A SENSITIVITY ANALYSIS OF THE SCALING OF TSHD'S

S.A. Miedema[1]

ABSTRACT

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. Lately Miedema & van Rhee (2007) made a comparison between the Camp model and the sophisticated 2DV model of van Rhee (2002) which showed that especially the overflow losses match. In 2008 Miedema added non-linear effects to the Camp model, such as the behavior of the layer of water above the overflow and an analytical model to determine scour.

The loading process of TSHD's contains a number of non-linearity's:

1. The real hopper load parameter will vary during the loading process.
2. The turbulence settling efficiency.
3. The behavior of the layer of water above the overflow.
4. The behavior of hindered settling.
5. The effective concentration in the hopper.
6. The so called storage effect.

Based on all these non-linearity's it is not expected that TSHD's can be scaled easily, however the research in this paper shows that with the right choice of scale laws the TSHD's can be scaled rather well. Four TSHD's are chosen, derived from Miedema & van Rhee (2007), but adapted to the scale laws. With each of these TSHD's simulations are carried out in 4 types of sand, 400 μm, 250 μm, 150 μm and 100 μm sand.

THE LOADING CYCLE OF A HOPPER DREDGE

The loading cycle of a TSHD is considered to start when the hopper is filled with soil and starts to sail to the dump area. The loading cycle then could consist 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.

Figure 1. Phase 1 of the loading cycle.

---

[1] Associate Professor of Dredging Engineering & Educational Director of Offshore Engineering, Delft University of Technology, Mekelweg 2, 2628CD Delft, The Netherlands, +31-15-2788359, s.a.miedema@tudelft.nl.

- Phase 2: Continue sailing to the dump area.

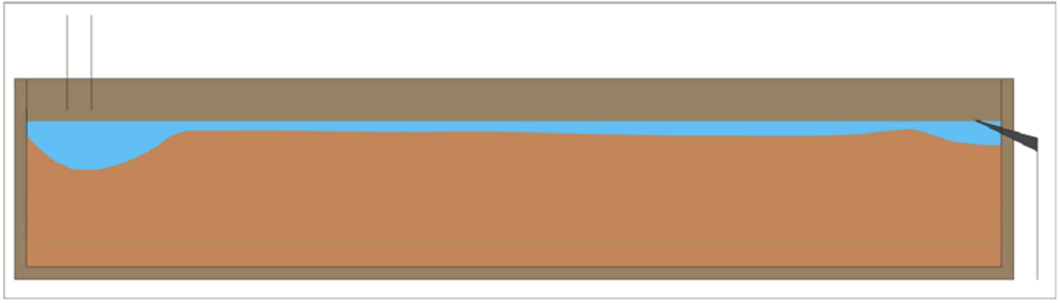


Figure 2. Phase 2 of the loading cycle.

- Phase 3: Dump the load in the dump area. Dumping can be carried out in 3 different ways, using the bottom dumping system, pumping ashore or rainbowing.

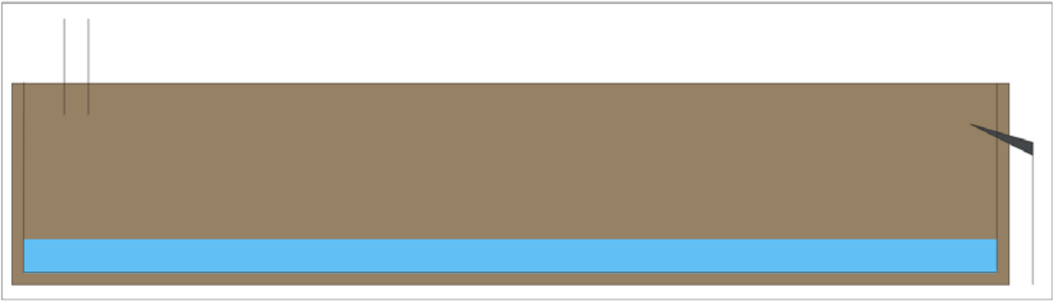


Figure 3. Phase 3 of the loading cycle.

- Phase 4: Pump the remaining water out of the hopper and sail to the dredging area. Often the water is not pumped out, but instead water is pumped in, to have the pumps as low as possible, in order to dredge a higher density, which should result in a shorter loading time.

Figure 4. Phase 4 of the loading cycle.

- 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.

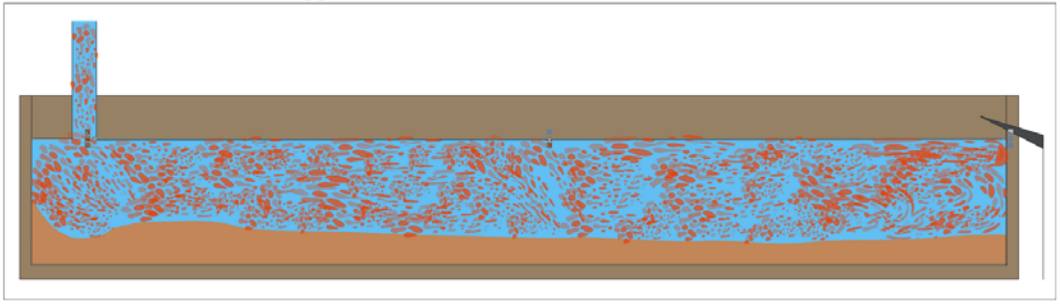


Figure 5. Phase 5 of the loading cycle.

- Phase 6: Continue loading with minimum overflow losses, during this phase a percentage of the grains will settle in the hopper. The percentage depends on the grain size distribution of the sand.

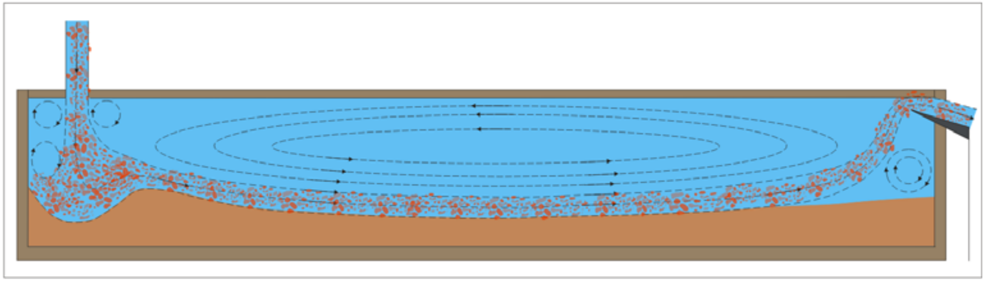


Figure 6. Phase 6 of the loading cycle.

- Phase 7: The maximum draught (CTS, Constant Tonnage System) is reached. from this point on the overflow is lowered.

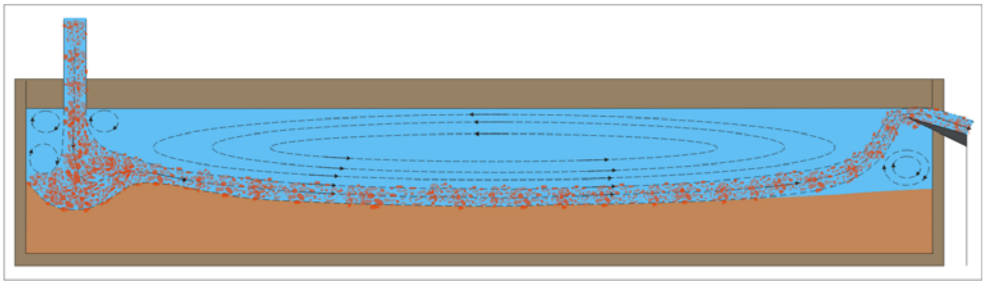


Figure 7. Phase 7 of the loading cycle.

- 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.

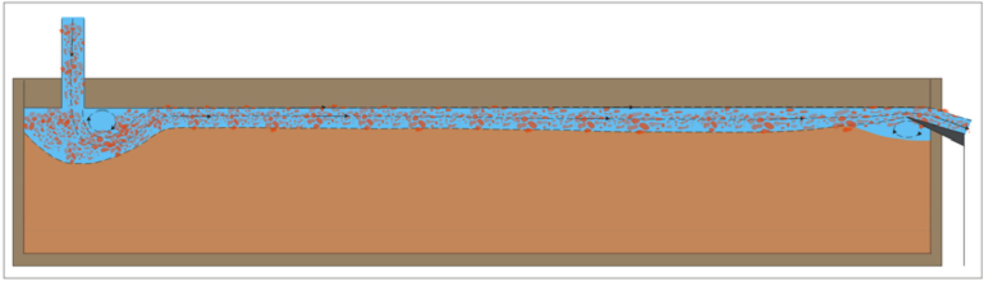


Figure 8. Phase 8 of the loading cycle.

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 $\mathbf{v}$ and the flow velocity above the sediment $\mathbf{s_0}$. Figure 9 shows a top view of the ideal settlement basin. Figure 10 shows the side view and Figure 11 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 $\mathbf{H_w}$ 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.

