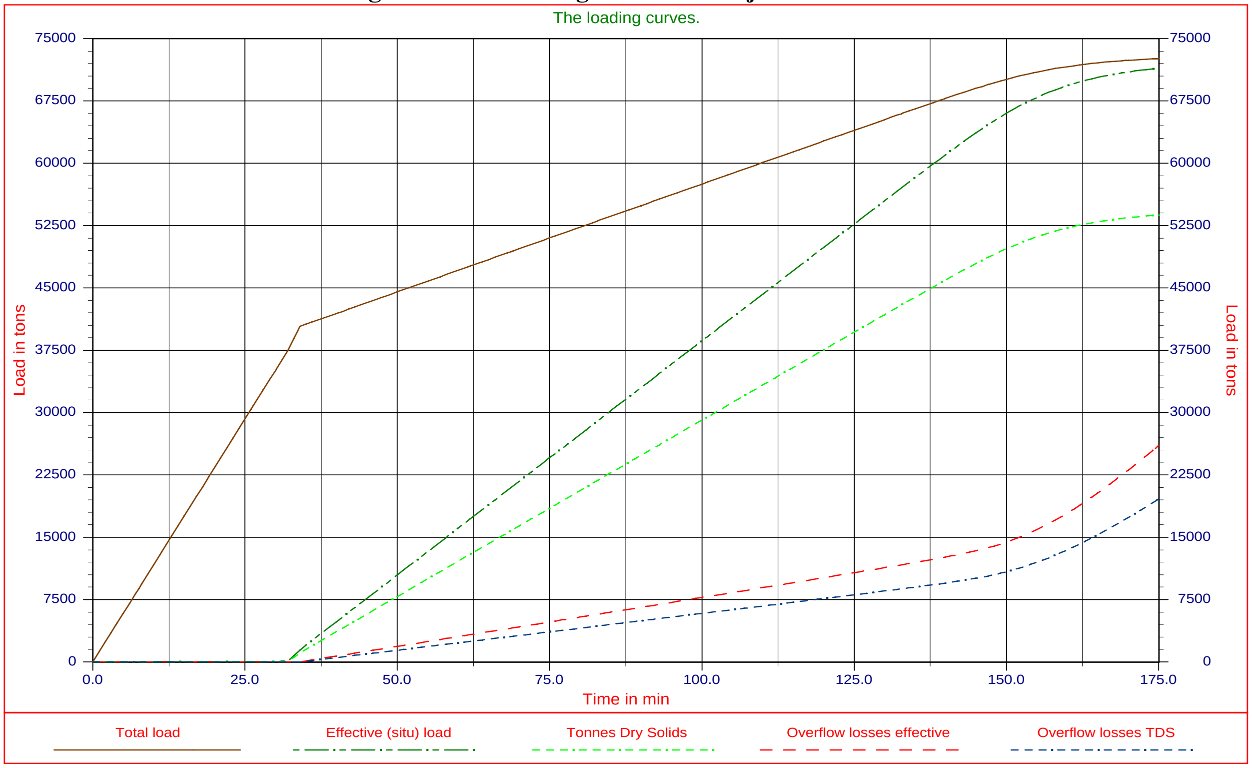

Figure 7. The loading curves of the mega TSHD.

It should be noted that the optimum loading time, the loading time with the maximum production, depends on the total cycle, including sailing times, dumping time, etc. Since the calculations with the 2DV model start with a hopper full of water, also here first the hopper is filled with water, so the two models can be compared.

THE 2DV MODEL

The settlement model described above provides a good approximation of the overflow losses. The influence of grain size, discharge, concentration, and hopper geometry can be taken into account. Some influences however are not included in the model. For instance the influence of the inflow location, variation of water level at the start of dredging is not included. To overcome this limitation the 2DV hopper sedimentation model was developed (Van Rhee, 2002a). The model is based on the Reynolds Averaged Navier Stokes equations with a k-epsilon turbulence model. The model includes the influence of the overflow level of the hopper (moving water surface) and a moving sand bed due to the filling of the hopper. The influence of the particle size distribution (PSD) is included in the sediment transport equations.

A summary of the model is described in Van Rhee, 2002c. The total model is based on three modules (see Figure 8).

