THEORY FOR HOPPER SEDIMENTATION.

Dr.ir. S.A. Miedema[1]

Prof.ir. W.J. Vlasblom[2]

ABSTRACT.

The sedimentation process in the hopper of a Trailing Suction Hopper Dredge (TSHD) is very complex. However it is debatable whether for estimation purposes it is necessary to model the processes involved in detail. For estimation purposes a black box approach may suffice. Based on the turbulent diffusion theory of Camp (1936, 1946) and Dobbins (1944) for sedimentation tanks, a method has been developed describing the sedimentation and thus the overflow losses in hoppers. The Camp theory considers particles of one diameter, but here the grain distribution is considered, which is the basis for calculating the overflow losses. In the time domain, a homogeneous flow above the sand bed is assumed. Using Camp as a first criterion, it is possible to determine which percentage of particles of a specified diameter will settle and which particles will have too small a settling velocity to settle. A second criterion is the scour velocity. If the velocity above the bed is greater than the scour velocity of a particle of a specified diameter, that particle will be re suspended. Both criteria will result in overflow losses. Given a specified mixture flow into the hopper, once the overflow losses are known, the loading curve can be determined. Since non-linearities are involved, the calculations are carried out in the time domain.

The model is implemented in a computer program, which also calculates the stratification of the grain distribution in the hopper and the grain distribution of the material leaving the hopper through the overflow as a function of time.

This paper is a follow-up of the paper of Vlasblom and Miedema (1995) at WODCON XIV. Some of the equations have been modified resulting in different loading curves. The implementation of scour has changed and a discussion about two-dimensional turbulent diffusion models has been added.

INTRODUCTION.

The sedimentation process in TSHD's has not been the subject for many publications. Although research has been carried out, there is not a good prediction model available. Models that exists are based on sediment flow in rivers or on sedimentation tanks. Camp (1946) and Dobbins (1944) developed a theory for ideal settling tanks. In these tanks an entrance zone, a settling zone and an overflow zone can be distinguished. Settled grains will be removed periodically, so the tank will not be filled until the overflow level is

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[1]Associate Professor, Chair of Dredging Technology, Delft University of Technology
[2]Professor, Chair of Dredging Technology, Delft University of Technology

reached as with TSHD's. Another difference with TSHD's is that the entrance and the overflow zone are not used for the settling process. In the hopper of a TSHD, although an entrance and an overflow zone exist, the hopper as a whole will be used for the settling process. In the hopper of a TSHD the flow velocity above the sediment is much higher then it is in a settling tank. With a few adaptations however the Camp and Dobbins theory can be applied to TSHD's. These adaptations are:

- The hopper as a whole is used for the sedimentation process.
- The sedimentation process continues until the hopper is economically full.
- The overflow level may change during the sedimentation process.
- A grain size distribution will be used.

To understand the adapted model, first the settling of grains will be considered. With this knowledge the ideal settling basin will be discussed. Before implementing the Camp and Dobbins theory to a TSHD, the loading cycle of the TSHD will be explained. With some case studies the use of the model as applied to TSHD's will be discussed.

THE SETTLING VELOCITY OF GRAINS.

The settling velocity of grains depends on the grain size, shape and specific density. It also depends on the density and the viscosity of the fluid the grains are settling in, it also depends upon whether the settling process is laminar or turbulent. In general, the settling velocity v can be determined with the following equation:

$$\mathbf{v} = \sqrt{\frac{\mathbf{4} \cdot \mathbf{g} \cdot \left(\rho_{\mathbf{q}} - \rho_{\mathbf{w}}\right) \cdot \mathbf{d} \cdot \psi}{\mathbf{3} \cdot \rho_{\mathbf{w}} \cdot \mathbf{C_d}}} \tag{1}$$

The Reynolds number of the settling process determines whether the process is laminar or turbulent. The Reynolds number can be determined by:

$$\mathbf{Re} = \frac{\mathbf{v} \cdot \mathbf{d}}{\nu} \tag{2}$$

The drag coefficient $\mathbf{C_d}$ depends upon the Reynolds number according to:

$$\mathbf{Re} < \mathbf{1} \quad \Rightarrow \quad \mathbf{C_d} = \frac{\mathbf{24}}{\mathbf{Re}} \tag{3}$$

$$\mathbf{1} < \mathbf{Re} < \mathbf{2000} \quad \Rightarrow \quad \mathbf{C_d} = \frac{\mathbf{24}}{\mathbf{Re}} + \frac{\mathbf{3}}{\sqrt{\mathbf{Re}}} + \mathbf{0.34} \tag{4}$$

$$\mathbf{Re} > \mathbf{2000} \quad \Rightarrow \quad \mathbf{C_d} = \mathbf{0.4} \tag{5}$$

Stokes, Budryck and Rittinger used these drag coefficients to calculate settling velocities for laminar settling (Stokes), a transition zone (Budryck) and turbulent settling (Rittinger) of sand grains. This gives the following equations for the settling velocity:

Laminar flow, **d<0.1 mm**, according to Stokes.

$$\mathbf{v = 424 \cdot \left(\rho_q - \rho_w\right) \cdot d^2} \tag{6}$$

Transition zone, **d>0.1 mm** and **d<1 mm**, according to Budryck.

$$\mathbf{v = 8.925 \cdot \frac{\left(\sqrt{\left(1 + 95 \cdot \left(\rho_q - \rho_w\right) \cdot d^3\right)} - 1\right)}{d}} \tag{7}$$

Turbulent flow, **d>1**, according to Rittinger.

$$\mathbf{v = 87 \cdot \sqrt{\left(\left(\rho_q - \rho_w\right) \cdot d\right)}} \tag{8}$$

In these equations the grain diameter is in mm and the settling velocity in mm/sec. Since the equations were derived for sand grains, the shape factor for sand grains is used for determining the constants in the equations. The shape factor can be introduced into the equations for the drag coefficient by dividing the drag coefficient by a shape factor ψ. For normal sands this shape factor has a value of 0.7. The viscosity of the water is temperature dependent. If a temperature of 10° is used as a reference, then the viscosity increases by 27% at 0° and it decreases by 30% at 20° centigrade. Since the viscosity influences the Reynolds number, the settling velocity for laminar settling is also influenced by the viscosity. For turbulent settling the drag coefficient does not depend on the Reynolds number, so this settling process is not influenced by the viscosity. Other researchers use slightly different constants in these equations but, these equations suffice to explain the basics of the settling process in hopper dredges.

The above equations calculate the settling velocities for individual grains. The grain moves downwards and the same volume of water has to move upwards. In a mixture, this means that, when many grains are settling, an average upwards velocity of the water exists. This results in a decrease of the settling velocity, which is often referred to as hindered settling. However, at very low concentrations the settling velocity will increase because the grains settle in each others shadow. Richardson and Zaki determined an equation to calculate the influence of hindered settling for volume concentrations $\mathbf{C_v}$ between 0 and 0.3. The coefficient in this equation is dependent on the Reynolds number. The general equation yields:

$$\mathbf{\frac{v_c}{v} = \left(1 - C_v\right)^{\beta}} \tag{9}$$

The following values for β should be used:

Re<0.2	β=4.65
Re>0.2 and Re<1.0	$\beta=4.35\cdot Re^{-0.03}$
Re>1.0 and Re<200	$\beta=4.45\cdot Re^{-0.1}$
Re>200	β=2.39

THE IDEAL SETTLEMENT BASIN.

The ideal settlement basin (Fig. 1 & 2) 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 $\mathbf{d_0}$ 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. The settling velocity of a grain with diameter $\mathbf{d_0}$ can be determined by:

$$\mathbf{v_o = s_o \cdot \frac{H}{L} = \frac{Q}{W \cdot L}} \tag{10}$$

With:

$$\mathbf{s_o = \frac{Q}{W \cdot H}} \tag{11}$$

The settling velocity $\mathbf{v_0}$ is often referred to as the hopper load parameter. A small hopper load parameter means that small grains will settle. 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 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. These grains have a settling efficiency of $\mathbf{v/v_0}$. If the fraction of grains with a settling velocity

