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A Method for measuring sludge settling characteristics in turbulent flows

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Abstract

A method for the determination of the settling velocity for sludge as a function of turbulence intensity and sludge concentration has been developed. The principle of the method is a settling column with a small net flow to obtain a steady state and uniform condition. An oscillating grid controls the level of turbulence. Settling characteristics measured this way can be utilized in fully distributed numerical models of sedimentation tanks, process tanks etc.

Introduction

In the field of activated sludge the settling velocity is often measured in the a batch test where the velocity of the sludge interface is measured directly (Smollen , M and Ekama, G. A, 1984). The test is performed with varying initial concentrations. Another frequently applied method is to photograph a few sludge flocs in stroboscopic light as they settles in a glass column. (Li, D. H. and Ganczarczyk, J. J. ,1987). In the area of sediment transport studies in natural waters the Owen tube principle (Owen, M. W.,1970) is the method which is used most often to determine the settling velocity. The experiment is a batch test too, where the concentration is measured in a fixed point in the column as a function of time.

A considerable effort has been used to relate settling characteristics with integral parameters like Sludge Volume Index (SVI), Stirred Sludge Volume Index (SSVI) or Diluted Sludge Volume Index (DSVI). The shortcomings of SVI have been pointed out early by e.g. Vesilin (Vesilin A. P., 1967): SVI is a problematic parameter to use for characterizing settling properties in general and should only be used for day-today comparisons. In respect of numerical modelling, the major objection one could make against e.g. SVI is that the index contains the combination of free settling, hindered settling and compression whereas the numerical modelling seeks to describe these characteristics separately.

The design of process tanks and secondary settling tanks has up to now been based on empirical relations between tank geometry and average physical sludge characteristics. Recently fully distributed numerical models have proved their applicability for design and optimization of secondary settling tanks (Dahl C., 1995). One of the advantages of the use of distributed numerical models is their capability of modelling varying geometry of the tanks. In such general numerical models the governing processes have to be formulated locally. The presented method determines the local varying settling velocity of sludge to be applied in numerical models.

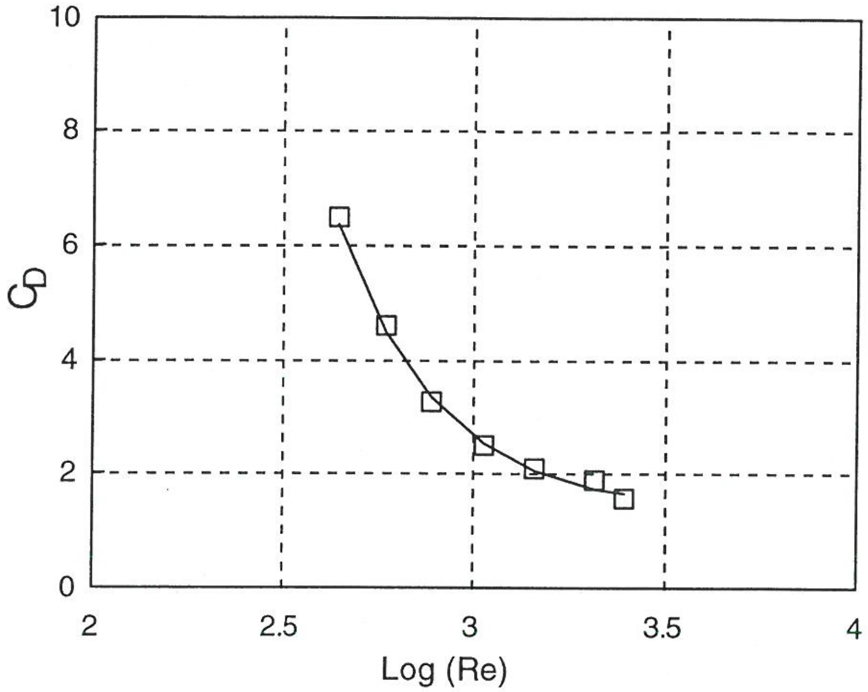

Fig 4 Measured C_D variations in oscillating flow ($\mathrm{Re} = \frac{u_{max} D}{\nu}$).

