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Modelling the role of self-weight consolidation on the morphodynamics of accretional mudflats

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ABSTRACT

We develop a consolidation module and merge it into a morphodynamic model to assess the role of consolidation on estuarine morphodynamics. We test the model using two settings: point models without hydrodynamic forcing to validate against two benchmark experimental datasets; and a profile model to simulate a mudflat restoration. The modelled self-weight consolidation influences the simulations by gradually reducing the bed level and decreasing the bed erodibility (i.e., increasing the critical bed shear stress). Both effects modify sediment transport processes on mudflats, leading to long-term morphodynamic effects. Depending on the initial bathymetry, the hydrodynamic forcing and the soil properties, the simulated morphological change of the restored mudflat may differ considerably with and without considering consolidation. The consolidation model developed can be utilised to assess the medium to long term effects related to estuarine development (e.g., wetland restoration) and aims to be a publicly available tool.

Software availability

Name: Consolidation module within Delft3D framework
Developers: Zeng Zhou, Mick van der Wegen, Bert Jagers and Giovanni Coco
Contact information: zhouzeng.cn@gmail.com
Hardware required: General-purpose computer
Software required: Microsoft Visual Studio 2010 and Intel Fortran Complier 11.1 (or higher)
Programming language: Fortran 90
Availability: The module is open-source and can be accessed via the repository of Deltares (http://oss.deltares.nl/). Contact the developers for details.

1. Introduction

Intertidal mudflats are commonly observed in sheltered coastal and estuarine environments where fine-grained sediment can be accumulated (Kirby, 2000; Friedrichs, 2011). Mudflats are of great importance when assessing nutrient cycling and provide a habitat to numerous coastal fauna and flora (Fagherazzi et al., 2013). Located at the land-sea boundary, intertidal flats also act as a crucial natural buffer against coastal flooding and erosion. However, a considerable amount of mudflats and wetlands worldwide have been reclaimed for their socio-economic benefits (e.g., agriculture, urban development and recreation). As an example, China transformed approximately 1.2 million ha of coastal wetlands accounting for roughly 55% of the total wetlands of the country, into other land uses between 1949 and 2002 (Cao and Wong, 2007). Extensive reclamation of intertidal mudflats can significantly alter the hydromorphodynamic and ecological processes of mudflat functioning and subsequently lead to environmental degradation and resource deterioration (Wang and Wall, 2010). Therefore, recent research and public awareness highlight an increasing need for the restoration and de-reclamation of intertidal mudflats and coastal wetlands (Elliott et al., 2007).

The morphodynamics of mudflats are governed by feedbacks between a variety of processes operating over different temporal and spatial scales (Coco et al., 2013). Tidal currents and waves are the two major hydrodynamic processes acting on intertidal flats

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and their individual influences have been demonstrated both analytically and numerically (Friedrichs and Aubrey, 1996; Friedrichs, 2011; Roberts et al., 2000). It is found that net import and export of sediment are favoured by the relative dominance of tidal currents and waves, respectively. Besides, numerical modelling shows that abundant sediment supply results in the seaward advance of tidal flats (e.g., Pritchard et al., 2002; van der Wegen and Jaffe, 2014). Depending on the local meteorological and landscape settings, intertidal mudflats may also be influenced by storms and fluvial discharge (Bartholdy and Aagaard, 2001; Schuerch et al., 2013; Zhou et al., 2014a) and by biophysical interactions (e.g., Murray et al., 2008; Fagherazzi et al., 2013).

However, despite being a common process in cohesive mudflats, self-weight consolidation has received limited attention. Self-weight consolidation can be defined as the process in which a reduction in volume takes place by expulsion of pore water. Referring to a typical sedimentation-consolidation framework (Kynch, 1952; Dankers and Winterwerp, 2007), consolidation starts during the permeability regime particularly when the gelling volume concentration (ϕ_{gel}) is reached. The process continues during the effective stress regime in which sediment particles interconnect and further compression occurs, and finally stops when a certain maximum volume concentration (ϕ_{max}) is attained (Fig. 1). Consolidation is mainly considered to occur for cohesive sediments while existing studies indicate that an addition of small amount of sand may enhance the consolidation process and hence highly affects the overall behaviour depending on the mineralogical and chemical composition of the mixed sediments (e.g., Torfs et al., 1996).

Inspired by laboratory settling column tests, a variety of methodologies have been developed to describe self-weight consolidation. Gibson et al. (1967) proposed a comprehensive one-dimensional vertical (1DV) framework to simulate the consolidation of saturated clay and the method is generally considered to be the state-of-the-art for engineering applications. Many researchers followed and subsequently extended this theory, particularly in terms of the constitutive relations for the hydraulic permeability and the effective stress to close the equations (Toorman, 1996, 1999; Merckelbach and Kranenburg, 2004a; Winterwerp and van Kesteren, 2004; Chauchat et al., 2013; