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OPTIMIZATION OF SAND TRAP AND SETTLER DESIGNS FOR EFFICIENT DEPOSITION OF SUSPENDED SEDIMENT

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Sediment traps are structures designed to allow the suspended sediment load, which enters river abstraction works or diversion canals, to deposit whilst relatively clean water passes through. The deposited sediment is then removed by making use of gravitational flushing. The sediment traps discussed in this paper are settlers and sand traps. The focus in this paper will be on optimizing the design of settlers and sand traps to propose a set of design guidelines for use in South Africa. This is done by investigating existing sediment traps within Southern Africa as well as numerically investigating some of the design properties of settlers and sand traps. A new concept of a sediment trap is also numerically investigated as a possible design.

KEY WORDS: Sand trap, settler, settling velocity, settling length, numerical models, CFD

NOTATION

w	Settling velocity (m/s)
v	Kinematic viscosity (m^2/s)
ρ_s	Density of sediment (kg/m^3)
ρ	Density of water (kg/m^3)
g	Gravitational acceleration (m/s^2)
d	Particle diameter (m)
L	Analytical settling length of a particle (m)
V	Mean flow velocity (m/s)
h	Height at which a particle enters the trap (m)
u^*	Shear velocity (m/s)
R	Hydraulic radius (m)

1. INTRODUCTION

Sand traps and settlers are relatively large structures that require a fair amount of building materials to be constructed, which makes them quite expensive. It is therefore important to design an economically efficient and functional structure to remove sediment and to ensure continuous supply of clean water to prevent pump or hydropower turbine damage.

Currently, there are no specific guidelines to design sand traps or settlers in South Africa and there have been reports that some of the existing sand traps and settlers

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constructed are not working efficiently. The problems may lay in the sediment concentration imbalances between the intake and outlet due to inadequate lengths, flushing ability, overall structural design or inefficient maintenance.

This paper investigates existing sediment traps in Southern Africa, as case studies, by collecting design and field measurements for analysing sediment transport within the traps. This is done in order to understand the problems (if any) and the performance of the designed sediment trap structures. Some of the properties of existing settlers and sand traps are numerically investigated by making use of ANSYS Fluent v18.1. The properties include the overall structural design such as the dimensions, slope, cross-section and type of inlet as well as the concentration intake.

A new concept of a settling basin developed at the Norwegian University of Science and Technology by Støle (1997), is then numerically investigated. This concept is expected to be more appropriate in projects where existing sediment exclusion facilities are inefficient.

2. SEDIMENT SETTLING THEORY AND SEDIMENT TRAP DESIGNS

The use of settlers or sand traps prevents damage to pumps used in high lift pump stations, hydropower turbines and sediment deposition in water conveyance systems. The finer the sediment that can be trapped in a sediment trap, the less need there will be for water treatment plants that uses flocculation methods to rid the water of fine sediment for potable use. The trapped sediment within is flushed back to the river and therefore helps in restoring a sediment mass balance within the river. Sediment that is abstracted at water treatment plants cannot be reintroduced to the river as it contains toxic chemicals that can affect aquatic life. The most important sediment properties regarding the design of settlers and sand traps are the settling velocity and the settling length of a sediment particle.

2.1 SETTLING VELOCITIES OF SEDIMENT PARTICLES

Settling velocity is one of the main variables in the study of sediment transport for understanding sediment suspension and deposition. Particle settling velocity is the speed at which a particle will settle to the bottom of a body of water. Van Rijn (1989) recommended to calculate the settling velocity of different sediment particles based on their diameter size. The sediment velocities for each particle used in the numerical simulations was calculated by making use of the following equations.