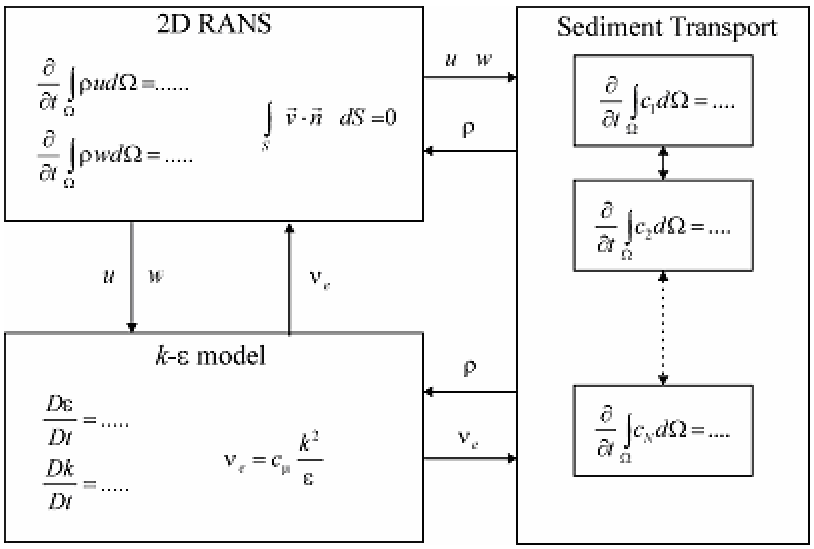

Figure 8. Overview of the 2DV model.

In the 2D RANS module the Reynolds Averaged Navier Stokes equations are solved (the momentum equations). The sediment transport module computes the distribution of suspended sediment in the hopper while the k-epsilon module is necessary for the turbulent closure. The modules have to be solved simultaneously because the equations are strongly coupled. In the momentum equations the density is present which follows from the sediment transport equations. The diffusive transport of sediment is governed by turbulence predicted by the k-epsilon model. The turbulence on the other hand is influenced by the density gradients computed in the sediment transport module.

Boundary conditions

The partial differential equations can be solved in case boundary conditions are prescribed. Different boundaries can be distinguished: Walls (sediment bed and side walls), water surface, inflow section and outflow section. At the walls the normal flow velocity is zero. The boundary condition for the flow velocity at the wall is computed using a so-called wall function (Rodi, 1993, Stansby, 1997). The boundary conditions for the turbulent energy **k** en dissipation rate **ε** are consistent with this wall function approach. For the sediment transport equations the fluxes through vertical walls and water surface is equal to zero since no sediment enters or leaves the domain at these boundaries. At the sand bed for every fraction the sedimentation flux $\mathbf{S_i}$ is prescribed (the product of the near bed concentration and vertical particle velocity of a certain fraction). The influence of the bottom shear stress on the sedimentation is modeled using a reduction factor **R**.

$$\mathbf{S_i = R \cdot c_i \cdot w_{zj}} \tag{11}$$

$$\mathbf{R} = \begin{cases} \mathbf{1} - \dfrac{\theta}{\theta_0} & \theta < \theta_0 \\ \mathbf{0} & \theta \geq \theta_0 \end{cases}$$

This simple relation between the reduction factor and Shields parameter $\boldsymbol{\theta}$ is based on flume tests (Van Rhee, 2002b). The critical value for the Shields parameter proved to be independent of the grain size for the sands tested (d50 < 300 μm). It will be clear that this approach can only be used when over all sedimentation (like in a hopper of a TSHD) will take place. When the Shields value exceeds the critical value no sedimentation will take place, but sediment already settled will not be picked up with this approach. Hence net erosion is not (yet) possible in the model.

At the inflow section the velocity and concentration is prescribed. The outflow boundary is only active when overflow is present, so when the mixture level in the hopper exceeds the overflow level. In that case the outflow velocity is prescribed, and follows simply from the ratio of the overflow discharge and the difference between the hopper and overflow level. For the other quantities the normal gradients are equal to zero (Neumann condition). At the water surface a rigid-lid assumption is used since surface wave phenomena are not important for the subject situation. A rigid-lid can be regarded as a smooth horizontal plate covering the water surface in the hopper. Depending on the total volume balance inside the hopper this “plate” will be moved up and down.

