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Impact of the flocculation state on hindered and compression settling: experimental evidence and overview of available modelling frameworks

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Summary of key findings

In order to move towards advanced 1-D models for secondary settling a more thorough understanding of compression is necessary. The inability of the current modelling frameworks to capture the variability in the compression phenomenon indicates that there is still something missing in the expression describing compressive settling. This can potentially be attributed to phenomena such as variations in the flocculation state and segregation of particles during settling which are not considered in the current modelling frameworks. In this work evidence is provided to support this hypothesis together with a brief overview of possible extensions/alternatives to the current modelling frameworks allowing for a changing flocculation state.

Background and relevance

Secondary settling tanks remain one of the most crucial operating units in WWTPs since they affect the effluent quality as well as the biomass inventory in the entire treatment plant. Consequently, the development of advanced 1-D settler models has gained increased attention in recent years (Plosz et al., 2007; Bürger et al., 2013; Li and Stenstrom, 2014). Several studies have shown that accounting for only hindered settling is insufficient to capture the complex settling behaviour of activated sludge (De Clercq et al., 2008; Ramin et al., 2014; Torfs et al., 2015). Therefore, an important aspect of advanced settler models is the phenomenon of compression, i.e. the resistance to compaction caused by the network of flocculated particles that arises at high concentrations.

Bürger et al. (2011, 2013) presented a new 1-D model which allows for more realistic simulations of secondary clarifiers based on the following partial differential equation (PDE) for the biomass concentration X at time t and depth z from the feed level:

$$\frac{\partial X}{\partial t} = -\frac{\partial}{\partial z}F(X,z,t,) + \frac{\partial}{\partial z}\left(v_{\mathrm{hs}}(X)\frac{\rho_s}{(\rho_s-\rho_f)gX}\frac{\partial \sigma_e(X)}{\partial X}\frac{\partial X}{\partial z}\right) + \frac{Q_f(t)\,X_f(t)}{A}\delta(t) \qquad (1)$$

in which the first term on the right-hand side models convective transport as well as hindered settling. The second term on the right-hand side accounts for compressive settling and finally a singular source term models the feed mechanism. The compression term is dependent on the hindered settling velocity, the densities of the solid ρ_s and fluid component ρ_f and on the derivative of the effective solid stress σ_e. Where the equation presented above finds its origin in established conservation laws, no convincing physically motivated expression of σ_e for activated sludge exists today. The effective solids stress is considered as a non-decreasing function of X when the concentration exceeds a certain critical concentration $X_{crit.}$ at which the solid particles are in permanent contact with each other.

$$\frac{d\sigma_e(X)}{dX} \begin{cases} = 0 & \text{for } 0 \leq X < X_{crit} \\ > 0 & \text{for } X > X_{crit} \end{cases} \quad (2)$$

In recent years, a number of studies have tried to extract an expression for σ_e from experimental batch settling data by means of inverse modelling (De Clercq et al., 2008; Ramin et al., 2014; Diehl, 2014). These studies concluded that the use of a solids stress function that is only depending on X is insufficient to describe the physics of compression and that some time varying phenomenon is occurring that is not captured by the current modelling framework. De Clercq et al. (2008) and Ramin et al. (2014) were able to overcome this problem by introducing a variable X_{crit}. However, no physical explanation for the observed variance was found and most importantly the introduced variability on X_{crit} was based on information that is only available in controlled batch experiments. Hence, applying the resulting functions to model full-scale dynamic systems is likely not feasible.

This contribution aims to investigate the physical or biological phenomenon behind the unexplained variability in the compression phenomenon. An important assumption that was made in the derivation of eq. (1) is that the suspended particles are monosized and cannot overtake each other. Hence, variations in the flocculation state and segregation of particles during settling that could potentially explain the nature of the variability in compression phenomenon are not included. This contribution presents evidence to support this hypothesis. Moreover it provides an overview of possible extensions/alternatives to the current modelling frameworks which would allow accounting for a changing flocculation state.

