Towards improved 1-D settler modelling: impact on control strategies using the Benchmark Simulation Model

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Abstract: A new 1-D model for the secondary clarifier was recently presented. The decisive difference to traditional layer models is that every detail of the implementation is in accordance with existing PDE theory. Moreover this new model does not only focus on hindered settling but also allows accounting for compressive settling. In this contribution, the behaviour of this new settler model is compared with the traditional settler model of Takács et al (1991) in terms of the impact on underflow predictions, sludge inventory in the plant and control actions by using the Benchmark Simulation Model n° 1. The numerical results show that the new settler model allows for more realistic predictions of the underflow concentration. The improved model clearly has a profound impact on the operation and control of the entire treatment plant and is recommended to be used as of now in WWTP modelling.

Keywords: Clarifier; Compression settling; Layer model; sludge inventory

INTRODUCTION

The operation and control of secondary clarifiers is still an important performance-limiting factor in conventional wastewater treatment plants (WWTP). Indeed, the performance of secondary clarifiers affects the effluent quality as well as the biomass inventory and distribution in the plant. As biomass is the driving force for conversion processes, secondary clarifier operation affects plant performance.

Traditional layer models used to date for secondary clarifiers and available in most commercial simulation platforms (e.g. the model by Takács et al. (1991)) do not sufficiently capture the settling dynamics. Under normal dry weather operating conditions, these models may behave reasonably well. However, their predictions under situations that diverge from normal operating conditions (e.g. peak flows due to rain events) loose realism. More recently 1-D models have been developed which try to explicitly account for dispersion and compression effects by incorporating a second order term in their PDE (Hamilton et al., 1992; Watts et al., 1996; Plósz et al.,2007). The drawback of this approach is that all the previously unmodelled phenomena are in these models lumped into one single term which is still too coarse to be able to sufficiently capture the true settling dynamics. Moreover, such an approach lacks flexibility.

A new 1-D model allowing improved and more realistic simulations of secondary clarifiers has recently been presented (Bürger et al., 2011; Bürger et al., 2012). All implementation details can be found in Bürger et al. (2013). This new model is based on the numerical solution of its governing partial differential equation (PDE) by appropriate methods.

The specific objective of this study is to investigate the effect of this newly proposed settler model on operation and control using the Benchmark Simulation Model n° 1 (BSM 1) (Copp, 2002). Moreover, we elucidate the specific added value of the settler model's features on the predictions of biomass concentrations throughout the system. The obtained results are compared to the case where the Takács model is used.

MATHEMATICAL MODEL
The new 1-D settling model is based on a spatially one-dimensional PDE for the biomass C at time t and depth z from the feed level. Additionally, the approach allows accounting for sediment compressibility and inlet mixing phenomena by extending the PDE with a compression function (d_{comp}) and a dispersion function (d_{disp}) which can be switched on or off by the user depending on the model study requirements. The resulting PDE is:

$$\frac{\partial C}{\partial t} = -\frac{\partial}{\partial z}F(C,z,t) + \frac{\partial}{\partial z}\left(\left\{d_{comp}(C) + d_{disp}(z,Q_f(t))\right\}\frac{\partial C}{\partial z}\right) + \frac{Q_f(t)C_f(t)}{A}\delta(t)$$

where the first term on the right-hand side represents convective transport (due to feed flow, underflow and overflow) as well as particle transport due to gravity settling. The second term includes the compression and dispersion functions. The last term is a singular source term modelling the feed mechanism (Q_f is volumetric flow rate, A is the constant cross-sectional area). To numerically solve this PDE, it is discretised by dividing the tank into a user-defined number of layers (N) around which a proper solids balance is imposed. The numerical method is presented in detail by Bürger et al. (2013). As the number of layers increases, the numerical solution becomes more accurate and converges to the physically correct solution of the PDE. This is not the case for the traditional layer models used to date (e.g. the model by Takács et al., 1991).