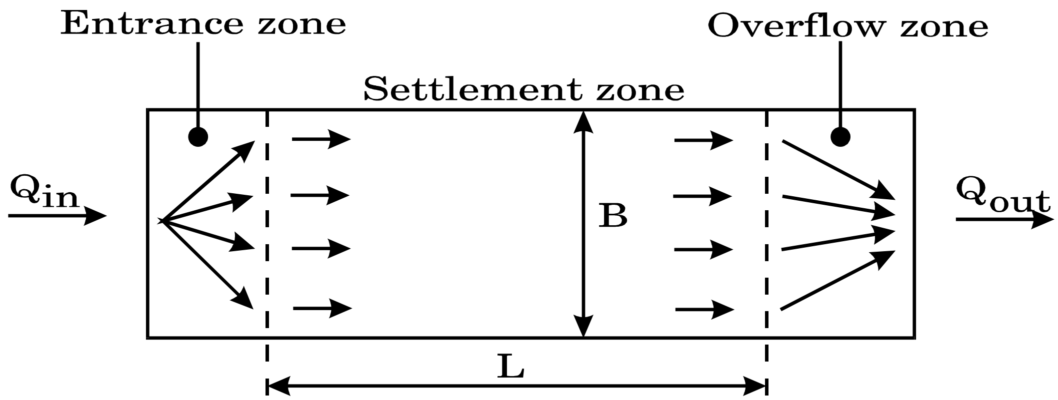


Figure 1

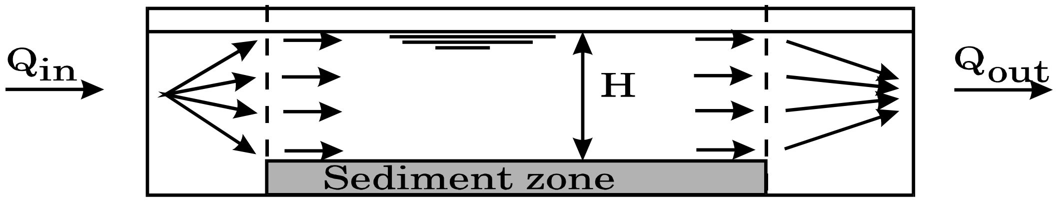


Figure 2

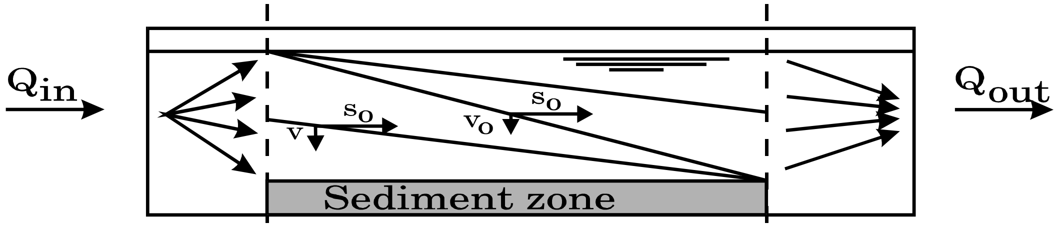


Figure 3

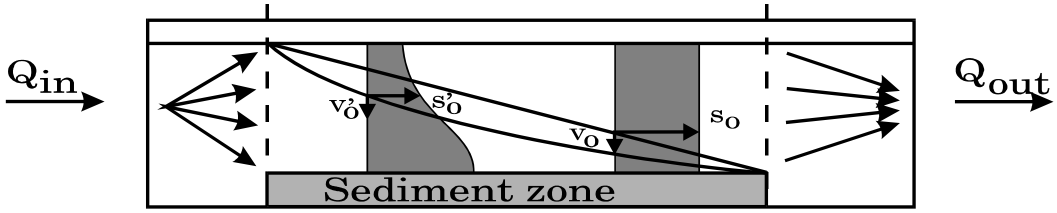


Figure 4

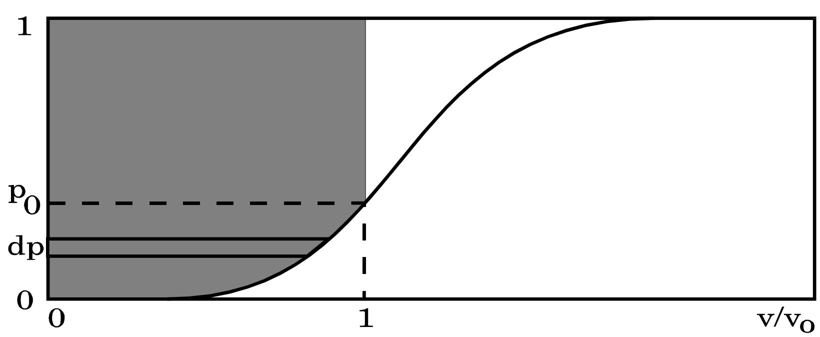


Figure 5

greater then $\mathbf{v_0}$ equals $\mathbf{p_0}$, then the settling efficiency for a grain distribution can be determined by integrating the grain settling efficiency:

$$\mathbf{r_g} = \left(\frac{\mathbf{v}}{\mathbf{v_o}} \right) \tag{12}$$

$$\mathbf{r_b} = \left(\mathbf{1} - \mathbf{p_o}\right) + \int_{\mathbf{0}}^{\mathbf{p_o}} \mathbf{r_g} \cdot \mathbf{dp} \tag{13}$$

This is illustrated in figure 5, showing a grain distribution curve, but instead of using the grain diameter on the horizontal axis, the settling velocity divided by the hopper load parameter is used. The hatched area is equal to the total settling efficiency **r**. Until now the flow velocity distribution has been considered uniform. If this distribution is not uniform, as shown in figure 4, it can be shown that the settling efficiency does not change (Camp 1946, de Koning 1977). For the ideal settlement basin laminar flow is assumed. Turbulent flow will reduce the settling velocity of the grains and thus the total settling efficiency. Whether turbulent flow occurs, depends on the Reynolds number of the flow in the basin. Using the hydraulic diameter concept this number is:

$$\mathbf{Re} = \frac{\mathbf{Q}}{\nu \cdot (\mathbf{W} + \mathbf{2} \cdot \mathbf{H})} \tag{14}$$

For a given flow **Q** and viscosity ν the Reynolds number depends on the width **W** and the height **H** of the basin. A large width and height give a low Reynolds number. However this does not give an attractive shape for the basin from an economical point of view, which explains why the flow will be turbulent in existing basins.

Dobbins (1944) and Camp (1944, 1946) use the two-dimensional turbulent diffusion equation to determine the resulting decrease of the settling efficiency.

$$\mathbf{s(z)} \cdot \frac{\partial \mathbf{c}}{\partial \mathbf{x}} = \varepsilon_{\mathbf{z}} \cdot \frac{\partial^2 \mathbf{c}}{\partial \mathbf{z}^2} + \left(\mathbf{v(c)} + \frac{\partial \varepsilon_{\mathbf{z}}}{\partial \mathbf{z}} \right) \cdot \frac{\partial \mathbf{c}}{\partial \mathbf{z}} + \varepsilon_{\mathbf{x}} \cdot \frac{\partial^2 \mathbf{c}}{\partial \mathbf{x}^2} \tag{15}$$

Assuming a parabolic velocity distribution instead of the logaritmic distribution, neglecting diffusion in the x-direction and considering the settling velocity independent of the concentration reduces the equation to:

$$\left(\mathbf{s_t} - \mathbf{k} \cdot (\mathbf{h} - \mathbf{z})^2 \right) \cdot \frac{\partial \mathbf{c}}{\partial \mathbf{x}} = \varepsilon_{\mathbf{z}} \cdot \frac{\partial^2 \mathbf{c}}{\partial \mathbf{z}^2} + \mathbf{v} \cdot \frac{\partial \mathbf{c}}{\partial \mathbf{z}} \tag{16}$$

Because of the parabolic velocity distribution, the turbulent diffusion coefficient ε_Z is a constant. A further simplification is obtained if the velocity **s** is assumed constant throughout the depth, meaning that the constant of the parabola **k** approaches zero. In this case the turbulent diffusion equation becomes:

$$\frac{\partial c}{\partial t} = s \cdot \frac{\partial c}{\partial x} = \varepsilon_z \cdot \frac{\partial^2 c}{\partial z^2} + v \cdot \frac{\partial c}{\partial z} \tag{17}$$

Huisman (1995) in his lecture notes, derives the diffusion-dispersion equation in a more general form, including longitudinal dispersion.

$$\frac{\partial c}{\partial t} + \frac{\partial (s \cdot c)}{\partial x} = \frac{\partial}{\partial x} \cdot \left(\varepsilon_x \cdot \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial z} \cdot \left(v \cdot c + \varepsilon_z \cdot \frac{\partial c}{\partial z} \right) \tag{18}$$

Assuming a steady and uniform flow, the longitudinal disperion coefficient is independent of **x** and the settling velocity **v** independent of **z.** This reduces the equation 18 to:

$$s \cdot \frac{\partial c}{\partial x} = \varepsilon_z \cdot \frac{\partial^2 c}{\partial z^2} + v \cdot \frac{\partial c}{\partial z} + \varepsilon_x \cdot \frac{\partial^2 c}{\partial x^2} \tag{19}$$

By means of computations Huisman (1995) shows that the retarding effect of dispersion may be ignored for the commonly applied width to depth ratio 3 to 5. This reduces equation 19 to equation 17 of Dobbins and Camp.

Groot (1981) investigated the influence of hindered settling and the influence of different velocity distributions using the following equation:

$$s \cdot \frac{\partial c}{\partial x} = v(c) \cdot \frac{\partial c}{\partial z} + c \cdot \frac{\partial v(c)}{\partial c} \cdot \frac{\partial c}{\partial z} + \frac{\partial}{\partial z} \cdot \left(\varepsilon(x,z) \cdot \frac{\partial c}{\partial z} \right) \tag{20}$$

The velocity distribution, the diffusion coefficient distribution and the distribution of the initial concentration did not have a significant influence on the computed results, but the results were very sensitive on the formulation of hindered settling. This formulation of course influences the settling velocity in general.