As the dissipatation is defined as the work *W* done on the water per mass, the dissipation for the oscillating grid can now be found to

$$\varepsilon = \frac{1}{T}\int_0^T \frac{W}{V\rho} dt = \frac{1}{V\rho}\frac{1}{T}\int_0^T F|u| dt \tag{9}$$

Assuming that the grid-velocity is described as a cosinus function, the integral is reduced to

$$\varepsilon = \left(\frac{\frac{1}{2} C_D k A_{grid}}{V}\right)\left(\frac{a2\pi}{T}\right)^3 \overbrace{\frac{1}{T}\int_0^T \mathrm{Cos}^2\left(\frac{2\pi}{T}t\right)\left|\mathrm{Cos}\left(\frac{2\pi}{T}t\right)\right| dt}^{2\alpha = 0.424} \tag{10}$$

where *k* is the number of grids in the column, *V* is the volume of the tank and *a* is the stroke. The last part of the equation is an integral independent of the grid and the length of stroke. This part is therefore a constant: $2\alpha = 0.424$.

The velocity gradient G can be found by combining equation (3) and (10):

$$G = \sqrt{\left(\frac{\alpha C_D k A_{grid}}{\nu V}\right)\left(\frac{2\pi a}{T}\right)^3} \tag{11}$$

Experimental results

Sludge from activated sludge treatment plants were chosen: A chemical industrial treatment plant and a municipal treatment plant. The sludge from the two plants was quit different in both composition and concentrations.

For oscillating flows the inline force *F(t)* on a grid rod can be found from Morisons equation (Morison, J. R et al., 1950):

$$F(t) = C_D \frac{1}{2} \rho u(t)|u(t)|\, D + C_M \rho \frac{\pi D^2}{4} \frac{du(t)}{dt} \tag{7}$$

where C_M is the inertia coefficient, which can be assumed constant in time. The inertia term does not contribute to the production of turbulence. A Fourier averaging technique can be used to extract the time averaged drag coefficient. By inserting $u = u_{max} \mathrm{Cos}(\theta)$ and the measured force into equation (7) and multiplying with $\mathrm{Cos}(\theta)$ as well as integrating over one period yields:

$$C_D = -\frac{3}{4} \int_0^{2\pi} \frac{F(\theta)\mathrm{Cos}(\theta)}{\rho D u_{max}^2} d\theta \tag{8}$$

To determine the C_D coefficient the in line force and the maximum velocity have to be known. This is done by measuring the force on the grids directly in the settling column and timing one cycle. An aluminium bar is inserted into a system mounted with strain gauges which measure the force as the grid moves up and downwards, see figure 3. The measurements of the force are synchronized with the grid movement so that the position and the velocity of the grid is known at all times.

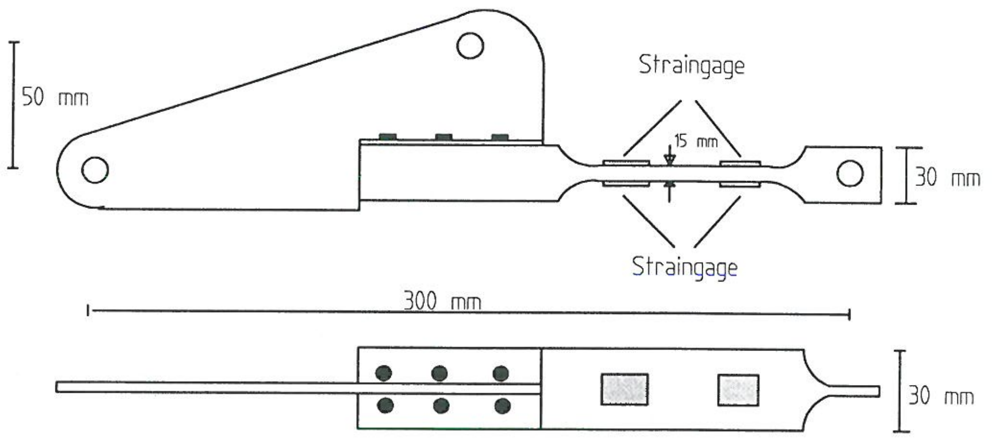

Fig. 3 Setup of top triangle for force measurements (see Fig. 1)

The measurements in combination with equation (8) figure 4:

investigated. The viscosity was kept constant by keeping the temperature constant - equal to the temperature in the treatment plant.