Numerical approach

The momentum and sediment transport equations are solved using the Finite Volume Method to ensure conservation. The transport equations for the turbulent quantities k and are solved using the Finite Difference method. A Finite Difference Method is allays implemented on a rectangular (Cartesian) grid. Although a Finite Volume Method can be applied on any grid it is advantageous to use a Cartesian approach for this method as well especially when a staggered arrangement of variables is used. In general the flow domain is however not rectangular. The water surface can be considered horizontal on the length scale considered, but a sloping bottom will not coincide with the gridlines. Different approaches are possible. The first method is to use a Cartesian grid and to adjust the bottom cells (cut-cell method). Another method is to fit the grid at the bottom. In that case a boundary fitted non-orthogonal grid can be used. A third method is using grid transformation. By choosing an appropriate transformation the equations are solved on a Cartesian domain in transformed co-ordinates. Although this transformation allows for a good representation of a curved topography the method has the disadvantage that due to truncation errors in the horizontal momentum equation artificial flows will develop when a steep bottom encounters density gradients. These unrealistic flows can be partly suppressed when the diffusion terms are locally discretisized in a Cartesian grid. (Stelling, 1994). Since however in a hopper both large density gradients as steep bottom geometry can be present it was decided to develop the model in Cartesian co-ordinates with a cut-cell approach at the bed.

The computational procedure can only be outlined here very roughly. The flow is not stationary hence the system is evaluated in time. The following steps are repeated during time:

- Update the velocity field to time $\mathbf{t_{n+1}}$ by solving the NS-equations together with the continuity equation using a pressure correction method (SIMPLE-method (Patankar, 1980) using the density and eddy viscosity of the old time step $\mathbf{t_n}$.
- Update the turbulent quantities to time $\mathbf{t_{n+1}}$ using the velocity field of $\mathbf{t_{n+1}}$. Compute the eddy-viscosity for the new time.
- Use the flowfield of $\mathbf{t_{n+1}}$ to compute the grain velocities for the next time and update the concentrations for all fractions and hence the mixture density to time $\mathbf{t_{n+1}}$.
- Compute the new location for the bed level and mixture surface in the hopper

RESULTS

The 2DV model is used to simulate the loading process for the three different cases. At the start of the simulation the hopper is filled with water. The results are shown in Figures 9, 10 and 11. In these figures the TDS in the hopper (settled in the bed and in suspension) and the cumulative overflow losses are plotted versus loading time.

