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Practical identifiability and uncertainty analysis of the one-dimensional hindered-compression continuous settling model

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ABSTRACT

The practical application of the one-dimension hindered-compression settling models remains a challenge, since the model calibration strongly depends on experimental observations with limited information. In this study, the identifiability of parameter subsets of the hindered-compression models is evaluated for various experimental layouts. Global sensitivity analysis is used to preliminarily select the influential parameters which can be reasonably estimated, while the identifiability analysis of parameter subsets is conducted based on the local sensitivity functions and collinearity measures. The batch settling curve observations are informative for calibrating hindered parameters, and to determine the compression parameters, the concentration profile observations may need to be collected. For different experimental layouts, at least three parameters are identifiable, and the number of identifiable parameters can potentially increase to five, if both batch settling curve and concentration observations are available. The parameter subset identifiability is sensitive to the choice of initial parameter values, and determining the initial values of hindered parameters and gel concentration by measuring the hindered settling velocities and the top concentration of the static sediment respectively allows efficient reduction of the sensitivity. Parameter subset estimates are sensitive to the values of fixed parameters, and reliable estimation of identifiable parameter subsets is possible to significantly decrease model prediction uncertainties.

1. Introduction

As the mostly used solids-liquid separation unit in wastewater treatment process, secondary settling tanks (SSTs) are able to remove finely dispersed solids to produce low turbidity effluent, and to concentrate the solids in an underflow for it to be recycled or disposed in the least volume. The two functions are known as clarification and thickening. The traditional SST design and operation strategies tend to be empirical and conservative, which may cause an unanticipated performance fluctuation of the SST itself and a low efficiency of energy and land use (Li and Stenstrom, 2014a,b).

For design and operation optimization purposes, various SST mathematical models have been developed to provide a reasonable prediction of the effluent solids concentration, underflow solids concentration, sludge blanket level and sludge inventory which are specifically important during hydraulic shock loading and sludge settleability deterioration. In most commercial simulators, one-dimensional (1-D) SST models are most often used due to their simplicity and less computation burden, especially if long term simulations are needed (Bürger et al., 2011). Most early 1-D models, such as the well-known Takács model (Takács et al., 1991), are derived considering only local mass conservation and hindered settling. In last decade, the improved understanding of activated sludge rheology has facilitated the development of phenomenological theory of sedimentation-consolidation, which provides a more rigorous description of the compression settling behavior (Bürger, 2000). The phenomenological theory is subsequently expressed in the 1-D model from the mass and linear momentum balance, allowing the development of hindered-compression models, such as the Bürger-Diehl model (Bürger et al., 2012, 2013). Compared with the hindered-only models, the hindered-compression models have the advantage of providing improved compression settling simulations, thus allowing more accurate predictions of the underflow concentration, sludge blanket level under unusual conditions, for example the wet-weather condition

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(Torfs et al., 2015).

Given the variety of simulation conditions, such as the sludge settleability and compressibility, 1-D settling models are not considered to be universal for all SST systems, and model parameter adjustment based on experiment data, usually referred as model calibration, is usually required for specific SST simulations. The calibration methodology of the hindered-only settling models are well developed, and can be classified into two categories: 1) the conventional approach using hindered settling velocities obtained from multiple batch settling tests; 2) the direct parameter estimation approach by fitting a single batch settling curve (Vanderhasselt and Vanrolleghem, 2000). It is noticeable that the hindered-compression settling models cannot be calibrated straightforwardly following these two approaches because of the inclusion of the additional compression parameters. Several proposed calibration methods require the use of advanced techniques, such as radiotracing, to measure the dynamic concentration distribution during batch settling experiments (Kinnear, 2002; De Clercq et al., 2005; De Clercq et al., 2008), which is beyond the accessibility of most practical application cases (Li and Stenstrom, 2014b; Ramin et al., 2014c). Therefore, to promote the application of the hindered-compression settling model, great efforts are needed to facilitate its calibration. For example Ramin et al. (2014b, 2014c) reported that calibrating the hindered-compression model based on the additional measurement of the batch bottom concentration, beside the batch settling curves, has achieved some degree of success.

The limited observational data of practical batch experiments naturally gives rise to the problem of the poorly identifiable parameters, which means it is difficult to identify a unique set of all parameters used in the hindered-compression models due to possible parameter correlation (Brun et al., 2002; Brockmann et al., 2008). To avoid this problem, it is important to understand the practical identifiability of the model and select a suitable subset of parameters which can be reliably identified by the available experiment measurements (Weijers and Vanrolleghem, 1997; Brun et al., 2001; Ruano et al., 2007).