The turbulence generated by a grid moved through air or water has historically been one of the fundamental experiments in the understanding of turbulence (Batchelor G.K, 1959). Laser Dobler Anometry experiments (Casson, L. W. and Lawler, D. F., 1990) with oscillating grids have shown that except for some less important large scale eddies (determined by the scale for the column and the length of stroke) the turbulent power spectrum of the velocity fluctuations is distributed according to the so-called turbulent energy cascade. This ensures that the experiment is independent of the geometry of the tank and the grids. Furthermore, an oscillating grid in a column is known to give a well defined turbulence also at relatively low Reynolds numbers (Thomson, S. M. and Turner, J. S., 1975, Hopfinger, E. J. and Toly J.-A., 1976, Casson, L. W. and Lawler, D. F., 1990, Matsunaga, N. et al., 1991) .

The oscillating movement of the grid creates areas of wakes around the grid bars. In these wakes the turbulence is non-isotropic and inhomogeneous. However, experiments performed by (Hopfinger, E. J. and Toly J.-A., 1976) demonstrate that grid generated turbulence rapidly becomes isotropic close to the grid (1.5 x mesh size). Consequently, the turbulence in the experiment setup can be expected to be isotropic for most of the cross section. The experiments of (Thomson, S. M. and Turner, J. S., 1975, Hopfinger, E. J. and Toly J.-A., 1976, Casson, L. W. and Lawler, D. F., 1990) use a grid with a very fine mesh (few mm) which should ensure a more homogeneous turbulence, but Matsunaga (Matsunaga, N. et al., 1991) demonstrated that the principle can be applied for grids with a larger grid size as well.

Measurement of the Dissipation

The dissipation of kinetic energy in the water in the column is equivalent to the work done by the grid per unit time when the system is in steady state. The dissipation rate ε averaged over one cycle with the period *T* can therefore be found as:

$$\varepsilon = \frac{1}{T}\int_0^T \frac{F_D u}{V\rho} dt \qquad (4)$$

were F_D is the dragforce, u is the grid velocity and V is the volume .

In steady state flow (not this situation) the dragforce is given by

$$F_D = C_D \frac{1}{2} \rho u^2 D \qquad (5)$$

where C_D is an empirical drag coefficient, ρ is the fluid density, *u* is the flow velocity and *D* is the rod diameter. The drag coefficient varies with the Reynolds number and cross section geometry. It has been recognized that the drag coefficient for steady state turbulent flow and for oscillating flow, respectively, differs considerably. Accordingly a precise determination of the dissipation necessitates a precise understanding of the C_D. In an oscillation flow, the wake will change from one side to another creating an area of higher turbulence around the bar. This kind of flow is classified by the Keulegan-Carpenter number *K* (Keulegan, G. H. and Carpenter, L. H., 1958):

$$K = \frac{u_{max} T}{D} \qquad (6)$$

where *D* is the diameter of the cylinder and u_{max} is the velocity amplitude. *K* can also be understood as the dimensionless amplitude in the oscillation compared with the diameter of the cylinder.

The grid in the settling column has a length of stroke of 10 cm and a cylinder diameter of 1 cm which gives a K number of 28. For $K < 1$-5,(Sarpkaya T, and Isaacson M., 1981) the flow around the bar can be described by potential theory and the force can be calculated theoretically. For $K > 20$ -50 the flow becomes quasi-stationary and C_D can be found from steady state conditions. In the intermediate region $1\text{-}5 < K < 20\text{-}50$ C_D can only be found experimentally.

turbulence and concentration (Fig. 2).