Results and discussion

Two types of experimental data were analysed in order to investigate the impact of the flocculation state of a sample on its settling behaviour. For the first set of experimental data a sample was collected from the biological reactor at the WWTP of Destelbergen (Belgium) and a number of batch settling tests were conducted in 2 liter columns with a diameter of 9 cm. The evolution of the sludge blanket height (SBH) was monitored during 30 minutes of settling. All tests were performed at the same initial sludge concentration (3.5 g/l) but at a different initial flocculation state obtained by applying different amounts of shear (force) to the sample prior to settling.

A second set of experimental data was collected by Locatelli et al. (2014) who developed an experimental procedure to measure settling velocities within the sludge blanket by means of an ultrasonic transducer. The experimental set-up consisted of a 1 m high settling column with a diameter of 0.4 m. These experiments resulted in complete settling velocity profiles during batch settling at different initial concentrations.

The results of two sets of batch settling test with the sludge sample from the WWTP of Destelbergen are shown in Figure 1. It can be seen that the evolution of the sludge blanket height (and thus the settling velocity at the top of the sludge blanket) changes noticeably between the different experiments. Since each of these tests was performed at exactly the same initial concentration the differences in settling behaviour cannot be attributed to variations in concentration but only to variations in the flocculation state. By stirring the sample, loosely bound flocs are broken up into more stable aggregates with better settling properties resulting in a faster decrease in the sludge blanket height. This can be explained by the release of EPS acting like a polymer to increase flocculation (Laurent et al., 2009). (Stirring the sample at high shear rates also resulted in increased supernatant turbidity due to the formation of colloids. However, modelling the clarification process is outside the scope of this contribution.)

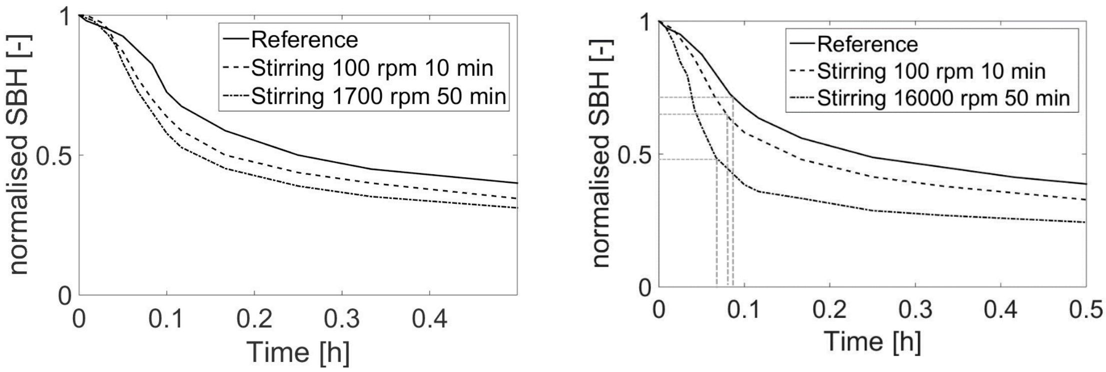

Figure 1: Evolution of the Destelbergen sludge blanket height during batch settling experiments at the same sludge initial concentration but different flocculation states (Reference = no stirring)

Moreover, Figure 1 (right) illustrates the impact of the flocculation state with respect to the onset of compression settling. The grey dotted lines indicate the point where the sludge blanket enters the compression zone. Hence, at this point the concentration at the top of the sludge blanket should equal X_{crit}. **However, when shear is applied prior to settling, the sludge water interface reaches the compression zone at a lower sludge blanket height and thus in a more concentrated state. A more concentrated sludge blanket at the onset of the compression zone indicates a higher critical concentration.** This confirms that changes in flocculation state can account for variations in the critical concentration. Due to the applied shear, larger, less stable flocs will be reduced to smaller, denser flocs with different packing properties resulting in a sample that can reach higher concentrations before the particles are in permanent contact.