In the wastewater treatment process modeling field, two alternative approaches have been most used to analysis the parameter identifiability problem. The first method is on the basis of scalar functions calculated from the Fisher Information Matrix (FIM), and the D and mod-E criteria can be used to select the best identifiable parameter subset (Weijers and Vanrolleghem, 1997). The second method developed by Brun et al. (2001) uses a diagnostic regression and focuses on the analysis of parameter interdependency by calculating the collinearity index. Both methods are proven to be efficient in selecting the best identifiable parameter subset from limited experiment measurements (Weijers and Vanrolleghem, 1997; Brun et al., 2001; Ruano et al., 2007; Brockmann et al., 2008). Recently, the Generalized Likelihood Uncertainty Estimation (GLUE) method has also been demonstrated as a reliable alternative for the identifiability analysis of the hindered-compression settling model by Torfs et al. (2013).

Nevertheless, despite the efficiency of the two most used approaches in addressing parameter identifiability problem, they still have drawbacks which may greatly impact the analysis results, at least in the hindered-compression settling model study. Both approaches are based on the calculation of local sensitivity functions for a set of reasonable parameters values within the parameter space, and in most activated sludge model (ASM) identifiability studies, the initial parameter set is determined as default values reported in literature. For example the practical identifiability analysis of ASM2d by Brun et al. (2002) used the default values presented by Henze et al. (1999) as the starting point values. Given the fact that very limited parameter values have been reported in hindered-compression settling model studies, especially those related to the compression rheology, the initial parameter set values cannot be determined by the default value strategy, which implies that the choice of the initial parameter values may significantly impact the parameter identifiability. Beyond that, fixing some parameters, such as the non-influential parameters determined by the local sensitivity analysis, at prior values according to lecture and practical experience can introduce bias to the parameter estimates, which have been reported in pervious investigations (Weijers and Vanrolleghem, 1997; Brun et al., 2001, 2002; Omlin et al., 2001; Brun et al., 2002).

From a practical point of view, the uncertainty analysis of wastewater treatment plant models is particularly important for design and operation decision making, and one of main uncertainty sources is the model input uncertainty, such as characterizing the model parameter values over a reliable range to reflect the limited knowledge of their exact values (Sin et al., 2009). To facilitate the practical application of the hindered-compression settling models by providing a guidance for experiment design, it is important to know which parameters can be obtained under what experimental conditions, and how large the model prediction uncertainties can be. This knowledge can be very beneficial in understanding the uncertainties of SST performance, such as the sludge blanket height (SBH), the recycle solids concentration under wet-weather and sludge settleability deterioration conditions.

The first objective of this paper is to evaluate the parameter identifiability of the hindered-compression model based on different experimental layouts to show which parameter is identifiable in which experimental layout, as well as to study the influence of initial parameter selection on parameter identifiability analysis. The second goal of this paper aims to investigate the influence of the choice of initial parameter values on parameter identifiability and the bias of the parameter estimates caused by fixing unidentifiable parameters. The third part focuses on the model prediction uncertainty analysis by showing how the estimates obtained from different layouts impact the model prediction uncertainty.

2. Materials and methods

2.1. Model structure

Although having a similar rheological basis, most established hindered-compression models can be distinguished by their modeling approach of the compression settling process (Li and Stenstrom, 2014b). In this study, we selected the recently presented Bürger–Diehl model (no hydrodynamic dispersion considered) as an example for identifiability and uncertainty analysis because of its flexibility in application and available implementation details (Bürger et al., 2011, 2013). The frame of the Bürger-Diehl model can be expressed as eq. (1):

$$\frac{\partial C}{\partial t}+\frac{\partial}{\partial x}F(C,x,t)=\frac{\partial}{\partial x}\left(d_{comp}(C)\frac{\partial C}{\partial x}\right)+\frac{Q_f(t)C_f(t)}{A}\delta(t) \quad (1)$$

where C is the solids concentration, t is time, x is deep from the SST bottom, d_{comp} is the compression function, A is SST surface area, Q_f is the feed flow rate, C_f is the feed solids concentration, δ is the Dirac delta distribution, and the solids transport flux F can be written as eq. (2):