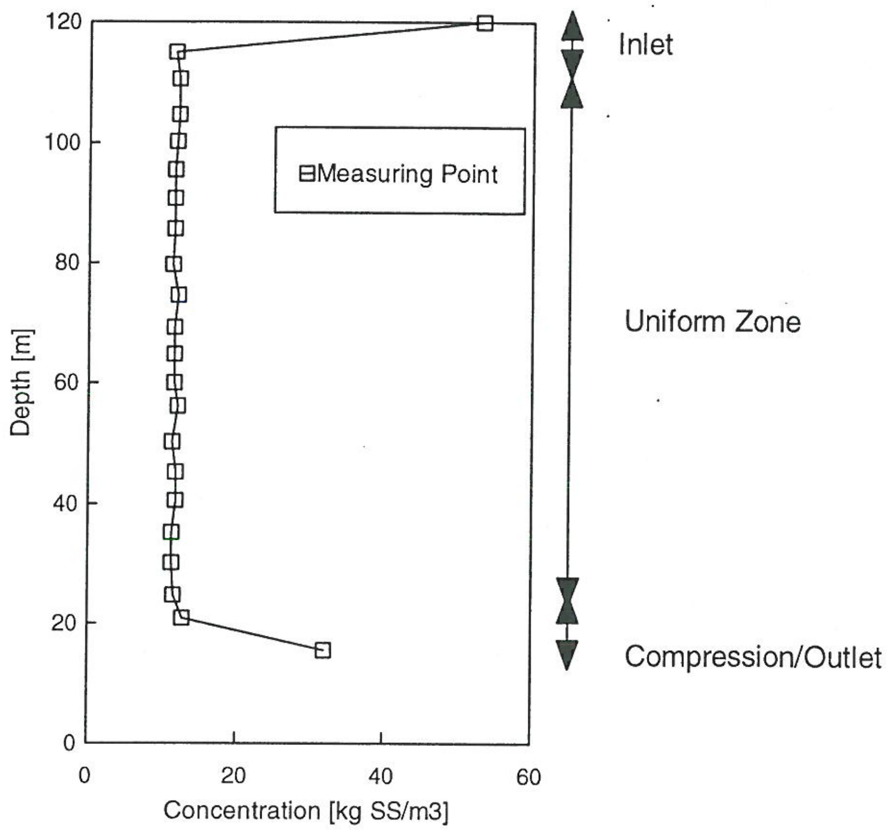

Fig. 2 Example of measured concentration profile in settling column

The oscillating grid induces vertical mixing to some extent, but the effect of the dispersive transport is eliminated because of the zero gradient in the uniform zone. The steady state and uniform conditions are essential for the calculation of settling velocity. Assuming constant sludge flux through the inlet cross-section and the measuring cross-section the mass conservation is reduced to:

$$W_s C_{inlet} = (W_0 + W_s) C_{eq} \tag{1}$$

or

$$W_s = \frac{W_0 (C_{inlet} - C_{eq})}{C_{eq}} \tag{2}$$

where W_s is the unknown settling velocity, W_o is the mean flow velocity due to pumping, C_{inlet} is the inlet concentration and C_{eq} is the average concentration in the middle of the column.

The Turbulent Velocity Gradient G

The characterization of the turbulence intensity by the turbulent velocity gradient G was introduced by Camp, T. R. and Stein, P. C., 1943:

$$G = \sqrt{\frac{\varepsilon}{\nu}} \tag{3}$$

where ε is the turbulent dissipation and ν is kinematic viscosity.

The relevance of characterizing the turbulence level by G has been discussed in literature (e.g. Cleasby, J. L. ,1984) and it still seems an open question whether G alone covers the effect of turbulence in respect of flocculation and disintegration of particles. In this study only the effect of the dissipation was

Instrumentation

The developed settling column is a 1.2 m high glass column with a width and depth of 0.30 m. The column is equipped with 12 grids which can be moved sinusoidal up and down in the fluid. The grids are spaced at an interval of 10 cm - equaling the length of stroke. Each grid consists of 6 PVC rods with a diameter of 1 cm.