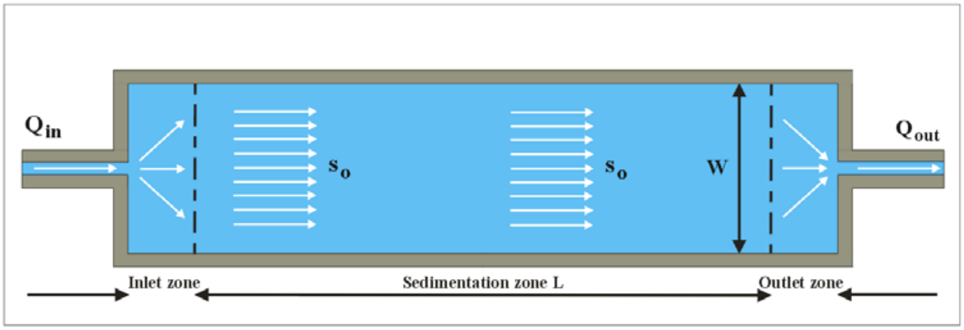


Figure 9. The top view of the ideal basin

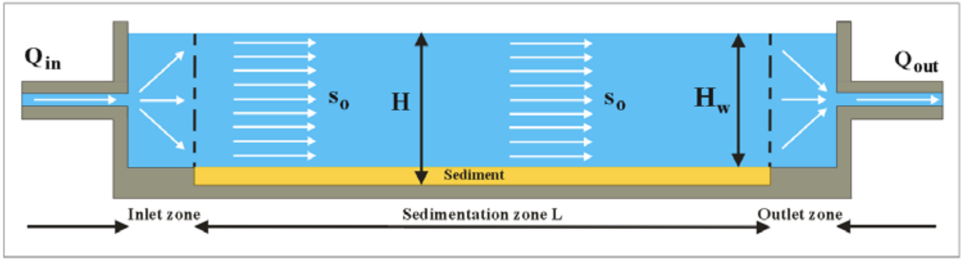


Figure 10. The side view of the ideal basin

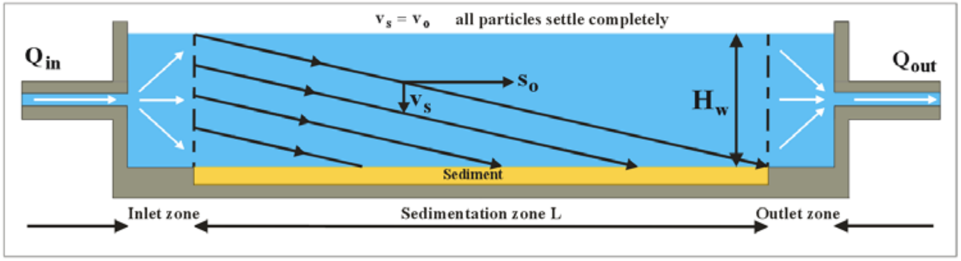


Figure 11. The path of a settling grain

Based on the average horizontal velocity s_0 in the basin:

$$s_o = \frac{Q_{in}}{W \cdot H_w} \qquad (1)$$

The hopper load parameter v_o can be determined according to:

$$\frac{v_o}{s_o} = \frac{H_w}{L} \quad \text{thus:} \quad v_o = s_o \cdot \frac{H_w}{L} = \frac{Q_{in}}{W \cdot L} \quad \text{or} \quad \frac{Q_{in}}{W \cdot L} - \frac{v_{sed}}{2} \quad \textbf{including the bed rise velocity} \qquad (2)$$

The settling velocity v_o is often referred to as the hopper load parameter. A smaller hopper load parameter means that smaller grains will settle easier. From Figure 11 the conclusion can be drawn that grains with a settling velocity greater then v_o will all reach the sediment layer and thus have a settling efficiency η_g of 1. Grains with a settling velocity smaller then v_o 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:

$$\eta_g = \left(\frac{v_s}{v_o} \right) \qquad (3)$$

If the fraction of grains with a settling velocity greater then v_o equals p_o, then the settling efficiency for a grain distribution η_b can be determined by integrating the grain settling efficiency for the whole grain distribution curve.

Table of Contents

$$\eta_b = \left(1 - p_o\right) + \int_{0}^{p_o} \eta_g \cdot dp \tag{4}$$

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 $\boldsymbol{\eta_g}$:

$$\eta_b = \left(1 - p_o\right) + \int_{p_s}^{p_o} \eta_g \cdot dp \quad \text{or} \quad \eta_b = \left(1 - p_s\right) \tag{6}$$

The effect of 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 than 1 for all grains according to the equations 7 and 8, the basin settling efficiency can be determined with equation 9, where $\mathbf{p_s}$ equals 0 as long as scour does not occur.

$$\eta_t = \eta_g^{0} \cdot \left(1 - 0.184 \cdot \eta_g^{+.885 - .20 \cdot \eta_g} \cdot \left(1 - \operatorname{TanH}\left(\eta_g^{-.13 - .80 \cdot \eta_g} \cdot \left(\operatorname{Log}\left(\frac{v_s}{s_o}\right) - .2614 - .5 \cdot \operatorname{Log}\left(\lambda\right) + \eta_g^{-.33 - .94 \cdot \eta_g}\right)\right)\right)\right) \tag{7}$$

$$\eta_t = \eta_g^{-1} \cdot \left(1 - 0.184 \cdot \eta_g^{-.69 - .38 \cdot \eta_g} \cdot \left(1 - \operatorname{TanH}\left(\eta_g^{+.77 - .08 \cdot \eta_g} \cdot \left(\operatorname{Log}\left(\frac{v_s}{s_o}\right) - .2614 - .5 \cdot \operatorname{Log}\left(\lambda\right) + \eta_g^{+1.01 - .18 \cdot \eta_g}\right)\right)\right)\right) \tag{8}$$

$$\eta_b = \int_{p_s}^{1} \eta_g \cdot \eta_t \cdot dp \tag{9}$$

SCALE LAWS

To compare TSHD's of different dimensions scale laws have to be applied in order to create identical loading processes. Scale laws should be based on the physical and the operational processes that occur. Further the shape of the hopper should be identical and the relation with the flow should match. It is however also important to decide which parameter or parameters to choose for the comparison of the TSHD's. When can the conclusion be drawn that two hoppers with different dimensions behave identical. The main parameter that is chosen for this comparison are the cumulative overflow losses. The cumulative overflow losses, are the overflow losses expressed as TDS (Tonnes Dry Solids) divided by the total amount of TDS that has entered the hopper, from the start of the loading process until the moment of optimum loading.

The first important parameter to consider is the hopper load parameter (HLP) as described in equation 2. Here the hopper load parameter without the effect of the bed rise velocity is considered, because the bed rise velocity changes during the loading process and would result in changing scale laws. As stated before, the hopper load parameter is the settling velocity of a grain that will settle for 100%. Larger grains will also settle for 100%, but smaller grains will settle with a smaller percentage.

$$\mathbf{v_o = s_o \cdot \frac{H_w}{L} = \frac{Q_{in}}{W \cdot L}} \tag{3}$$

If two TSHD's with different dimensions have the same hopper load parameter, it can be expected that under similar conditions, the momentary overflow losses are equal and thus also the cumulative overflow losses. However the hopper load parameter does not take into consideration the effects of turbulence efficiency, hindered settling, the storage effect and so on.

A second scale law could be that the ratio's between Length, Width and Height are identical. If a length scale λ is considered this gives:

$$\boldsymbol{\lambda = \frac{L_1}{L_2} = \frac{W_1}{W_2} = \frac{H_1}{H_2} \quad \text{and} \quad \frac{HLP_1}{HLP_2} = 1 \quad \text{and} \quad \frac{Q_1}{Q_2} = \lambda^2 \quad \text{and} \quad \frac{T_{f1}}{T_{f2}} = \frac{V_1 / Q_1}{V_2 / Q_2} = \lambda} \tag{4}$$

Because the hopper load parameter is considered to be a constant, the flow Q will scale with the square of the length scale λ. The filling time T_f, which is the time to fill the hopper up to the overflow level also scales with the length scale λ. To have similar processes for determining the optimum loading time, the travelling time, which is the sum of the sailing time to and from the dump area and the dumping time, should also be scaled with the length scale, assuming that the loading time is proportional to the filling time. Since the horizontal flow velocity in the hopper equals the flow Q divided by the Width W and the Height H of the hopper, the horizontal flow velocity is a constant and does not depend on the length scale. This also follows from the fact that the hopper load parameter is a constant. If it is assumed that the maximum line velocity in the suction pipes is a constant, for example 7 m/s and because the line velocity equals the flow velocity divided by 2 and divided by the cross section of one pipe, this implies that the pipe diameter should be proportional to the square root of the flow and thus be proportional to the length scale λ.