Equation 17 can be solved analytically using separation of variables. The boundary conditions used by Camp and Dobbins describe the rate of vertical transport across the water surface and the sediment for $x=\infty$ and the concentration distribution at the inlet, these are:

$$\varepsilon \cdot \frac{\partial \mathbf{c}}{\partial \mathbf{z}} + \mathbf{v} \cdot \mathbf{c} = \mathbf{0}$$ at the water surface

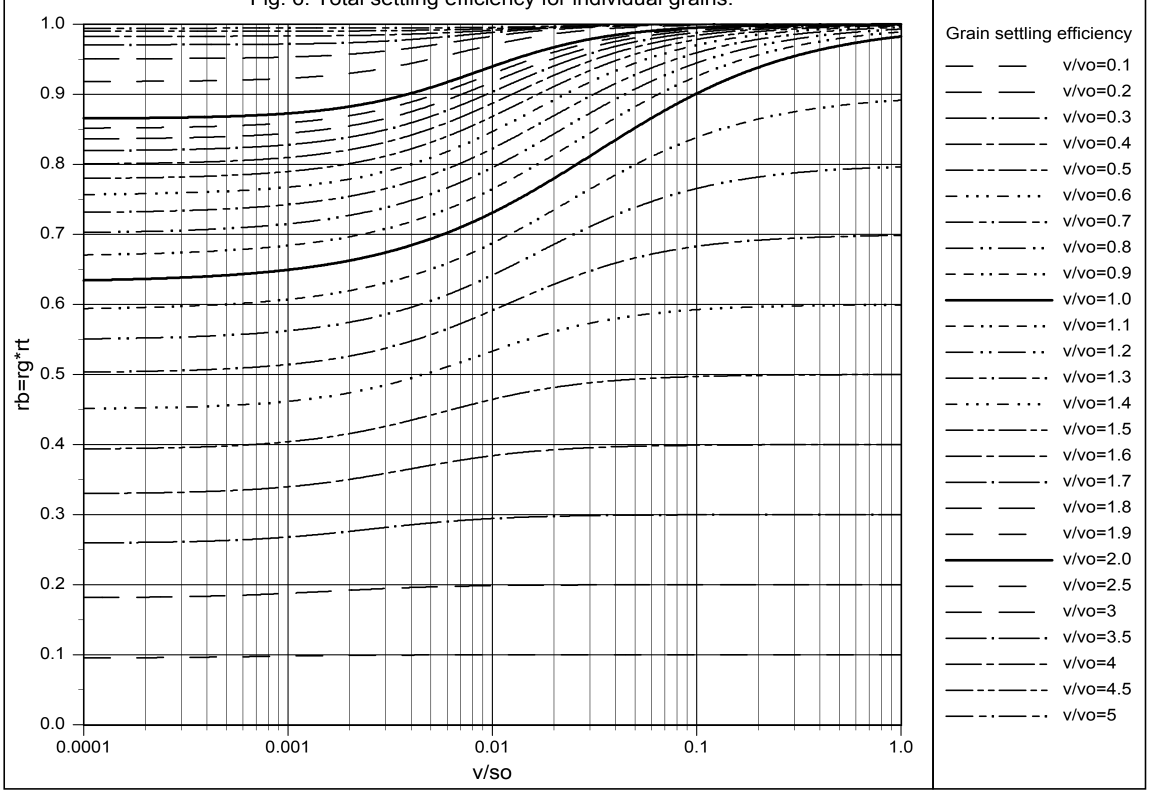
$$\varepsilon \cdot \frac{\partial \mathbf{c}}{\partial \mathbf{z}} + \mathbf{v} \cdot \mathbf{c} = \mathbf{0}$$ at the sediment for x=∞, for the no-scour situation

$$\mathbf{c} = \mathbf{f}(\mathbf{z})$$ at the entrance for x=0

This method, resulting in figure 6, gives the removal ration due to turbulence for a single grain. The removal ratio can be determined by summation of a series. Solving equation 17 gives ($v \cdot H/2 \cdot \varepsilon_Z$) as the independent parameter on the horizontal axis and the removal ratio (v/v_O=settling efficiency) on the vertical axis. Using a parabolic velocity distribution this can be substituted by:

$$\frac{\mathbf{v} \cdot \mathbf{H}}{\mathbf{2} \cdot \varepsilon_{\mathbf{z}}} = \frac{\mathbf{v}}{\mathbf{s_o}} \cdot \frac{\mathbf{3}}{\kappa} \cdot \sqrt{\frac{\mathbf{8}}{\lambda}} = \mathbf{122} \cdot \frac{\mathbf{v}}{\mathbf{s_o}} \quad \text{with: } \kappa = 0.4 \text{ and } \lambda = 0.03 \tag{21}$$

Fig. 6: Total settling efficiency for individual grains.



It is however of interest how the removal ratio (settling efficiency) of a grain can be split up in a part determined by laminar flow in the basin according to equation (12) and a part caused by turbulence. Vlasblom and Miedema (1995) give relations for the effect of turbulence only (fig. 7), as derived by Miedema (1991):

$$\mathbf{r_t = r_g^{0} \cdot \left(1 - 0.184 \cdot r_g^{+.88-.20 \cdot r_g} \cdot \left(1 - TanH\left(r_g^{-.13-.80 \cdot r_g} \cdot \left(Log\left(\frac{v}{s_o}\right) + .5 - r_g^{-.33-.94 \cdot r_g}\right)\right)\right)\right)} \tag{22}$$

For values of $\mathbf{v/v_0}$ greater then 1 the following equation should be used.

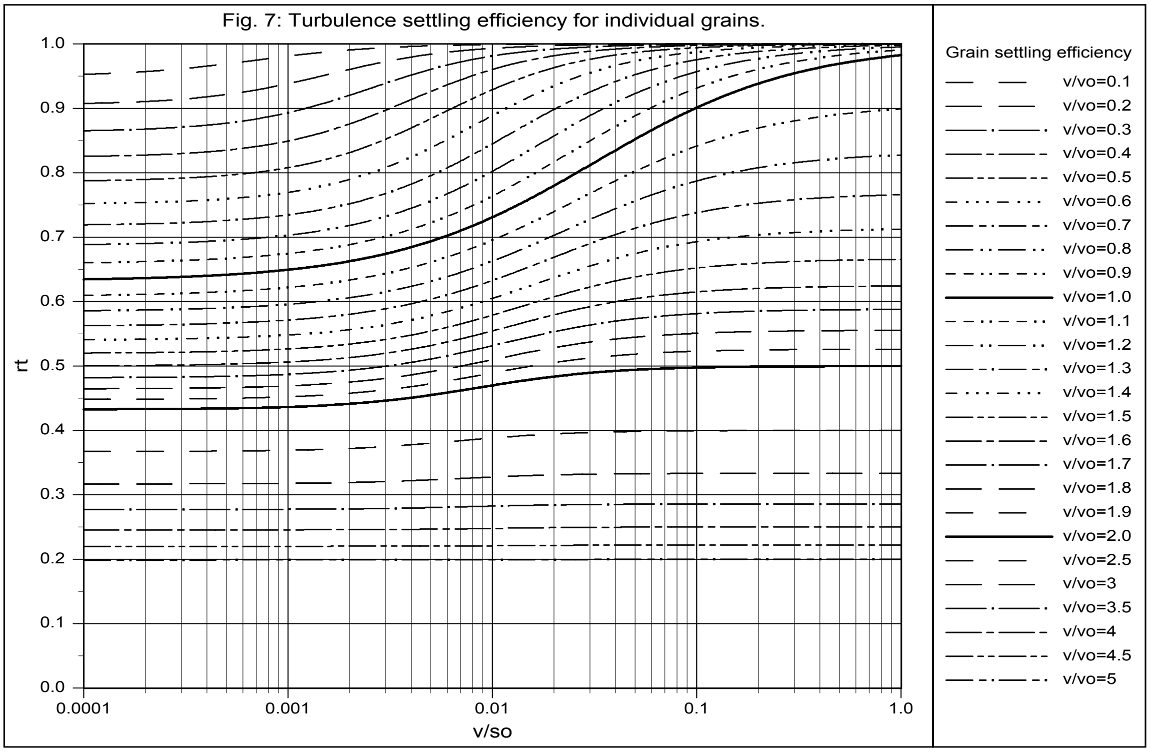
$$\mathbf{r_t = r_g^{-1} \cdot \left(1 - 0.184 \cdot r_g^{-.69-.38 \cdot r_g} \cdot \left(1 - TanH\left(r_g^{+.77-.08 \cdot r_g} \cdot \left(Log\left(\frac{v}{s_o}\right) + .5 - r_g^{+1.01-.18 \cdot r_g}\right)\right)\right)\right)} \tag{23}$$