$$w = \frac{v}{18}\left(\frac{\rho_s}{\rho} - 1\right) g d^2 \qquad \text{for } d \leq 0.1 \text{ mm}$$

$$w = 10\,\frac{v}{d}\left[\left(1 + 0.01\left(\frac{\rho_s}{\rho} - 1\right)\frac{g d^3}{v^2}\right)^{0.5} - 1\right] \qquad \text{for } 0.1 < d < 1.0 \text{ mm}$$

$$w = 1.1\left(\left(\frac{\rho_s}{\rho} - 1\right) g d\right)^{0.5} \qquad \text{for } d \geq 1.0 \text{ mm}$$

2.2 ANALYTICAL SETTLING LENGTH

The actual settling length of a specific sediment particle within a trap depends on the height at which the particle enters and the flow velocity. In designing a sediment trap, one must consider how long the trap must be to deposit all sediment down to a desired size. Bouvard (1992) recommends using the following empirical formulas to determine the length of the sediment trap. It is recommended that the length of the sediment trap is extended by 10 to 20% in order to compensate for the excessive turbulence within the transition zone at the inlet of the trap.

$$L = V\,x\,\frac{h}{w-u^*} \qquad \text{with} \qquad u^* = \frac{4.2V}{100}\,x\,\frac{1}{R^{1/6}}$$

2.3 SETTLER AND SAND TRAP DESIGN

A sediment trap is primarily designed according to the maximum size (d_{max}) of the sediment it needs to convey and the minimum diameter (d_o) of the sediment that has to be removed. Attention is centred on the minimum sediment diameter and the velocity (V_{d_o}) required for deposition, as well as the minimum length required for the deposition of the sediment.

Settlers are designed for a low discharge and flow velocity (0.1 to 0.2 m/s) to be able to settle sediment particles larger than 0.3 mm if they have sufficient length. A settler is flushed periodically and the particle size that can be removed is based on its slope. Sand traps can handle a high discharge and therefore higher flow velocities (0.2 - 0.5 m/s) which makes it difficult for these traps to deposit particles smaller than 0.3 mm. Sand traps are flushed continuously at the outlet or distributed sediment scour holes. Optimisation of the geometry of the cross-section of a canal is an important factor to consider in reducing the costs of excavation and lining. A rectangular cross-section has the best hydraulic efficiency if its water depth is half of the channel width. A trapezoidal cross-section is most economical when the top width is double the length of one sloping side. Figure 1 shows the cross-sectional specifications for the efficient design of a rectangular or trapezoidal channel. These specifications were used to design the cross-sections of the rectangular and trapezoidal settler models which is then numerically tested.

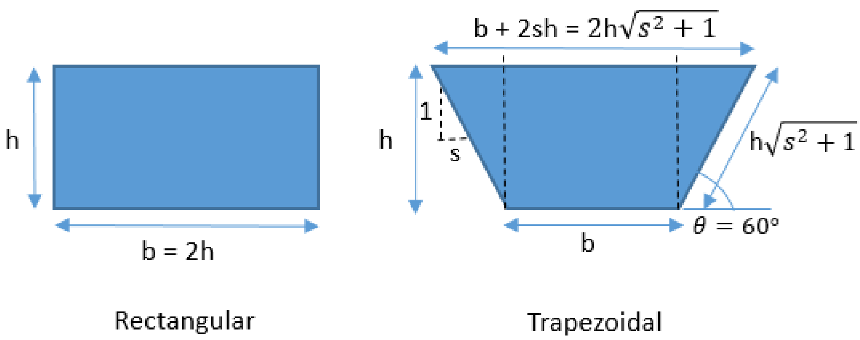

Figure 1. Cross-sectional specifications for most efficient cross-sections

The slope of the settler is designed according to the maximum size of sediment to be settled out and flushed and to help with the deposition of fine sediment. Basson (2015) suggested that the slope of a typical settler should be between 2 – 3%. There are no specific guidelines for the inlet conditions of sediment traps, only that when designing one should minimize the turbulence and velocity at the inlet transition zone.