Because sand is difficult to scale and in reality the sand will be the same independent of the TSHD used, it is assumed that the sand is the same for all hopper sizes. This implies that the settling velocities are the same and looking at the equations 7 and 8 this means that the grain settling efficiency ηg does not depend on the hopper size and the ratio v_s/s_o does not depend on the hopper size, since the horizontal flow velocity s_o does not depend on the hopper size. The resulting turbulence efficiency as calculated with equation 7 and 8 is thus not dependent on the hopper size, although it will change during the loading process.

THE TSHD'S USED

Based on the scale laws and based on Miedema & van Rhee 2007, 4 TSHD's are chosen in a range from small to Mega. The main dimensions and additional parameters of these hoppers can be found in table 1 and 2.

Table 1. The main dimensions of the 4 TSHD's.

Hopper	Length (m)	Width (m)	Empty height (m)	Volume (m^3)	Design density (ton/m^3)	Maximum load (ton)	HLP (m/sec)
Small	40	10	5.0	2000	1.5	3000	0.008
Large	60	15	7.5	6750	1.5	10125	0.008
Jumbo	80	20	10.0	16000	1.5	24000	0.008
Mega	100	25	12.5	31250	1.5	46875	0.008

Table 2. Additional and derived quantities.

Hopper	Flow (m^3/sec)	Pipe diameter (m)	Filling time (min)	Sailing time (min)	Hydraulic diameter (m)	Reynolds number	Mixture density (ton/m^3)
Small	3.2	0.54	10.4	104	10	$0.64*10^6$	1.3
Large	7.2	0.81	15.6	156	15	$0.96*10^6$	1.3
Jumbo	12.8	1.08	20.8	208	20	$1.28*10^6$	1.3
Mega	20.0	1.35	26.0	260	25	$1.60*10^6$	1.3

Tables 1 and 2 show a wide range of TSHD's from small (2000 m^3) to Mega (31250 m^3). As can be noted in the tables, the hopper load parameters are constant at 0.008 m/sec, which is the settling velocity of a grain a bit bigger than 100 μm. The design density of the TSHD's is chosen at 1.5 ton/m^3, which implies that the loading process will follow the Constant Tonnage Loading process. The total sailing and dumping time is chosen 10 times the filling time, which of course is arbitrary, but the resulting sailing times seem to be representative for the reality. The mixture density is chosen at 1.3 ton/m^3, which is high enough to take the influence of hindered settling into account. It should be noted that the Reynolds numbers of the horizontal flow in the hopper are not constant. The Reynolds numbers are proportional to the length scale λ. The question is whether or not this will influence the loading process. As stated before, it does not influence the turbulent settling efficiency, but it could influence the scour in the final phase of the loading process. Scour is influenced by the viscous friction of the fluid flowing over the bed. This friction depends on the relative roughness and the Reynolds number. The roughness of the sediment has the magnitude of the grain diameter which is in the range of 0.1-0.5 mm, while the hydraulic diameters of the 4 TSHD's are in the magnitude of 10-25 m. The largest relative roughness would occur for an 0.5 mm grain and a hydraulic diameter of 10 m, giving 0.0005/10=0.00005. The friction coefficient will be between 0.0175 and 0.0171, which hardly has an effect on the scour. Although there will always be some effect, it is not expected that this effect will have a big influence on the similarity of the loading processes of the 4 TSHD's. The sediment density is chosen at 1.9 ton/m^3, which means that the TDS is about 76% of the weight of the wet sediment.

For carrying out the simulations 4 grain distributions are chosen. All 4 grain distributions have a d_{15} for grains with a settling velocity smaller than the hopper load parameter in order to be sure there will be significant overflow losses. If grain distributions were chosen with almost 100% of the grains having a settling velocity above the hopper load parameter, this would result in very small cumulative overflow losses and a good comparison would be difficult. Table 3 gives the d_{15}, d_{50} and d_{85} of the 4 grain distributions, while Figure 12 shows the full PSD's.

Table 3. The characteristics of the 4 grain distributions.

	400 μm	250 μm	150 μm	100 μm
d_{15}	70 μm	80 μm	80 μm	50 μm
d_{50}	400 μm	250 μm	150 μm	100 μm
d_{85}	2000 μm	750 μm	300 μm	200 μm

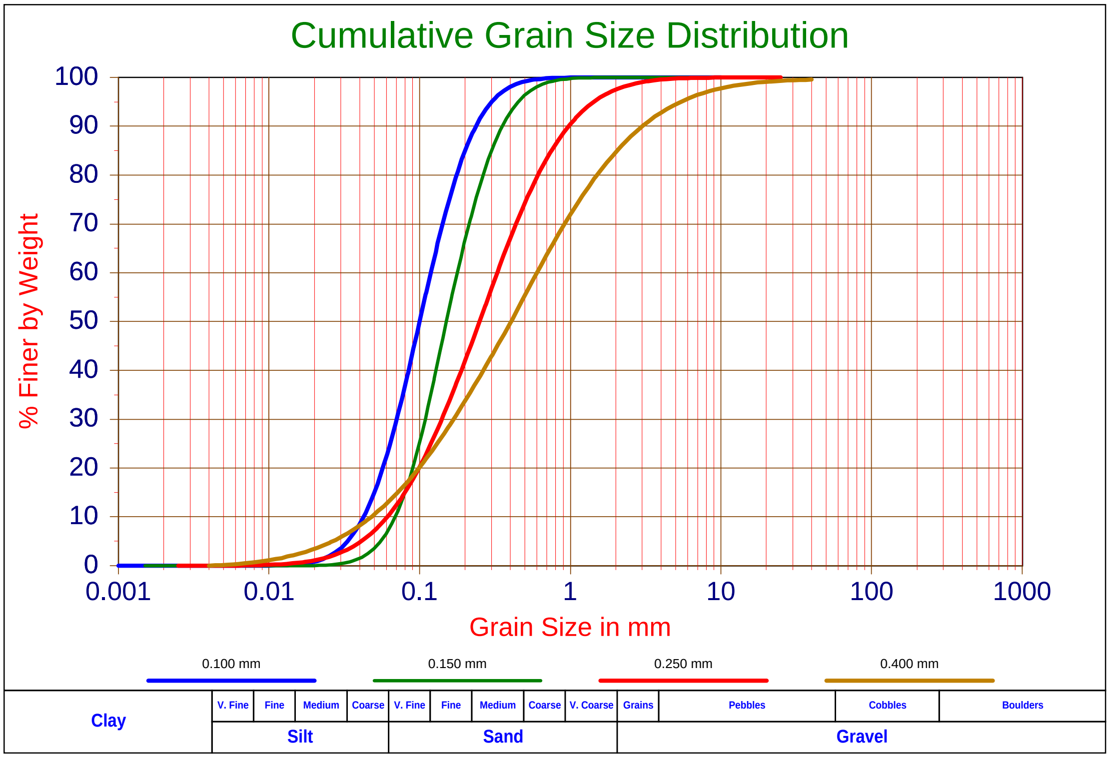


Figure 12. The 4 grain distributions.

SIMULATION RESULTS

The simulations of the loading process of the 4 TSHD's are carried out with software based on the model published by Miedema 2008, including turbulence efficiency, hindered settling, the storage effect, the layer of water above the overflow and more. The results of these simulations are summarized in Tables 5, 6, 7 and 8.

Table 4. The simulation results with the 0.400 mm sand.

400 µm sand	Loading time (min)	TDS (ton)	Overflow losses TDS (ton)	Cumulative overflow losses (%)	Production (ton/min)
Small	31.0	2174	476	18.0%	16.1
Large	46.5	7349	1594	17.8%	36.2
Jumbo	62.0	17440	3758	17.7%	64.5
Mega	77.5	34089	7313	17.7%	100.9

Table 5. The simulation results with the 0.250 mm sand.

250 µm sand	Loading time (min)	TDS (ton)	Overflow losses TDS (ton)	Cumulative overflow losses (%)	Production (ton/min)
Small	31.0	2146	503	19.0%	15.9
Large	46.5	7258	1685	18.8%	35.8
Jumbo	61.8	17218	3923	18.6%	63.7
Mega	77.3	33662	7651	18.5%	99.7

Table 6. The simulation results with the 0.150 mm sand.

150 µm sand	Loading time (min)	TDS (ton)	Overflow losses TDS (ton)	Cumulative overflow losses (%)	Production (ton/min)
Small	32.2	2104	645	23.5%	15.4
Large	48.2	7114	2149	23.2%	34.8
Jumbo	64.2	16887	3923	23.0%	62.0
Mega	80.3	33030	7651	23.0%	96.9

Table 7. The simulation results with the 0.100 mm sand.