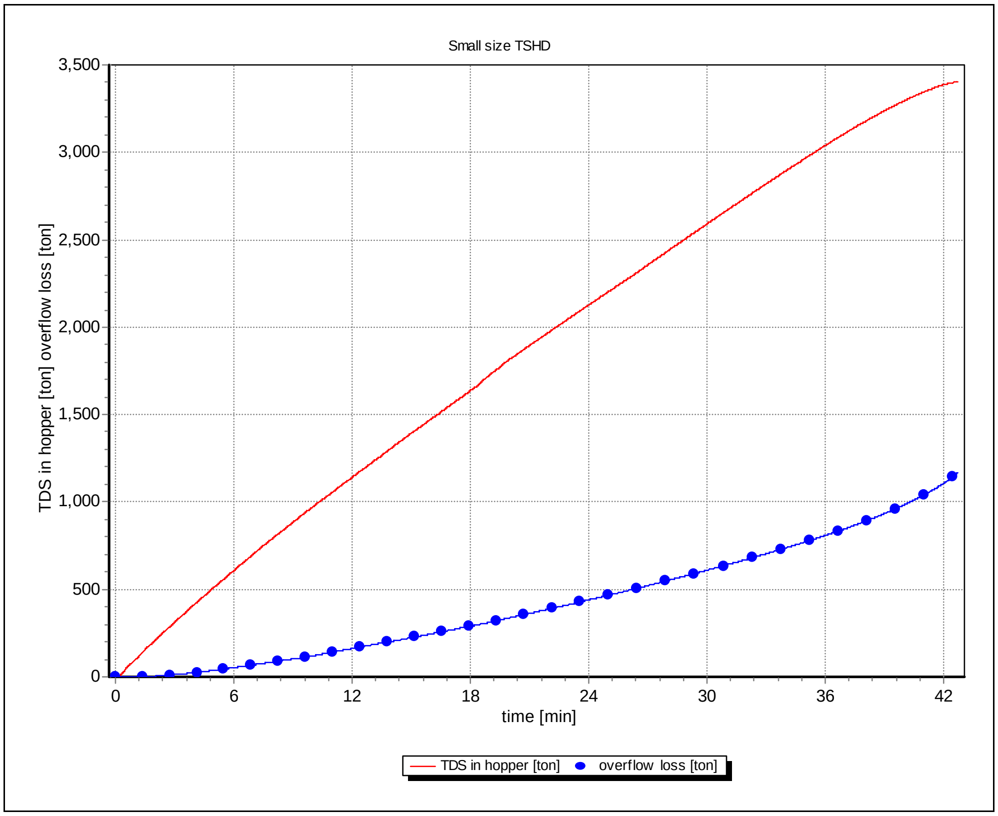

Figure 9. Loaded TDS and overflow losses as a function of time for a small size TSHD.

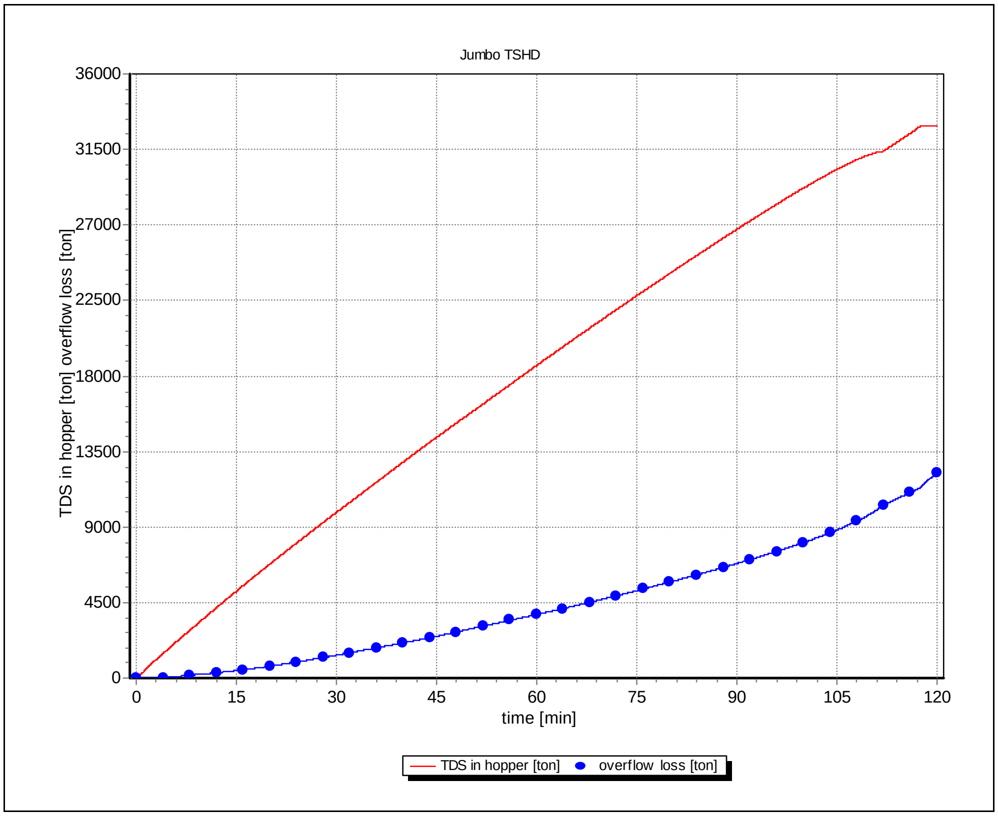

Figure 10. Loaded TDS and overflow losses as a function of time for jumbo TSHD.