This study focuses specifically on the added value of the compression function since sediment compressibility significantly influences the prediction of the return sludge concentration and the height of the sludge blanket in the settler, which are two important operation and control variables during a storm weather event or when operating under higher solids loads. The following constitutive function is one way to describe the sediment compressibility with only two parameters:

$$d_{comp}(C) = \begin{cases} 0 & \text{if } 0 \leq C < C_{crit} \\ \dfrac{\rho_s \cdot \alpha \cdot v_s(C)}{g(\rho_s - \rho_f)} & \text{if } C \geq C_{crit} \end{cases}$$

Here ρ_s and ρ_f are the densities of the solids and the fluid, respectively, g is the constant of gravity, v_s the settling velocity function and α a compression parameter. The compression term is active wherever the concentration exceeds a critical concentration (C_{crit}).

RESULTS AND DISCUSSION

The results shown in this contribution were obtained by simulating the Benchmark Simulation Model n° 1 with different settler models in WEST (http://www.mikebydhi.com, Denmark). All simulations were performed under storm weather conditions and used the double exponential settling velocity function of

Takács et al. (1991) with default BSM1 parameters. The parameters of the compression function were chosen as: ρ_s=1050 kg/m³, ρ_f= 998 kg/m³, α=0.8 m²/s², C_{crit}=4 kg/m³.

Figure 1 demonstrates the effect of adding compression on the predictions of the underflow concentration (left) and the sludge blanket height (right). By accounting for compressive settling, the sludge blanket level can be modelled in a more realistic way. An increased solids loading to the clarifier will cause the sludge blanket to rise and result in a modest increase in underflow concentration. These trends correspond to observations made in reality. Figure 2 (left) shows on-line clarifier data from the WWTP of Eindhoven (The Netherlands). When a hydraulic peak hits the clarifier, its effect will mainly be seen by an increase in the sludge blanket height. This contrasts with a very drastic increase in the underflow concentration and almost no effect on the sludge blanket in the currently used 10-layer models (Figure 1, right).

Adding compression settling is thus especially interesting to use when variations in underflow concentrations occur (e.g. storm events) as this will affect the biomass concentration in the bioreactors (Figure 2, right) and, hence, the conversion rates, which might "force" modellers to calibrate biomass kinetic parameters for the wrong reasons.
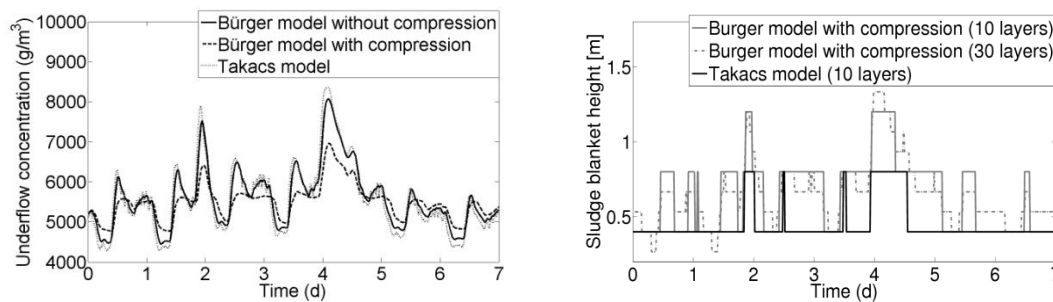

Figure 1: Dynamic simulation of the underflow concentration (left) and the sludge blanket height (right) under storm weather conditions.
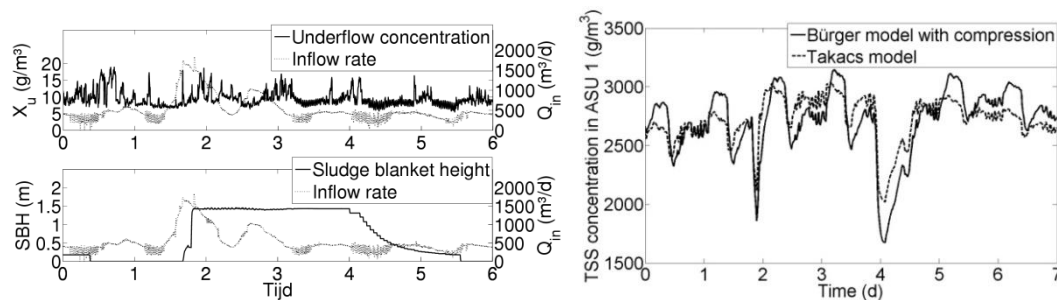