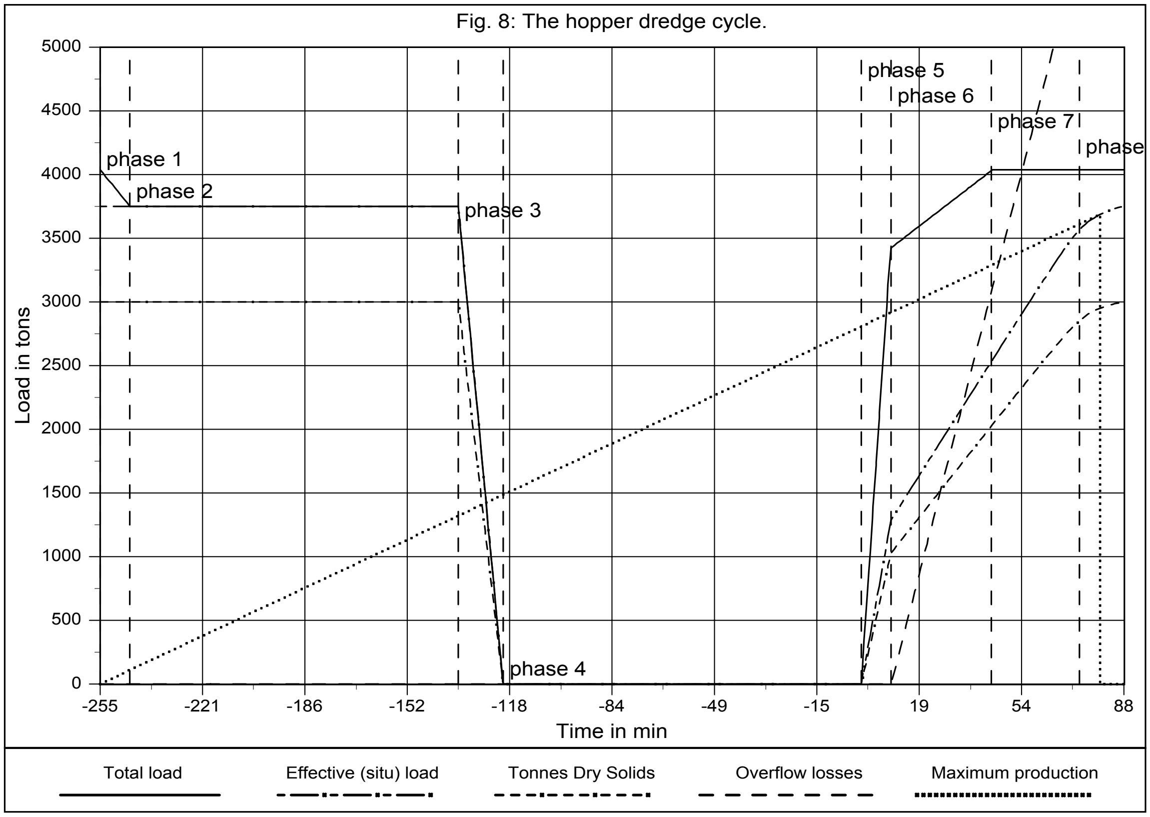
Equations 22 and 23 have been revised since Vlasblom and Miedema (1995) to match the results of equation 17 more closely. For other values of the viscous friction factor λ, the constant .5 should be taken as: $.5 + .5 \cdot Log(0.03/\lambda)$

The resulting basin settling efficiency is equal to the grain settling efficiency times the turbulence settling efficiency, according to figure 6. The total settling efficiency for the basin can now be determined by:

$$\mathbf{r_b = \int_0^1 r_g \cdot r_t \cdot dp} \tag{24}$$

Fig. 7: Turbulence settling efficiency for individual grains.





When the height of the sediment increases and the hopper load parameter remains constant, the horizontal flow velocity above the sediment also increases. Grains that have already settled will be re suspended and leave the basin through the overflow. This is called scouring. The scour velocity $\mathbf{s_s}$ for a grain with a diameter $\mathbf{d_s}$ is according to Camp (1946):

$$\mathbf{s_s} = \sqrt{\frac{\mathbf{8 \cdot (1-n) \cdot \mu \cdot (\rho_q - \rho_w) \cdot g \cdot d_s}}{\boldsymbol{\lambda \cdot \rho_w}}} \tag{25}$$

Grains that are re suspended due to scour, will not stay in the basin and thus have a settling efficiency of zero. In this equation λ is the viscous friction coefficient mobilized on the top surface of the sediment and has a value in the range of 0.01-0.03, depending upon the Reynolds number and the ratio between the hydraulic diameter and the grain size (surface roughness). The value of λ should be choosen equal to the value in equation 21. The porosity **n** has a value in the range 0.6-0.4, while the friction coefficient μ depends on the internal friction of the sediment and has a value in the range of 0.1-0.6 for sand grains. To prevent scour for a specified grain diameter, the flow velocity has to be smaller then the scour velocity. The total settling efficiency changes due to scour, according to:

$$\mathbf{r_b} = \int_{\mathbf{p_s}}^{\mathbf{1}} \mathbf{r_g} \cdot \mathbf{r_t} \cdot \mathbf{dp} \tag{26}$$

If the settling process does not occur in some parts of the basin, owing to a concentrated inflow of mixture, vortexes, etc. the effective hopper load parameter will increase and the settling efficiency will decrease. The homogeneity of the flow depends on the stability of the flow. The stability is indicated by the Froude number of the basin. This Froude number is:

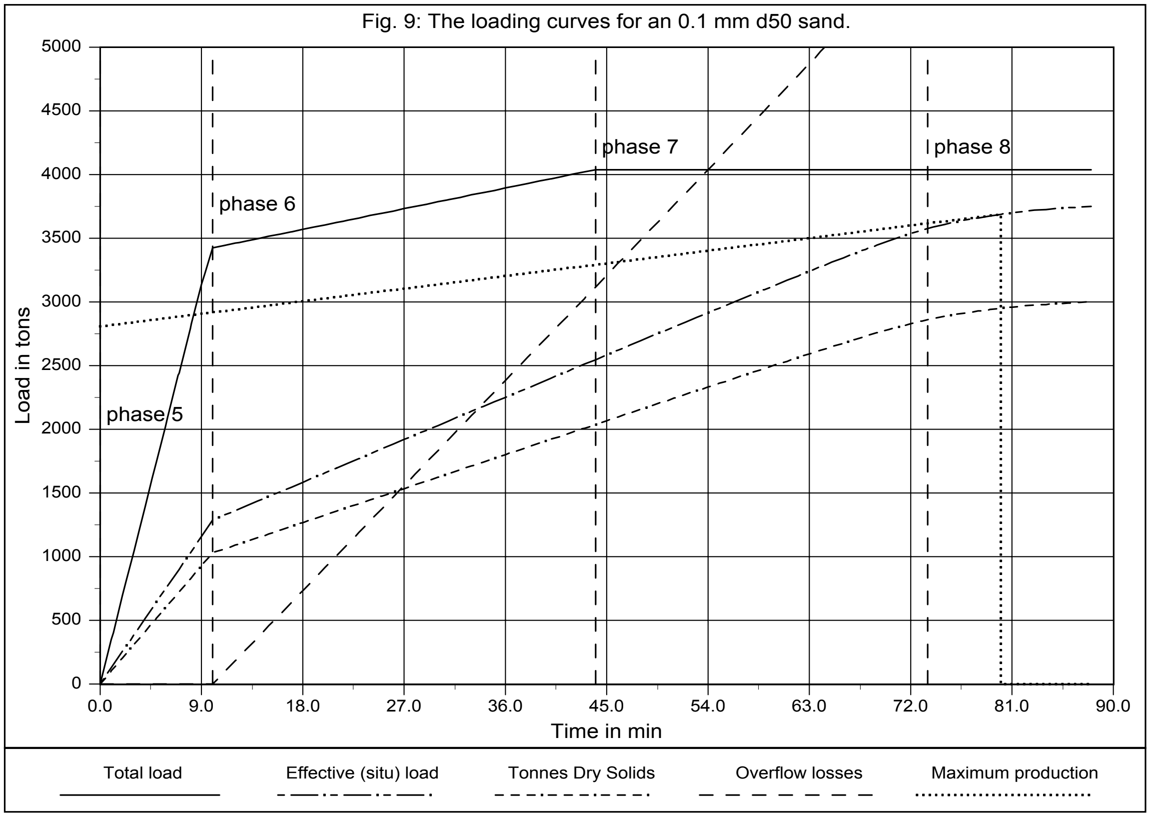
$$\mathbf{Fr} = \frac{\mathbf{Q^2 \cdot (W + 2 \cdot H)}}{\mathbf{g \cdot W^3 \cdot H^3}} \tag{27}$$

A higher Froude number indicates higher stability to the flow in the basin. This results in a narrow basin with a small height. With respect to turbulence the demand for a high Froude number conflicts with the demand for a small Reynolds number, which is associated with a wide deep basin.