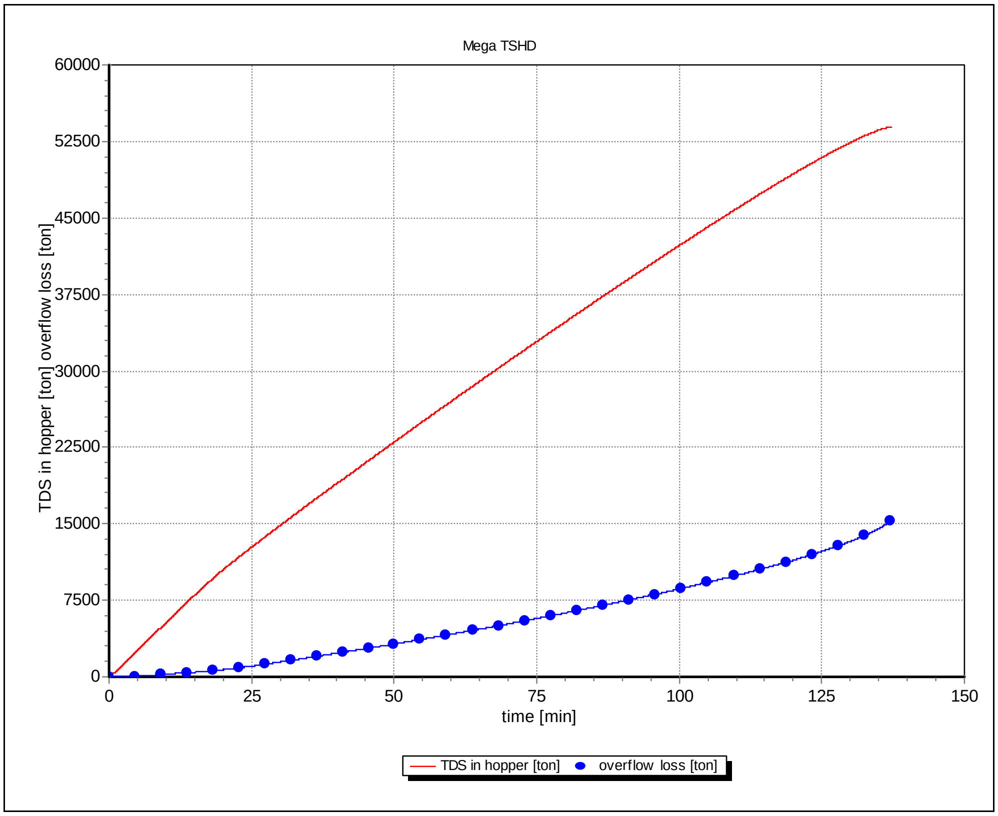

Figure 11. Loaded TDS and overflow losses as a function of time for a mega TSHD.

COMPARISON OF THE TWO MODELS

To compare the results of the two methods, first the differences in the models are summarized:

1. The physical modeling of the two methods is different, Vlasblom/Miedema is based on the Camp approach, while the 2DV model is based on the Reynolds Averaged Navier Stokes equations.
2. The van Rhee model starts with a hopper full of water, while the Miedema/Vlasblom model starts with an empty hopper.
3. The Miedema/Vlasblom model assumes 100% settling of the grains during the filling phase of the hopper.
4. The van Rhee model includes a layer of water above the overflow level, while the Miedema/Vlasblom model doesn't by default. But to compare the two models the height of the overflow level has been increased by the thickness of this layer of water and the results are show in the figures 12, 13 and 14. With the layer thickness according to: $\mathbf{H_l} = \left(\frac{\mathbf{Q}}{\mathbf{1.72 \cdot b}}\right)^{2/3}$, where the constant 1.72 may vary. The width **W** is chosen for the width of the overflow **b** in the calculations. This gives a layer thickness of 34 cm for the small hopper and 51 cm for the Jumbo and the Mega hopper.

The results of the small hopper and the Jumbo hopper are similar due to the same hopper load parameter of 0.0079 m/sec. The Mega hopper has a smaller hopper load parameter of 0.0051 m/sec, resulting in relatively smaller overflow losses. To compare the two models the graphs of the two models are combined and similarities and differences are discussed:

Similarities:

1. The overflow rate seems to be quite similar for all 3 hoppers, until the Miedema/Vlasblom approach reaches the scour phase. From this moment on the overflow rate increases rapidly.

2. It is obvious that at the end of the loading both models find the same amount of sand in all cases, since this matches the maximum loading capacity of the hopper in question. This observation explains the fact that the overflow losses of both models are almost the same at the time where the van Rhee simulation stops (42 minutes for the small hopper, 112 minutes for the Jumbo hopper and 137 minutes for the Mega hopper).