3. CASE STUDIES: TIENFONTEIN SETTLER AND LUSIP SAND TRAP

The Tienfontein settler is located near the Caledon River in the Free State Province of South Africa. It has a length of 92 m, a width of 2.5 m and has been constructed with a slope of 0.9% to allow for sediment deposition and flushing. The settler consists of three operational canals and one standby canal which are all constructed in parallel. The flow through each canal is 0.6 m^3/s. The main objective of the Tienfontein settler is to remove sediment coarser than 0.3 mm. Field measurements have shown that the settler effectively settles sediment coarser than 0.14 mm due to its sufficient length.

The Lower uSuthu Smallholder irrigation plant (LUSIP) sand trap is located near the uSuthu River in eSwatini. It has a length of 70 m and a width of 8 m. Its effective settling length is only 35 m due to turbulence caused by the upstream Avio gate. The sand trap has an inlet discharge of 15.5 m^3/s and a distributed scour discharge amounting to 2 m^3/s. The main objective of the LUSIP sand trap is to remove sediment coarser than 1 mm. The LUSIP sand trap has reportedly not been functioning correctly. According to field measurements done, sediment coarser than 1 mm escapes the trap and debris entering the trap causes blockage of the scour holes. This means that both the sand trap and feeder canal require regular manual cleaning.

The proposed solutions to this problem are to reduce the turbulence downstream of the gate by installing baffle plates. This will increase the effective settling length. Another solution is to construct another sand trap in parallel to reduce the flow and velocity within the trap or to insert fine screens upstream of the sand trap to prevent debris from entering and blocking the scour holes. Figure 2 below shows the LUSIP sand trap on the left and the Tienfontein settler on the right.

Figure 2. The LUSIP sand trap (LHS) and the Tienfontein settler (RHS)

4. NUMERICAL INVESTIGATION OF DESIGN PROPERTIES

Fully three-dimensional numerical models coupled in terms of flow field and sediment transport are investigated by making use of ANSYS FLUENT v18.1. This Computational Fluid Dynamics (CFD) package is equipped with a special feature named User Defined Function (UDF) which allows the user to input their own functions in the simulations. The concentration and settling velocities of different particle sizes was introduced to the model by making use of the UDF and customised code. The numerical model validation is discussed in Sawadogo (2015).

4.1 DESIGN PARAMETERS TESTED

The two basic settler models are tested; the first one has a rectangular cross-section and the second one has a trapezoidal cross-section. Both models are 100 m in length and does not have a longitudinal slope. Both these models are used to investigate the length required to settle sediment diameters of 0.1, 0.2 and 0.3 mm with a settling velocity of 0.09, 0.026 and 0.044 m/s respectively.

For each sediment particle a simulation was carried out with the following varying parameters: a sediment concentration (c) inlet of 1 and 10 kg/m^3, heights of concentration entering at the full depth and through the top third of the canal, and for inlet flow velocities (v) of 0.1 and 0.2 m/s.

The effect of a 3% positive and 3% negative slope was then tested on both models again with the sediment concentrations and inlet velocities varying, but a particle size of 0.1 mm and the height of concentration entering at full depth remained constant. The numerical simulation results of the settling lengths were then compared to analytical calculated settling lengths by making use of the equation mentioned in Section 2.2.

4.2 RESULTS OBTAINED

The analytical settling lengths were calculated by making use of the equations given to calculate the settling velocities of sediment particles of a certain diameter for a velocity of 0.1 m/s and 0.2 m/s and a constant inlet height and hydraulic radius at both rectangular and trapezoidal cross-sections.

The mesh used in the numerical model simulations are made out of tetrahedrons with a maximum size of 0.2 m. The quality of the mesh is 0.8, which is very good. The velocity was specified as an inlet condition and the concentration and settling velocity was introduced to the model by making use of the UDF and code. The settling length was determined after each simulation by looking at the concentration profiles taken in the middle throughout the length of the settler. The particles settle out when the concentration profile becomes constant, defining the settling length of the particle. The following tables (Table 1 to Table 3) provide the numerical settling length results obtained from each simulation.

Table 1

Rectangular settler model without a slope - Numerical simulated settling lengths

			V = 0.1 m/s			V = 0.2 m/s		
Inlet height	**Sediment diam.**	**(mm)**	**0.1**	**0.2**	**0.3**	**0.1**	**0.2**	**0.3**
	Settling velocity	**(m/s)**	**0.009**	**0.026**	**0.044**	**0.009**	**0.026**	**0.044**
	Analytical set. L	(m)	23.4	4.8	2.6	459.0	12.0	6.0
Whole_depth	c = 1 kg/m^3	(m)	25	9	5	*90	20	11
	c = 10 kg/m^3	(m)	25	9	5	*90	20	11
Top_only	c = 1 kg/m^3	(m)	25	9	5	*90	20	10
	c = 10 kg/m^3	(m)	25	9	5	*90	20	10

Note: * does not settle 100% effectively, there is still some sediment in suspension

Table 2

Trapezoidal settler model without a slope - Numerical simulated settling lengths

			V = 0.1 m/s			V = 0.2 m/s		
Inlet height	**Sediment diam.**	**(mm)**	**0.1**	**0.2**	**0.3**	**0.1**	**0.2**	**0.3**
	Settling velocity	**(m/s)**	**0.009**	**0.026**	**0.044**	**0.009**	**0.026**	**0.044**
	Analytical set. L	(m)	23.4	4.8	2.6	459.0	12.0	6.0
Whole_depth	c = 1 kg/m^3	(m)	25	9	5	*90	20	10
	c = 10 kg/m^3	(m)	25	9	5	*90	20	10
Top_only	c = 1 kg/m^3	(m)	25	9	5	*90	20	10
	c = 10 kg/m^3	(m)	25	10	5	*90	20	11

From the results in Table 1 and Table 2, it is evident that the concentration inlet quantity (1 and 10 kg/m^3) and inlet position (whole depth and top only) does not affect the settling lengths for the different particles. The numerical settling lengths for both rectangular and trapezoidal models are exactly the same, meaning that the cross-section does not play a role in the numerical settling lengths of the particles. The analytical settling lengths underestimates the numerical lengths by almost 50% for both the rectangular and trapezoidal models. It is found that the settling length increases with approximately 100% with an increase in velocity from 0.1 m/s to 0.2 m/s. It is evident that a flow velocity of 0.2 m/s cannot effectively deposit a sediment particle of 0.1 mm. The critical velocity for a 0.1 m particle is 0.1 m/s.

Table 3

Rectangular and Trapezoidal settler model with a slope - Numerical model simulated settling lengths

			Rectangular	Trapezoidal
Inlet velocity **Inlet height**	**Sediment diam.**	**(mm)**	**0.1**	**0.1**
	Settling velocity	**(m/s)**	**0.009**	**0.009**
V = 0.1 m/s **Whole_depth**	No slope	(m)	25	25
	+3% slope	(m)	15	15
	-3% slope	(m)	-	-
V = 0.2 m/s **Whole_depth**	No slope	(m)	*80	*90
	+3% slope	(m)	50	50
	-3% slope	(m)	-	-

Note: * does not settle 100% effectively, there are still some sediment in suspension
- does not settle, particles escape settler

From the results in Table 3 it is seen that, for an inlet velocity of 0.1 m/s and 0.2 m/s, a slope of +3% shortens the settling length of the 0.1 mm particle whereas for a slope of -3%, the particles escape the settler through the outlet and does not settle at all. This is due to fact that for a positively sloped settler, the cross-sectional area will increase going downstream of the inlet, which will in turn cause the velocity to decrease and therefore the particle will deposit over a shorter length. For a settler with a negative slope, the cross-section will decrease, which will cause an increase in velocity. The velocity is higher than the critical velocity of the sediment particle, which means it will be carried in suspension and not deposit within the trap. It is therefore recommended to have a positively sloped settler of +3%, to shorten the settling lengths of 0.1 mm particles and to effectively deposit within the settler.

5. NUMERICAL INVESTIGATION OF A NEW SEDIMENT TRAP

A new concept has been developed at the Norwegian University of Science and Technology (NTNU), by Dr. Støle in 1997. This concept is known as the “split and settle” concept which directly refers to dividing the flow in a sand trap into sediment-free and sediment-laden water and then removing the sediment from the water. As sediment-laden water flows within a channel, the suspended sediment concentration increases near the bottom. The split and settle concept then take advantage of the variation in sediment concentration over the depth of flow by dividing the flow into an upper and lower part. Figure 3 shows a side view illustration of the split and settle concept shaped by Støle.

Instead of settling all the specific suspended sediment in one operation, the flow is divided into two or more channels and the same process is repeated until the water is of satisfactory quality (Støle, 1993). The concept is said to be used for both pressurised and gravitational flow conditions.

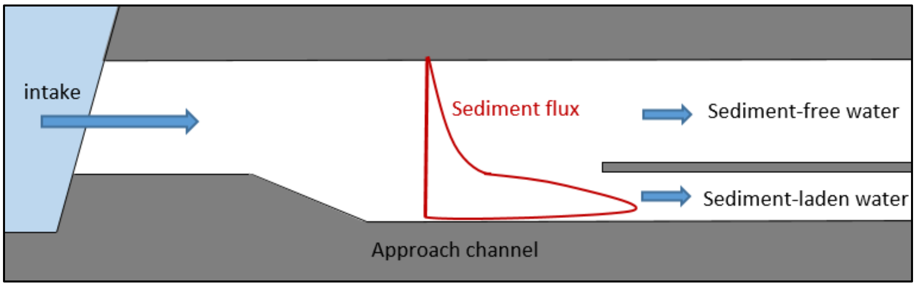

Figure 3. Side view illustration of the split and settle concept (Adapted from: (Støle, 1993))

5.1 SET-UP OF NUMERICAL MODEL

The numerical settling length obtained from the previous rectangular model CFD simulations showed that the settling length of a particle with a diameter of 0.1 mm is approximately 25 m. Therefore, the split and settle model was estimated to be 30 m long with a split at 25 m. The split plate is situated 450 mm from the bottom and is 50 mm thick. A velocity of 0.1 m/s was set at the inlet of the model which results in an inlet discharge of 0.2 m^3/s. The inlet concentration of sediment particles of size 0.1 mm was set at 1 kg/m^3.

5.2 RESULTS OF NUMERICAL MODEL

The velocity vectors seen from the side of the canal and the velocity profiles throughout the length of the model can be seen in Figure 4. The velocity magnitude vectors in the model shows that it is constant at approximately 0.1 m/s throughout the length of the canal and decreases underneath the split and increases at the top of the split. The decreased velocities underneath the split is advantageous for the quicker deposition of sediment particles.

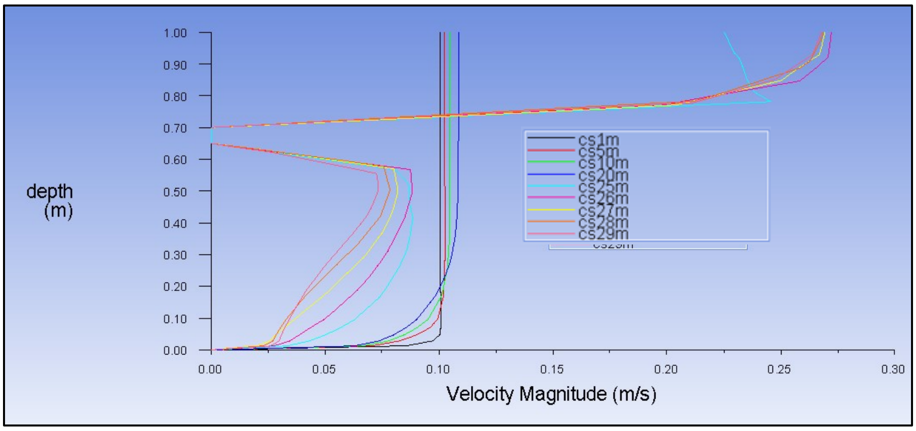

Figure 4. Velocity profiles over depth along the length of the model

The suspended sediment concentration map seen from the top of the canal and concentration profiles over depth along the length of the model can be seen in Figure 5 and Figure 6 respectively. From the concentration profiles along the depth of the canal it is evident that sediment particles continue to deposit underneath the split and no sediment concentration is observed above the split. From these results, it seems that the new model is working as it should, but more numerical and physical model tests are recommended to see how effective the design is and if it can be optimized.

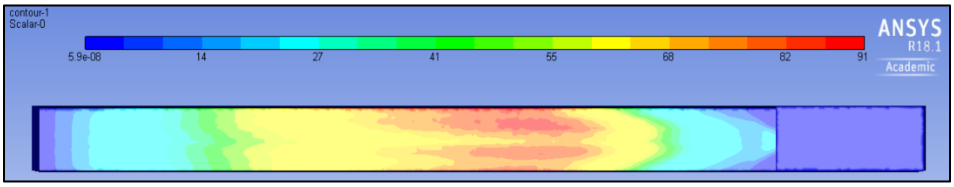

Figure 5. Concentration map seen from the top of the canal (kg/m^3)

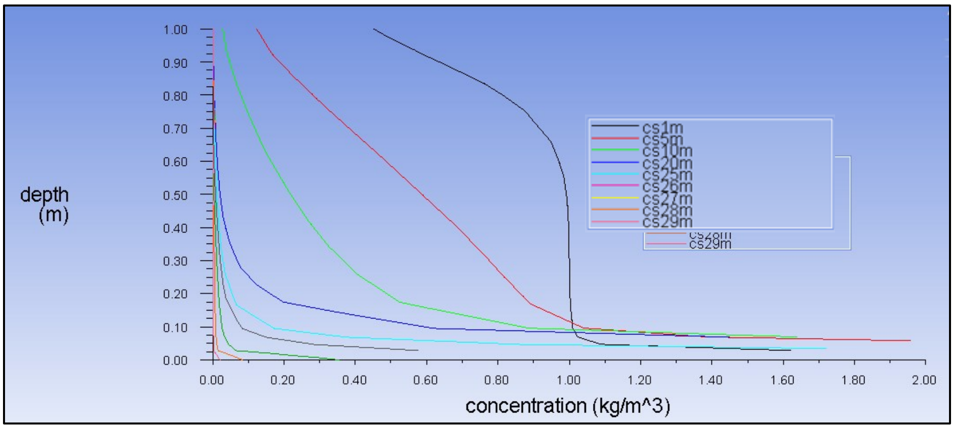

Figure 6. Concentration profiles over depth along the length of the model

6. CONCLUSIONS

From the numerical investigation of the design properties it was found that the numerical settling lengths for both rectangular and trapezoidal models for the same flow velocities are exactly the same, meaning that the cross-section does not play a role in the numerical settling lengths of the particles. The analytical settling lengths underestimates the numerical lengths by almost 50% for both the rectangular and trapezoidal models. The analytical settling length does not take the transition zone at the inlet into account. It is found that the settling length increases with approximately 50% with an increase in velocity from 0.1 m/s to 0.2 m/s. It is evident that a flow velocity of 0.2 m/s cannot effectively deposit a sediment particle of 0.1 mm, but a settler with a +3% slope can deposit the particle. This coincides with the case study results for the Tienfontein settler where field measurements have shown that it effectively settles sediment coarser than 0.14 mm due to its sufficient length and +0.9% slope. The new split and settle model seems to be working as it should, but more numerical and physical model tests are recommended to see how effective the design is. Although the length of the trap is shortened which makes construction more economical, one should also consider the amount of water used for continuous flushing of sediment in the model and if it is feasible.

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