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Mathematical modelling of batch sedimentation subject to slow aggregate densification

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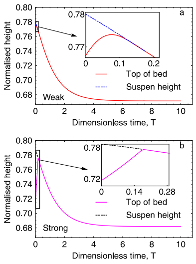
HIGHLIGHTS

- Model presented for suspension batch settling subject to aggregate densification.
- Suspension is assumed to be gelled even before it starts settling/consolidating.
- Unconsolidated/consolidated material boundary readily located for slow densification.
- No unconsolidated material remains once gel point reaches initial solids fraction.
- For weak gels, unconsolidated column height tends to collapse even earlier than this.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper considers an initially networked suspension in a batch settler subjected to very slow aggregate densification. The so-called pseudo-steady state aggregate densification theory developed by van Deventer (2012) has been extended to the case of initially networked suspensions. The solids behaviour and the evolutions of the suspension height and the consolidated bed height in the batch settler have been predicted using the extended pseudo-steady state theory. Different formulae for the weight-bearing strength of the consolidated bed (so-called weak gel and strong gel formulae, which differ near the top of the bed) are considered. The suspension height approaches the consolidated bed height far more quickly when using the weak gel formula than when using the strong gel one. This paper also investigates how the initial feed solids volume fraction and the initial suspension height affect the evolutions of the heights of the suspension and the consolidated bed, as well as the determinations of the solids volume fractions obtained at the bottom of the batch settler. When the initial feed solids fraction is sufficiently large and/or the initial suspension is sufficiently tall, the densification process has little effect on the solids fraction observed at the bottom of the settler.
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1. Introduction

Batch settling under gravity is an elementary solid–liquid separation process, concentrating typically denser solids relative to surrounding less dense liquid (Kynch, 1952). It is important not only in its own right, but also as a technique for extracting suspension rheological properties (Kynch, 1952; Lester et al., 2005; Diehl, 2007; Stickland et al., 2008; Grassia et al., 2008, 2011),

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these properties subsequently being used for designing other solid–liquid separation devices, including continuous thickeners (Landman et al., 1988; Bürger and Concha, 1998; Bürger et al., 1999; Martin, 2004; Usher and Scales, 2005), pressure filters (Landman et al., 1995; Landman and White, 1997), or centrifuges (Berres et al., 2005; Stickland et al., 2006).

Often in batch settling and related dewatering processes, one is dealing with flocculated suspensions (Landman and White, 1994), flocculants being added to the system to bind solids together into aggregates. Such aggregates generally contain a significant amount of liquid in addition to solids. However if the aggregate is sheared (e.g. under the action of a rake, Farrow et al., 2000, and/or by being buffeted by neighbouring aggregates, Spehar et al., 2014), it can undergo a process of *densification*, i.e. the solids in the aggregate bind together more tightly by expelling liquid (Farrow et al., 2000). Shear can therefore have a very significant effect on suspension dewatering (Gladman, 2004; Gladman et al., 2005, 2010).

The end state of the batch settling process (Howells et al., 1990) typically involves a consolidated bed of solid–liquid aggregates networked together, with clear liquor (free of solids) situated higher up. The more tightly the aggregates bind together as a result of densification, the higher the overall solids fraction in the networked bed (overall solids fraction being the product of the solids fraction in the aggregates and the fraction of space filled by them), and hence the better the solid–liquid separation that is achieved.

In addition to affecting the end state of the solid–liquid separation process, shear-induced aggregate densification also affects the rate of achieving that separation. Given that a densified aggregate has the same buoyancy force relative to surrounding liquid as it had prior to densification, but experiences less viscous drag, it therefore settles faster (Usher et al., 2009).

There have been a number of recent studies in the literature attempting a mathematical description of aggregate densification (Usher et al., 2009; van Deventer et al., 2011), and its effects on suspension dewatering processes (Zhang et al., 2013a,b; Grassia et al., 2014). These introduced a so-called densification rate parameter (van Deventer et al., 2011; Zhang et al., 2013a; Grassia et al., 2014), the reciprocal of this rate parameter giving a characteristic time for aggregates to densify. There are, as a result, *three* relevant time scales applicable to solid–liquid separation in a sheared batch settler: a characteristic sedimentation time (i.e. the suspension height divided by the suspension settling speed), the residence time of the suspension in the batch settler, and the aforementioned densification time.