Differences:

1. The overflow losses in the van Rhee model are lower in the first phase, because in the Miedema/Vlasblom approach this occurs instantly while the van Rhee approach considers the time the mixture needs to flow through the hopper and the effect of scour is very limited because a uniform flow velocity distribution over depth is assumed (leading to very low horizontal flow velocities) in this model. Only at the end of the loading stage the effect of the horizontal flow velocity on sedimentation becomes noticeable. For instance for the small hopper the TDS loading curve is a straight line from the start of overflow up to 33 min after start dredging. After that time the loading rate decreases as a result of the increasing horizontal velocity. At t = 45 min the hopper is completely filled. Hence the influence of the velocity during the final loading stage is present for about 12 minutes.
2. In the 2DV model velocity distribution is not prescribed, but is determined by physics and depends on the inflow conditions. In general, due to the large density difference between the inflowing mixture and fluid already present in the hopper, density currents will develop. This will lead to a larger velocity close to the sand bed surface. Hence the effect of the flow velocity on sedimentation will be present from the start of dredging. This influence does not increase much during loading. The effect is more spread out over the loading cycle. The loading rate decreases gradually, but remains on a reasonable level unto the moment that the hopper is fully loaded. In the Vlasblom Miedema loading rate reduces to zero at full load.
3. If optimum loading time is considered, the two models differ in that the van Rhee model gives 43, 112 and 137 minutes, while this will be around 38, 99 and 120 minutes in the Miedema/Vlasblom approach. Both models start with a hopper full of water, so this should be considered. The overflow losses in the final phase of the loading process are similar for both models.

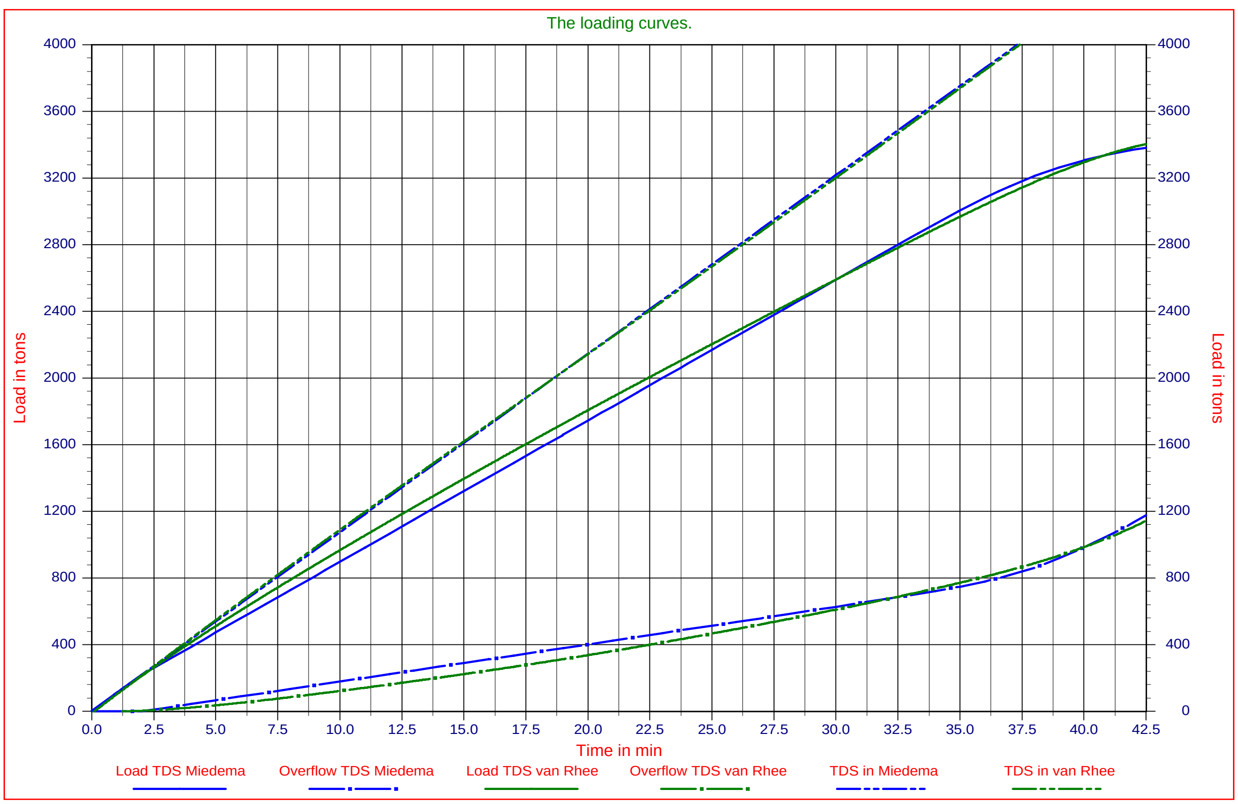

Figure 12. Comparison of the two models for the small hopper.