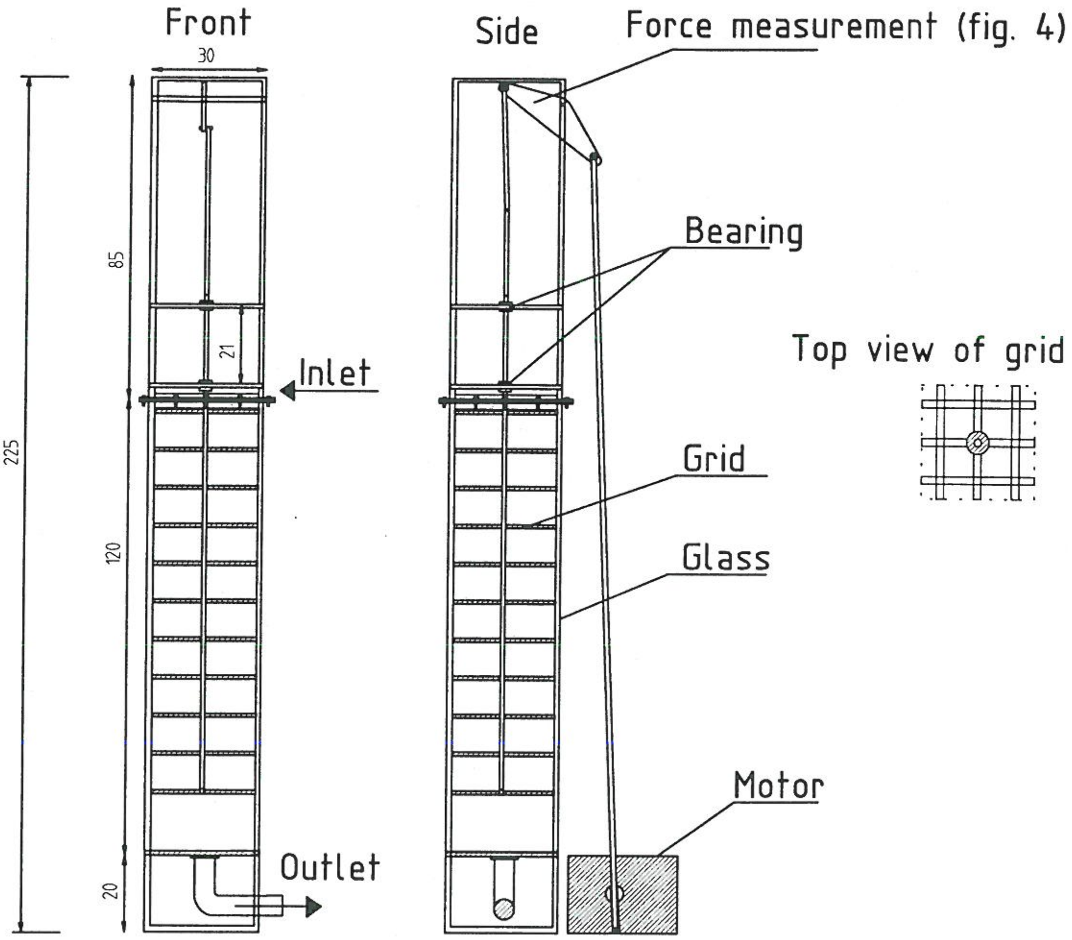

Fig. 1 The settling column (all figures in cm)

A pump conduct the suspended sludge continuously into the top of the column, where a diffuser distributes the suspension evenly across the cross section. At the bottom of the column is an outlet where the sludge is removed continuously. The sludge concentration is measured by an OSLIM light transmission type sensor (Delft Hydraulics, 1991). The sludge is pumped into the sensor from a sample tube which can be moved up and down in the column. The inlet concentration is measured in the inlet pipe just upstream the column by the same sensor.

Experimental principle

The idea behind the settling column is to establish a steady state one-dimensional settling which is also uniform (spatially constant) in the central part of the column. This is obtained by pumping a small downward through flow. The sludge is disintegrated in the diffuser before entering the column, which ensures a constant inlet boundary. As the sludge moves downwards in a combination of settling and convective transport it flocculates into large particles, which normally settle faster than the particles at the top. A uniform concentration is reached at a short distance below the inlet point depending on through flow, *Chemical industry*

The plant is treating the effluent from a large chemical plant producing - among other things - insecticides for the agriculture. The insecticides are in low concentrations biodegradable by specially selected microorganisms. The temperature is kept approximately at 34° C for optimal treatment. The mean hydraulic retention time is in dry conditions 7 -10 days, whereas the sludge age is approximately 19 days. The sludge is inorganic, it has a high content of inorganic species, especially phosphorus.

The mean sludge concentration in the process tanks was 28 kg/m^3 ,which is a relatively high concentration compared to ordinary sewage treatment plants. Due to the high concentrations only hindered settling can be expected to be dominant. The settling experiments were performed beside the main process tanks in order to measure on "fresh" sludge and to avoid temperature differences.

The experiments covered concentrations of 0 - 60 kg/m^3 . Low concentrations were obtained by mixing with the supernatant from the secondary settling tanks and higher concentrations were obtained by letting the sludge first pass a reservoir where it was concentrated. The sludge continually passed through the settling column by gravity to avoid mechanical stress and the sludge only passed once through the column.

19 different combinations of concentration and G-value were used in the experiment to cover the range expected in the process tanks. At each experiment the vertical concentration profile was measured to ensure steady state conditions. The experimental results are listed in table 1 in the Appendix .

The experiment is performed with 4 low concentrations (approx. 14 kg SS/m^3), 7 average concentrations (approx. 28 kg SS/m^3) and 8 at high concentrations (approx. 50 kg SS/m^3). The results are presented in figure 5. The areas between the measured points are interpolated.

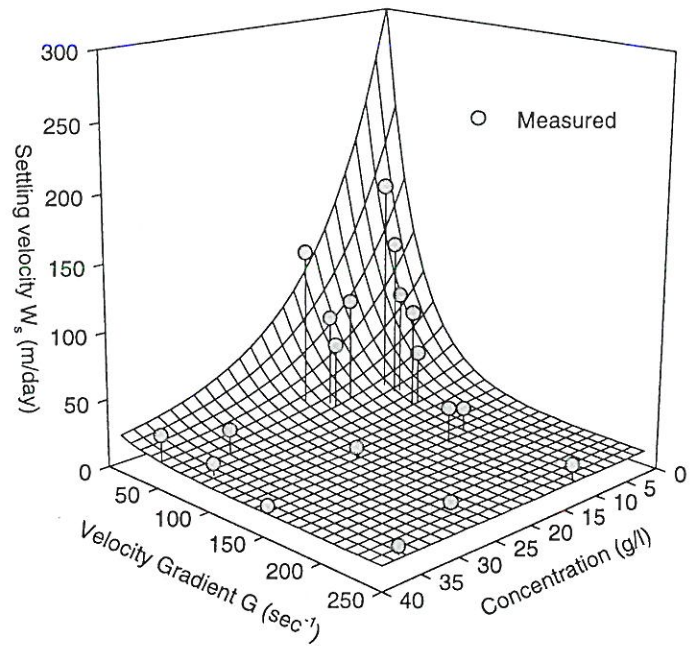

Fig. 5 Surface plot of settling velocity as a function of concentration and G - value.

The maximum settling velocity is obtained at low concentrations and low G values.

Municipal Plant

The sludge is from a municipal activated sludge plant with biological nutrient removal. The average concentration in the process tanks is 4 kg SS/m^3. The sludge in the experiment was taken directly from the inlet to the secondary settling tank. The sludge was circulated from the bottom of the column to the top. The sludge was therefore reused in the experiment. At high concentrations concentrated sludge from the outlet from the secondary settling was added to the column and at low concentration supernatant from thė secondary settling tank was added.

22 different combinations of average concentration and G-value were used. The profiles were constant in the depth. The range of G-values was kept at a low level as the sludge was more sensitive for turbulence than the high concentrated chemical sludge. 4 different concentrations were examined: 0.13, 0.35, 2 and 4 kg SS/m^3.

The experimental results are listed in table 2 in the Appendix .The results are presented in figure 6.

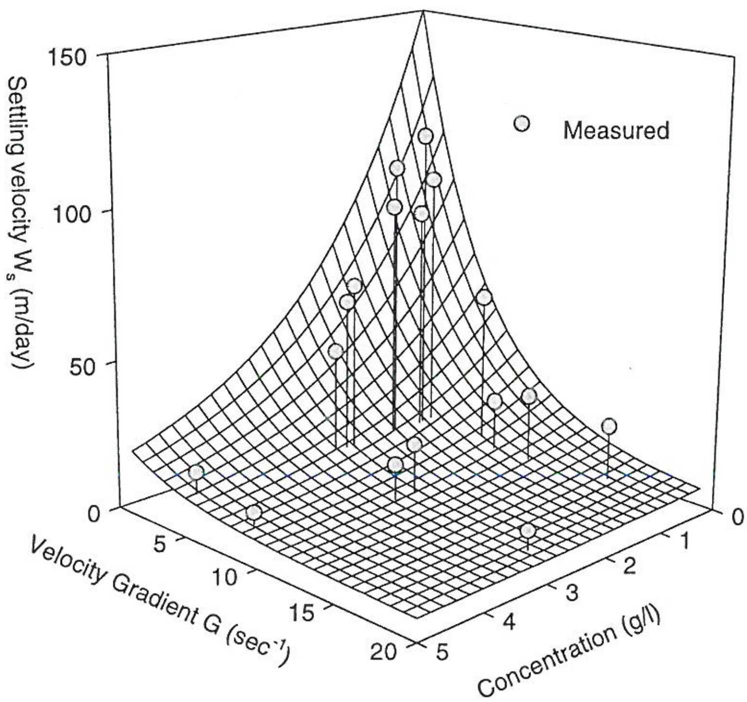

Fig. 6 Surface plot of settling velocity as a function of concentration and G - value.

It appears that the shape of the figure for the activated sludge is similar to that of the chemical sludge. This indicates that the mechanism of settling - despite the difference in sludge composition - is similar. The maximal settling velocity is reached at low concentration and turbulence.

The surfaces shown on fig. 5 and 6 can be fitted to the following empirical formula

$$W_s = \beta e^{(\gamma G + \omega C)} + \lambda \qquad (12)$$

where β [m/day] is the maximal settling velocity, γ [sec] and ω [m^3/kg] are empirical constants and λ [m/day] is the minimal settling/compression velocity. Equation (12) was used for making the interpolated grid in figure 5 and 6.

TABLE 1: CONSTANTS IN EMPIRICAL FORMULA

	β	γ	ω	λ	R^2
Chemical sludge	291	-0.0299	-0.0867	9.78	0.93
Activated sludge	147	-0.2167	-0.4825	3.53	0.93

Discussion

The functional relation suggested by equation (12) is an extension of the "standard" exponential model proposed by Vesilin, (Vesilin, P. A.,1968). Also Smollen and Ekama (Smollen , M. and Ekama, G. A., 1984) found that the exponential model gave more consistent results from both a practical and a theoretical point of view. The extension suggested here, includes the effect of turbulent flows in order to cover the span of turbulence present in secondary settling tanks.

The two types of sludge differ as expected on the following points

- the maximum settling velocity for the chemical sludge was higher than the activated sludge
- at the same concentration and turbulence level the settling velocity for the chemical sludge was always higher than the activated sludge

3 effects can cause the difference in settling velocity: difference in floc size, difference in floc density and difference in flocculation characteristics.

For high turbulence the flocs are more or less disintegrated. The higher settling velocities of the chemical sludge indicate a higher settling velocity of the basic particles, probably primarily caused by a higher density.

The γ parameter describes the strength of the sludge flocs towards turbulent shear. A high value indicates a weak structure while a low value indicates a strong structure. The chemical sludge seems to be significantly more resistant in this respect.

Conclusion

The experimental procedure for the determination of the settling velocity as function of turbulence intensity and sludge concentration developed in this study has proved efficient, precise and applicable in practice. The method was tested on 2 distinct types of sludge. Qualitatively the two types showed an almost similar behavior with highest settling velocities for low concentrations and low turbulence, although the numerical values differed significantly

References

Argaman, Y. and Kaufman, W. J. (1970), Turbulence and flocculation, *J. Sanitary Engineering Div.*, ASCE, **SA2**, 223-241

Batchelor, G. K. (1959) The theory of homogeneous turbulence, Cambridge monographs on mechanics and applied mathematics, Cambridge university press.

Camp, T. R. and Stein, P. C. (1943), Velocity gradients and internal work in fluid motion, Journal of the Boston society of civil Engineers.

Casson, L. W. and Lawler D. F. (1990), Flocculation in turbulent flow: Measurement and modeling of particle size distribution. *J. Amer. Water Works Assoc.*,**63**, 8 , 54-68

Cleasby, J. L.(1984), Is velocity gradient a valid turbulent flocculation parameter? Journal of Environmental Engineering , **110** , 5.

Dahl, C. (1995), Numerical Modelling of Flow and Settling in Secondary Settling Tanks, Ph. D. Thesis, Aalborg University, Department of Civil Engineering, Series Paper no. 8

Hopfinger, E. J. and Toly, J.-A. (1976) Spatially decaying turbulence and its relation to mixing across density interfaces, *J. Fluid Mech.*, **78**, 155-175

Ignacio, K. A. (1943) , Measurement of Work Input in Liquids by Reciprocating Mixing Devices, Master's Thesis, M.I.T.

Keulegan, G. H. and Carpenter, L. H. (1958), Forces on Cylinders and Plates in a Oscillating Fluid, J. Res. Nat Bur. Stand, Vol 60 no.5.

Li, D. and Ganczarczyk, J. J. (1987) Stroboscopic determination of settling velocity, size and porosity of activated sludge flocs *Wat. Res.* **21**, 257-262

Matsunaga, N. , Sugihara, Y. and Komatso, T. (1991) , A numerical simulation of oscillating-grid turbulence by using the k-e turbulence model, Proc. Environmental hydraulics, Lee & Cheung (eds.)