THE LOADING CYCLE OF A HOPPER DREDGE.

The loading cycle is considered to start when the hopper is filled with soil and starts to sail to the dump area. This point in the loading cycle was chosen as the starting point to show the optimal load in a graph. The loading cycle then consists of the following phases:

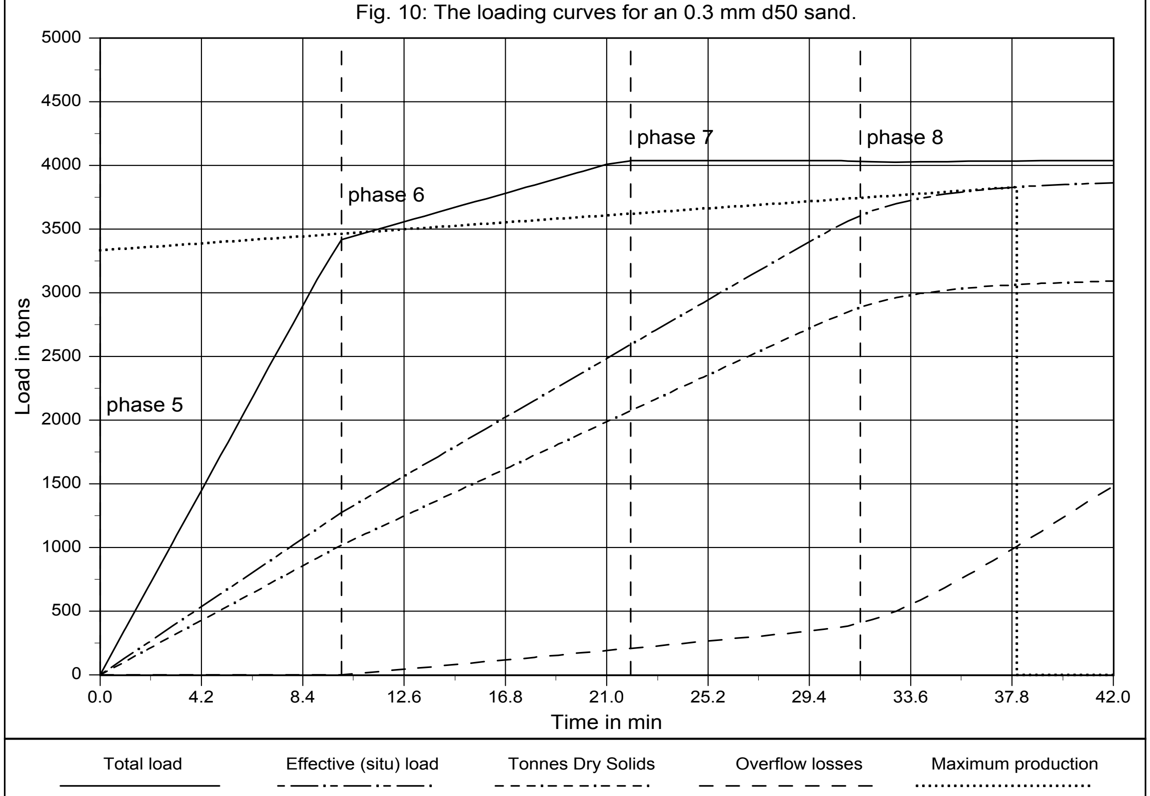
Phase 1: The water above the overflow level flows away through the overflow. The overflow is lowered to the sediment level, so the water above the sediment can also flow away. In this way minimum draught is achieved. Sailing to the dump area is started.
Phase 2: Continue sailing to the dump area.
Phase 3: Dump the load in the dump area.
Phase 4: Pump the remaining water out of the hopper and sail to the dredging area.
Phase 5: Start dredging and fill the hopper with mixture to the overflow level, during this phase 100% of the soil is assumed to settle in the hopper.
Phase 6: Continue loading with minimum overflow losses, during this phase, according to equation 26, a percentage of the grains will settle in the hopper. The percentage depends on the grain size distribution of the sand.
Phase 7: The maximum draught (CTS, Constant Tonnage System) is reached. from this point on the overflow is lowered. Equation 26 is still valid.
Phase 8: The sediment in the hopper is rising due to sedimentation, the flow velocity above the sediment increases, resulting in scour. This is the cause of rapidly increasing overflow losses.



These phases are shown in fig. 8. The way each phase occurs in the cycle, depends on the type of hopper dredge, the working method and of course, the type of soil to be dredged.

The sedimentation in the hopper occurs during the phases 5, 6, 7 and 8. During phase 5 the hopper is filled with mixture until the overflow level is reached. During this phase 100% of the soil is assumed to stay in the hopper and settle. When the overflow level is reached, phase 6, depending on the grain distribution, a specified percentage of the soil will not settle and will leave the hopper via the overflow. During this phase scouring does not have much influence on the sedimentation process. When the maximum weight of the hopper contents is reached, the overflow will be lowered continuously in order to keep the weight of the hopper contents constant at its maximum. When the sediment level rises, phase 8, the flow velocity above the sediment increases and scouring will re suspend settled particles. The overflow losses increase with time. The transition between phase 5 and 6 is very sharp, as is the transition between the phases 6 and 7 for the graph of the total load, but this does not exist in the graph of the effective load (fig. 8). However, the transition between the phases 7 and 8 is not necessarily very sharp. When this transition occurs depends on the grain distribution of the soil dredged. With very fine sands this transition will be near the transition between phases 6 and 7, so phase 7 is very short or may not occur at all. With very coarse sands and gravel scouring is minimal, so phase 8 is hardly present. In this case the sediment level may be higher then the overflow level. With silt the phases 7 and 8 will not occur, since after reaching the overflow level the overflow losses will be 100%.

Fig. 10: The loading curves for an 0.3 mm d50 sand.



So far the total load in the hopper has been described. A contractor is, of course, interested in the "Tonnes Dry Solids" (TDS) or situ cubic meters. The total load or gross load consists of the sediment with water in the pores and a layer of water above the sediment. The TDS consists of the weight of the soil grains only. The net weight in the hopper consists of the weight of the sediment, including the weight of the pore water. If the porosity of the sediment is considered to be equal to the in-situ porosity, then the volume of the sediment in the hopper equals the removed situ-volume. Although, in practice, there will be a difference between the in-situ porosity and the sediment porosity, here they will be considered equal. The net weight can be calculated according to:

$$\mathbf{W_s = W_h - W_w} \tag{28}$$

$$\mathbf{V_s = V_h - V_w} \tag{29}$$

$$\mathbf{V_s \cdot \rho_s = W_h - V_w \cdot \rho_w \quad and \quad V_w = V_h - V_s} \tag{30}$$

$$\mathbf{V_s \cdot \rho_s = W_h - (V_h - V_s) \cdot \rho_w} \tag{31}$$

$$\mathbf{V_s \cdot (\rho_s - \rho_w) = W_h - V_h \cdot \rho_w} \tag{32}$$

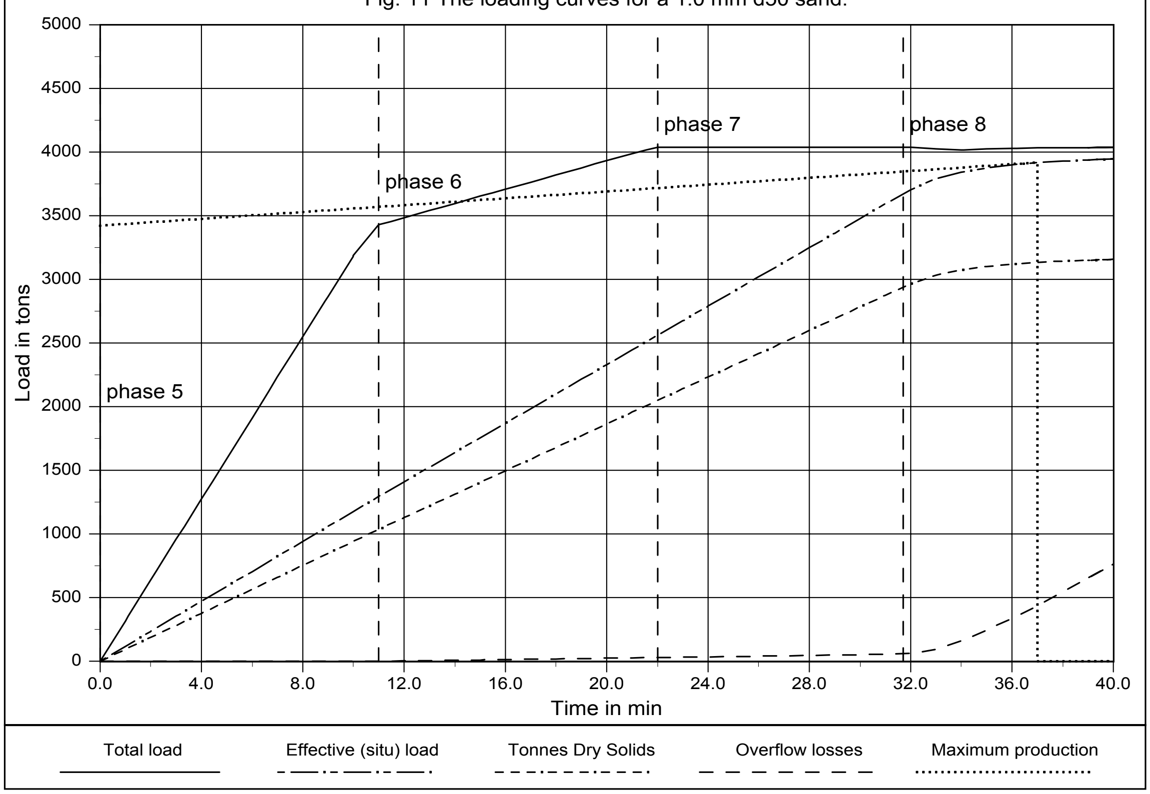
$$\mathbf{V_s = \frac{(W_h - V_h \cdot \rho_w)}{(\rho_s - \rho_w)}} \tag{33}$$

$$\mathbf{W_s = V_s \cdot \rho_s = \frac{(W_h - V_h \cdot \rho_w) \cdot \rho_s}{(\rho_s - \rho_w)}} \tag{34}$$

$$\mathrm{TDS} = \mathrm{W_s} \cdot \frac{\rho_s - \rho_w}{\rho_q - \rho_w} \cdot \frac{\rho_q}{\rho_s} = \frac{(\mathrm{W_h} - \mathrm{V_h} \cdot \rho_w) \cdot \rho_q}{(\rho_q - \rho_w)} \tag{35}$$

The net weight (situ weight) according to equation 34 can be approximated by the total weight of the load in the hopper minus the weight of the same volume of water and the result multiplied by 2. For the TDS this factor is about 1.2, according to equation 35. This is of course only valid for a specific density of the sediment of 2 tons per cubic meter.

Fig. 11 The loading curves for a 1.0 mm d50 sand.



With these equations the hopper cycle for the net weight and the TDS can be derived, this is shown in the figures 8 to 11. The hopper dredge is optimally loaded, when the effective load (weight) or the TDS divided by the total cycle time **dW_s/dt** reaches its maximum. This is shown in figures 8 to 11 and is the reason for the starting point of the loading cycle in figure 8.

THE CALCULATION MODEL.

The previous paragraphs explain the basics of the settling velocity of grains, the ideal settlement basin and the loading cycle of a hopper dredge. These basic theories will now be applied to the sedimentation process in a hopper.
Consider a rectangular hopper of width **W,** height **H** and length **L**. A mixture with a mixture density ρ_m and with a specified grain distribution is being dredged. Depending on the operational conditions such as dredging depth, the pump system installed and the grain distribution and mixture density, a mixture flow **Q** will enter the hopper. If the porosity **n** of the sediment is known, the flow of sediment can be determined according to:

The mass flow of the mixture is:

$$\mathbf{Q} \cdot \rho_m = \mathbf{Q} \cdot (\rho_w \cdot (1 - C_v) + \rho_q \cdot C_v) \tag{36}$$

The mass flow of the solids is now:

$$\mathbf{Q} \cdot \rho_q \cdot \frac{(\rho_m - \rho_w)}{(\rho_q - \rho_w)} = \mathbf{Q} \cdot C_v \cdot \rho_q \tag{37}$$

From this, the mass flow of sediment is:

$$\frac{dW_s}{dt} = \mathbf{Q} \cdot C_v \cdot (\rho_q + e \cdot \rho_w) \cdot r_b \tag{38}$$

With:

$$e = \frac{n}{(1 - n)} \tag{39}$$

Part of this mass flow will settle in the hopper and another part will leave the hopper through the overflow. The ratio between these parts depends on the phase of the loading process. During phase 5 the hopper is loaded to the overflow level, so the mass flow into the hopper will stay in the hopper. This means that the total settling efficiency during this phase equals 1. During phase 6 the loading continues until the maximum load in the hopper is reached. If scouring does not occur, the mass flow that will settle into the sediment can be calculated with equation 38, where the settling efficiency should be determined with equation 24.

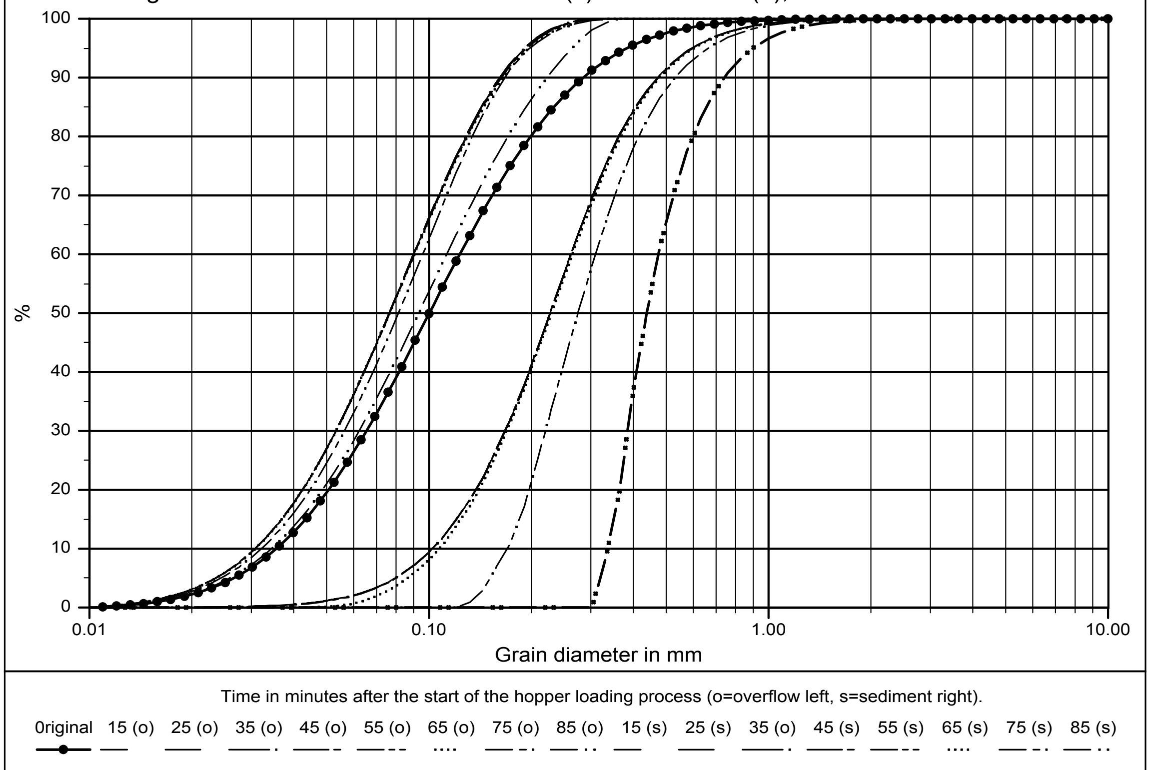
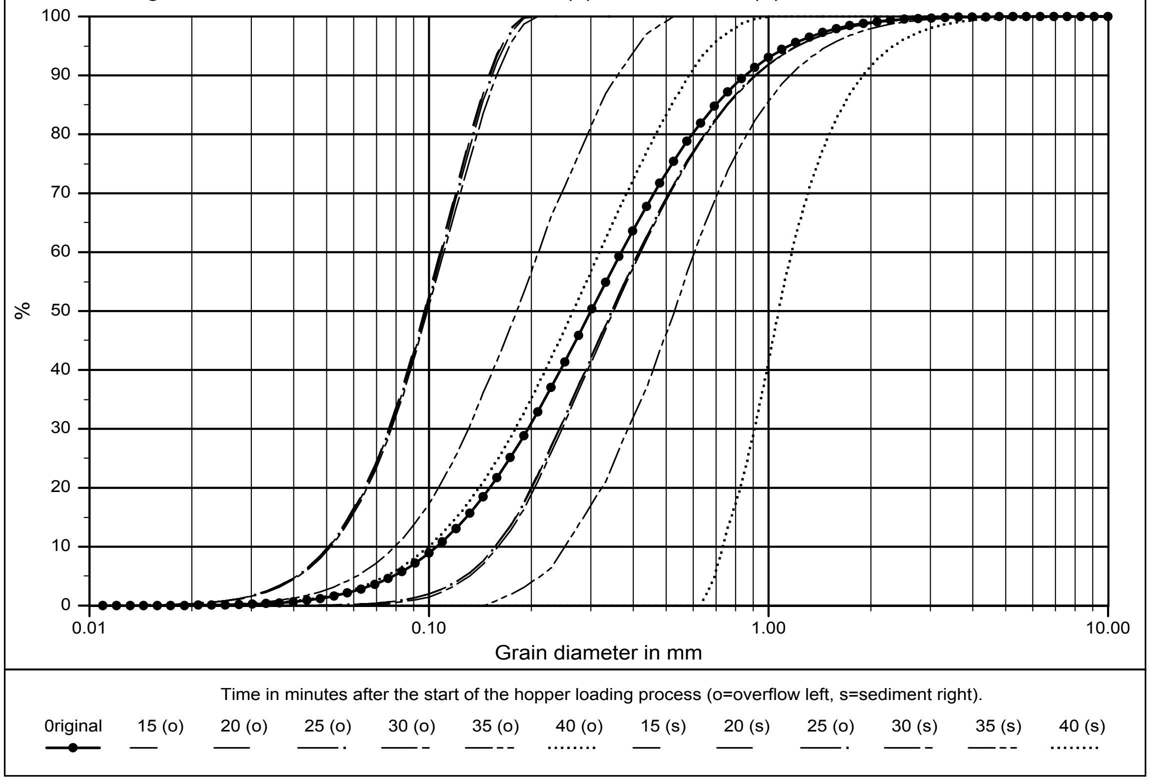


Fig. 12: Grain distributions of sediment (s) and overflow (o), for an 0.1 mm d50 sand.