Figure 2 shows two velocity profiles measured by Locatelli et al. (2014) at initial sludge concentrations of 1.5 g/l and 4.6 g/l. On these profiles, two regions with different settling behavior can be distinguished. The top of the profiles corresponds to the hindered settling region and should be characterized by a vertical trend. At the bottom of the profile a downward decreasing trend can be observed corresponding to the compression region.

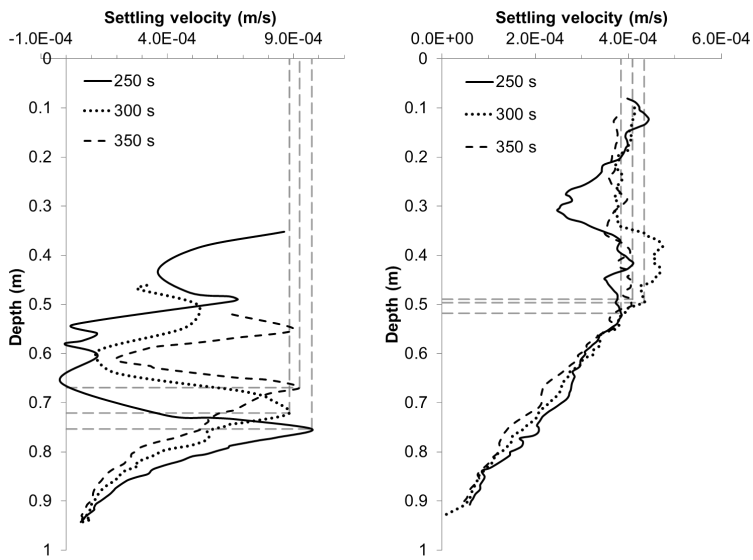

Figure 2: Settling velocity profiles recorded with an ultrasonic transducer during batch settling at an initial concentration of 1.5 g/l (left) and 4.6 g/l (right).

In the hindered settling zone the measured velocity profile does not show one fixed velocity but a vertical trend with horizontal fluctuations. Analysis of the velocity profile over time indicates that these fluctuations are not random but can be tracked throughout the settling process. Moreover, by comparing the two graphs in Figure 2, it clearly appears that the magnitude of the velocity fluctuations decreases when the concentration increases. This observation was confirmed by other measurements obtained with different concentrations and quantified by calculating the derivative of the settling velocity with respect to depth in the hindered settling region (see Table 1).

Table 1: Standard deviations (s^{-1}) of the derivative of the settling velocity with respect to depth in the zone settling region.

		Concentration			
		1.5 g/L	2.7 g/L	3.2 g/L	4.6 g/L
Time	250 s	1.3E-02	7.8E-03	5.2E-03	1.7E-03
	300 s	1.2E-02	7.0E-03	3.9E-03	1.4E-03
	350 s	8.4E-02	5.1E-03	2.8E-03	1.2E-03

Since the observed fluctuations in the hindered settling region are not random, we suggests that the fluctuations correspond to variations in the internal properties of the sludge blanket, such as heterogeneities in the floc size distribution and that a segregation of particles with different size is occurring in the hindered settling region. This is supported by the decrease in magnitude of the fluctuations with increasing concentration. Indeed, at higher concentrations the flocs are more densely packed making a distinct segregation of particles physically more difficult. Local variations in floc size distribution and the segregation of particles over the depth of the hindered settling region will cause variations in the critical concentration as changes in particle size will influence the formation of a compressive network.

From the experiments above it becomes clear that the flocculation state of a sludge sample prior to settling has a profound influence on its settling behaviour and the concentration (X_{crit}) at which the sample starts to form a compressive network. Moreover, segregation of particles during the settling process may cause the critical concentration to vary over time.