100 µm sand	Loading time (min)	TDS (ton)	Overflow losses TDS (ton)	Cumulative overflow losses (%)	Production (ton/min)
Small	43.0	2111	1564	42.6%	14.3
Large	64.7	7145	5292	42.6%	32.3
Jumbo	86.0	16952	12452	42.3%	57.6
Mega	107.7	33149	24368	42.4%	90.1

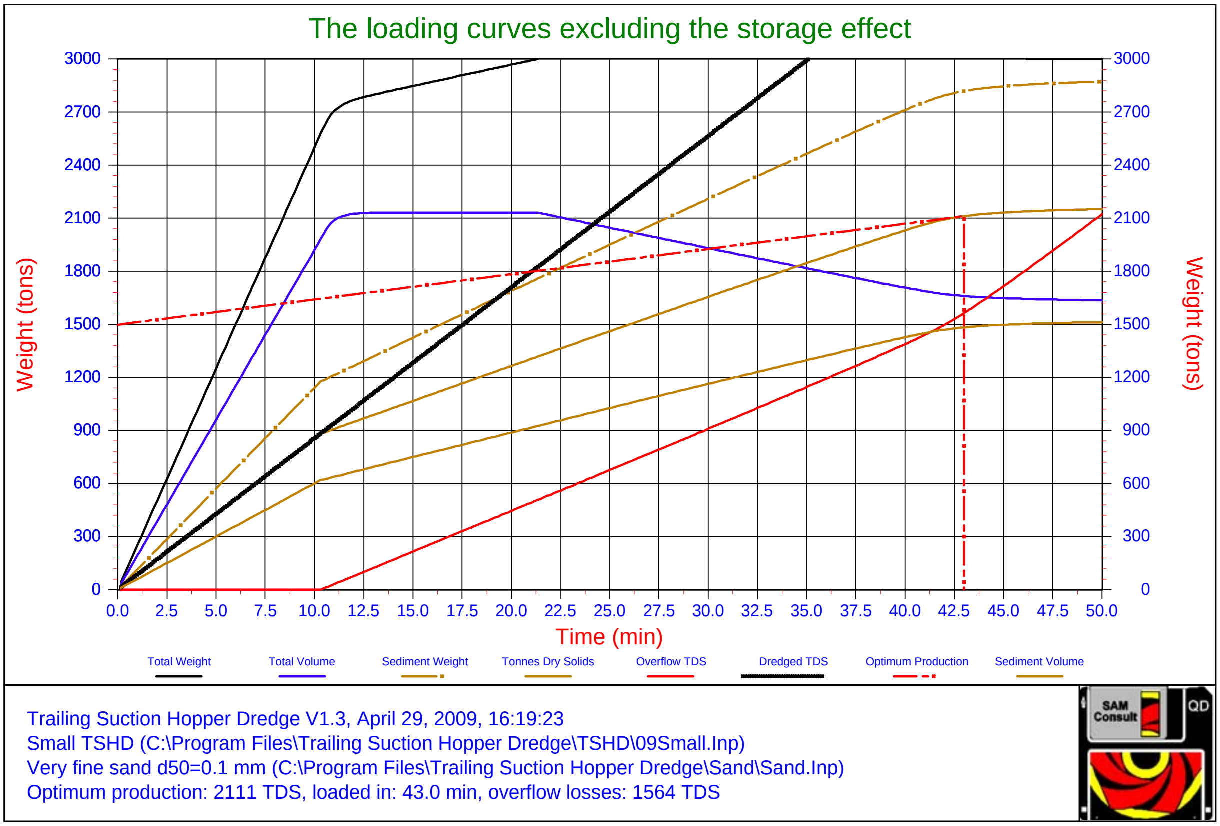
To visualize the simulations, the graphs of the simulations of the Small TSHD and the Mega TSHD can be found in the Figures 13-20. From these graphs and the above tables it will be clear that the cumulative overflow losses do not depend on the size of the TSHD in quantity and in shape op de loading and overflow curves. To understand the above tables and the following figures, they will be explained and discussed each.

The Tables 4-7 show the loading times in the second column, it is clear that the loading times are almost proportional to the length scale λ and they increase with increasing overflow losses. The finer the sand, the longer the loading time. The third column gives the TDS at the point of optimum loading. The TDS of a hopper filled with sediment is about 76% of the weight of the sediment, but since there is still some water on top of the sediment at the moment of optimum loading the TDS is a bit less. This means that the maximum TDS of the Small TSHD is 2280 tons, for the Large TSHD 7695 tons, for the Jumbo TSHD 18240 tons and for the Mega TSHD 35625 tons, so the assumption is correct. The TDS does not depend on the type of sand. The fourth column gives the overflow losses in tons TDS. Again TDS means, only the weight of the solids, excluding the pore water and the water on top of the sediment. The fifth column gives the cumulative overflow losses, which are almost constant for each type of sand. For the 400 µm sand about 17.8%, for the 250 µm about 18.7%, for the 150 µm sand about 23.2% and for the 100 µm sand about 42.4%. These cumulative overflow losses are the overflow losses in TDS, divided by the total amount of TDS that has entered the hopper. It is clear that the cumulative overflow losses do not seem to depend on the size of the TSHD, given the scale laws applied in the simulations. Apparently the scale laws applied are the correct scale laws for scaling TSHD's in order to get similar loading and sedimentation processes. It is interesting however to compare the cumulative overflow losses with the grain size distribution curves of the sands used. The hopper load parameter of 0.008 m/s matches a grain with a diameter of 0.112 mm. If the percentage of grains smaller than this diameter is considered and compared we the overflow losses, the following numbers are found. For the 400 µm sand, about 20% smaller than 0.112 mm and cumulative overflow losses of 17.8%, for the 250 µm sand, about 20% smaller than 0.112 mm and 18.7% cumulative overflow losses, for the 150 µm sand, about 26% smaller than 0.112 mm and 23.2% cumulative overflow losses and for the 100 µm sand, about 52% smaller than 0.112 mm and 42.4% cumulative overflow losses. Apparently, but not unexpected, the cumulative overflow losses have a strong relation with the percentage of the grains smaller than the grain diameter matching the hopper load parameter. There is however not a fixed relation, because the grains smaller than the diameter matching the hopper load parameter will still settle partially and this depends strongly on the steepness of the cumulative grain size distribution. In the examples given it is clear that the 400 µm sand and the 250 µm sand, both have about 20% smaller and both have a cumulative overflow loss of about 20%. The simulations however also take hindered settling, the effect of the concentration on the settling velocity, into account and in reality the TSHD might make turns, resulting in a more complicated loading process. The overflow losses will also depend on the concentration as will be discussed later. The last column shows the production and of course the production is decreasing if the cumulative overflow losses are increasing.

Figures 13 and 14 give the loading curves of the Small and the Mega TSHD in order to see if not only the cumulative overflow losses are independent of the size of the TSHD, but also the shape of the loading curves. To understand these graphs the different curves are explained. The loading process starts with an empty hopper, so there is no water in the hopper. First for 10.4 minutes for the Small hopper and 26.0 minutes for the Mega hopper, the hopper is filled with mixture of 1.3 ton/m3. After that the loading continues until after about 22.4 minutes for the Small hopper and 57 minutes for the Mega hopper, the maximum load is reached as can be found in table 1, seventh column. After reaching the maximum load, the loading continues while the overflow is lowered in such a way that the total load in the hopper remains constant, replacing water above the sediment with sediment. After about 40 minutes for the Small hopper and about 100 minutes for the Mega hopper, the sediment level is so high and the layer of water above the sediment is so thin, that very high flow velocities occur above the sediment, preventing the grains the settle and resulting in scour. After a short while hardly any grains will settle and the optimum loading point is reached. Continuing after this point will result in a decrease of production and is thus useless.