During phase 7 the loading continues, but with a CTS, the overflow is lowered to ensure that the total weight in the hopper remains constant. As scour does not yet occur, the above equation is still valid. During phase 8 scouring occurs. If scouring does occur, the mass flow that will settle into the sediment can be calculated also with equation 38, but the settling efficiency should be determined with equation 26. Scouring is the cause of increasing overflow losses. Scour depends upon the velocity of the flow above the sediment. Since in a hopper the sediment is not removed, the sediment level rises during the loading of the hopper. This means that the height of the mixture flow above the sediment decreases during the loading process, resulting in an increasing flow velocity. The scour velocity can now be determined by:

$$\mathbf{s_s = \frac{Q}{B \cdot H_w}} \tag{40}$$

Fig. 13: Grain distributions of sediment (s) and overflow (o), for an 0.3 mm d50 sand.



With:

$$\mathbf{H_w = H - H_s = H - \frac{W_s}{\rho_s \cdot B \cdot L}} \tag{41}$$

The height **H** is a constant for a Constant Volume System (CVS), but this height changes for a CTS, because the overflow is lowered from the moment, the maximum weight in the hopper is reached. If a maximum weight $\mathbf{W_m}$ is considered, the height of the layer of water above the sediment for a CTS can be determined by:

$$\mathbf{H_w = \frac{W_m - \rho_s \cdot H_s \cdot B \cdot L}{\rho_w \cdot B \cdot L}} \tag{42}$$

The hopper loading curve can now be determined by first calculating the time required to fill the hopper (phase 6), given a specified mixture flow **Q**. From the mixture density $\boldsymbol{\rho_m}$ the mass and given a specified porosity, the volume of the sediment can be calculated. From this point the calculations are carried out in small time steps (phases 7 and 8). In one time step, first the height of the sediment and the height of the water layer above the sediment are determined. The height of the water layer can be determined with equation

41 for a CVS hopper and equation 42 for a CTS hopper. With equation 40 the scour velocity can now be determined. Using equation 25 the fraction of the grains that will be subject to scour can be determined. If this fraction $\mathbf{p_s}$ is zero equation 24 has to be used to determine the mass flow that will stay in the hopper. If this fraction is not equal to zero equation 26 has to be used. Equation 38 can now be used to determine the mass flow. This mass flow multiplied by the time step results in an increment of the sediment mass that is added to the already existing mass of the sediment. The total sediment mass is the starting point for the next time step. This is repeated until the overflow losses are 100%. When the whole loading curve is known, the optimum loading time can be determined. This is shown in Figure 8, where the dotted line just hits the loading curve of the effective (situ) load. The point determined in this way gives the maximum ratio of effective load in the hopper and total cycle time.

THE HOPPER OF A TRAILING SUCTION HOPPER DREDGE AS AN IDEAL SETTLEMENT BASIN.

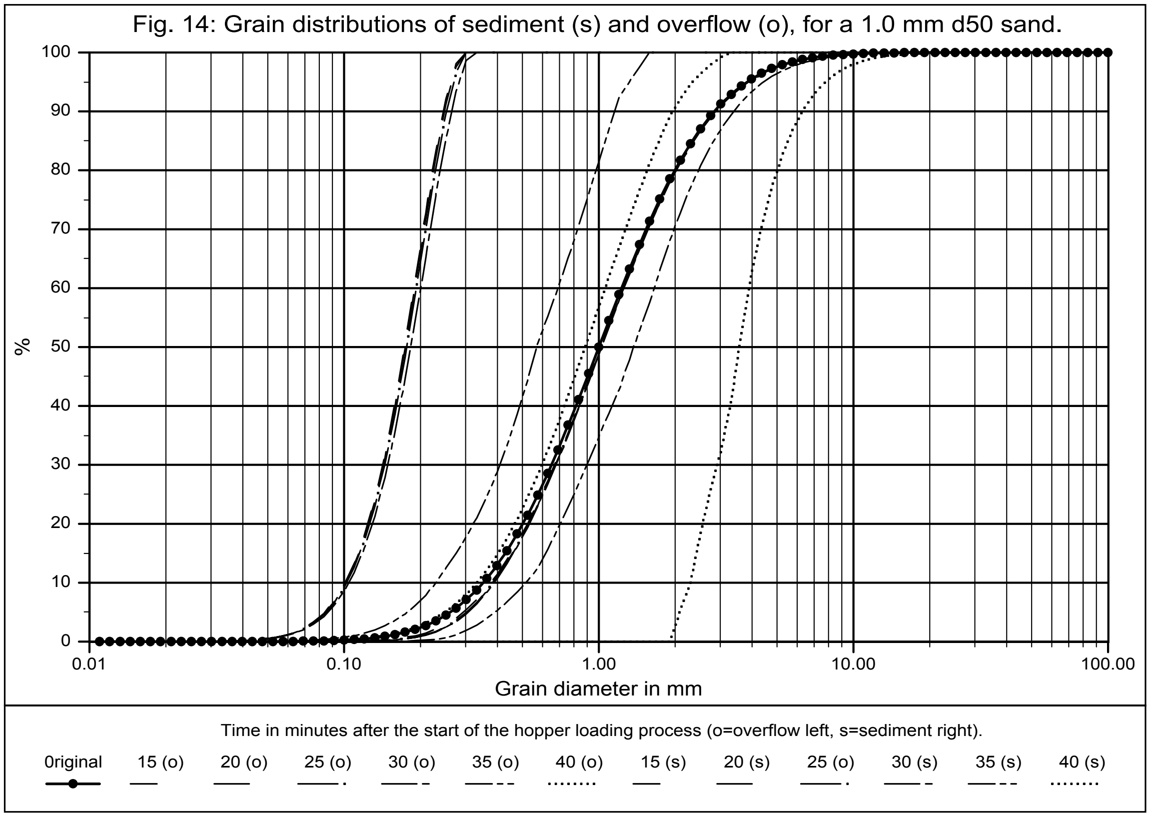
As stated before, the ideal settlement basin is a rectangular basin with an entrance zone, a settlement and sedimentation zone and a overflow zone. The hopper geometry and configuration aboard of the TSHD can be quite different from the ideal situation, so a method to schematise the hopper dimensions is required.

1. The height **H** of the hopper can be defined best as the hopper volume divided by the hopper area $\mathbf{L \cdot W}$. This means that the base of the ideal hopper, related to the maximum overflow height is at a higher level than the ship's base. This assumption results in a good approximation at the final phases (7 and 8) of the loading process, while in phase 6 of the loading process the hopper is filled with mixture and so the material stays in the hopper anyway.

2. Near the loading chute of the hopper or in cases where a deep loading system is used, the turbulence of the flow results in a good and sufficient distribution of the concentration and particle size distribution over the cross-section of the hopper, so the entrance zone can be kept small. For example between the hopper bulkhead and the end of the loading chute.

3. In the ideal settlement basin there are no vertical flow velocities except those resulting from turbulence. However in reality vertical velocities do occur near the overflow, therefore it is assumed that the overflow zone starts where the vertical velocities exceed the horizontal velocities. An estimate of where this will occur can easily be made with a flow net.

4. Although the presence of beams and cylinder rods for the hopper doors does increase the turbulence, it is the authors opinion, that an additional allowance is not required, neither for the hopper load parameter, nor for the turbulence parameter.



CASE STUDIES.