Accurate description of this behaviour will require refinement of the currently used modelling framework. Polydispersed systems undergoing break-up and flocculation have already been extensively studied in many chemical engineering applications and different modeling frameworks are available in literature. Therefore, we should not aim to develop a completely new modelling framework but look over the fence to investigate possible extensions of the current model. The available frameworks in literature include very detailed models consisting of a system of n coupled PDEs (with n a chosen number of particle size classes). These models can account for polydisperse sedimentation where particles of different sizes overtake one another (Berres et al., 2005) or can even be further extended to include reaction terms for flocculation and break-up (i.e. Population Balance Models) (Nopens et al., 2015). Such detailed models will of course come at a cost of an increased simulation time and are therefore less suitable to be used for operational and control purposes. More simplified models that only introduce one additional PDE have also been developed. Gustavsson et al. (2001) introduced a memory function that stores the maximum volume fraction a particle has encountered during sedimentation to describe irreversible changes in permeability. A second example is the work by Betancourt et al. (2014) who developed a model for continuous sedimentation that is able to account for the influence of flocculant dosage on the settling velocity. The authors introduced one additional variable (one additional PDE) which tracks the local flocculation state and allows having a settling velocity that varies with changes in the flocculation state.

References

Berres, S., Bürger, R. and Tory E.M. (2005). Applications of polydisperse sedimentation models. Chem. Eng. J. 111, 105-117.

Betancourt, F., Bürger, R., Diehl, S. and Farås, S. (2014). Modelling and controlling clarifier-thickeners fed by suspensions with time-dependent properties. Miner. Eng., 62, 91-101.

Bürger, R., Diehl, S., and Nopens, I. (2011). A consistent modelling methodology for secondary settling tanks in wastewater treatment. Water res. , 45(6), 2247–60

Bürger, R., Diehl, S., Farås, S., Nopens, I., and Torfs, E. (2013). A consistent modelling methodology for secondary settling tanks: a reliable numerical method. Water Sci. Technol., 68(1), 192-208.

De Clercq, J., Nopens, I., Defrancq, J., and Vanrolleghem, P.A. (2008). Extending and calibrating a mechanistic hindered and compression settling model for activated sludge using in-depth batch experiments. Water Res., 42(3), 781–791.

Diehl, S. (2014). Numerical identification of constitutive functions in scalar nonlinear convection-diffusion equationswith application to batch sedimentation. Appl. Num. Math.(http://dx.doi.org/10.1016/j.apnum.2014.04.002).

Gustavson, K., Oppelstrup, J. and Eiken, J. (2001). Consolidation of concentrated suspensions – shear and irreversible floc structure rearrangement. Comput Visual Sci 4: 61–66

Laurent, J., Pierra, M., Casellas M., Pons, M.N. and Dagot, C. (2009). Activated sludge properties after ultrasonic and thermal treatments and their potential influence on dewaterability. *Journal of Residuals Science & Technology,* 6(1), 159-167.

Locatelli, F., François, P., Laurent, J., Lawniczak, F., Dufresne, M., Vazquez, J. and Bekkour, K. (2014). Detailled velocity and concentration profiles measurement during activated sludge batch settling using an ultrasonic transducer. Separ. Sci. Technol. (accepted, DOI:10.1080/01496395.2014.980002).

Nopens, I., Torfs, E., Ducoste, J., Vanrolleghem, P.A. and Gernaey, K. (2015). Population balance modelling: a useful complimentary modelling framework for future WWTP modelling. Water Sci. Technol., 71(2),

Ramin, E., Wagner, D.S., Yde, L., Binning, J.B., Rasmussen, M.R., Mikkelsen, P.S. and Plósz, B.G. (2014). A new settling velocity model to describe secondary sedimentation. Water Res., 66, 447-458.

Li, B. and Stenstrom, M.K. (2014). Research advances and challenges in one-dimensional modeling of secondary settling tanks – A critical review. Water res., 65, 40-63.

Torfs, E., Maere, T., Bürger, R., Diehl, S. and Nopens. I. (2015). Impact on sludge inventory and control strategies using the Benchmark Simulation Model No. 1 with the Bürger-Diehl settler model.(submitted).