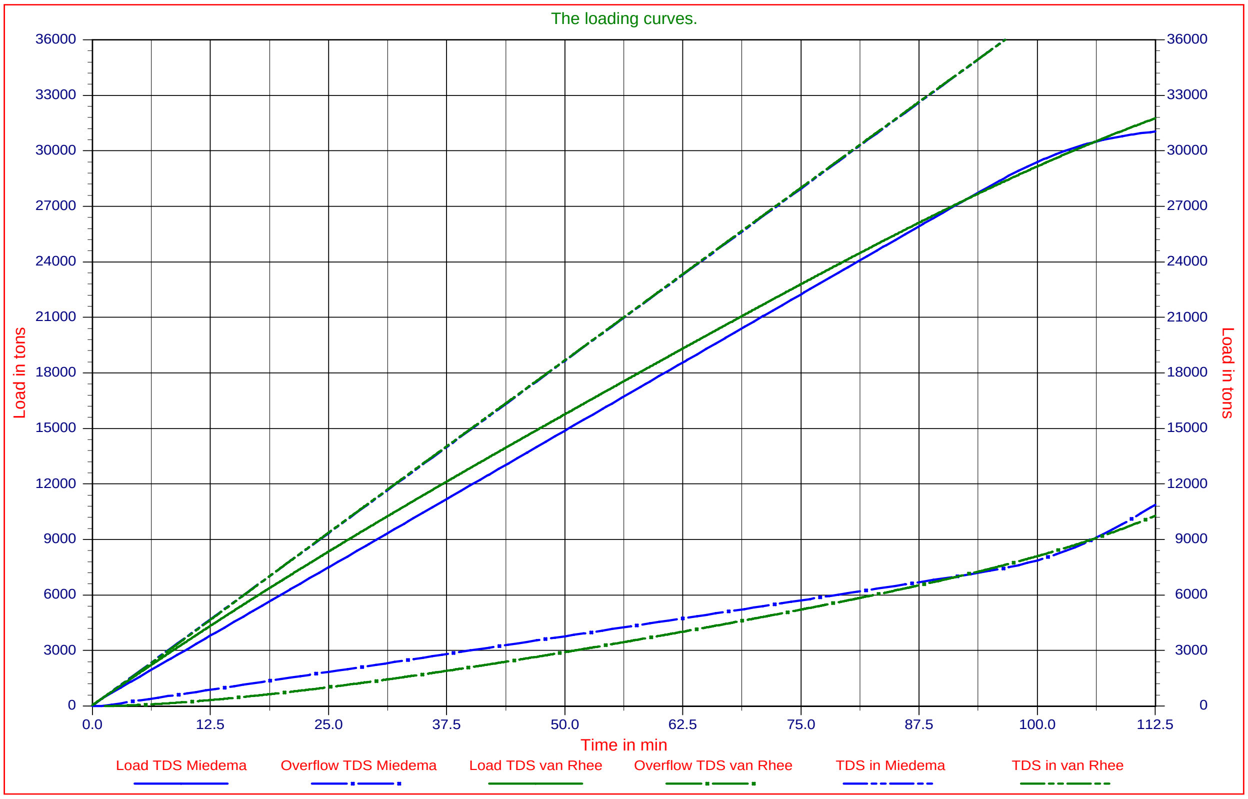

Figure 13. Comparison of the two models for the jumbo hopper.