To give an impression of the behaviour and the sensitivity of the Camp and Dobbins model, three cases are calculated with the computer program TSHD (Miedema 1991). The rectangular hopper used, has a length **L**, of 46.3 m, a width **W**, of 9.8 m and a height **H**, of 6.0 m. At the entrance zone the mixture enters the hopper at a flow rate of approximately 4.6 m^3/sec and a mixture density of 1.25 tons/m^3. The hopper has a design density of 1.48 tons/m^3. The hopper loading cycle consists of sailing to the dump area (phase 1 + 2); 120 min., dumping (phase 3); 15 min., sailing back to the dredging area (phase 4); 120 min., filling the hopper up to the overflow level (phase 5); about 10 min. and continue loading until the optimum loading cycle production is reached (phase 6, 7 and 8). The hopper is of the CTS type (de Koning 1977), so the overflow will be lowered when the maximum weight is reached.

The flow rate and mixture density are chosen relatively high to emphasise the overflow losses.

The calculations are carried out with three sands. A sand with a d_{50} of 100 μm (sand A), a sand with a d_{50} of 300 μm (sand B) and a sand with a d_{50} of 1000 μm (sand C).

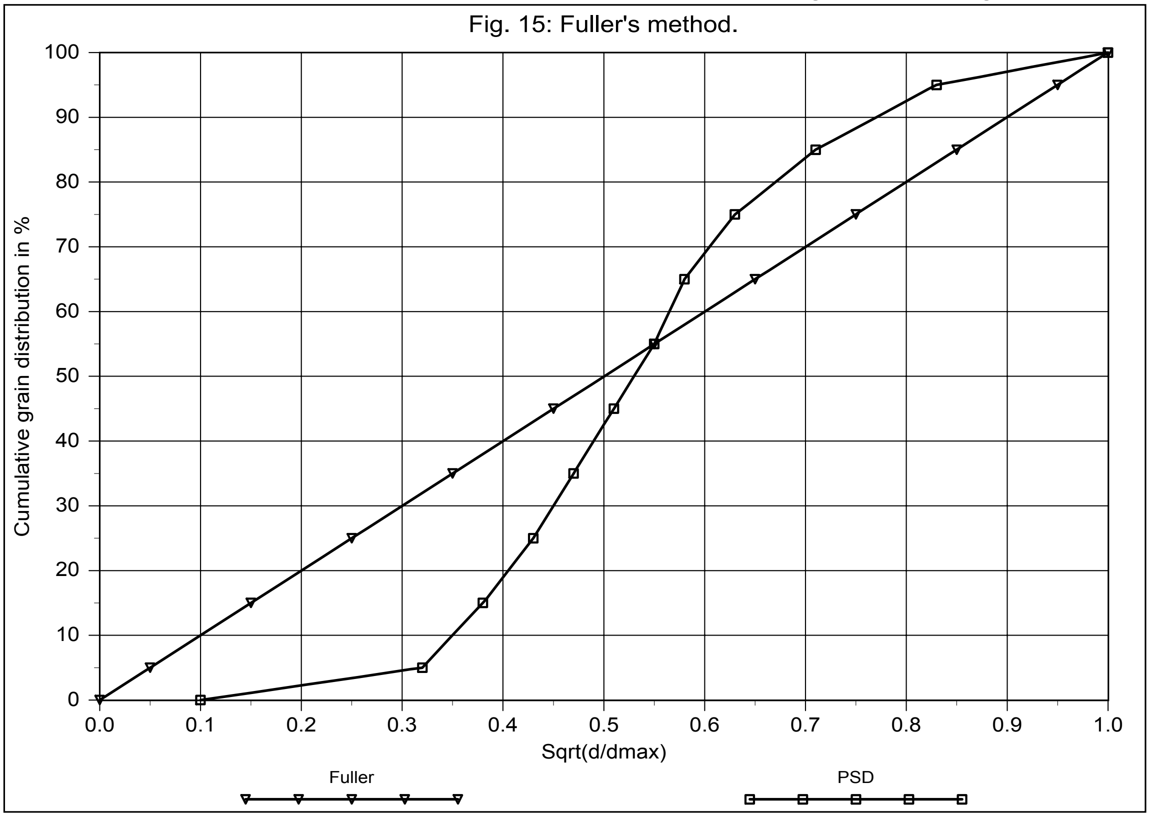
The grain distributions are determined by integration of a Gauss distribution, where the d_{50} is equivalent to the mean value and (d_{50}-d_{85}) is equivalent to the variance of the Gauss distribution. The cumulative grain distribution is determined at 100 grain

diameters. This way the total settling efficiency, according to equation 25, can be determined accurate enough. For each grain diameter at each time step, the fraction that settles and thus the fraction that leaves the hopper through the overflow can be determined. The result of this is, that the cumulative grain distribution of the sand at the top of the sedimentation zone and of the sand leaving through the overflow can be generated.
For determining the scour velocity, a porosity **n** of 0.4, a friction coefficient μ of 0.577 (30°) and a viscous friction coefficient λ of 0.03 are used.
For sand A the total loading cycle is shown in figure 8. Figure 9 is a close-up of the phases 5, 6, 7 and 8. Figure 12 shows the original grain distribution (the thick solid line in the middle), at the left of the original distribution, the grain distributions of the sand leaving the hopper at time intervals of 5 min. and at the right of the original distribution, the grain distributions at the top of the sedimentation zone, also at intervals of 5 min. The dotted line in figures 8 and 9 shows optimal loading. In the graphs the loading is continued for several minutes after this optimal point to emphasise the overflow losses. Figures 10 and 13 give the same information for sand B and Figures 11 and 14 give this information for sand C.
These figures show that the optimal loading time decreases with an increasing grain diameter. The overflow losses also decrease with an increasing grain diameter, which is evident. The tendencies as they are calculated match practice, however the model has to be tuned to every specific dredge to be a tool for estimating purposes.

CONCLUSIONS AND DISCUSSION.

The Camp and Dobbins model can be used to estimate loading time and overflow losses, however, the model should be tuned with measurements of the overflow rate in tons/sec as well as the particle size distribution in the overflow, as a function of time. The model can then also be used for the calculation of the decaying of the overflow plume in the dredging area.
If the model is used for the calculation of the production rate of the dredge a distinction has to be made whether the production is expressed in T.D.S./sec or in m^3/sec. In the first case the theory can be applied directly, while in the second case it has to be realised, that the overflow losses in T.D.S./sec do not always result in the same overflow loss in m^3/sec, since fine particles may situate in the voids of the bigger ones. The loss of fines does not reduce the total volume, but increases the void ratio. Although the fines leave the hopper in this case, they do not result in a reduction of the volume of the settled grains.
Those fractions which can be considered to apply to the overflow losses and those which do not, can be estimated from the difference between the real particle size distribution and the optimal particle size distribution, giving a maximum dry density, the so called Fuller distribution. If the gradient of the distribution curve for the fines is less steep then the corresponding gradient of the Fuller distribution, than that fraction of fines will not

effectively contribute to the overflow losses if they are expressed in m^3/sec. In such a case, in-situ, the fines were situated in the voids of the courser grains. If the gradient is



however steeper, the fines also form the grain matrix and the volume of settled grains will decrease if the fines leave the hopper through the overflow. Figure 15 gives an example of the Fuller distribution compared with a real grain distribution.

In the model a number of assumptions are made. Except from numerical values for the parameters involved, the Camp and Dobbins approach is used for the influence of turbulence, while seperately the influence of scour is used instead of using it as a boundary condition. During phase 8 of the loading process scour dominates the overflow losses. This of course depends on the way scour is modelled. In the case studies equation 25 according to Camp (1946) is used. Whether this is correct will be one of the subjects of further research.
Until now it is very difficult to get correct data from the field to verify this theory. It is not only necessary to have loading curves, but also grain distributions of the sediment and in the overflow, which are hard to obtain.

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NOMENCLATURE.

C_d	Drag coefficient	-
C_v	Volumetric concentration	-
d	Grain diameter m	
d_s	Grain diameter (scour)	m
e	Void ratio	-
g	Gravitational constant (9.81)	m/sec^2
H	Height of basin	m
H_s	Height of sediment layer in basin	m
H_w	Height of water layer in basin	m
L	Length of basin	m
n	Porosity	-
p_o	Fraction of grains that settle partially (excluding turbulence)	-
p_s	Fraction of grains that do no settle due to scour	-
p_t	Fraction of grains that settle partially (including turbulence)	-
Q	Mixture flow	m^3/sec
r_b	Settling efficiency for basin	-
r_g	Settling efficiency individual grain	-
r_t	Turbulence settling efficiency for individual grain	-

s_o	Flow velocity in basin	m/sec
s_s	Scour velocity	m/sec
v	Settling velocity	m/sec
v_c	Settling velocity with hindered settling	m/sec
v_o	Hopper load parameter	m/sec
V_h	Volume of sediment + water in hopper	tons
V_s	Volume of sediment in hopper	tons
V_w	Volume of water in hopper	tons
W	Width of basin	m
W_h	Weight of sediment + water in hopper	tons
W_s	Weight of sediment in hopper	tons
W_w	Weight of water in hopper	tons
α	Factor (scour)	-
β	Power for hindered settling	-
λ	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
ψ	Shape factor	-
ν	Kinematics viscosity	m^2/sec