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Hindered settling of mud flocs: Theory and validation

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Abstract

This paper deals with settling of highly concentrated cohesive sediment suspensions. We evaluate a new hindered settling formula. New settling experiments on these highly concentrated suspensions are described to test this formula. For the analysis of the experiments both an analytical and a numerical method are used. Kynch's analytical theory, based on the method of characteristics is used to study the type of settling. Furthermore, a 1DV-point model is used for analysis of the settling process. We have implemented the new hindered settling formula in this model, which is tested against experimental data. It is concluded that the data are described fairly well. The analysis with the theory of Kynch [1952. A theory of sedimentation. Transactions of the Faraday Scociety 48, 166–176] and the model show that highly concentrated suspensions can settle with either one interface or with two interfaces, depending on the initial concentration and the shape of the settling flux function.

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1. Introduction

In the past decades knowledge on the properties and behaviour of cohesive sediment has increased gradually, motivated by the awareness of the importance of cohesive sediments in the ecosystem, amongst other things. It was understood that cohesive sediment has important properties, such as its ability to adhere heavy minerals and other contaminants, and the fact that it may contain a high amount of organic material, a source of food for many organisms.

Much research has been carried out on the settling of low-concentration mud suspensions and on consolidation. Been (1980) and Sills (1997), amongst others, performed experiments on settling and consolidation of natural mud, and Merckelbach (2000) developed a consolidation model that was validated against experiments with natural mud. In contrast, little research has been published on the

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settling behaviour of highly concentrated mud suspensions in general, and on the behaviour of highly concentrated mud–sand mixtures in particular. Yet, this is an important subject when studying, for instance, the transport and fate of dredging plumes and their effect on the ecosystem, and the siltation of navigation channels and harbour basins. The lack of proper understanding of hindered settling and its modelling is partly due to a lack of proper data.

In this paper, we report on the behaviour of highly concentrated mud suspensions only; mud–sand mixtures are treated in another paper. The goal of this research was to create a data set on the settling of highly concentrated mud suspensions, to describe and analyse their behaviour with Kynch's (1952) theory on hindered settling, and to develop a model for settling suspensions in the hindered settling regime. To reach this goal, experiments on highly concentrated cohesive sediment suspensions have been performed in the Environmental Fluid Mechanics Laboratory at Delft University of Technology. In this paper, we attempt to analyse the behaviour of these suspensions with the method of characteristics, a well known method for settling suspensions. Next, a 1DV model is used for further analysis of the experiments. The model consists of two parts, one for the mud fraction and the other for the sand fraction. Here, only the part of the model that describes the settling of highly concentrated mud suspensions is used.

2. Theories on hindered settling

2.1. Kynch's theory

A single particle or floc settling in still water has a specific settling velocity ($w_{s,0}$), which is a function of its shape, size, density and the viscosity of the fluid. When the concentration of particles increases, they start to interfere and hinder each other, thereby reducing their settling velocity. This is called hindered settling and the settling velocity is referred to as the effective settling velocity (w_s). When the concentration increases further, the particles tend to be in constant contact with each other, and a particle framework builds up. The change from a water supporting system to a sediment supporting system is called gelling and the gelling concentration (c_{gel}) is the concentration of the suspension at that point. Also, from this point early consolidation starts, water is squeezed out and effective stresses become measurable. Hindered settling of cohesive sediment flocs occurs when mass concentrations are larger than a few kg/m^3 (Mehta, 1986).

The theory of sedimentation of highly concentrated suspensions was first studied by Kynch (1952) and elaborated by, amongst others, Kranenburg (1992). Kynch (1952) introduced an empirical relationship between the effective settling velocity and the local sediment concentration (herein the local volumetric sediment concentration of the solids $\phi = c/c_{gel}$ is used), assuming that everywhere in the suspension the settling velocity of particles depends on the local concentration of particles only:

$$w_s = w_{s,0} f(\phi). \tag{1}$$

Here $w_{s,0}$ is the settling velocity of a single particle in still water in a Eulerian reference frame, positive downward, and $f(\phi)$ is a function that describes the effect of the concentration on the settling velocity, i.e., $f(0) = 1$ and $f(1) = 0$. Hence, the following 1-D vertical volume balance is derived:

$$\frac{\partial \phi}{\partial t} + w_{s,0} F(\phi) \frac{\partial \phi}{\partial z} = 0, \tag{2}$$

where

$$F(\phi) = \frac{\mathrm{d}}{\mathrm{d}\phi}[\phi f(\phi)] \tag{3}$$

and where t is time and z is the vertical coordinate, positive downwards. Eq. (2) is a 1-D simple wave equation, which is hyperbolic and its solution allows for the formation of shocks, also called interfaces. It can be solved by integrating along characteristic lines, i.e. lines of equal concentration (ϕ), in the (z, t) plane. These lines are given by

$$\frac{\mathrm{d}z}{\mathrm{d}t} = w_{s,o} F(\phi) = C_c, \tag{4}$$

where C_c is the celerity (wave speed). The position of the characteristics in time t is given by

$$z(t) = z_0(\phi) + w_{s,0} F(\phi) t, \tag{5}$$

where $z_0(\phi)$ represents the initial height of a specific concentration or characteristic. Two characteristic lines converge if $\mathrm{d}z/\mathrm{d}z_0$ decreases with time. Differentiating Eq. (5) gives

$$\frac{\mathrm{d}z}{\mathrm{d}z_0} = 1 + w_{s,0} \frac{\mathrm{d}F}{\mathrm{d}\phi} \frac{\mathrm{d}\phi}{\mathrm{d}z_0} t. \tag{6}$$

If the concentration increases with depth ($\mathrm{d}\phi/\mathrm{d}z_0 > 0$), and as an interface develops when characteristic paths converge, Eq. (6) implies that an interface in a settling suspension will develop when