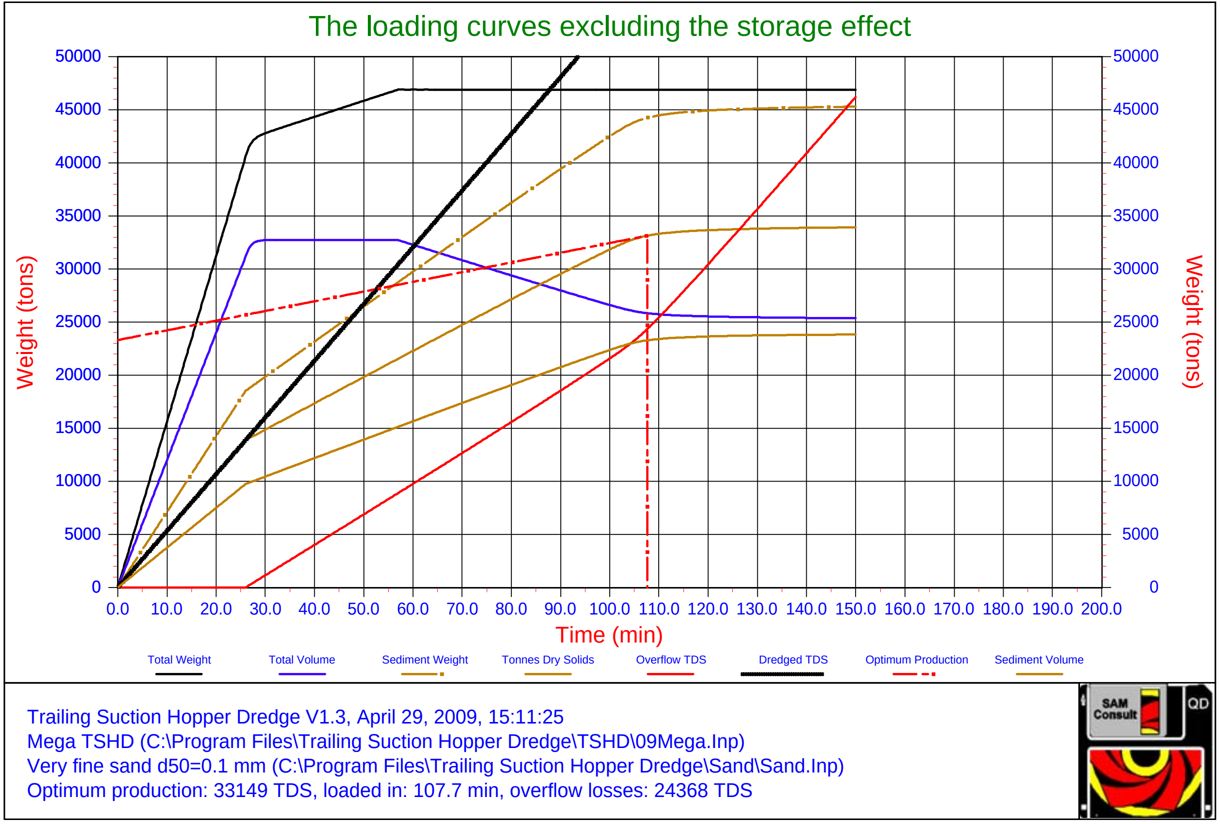
The black solid line at the top is the total load in the hopper and it is obvious that this line stays at the maximum load once this is reached. The blue solid line is the total volume in the hopper, it can be seen that after reaching the maximum load, the total volume is decreasing because the overflow is lowered. The dashed red line shows the tangent method to determine the optimum loading point. The dashed brown line shows the weight of the sediment in the hopper, including the weight of the pore water. At the end of the loading this line is just below the maximum load line, because there is still a layer of water above the sediment, which does not count in the sediment weight. The black solid straight line gives the amount of TDS that enters the hopper, so the sum of sediment TDS and overflow TDS should be equal to this line. The highest solid brown line is the amount of TDS in the hopper, while the lowest solid brown line is the sediment volume. Finally the solid red line gives the overflow losses in TDS. It can be seen that until the mixture in the hopper reaches the overflow level, there are no overflow losses. After the hopper is filled the overflow losses follow an almost straight line, which curves to a steeper line when scour starts to occur.

Although the scales of Figures 13 and 14 are different, it is clear that the different loading curves have similar shapes, so not only the cumulative overflow losses are independent of the size of the hopper, also the momentary overflow losses are.



Trailing Suction Hopper Dredge V1.3, April 29, 2009, 16:19:23
Small TSHD (C:\Program Files\Trailing Suction Hopper Dredge\TSHD\09Small.Inp)
Very fine sand d50=0.1 mm (C:\Program Files\Trailing Suction Hopper Dredge\Sand\Sand.Inp)
Optimum production: 2111 TDS, loaded in: 43.0 min, overflow losses: 1564 TDS

Figure 13. The loading curves for the Small TSHD.



Trailing Suction Hopper Dredge V1.3, April 29, 2009, 15:11:25
Mega TSHD (C:\Program Files\Trailing Suction Hopper Dredge\TSHD\09Mega.Inp)
Very fine sand d50=0.1 mm (C:\Program Files\Trailing Suction Hopper Dredge\Sand\Sand.Inp)
Optimum production: 33149 TDS, loaded in: 107.7 min, overflow losses: 24368 TDS

Figure 14. The loading curves for the Mega TSHD.

Figures 15 and 16 show the loading curves including the storage effect. So what exactly is this storage effect? When grains enter the hopper, it can already be calculated which fraction of the grains will settle and which fraction of the grains will leave the hopper through the overflow. Figures 13 and 14 are based on such a calculation. Grains that will leave through the overflow however, first have to travel through the hopper before they actually leave the hopper through the overflow. One can say that these grains are temporary stored in the hopper, the so called storage effect. This means that if suddenly the loading process would stop before the optimum is reached, there are more grains and thus TDS in the hopper then would follow from the Figures 13 and 14. It also means that the overflow losses at such a moment would be less. The amount of grains that will leave the hopper, but are still inside, depends on the time it takes for a particle to move from the entrance to the overflow and this depends on the flow velocity. The flow velocity will increase when the sediment level increases and at the end of the loading cycle this velocity is so high that the storage effect can be neglected. In the Figures 15 and 16 the top thick solid black lines show the amount of TDS in the hopper (compare with Figures 13 and 14, these contain the same lines but solid brown). Just above the thick solid black lines are the thin solid green lines. The difference between the thick solid black line and the thin solid green line is the amount of TDS that will leave through the overflow, but has not yet left. The thin solid brown line below the thick solid black line show how many grains have already settled, the difference between the two lines is the amount of grains that will settle, but has not yet settled. Finally the thick solid black line at the bottom gives the overflow losses as have already been shown in Figures 13 and 14. The thin red line below this line gives the amount of TDS that have already left the hopper.

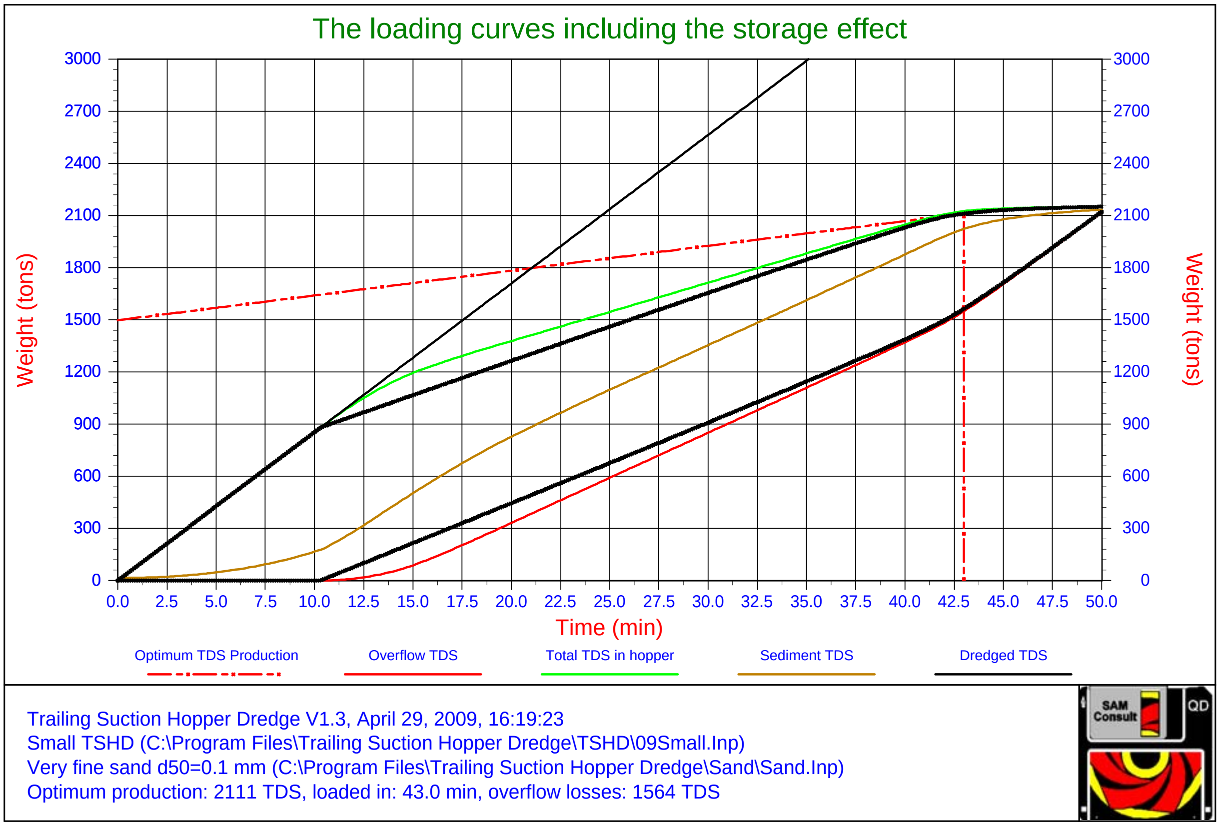
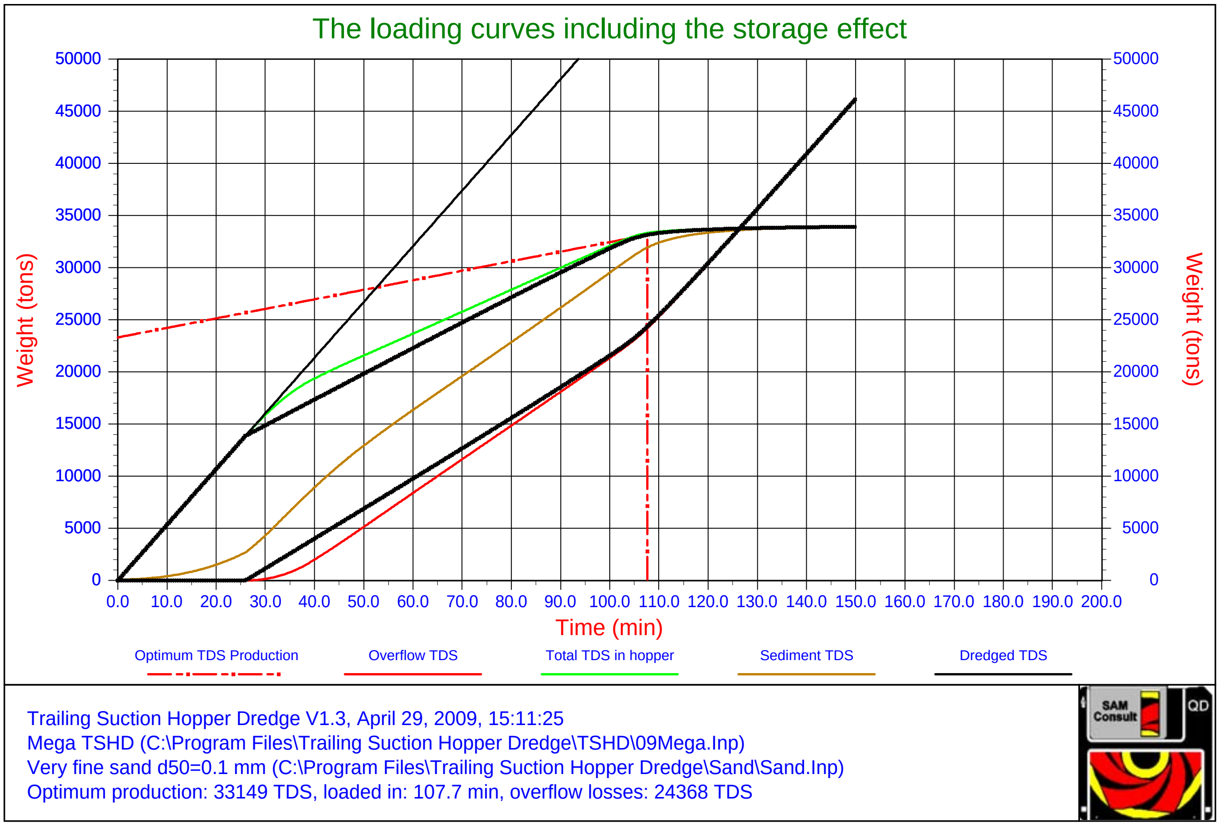