Figure 2: On-line data of sludge blanket height (SBH), underflow concentration (X_u) and inflow rate (Q_{in}) from the WWTP of Eindhoven (left) and dynamic simulation results of the BSM1 MLSS concentration in the first activated sludge tank (right).

Figure 2 (right) shows the different predictions for the Total Suspended Solids concentration (TSS) in the first Activated Sludge Unit (ASU 1). Adding compression settling increases the effect of a storm peak on the MLSS concentration. Due to the dampening effect of compression on the underflow concentration, less sludge is returned to the biological reactor resulting in less recovery and a more pronounced effect of the storm peak. This implies that traditional settler models, which do not account for compressive settling, might underestimate the effect of a storm event.

As the sludge inventory and distribution is the driving force behind the performance of a WWTP, a pronounced difference in the predictions of the biomass concentrations will also influence plant-wide control strategies. To investigate the significance of this influence, a control strategy was implemented to maintain the MLSS concentration at a desired level. Since the recycle flow will have a profound impact on the biomass concentration in the biological reactor, a PI controller (K_c=100 and τ_I=1) was implemented that controls the MLSS concentration at a desired setpoint (2800 g/m³) by manipulating the underflow rate based on a measurement of the MLSS concentration in ASU 1. The limits for manipulation of the underflow rate are set to 0.33 and 1.5 times the incoming flow rate (Tchobanoglous et al. 2003).

The resulting manipulations in the underflow concentration and the predictions of the MLSS concentration are shown in Figure 3. It can be seen that implementing the same controller with two different settler models results in quite deviating control actions on the underflow rate.
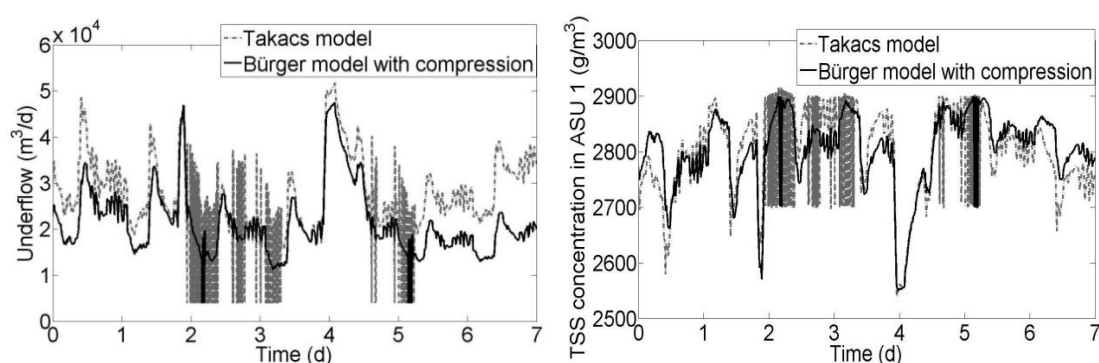

Figure 2: Dynamic simulation with the implementation of an MLSS control strategy. Manipulation in underflow rate (left) and MLSS concentration in the first activated sludge tank (right) under storm weather conditions.

It can thus be concluded that the choice of the settler model not only influences the predictions of the settling process itself but also significantly impacts the system's sludge inventory and related control actions in the entire system. Hence, it impacts controller design and evaluation of strategies which the BSM frameworks were designed for. Therefore, we need to step away from traditional layer models towards models that reflect more realism by accounting for both hindered and compression settling. Moreover, convergence of the numerical solution is ensured at all times. The additional computational cost can nowadays be borne by IT infrastructure.

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