There is a physically meaningful limit corresponding to 'slow shear' (van Deventer, 2012) for which the characteristic sedimentation time is much shorter than either the residence time or the densification time.[1] In this 'slow shear' limit, the suspension dewaters to the equilibrium state of an *undensified* suspension, but then continues to undergo further dewatering through a sequence of 'pseudo-steady states' as densification proceeds, binding solids in aggregates together increasingly tightly, allowing more and more liquid to be expelled.

The pseudo-steady state work of van Deventer (2012), even though it considered the final state of the suspension to be a networked bed (this networked bed being sufficiently strong to bear the suspension's weight), assumed the initial solids fraction to be sufficiently low that aggregates were isolated from one another (i.e. not networked together).

Another situation can however be contemplated: even in the initial state, the solids instead of being isolated from each other could be slightly overlapped. Hence they form a network, albeit a weak one. Situations in which such a state could arise include laboratory characterisation of gelled suspensions and also consolidation in tailings impoundments. Whilst the weak network can bear some weight, it cannot bear the full weight of the suspension that is present, so some consolidation (typically towards the bottom of the suspension) definitely must occur. However some solids (towards the top) remain at the initial solids fraction (Buscall and White, 1987).

Adding shear (and thereby aggregate densification) to the case of an initially networked suspension can now lead to some quite complex behaviours. Since individual aggregates bind together more tightly as they densify, the degree of overlap with neighbours can reduce over time for a given overall solids fraction. Thus as a result of the action of shear, the weight bearing strength of the material decreases (Channell and Zukoski, 1997). Moreover the amount of suspension that is retained at the initial solids fraction without having yet consolidated gradually becomes less, and (depending on the system under consideration) might or might not disappear altogether. The aim here is to explore quantitatively the range of behaviours that can arise for an initially networked suspension subject to aggregate densification in the pseudo-steady state limit.

The remainder of this work is laid out as follows. Section 2 describes the pseudo-steady state batch settling model for networked suspensions incorporating aggregate densification and sets up a number of case studies. Results of these case studies are presented in Section 3. Conclusions are given in Section 4.

2. Model and governing equations

In this section a description is given of the pseudo-steady state batch settling model including the effects of aggregate densification. The discussion is organised as follows. Section 2.1 explains how to determine the pseudo-steady state given the initial suspension solids fraction, the initial height of suspension, and the suspension's rheological material properties. Section 2.2 then details the rheological material properties that must be considered, with two slightly different possible rheologies being discussed. After that Section 2.3 explains how aggregate sizes evolve due to densification. The effects of densification upon the suspension rheological properties are described in Section 2.4. For any given initial solids fractions, the particular rheologies that are assumed, coupled to the initial suspension height, turn out to affect the solids fraction at the bottom of the suspension: this is explained in Section 2.5. Following this, Section 2.6 defines a number of case studies that will be analysed later on in the results section of the paper. For increased generality, case study results will be presented in dimensionless form using a set of conversions outlined in Section 2.7.

More information about the models and underlying assumptions can be found in Usher et al. (2009), van Deventer et al. (2011), Zhang et al. (2013a,b), and Grassia et al. (2014).

2.1. Pseudo-steady state suspension

An initially uniform networked suspension (at an initial 'feed' solids volume fraction ϕ_f) that settles to (pseudo-)steady state generally consists of a consolidated bed with solids fraction $\phi > \phi_f$ below, a clear liquor zone (with no solids) above, and a column of unconsolidated material (still with $\phi = \phi_f$) retained between the two: see Fig. 1.

The (pseudo-)steady state network stress in the suspension P_s satisfies

$$\frac{\partial P_s}{\partial z} + \Delta\rho\, g\, \phi = 0 \qquad (1)$$

where $\Delta\rho$ is the density difference between solid and liquid (chosen to be 2200 kg m^{-3} here), g is the gravity acceleration (9.8 m s^{-2}) and

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[1] Such a limit could not normally be contemplated in another device such as a continuous thickener (Usher and Scales, 2005), because for a thickener, characteristic sedimentation time and the residence time in the device tend to be comparable (by design).

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