Figure 15. The loading curves including the storage effect for the Small TSHD.

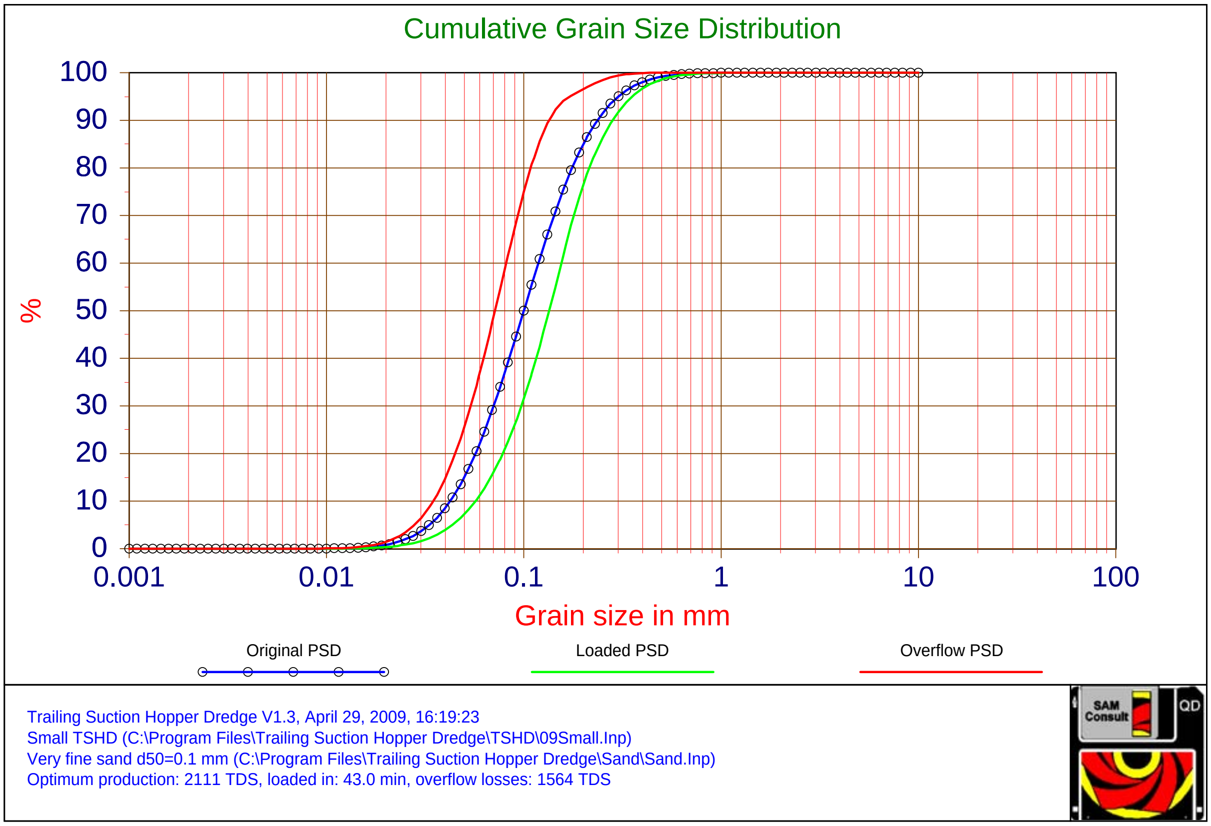


Trailing Suction Hopper Dredge V1.3, April 29, 2009, 15:11:25
Mega TSHD (C:\Program Files\Trailing Suction Hopper Dredge\TSHD\09Mega.Inp)
Very fine sand d50=0.1 mm (C:\Program Files\Trailing Suction Hopper Dredge\Sand\Sand.Inp)
Optimum production: 33149 TDS, loaded in: 107.7 min, overflow losses: 24368 TDS

Figure 16. The loading curves including the storage effect for the Mega TSHD.

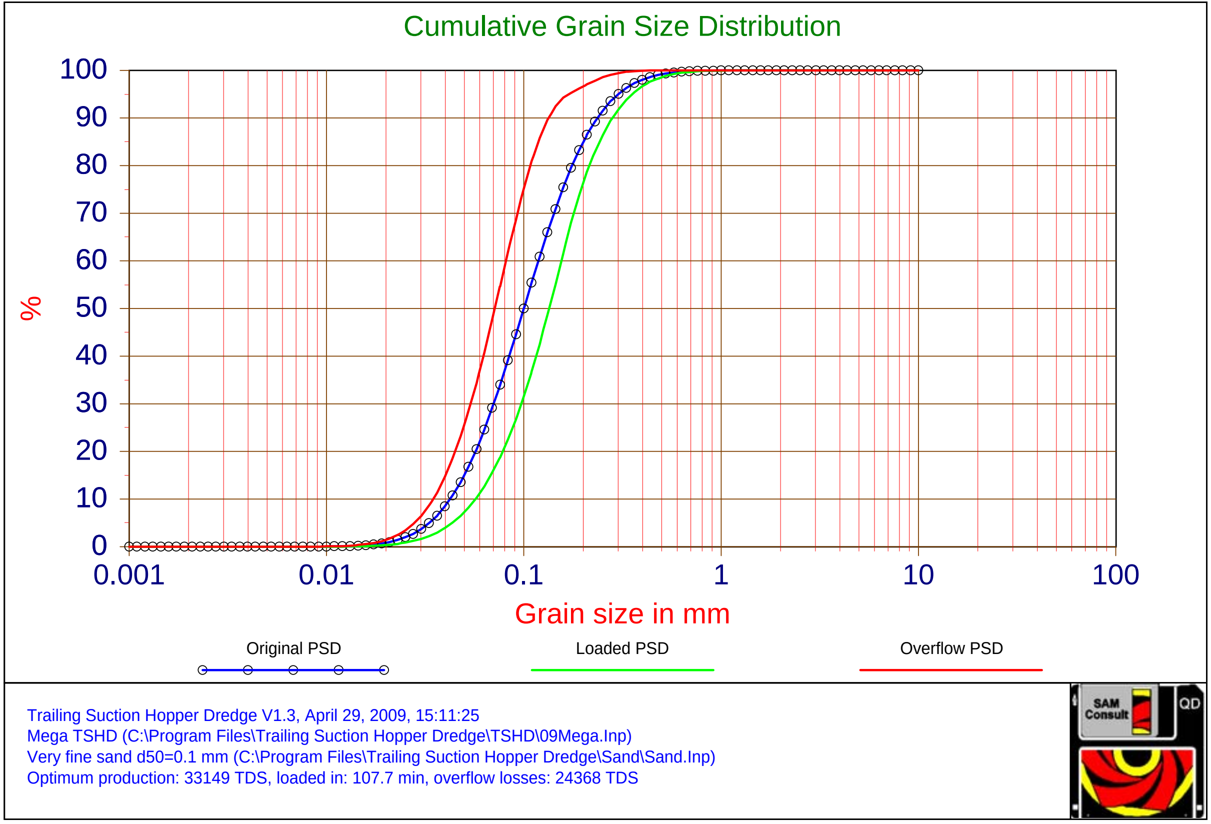
Figures 17 and 18 show the grain distribution curves of the 100 µm for the Small and the Mega TSHD. The original distribution are the lines with the dots. Left from these are the red lines which give the distribution of the grains leaving the overflow, on average from the start of the loading until the optimum loading point. Right from the original distribution is the solid green line, showing the average distribution in the hopper. It can be concluded that the grain distributions are similar for the Small and the Mega TSHD.