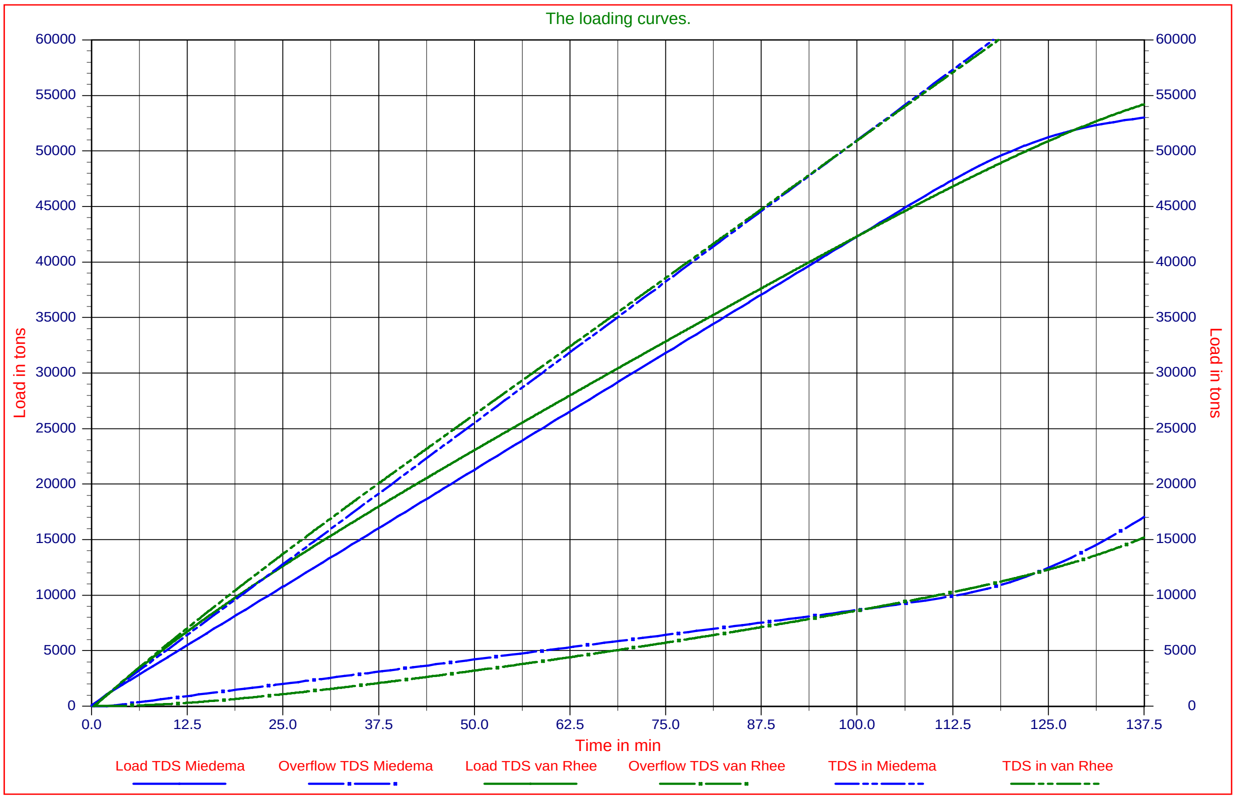

Figure 14. Comparison of the two models for the mega hopper.

CONCLUSIONS AND RECOMMENDATIONS

- The two models give the same magnitude for the overflow losses, but the shape of the curves is different due to the differences in the physical modeling of the processes.
- Due to the lower losses the computed optimal loading time will be shorter for the Vlasblom /Miedema approach.
- The strong point of the van Rhee model is the accurate physical modeling, giving the possibility to model the geometry of the hopper in great detail, but also describing the physical processes in more detail.
- The van Rhee model is verified and validated with model and prototype tests and can be considered a reference model for other models.
- The strong point of the Miedema/Vlasblom model is the simplicity, giving a transparent model where result and cause 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. One can think of:
  - 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.
  - Implementing a varying inflow and density of mixture.

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NOMENCLATURE

c_i	Volume concentration	-
d	Grain diameter	m
d_s	Grain diameter (scour)	m
g	Gravitational constant (9.81)	m/sec^2
H	Height of basin	m
L	Length of basin	m
n	Porosity	-
P_0	Fraction of grains that settle partially (excluding turbulence)	-
p_s	Fraction of grains that do no settle due to scour	-
Q	Mixture flow	m^3/sec
R	Reduction factor	-
S	Sedimentation flux	
w_{zj}	Vertical particle velocity	m/sec
η_b	Settling efficiency for basin	-
η_g	Settling efficiency individual grain	-
η_t	Turbulence settling efficiency for individual grain	-
s_0	Flow velocity in basin	m/sec
s_s	Scour velocity	m/sec
v	Settling velocity	m/sec
v_0	Hopper load parameter	m/sec
W	Width of basin	m
λ	Viscous friction coefficient	-
ρ_m	Density of a sand/water mixture	ton/m^3
ρ_q	Density of quarts	ton/m^3
ρ_s	Density of sediment	ton/m^3
ρ_w	Density of water	ton/m^3
θ	Shields parameter	-
μ	Friction coefficient	-