McLaughlin, R. T.(1959), The settling properties of suspensions, Proc. ASCE, **85** Hy 12,.

Morison, J. R. , O'Brien M. P., Johnson ,J. W. and Schaff S. A.(1950), The Force Exerted by Surface Waves on Piles, Petrol. Trans., AIME, Vol 189.

OSLIM manual (1991), Delft Hydraulics.

Owen, M. W. (1970), A detailed study of settling velocities of an estuary mud, Report No. INT 78, Hydraulics Research Station, Wallingford.

Rodi, W.(1984) Turbulence models and their application in hydraulics - State of the art paper, IAHR.

Sarpkaya, T. and Isaacson M. (1981), Mechanics of wave forces on Offshore structures, Van Nostrand Reinholdt Company Inc.

Smollen, M. and Ekaman, G. A. (1984) Comparison of empirical settling velocity equations in flux theory for secondary settling tanks, *Water S. A.,* **10**, 175

Thomson, S. M. and Turner, J. S. (1975) Mixing across an interface due to turbulence generated by an oscillating grid, *J. Fluid Mech.*, **67**, 349-368

Tørum, A. (1985), Wave forces on a pile in the surface zone. Regular non-breaking waves. Technical report, NTMF - Marine Structures Program.

Vesilin, A. P. (1969) The use and misuse of the Sludge Volume Index, VANN , 1 , 69.

Vesilin, A. P. (1968), Discussion of "Evaluation of Activated Sludge Thickening Theories" by R. I. Dick and B. B. Eving, Journal of the Sanitary Engineering Division, ASCE, Vol 94, SA 1.

Appendix

TABLE 1 RESULTS FROM EXPERIMENT WITH CHEMICAL SLUDGE

Sample nr	Concentration at the inlet [kg SS/m^3]	W_o [m/h]	Average concentration [kg SS/m^3]	G [S^{-1}]	W_s [m/h]
1	13.7	0.63	2. 2	30.8	3.276
2	13.8	0.6372	3.8	58.8	1.692
3	14	0.6372	6.5	118	0.72
4	14.1	0.63	8.4	223	0.432
5	28.6	0.558	2.3	15.6	6.84
6	26.4	1.5516	8.4	18.9	3.312
7	28.3	0.5976	3	30	5.04
8	28.5	0.5976	4.6	58.3	3.096
9	27.4	0.9288	20.2	102	0.3312
10	28.3	0.594	10	125	1.08
11	27.4	0.936	22.6	201	0.198
12	37.7	1.1808	11	15	2.88
13	57.9	1.4076	12.6	0	5.04
14	60.4	1.1592	35.5	18	0.828
15	53.1	0.576	11.5	24.3	2.088
16	50.2	1.0584	29	38,5	0.756
17	54	0.5688	33.8	57.8	0.3384
18	48.7	0.5724	36.1	126	0.198

19	46.8	0.5724	33.5	223	0.2268

TABLE 2 RESULTS FROM EXPERIMENT WITH ACTIVATED SLUDGE

Sample nr	Concentration at the inlet [kg SS/m³]	W_0 [m/h]	Average concentration [kg SS/m³]	G [S^{-1}]	W_s [m/h]
1	4.53	0.862	0.8	1.4	4.04
2	4.22	0.862	0.84	1.4	3.45
3	6.09	0.862	1.71	1.6	2.21
4	6.06	0.862	1.59	1.6	2.43
5	3.94	0.862	2.17	8.4	0.7
6	2.56	0.862	2.01	20.3	0.23
7	0.66	0.862	0.12	1.4	3.74
8	0.43	0.862	0.12	5.2	2.13
9	0.26	0.862	0.13	13.9	0.78
10	1.9	0.862	0.31	1.5	4.44
11	0.71	0.862	0.34	9.3	0.95
12	0.58	0.862	0.35	20.3	0.57
13	1.89	0.862	0.39	1.6	3.27
14	0.66	0.862	0.36	7	0.71
15	0.42	0.862	0.34	20.6	0.21
16	5.07	0.862	1.86	1.4	1.49
17	3.94	0.862	2.49	8.4	0.5
18	3.25	0.862	2.47	17	0.27
19	5.6	0.862	4.1	1.3	0.32
20	4.99	0.862	4.2	6	0.16
21	4.41	0.862	4.25	43.7	0.03
22	6.11	0.862	5.17	1.5	0.16