Figures 19 and 20 show the influence of the concentration and the amount of water in the hopper at the moment the loading starts, on the cumulative overflow losses and the cumulative efficiency. The dot in both graphs shows the result of the simulation carried out. It is obvious that Figures 19 and 20 show similar graphs. The lines in the graphs are determined by an equation, derived as an attempt to predict the overflow losses with just one equation. The green solid line shows the cumulative overflow losses when the hopper is completely empty at the start of the loading process. The blue line when the hopper is filled with 50% water and the red line when its filled with 100% water. The graph shows the overflow losses as a function of the mixture concentration. These graphs are still experimental, but give good tendencies of the overflow losses.



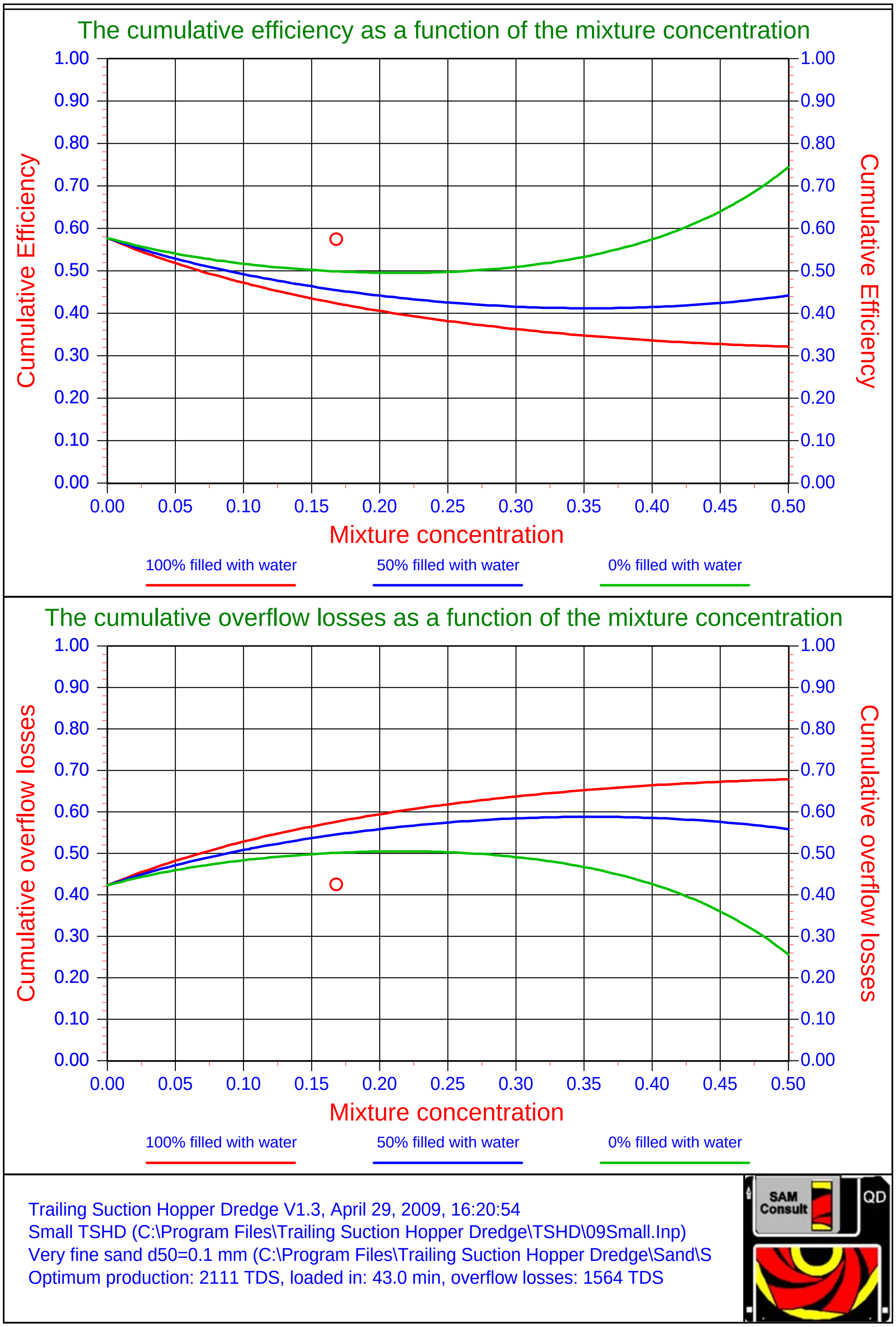
Trailing Suction Hopper Dredge V1.3, April 29, 2009, 16:19:23
Small TSHD (C:\Program Files\Trailing Suction Hopper Dredge\TSHD\09Small.Inp)
Very fine sand d50=0.1 mm (C:\Program Files\Trailing Suction Hopper Dredge\Sand\Sand.Inp)
Optimum production: 2111 TDS, loaded in: 43.0 min, overflow losses: 1564 TDS

Figure 17. The grain distribution curves, original, overflow losses and sediment for the Small TSHD.



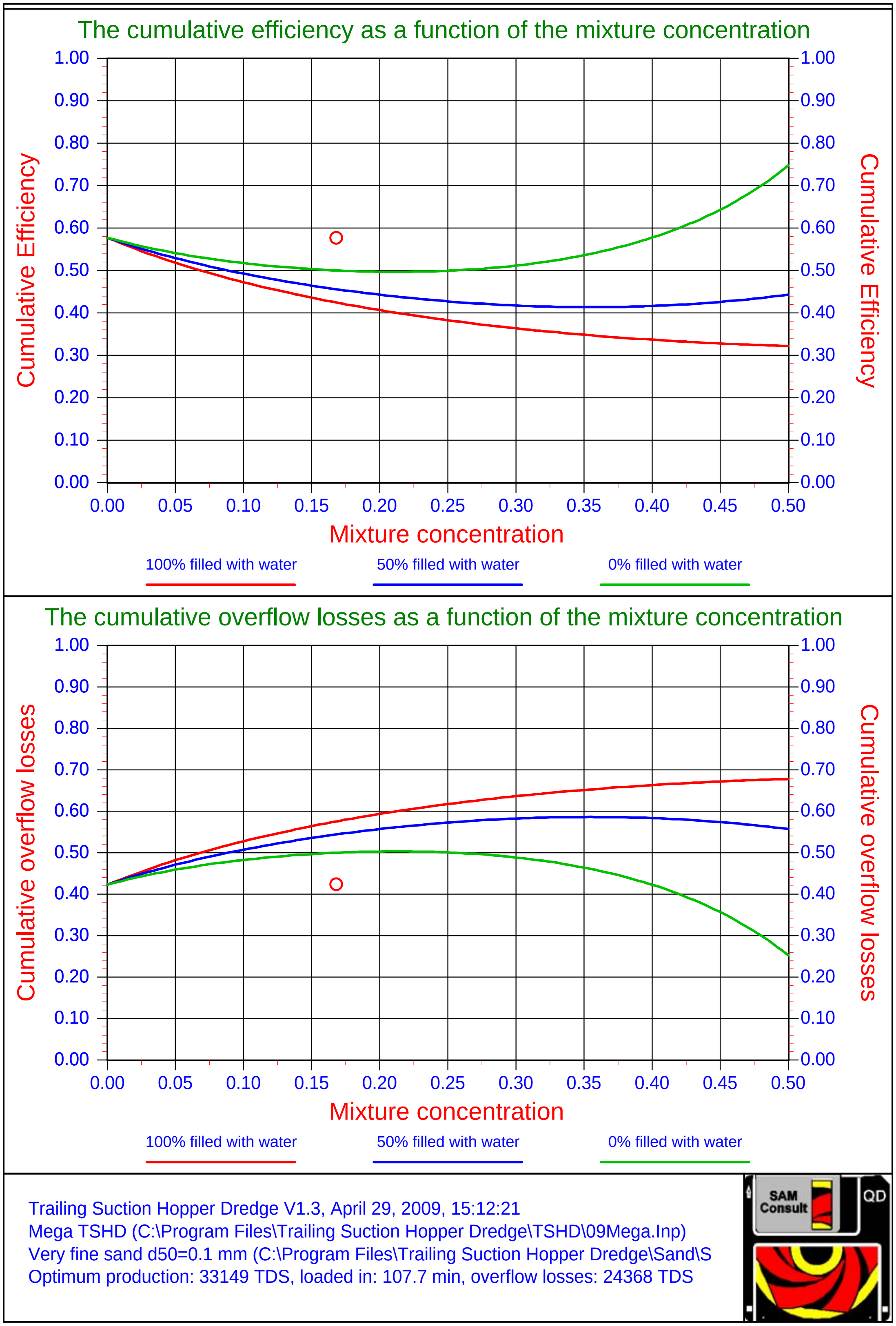
Trailing Suction Hopper Dredge V1.3, April 29, 2009, 15:11:25
Mega TSHD (C:\Program Files\Trailing Suction Hopper Dredge\TSHD\09Mega.Inp)
Very fine sand d50=0.1 mm (C:\Program Files\Trailing Suction Hopper Dredge\Sand\Sand.Inp)
Optimum production: 33149 TDS, loaded in: 107.7 min, overflow losses: 24368 TDS

Figure 18. The grain distribution curves, original, overflow losses and sediment for the Mega TSHD.



Trailing Suction Hopper Dredge V1.3, April 29, 2009, 16:20:54
Small TSHD (C:\Program Files\Trailing Suction Hopper Dredge\TSHD\09Small.Inp)
Very fine sand d50=0.1 mm (C:\Program Files\Trailing Suction Hopper Dredge\Sand\S
Optimum production: 2111 TDS, loaded in: 43.0 min, overflow losses: 1564 TDS

Figure 19. The overflow losses compared with an analytical model for the Small TSHD.



Trailing Suction Hopper Dredge V1.3, April 29, 2009, 15:12:21
Mega TSHD (C:\Program Files\Trailing Suction Hopper Dredge\TSHD\09Mega.Inp)
Very fine sand d50=0.1 mm (C:\Program Files\Trailing Suction Hopper Dredge\Sand\S
Optimum production: 33149 TDS, loaded in: 107.7 min, overflow losses: 24368 TDS

Figure 20. The overflow losses compared with an analytical model for the Mega TSHD.

Table of Contents

DISCUSSION & CONCLUSIONS

The question before this research started, was how do the cumulative overflow losses behave when TSHD's are scaled from small to very big. The second question was, are that scale laws that should be applied when scaling TSHD's in order to create similar or maybe even identical processes.

First the answer on the second question, there are scale laws that should be applied and the main law is, to keep the hopper load parameter constant and from there derive the scale laws for the flow and other dimensions, but don't scale the sand.

If the scale laws are applied correctly, the simulations show that scaling the TSHD has hardly any influence on the cumulative overflow losses and the loading processes are similar.

The overflow losses however depend strongly on the position of the grain diameter match the hopper load parameter in the particle size distribution diagram. The fraction of the sand with diameters smaller than this diameter has a very strong relation with the cumulative overflow losses.

NOMENCLATURE

b	Width of the weir	m
c_b	Near bed concentration	-
c_{bed}	Bed concentration	-
c_{in}	Volume concentration	-
C_d	Coefficient	-
C_D	Drag coefficient	-
d	Grain diameter	m
d_s	Grain diameter (scour)	m
F_w	Submerged weight	kN
g	Gravitational constant (9.81)	m/sec^2
h	is the overfall height (measured about a distance of 5h upstream from the crest)	m
h_{max}	Maximum water layer thickness	m
H	Height of basin	m
H_w	Height above the sediment	m
L	Length of basin	m
M	Height of the weir crest above the headwater bottom	m
n	Porosity	-
ov_{cum}	Cumulative overflow losses	-
p_o	Fraction of grains that settle partially (excluding turbulence)	-
p_s	Fraction of grains that do not settle due to scour	-
p_0	Atmospheric pressure	kPa
$Q_{in, out}$	Mixture flow (in or out)	m^3/sec
R_d	Relative density	%
s_o	Flow velocity in basin	m/sec
s_s	Scour velocity	m/sec
v	Mean velocity in the headwater this is equal to **$Q/b\ (M + h)$**	m/sec
v_c	Settling velocity including hindered settling	m/sec
v_s	Settling velocity	m/sec
v_o	Hopper load parameter	m/sec
v_{sed}	Sedimentation or bed rise velocity	m/sec
W	Width of basin	m
η_g	Settling efficiency individual grain	-
η_b	Settling efficiency for basin	-
η_t	Turbulence settling efficiency for individual grain	-
η_{cum}	Cumulative settling efficiency	-
$\boldsymbol{\tau}$	Time constant	sec

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
ν	Kinematic viscosity	St
θ	Shields parameter	-
μ	Friction coefficient	-

REFERENCES

Camp, T.R. 1936, "Study of rational design of settling tanks". Sen. Works Journal, Sept. 1936, page 742.

Dobbins, W.E. 1944, "Effect Of Turbulence On Sedimentation". ASCE Trans. 19443, page 629.

Camp, T.R. 1946, "Sedimentation and the design of settling tanks". ASCE Trans. 1946, page 895.

Camp, T.R. 1953, "Studies of sedimentation design". Sen. Ind. Wastes, Jan. 1953.

Groot, J.M., 1981, “Rapport Beunbezinking”, Royal Boskalis Westminster (in Dutch).

Huisman, L. 1980, "Theory of settling tanks". Delft University of Technology 1980.

Huisman, L. 1995, "Sedimentation and Flotation". Lecture Notes, Delft University Of Technology 1973-1995.

Groot, J.M. 1981, "Rapport Beunbezinking. Boskalis 1981. (From lecture notes of v/d Schrieck 1995).

Koning, J. de 1977, "Constant Tonnage Loading System of Trailing Suction Hopper Dredge's". Proc. Modern Dredging, The Hague, The Netherlands 1977.

Miedema, S.A. 1981, "The mixture flow and settlement of particles in Trailing Suction Hopper Dredges". Report Sc0/81/103 (in Dutch), Delft University of Technology, 1981.

Miedema, S.A. 1991, "T.S.H.D.". Computer program for the calculation of hopper loading cycles, Delft, 1991.

Miedema, S.A. & Vlasblom, W.J., 1996, “Theory For Hopper Sedimentation”. 29th Annual Texas A&M Dredging Seminar. New Orleans, June 1996.

Miedema, S.A. & Rhee, C. van, (2007), “A sensitivity analysis on the effects of dimensions and geometry of trailing suction hopper dredgers”. WODCON ORLANDO, USA, 2007.

Miedema, S.A., (2008), “An Analytical Approach To The sedimentation Process In Trailing Suction Hopper Dredgers”. Terra Et Aqua, September 2008.

Miedema, S.A., (2008), “An Analytical Method To Determine Scour”. WEDA XXVIII & Texas A&M 39. St. Louis, USA, June 8-11, 2008

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.

Patankar, S. V., 1980, “Numerical Heat Transfer and Fluid Flow”, McGraw-Hill, New York.

Rhee, C. van, 2002a, “On the sedimentation process in a Trailing Suction Hopper Dredger”. PhD thesis, Delft University, 2002.

Rhee, C. van, 2002b, “The influence of the bottom shear stress on the sedimentation of sand”, 11th Int. Symposium on Transport and Sedimentation of Solid Particles, Gent.

Rhee, C. van, 2002c, “Numerical modeling of the flow and settling in a Trailing Suction Hopper Dredge”, 15th Int. Conference on Hydrotransport, Banff, Canada.

Richardson, J.F. & Zaki, W.N., 1954, “Sedimentation and Fluidization: I”, Trans. Inst. Chem. Eng. 32, 35, 1954.

Rodi, W., 1993, ”Turbulence Models and their Application in Hydraulics, A state of the art review”, IAHR, Third Edition.

Stansby, P.K., 1997, “Semi-Implicit Finite Volume Shallow-Water Flow and Solute Transport Solver with k-epsilon Turbulence Model”, Int. Journal for Numerical Methods in Fluids, Vol. 25, pp 285 - 313.

Stelling, G. S., Kester, J. A. Th. M. van, 1994, “On the approximation of Horizontal Gradients in Sigma Co-ordinates for Bathymetry with steep bottom slopes”, ”, Int. Journal for Numerical Methods in Fluids, Vol. 18, pp. 915-935.

Vlasblom, W.J. & Miedema, S.A. 1995, "A theory for determining sedimentation and overflow losses in hoppers". Proc. WODCON XIV, Amsterdam 1995.

Yagi, T., 1970, “Sedimentation effects of soil in hopper”, Proc. WODCON I, 1970.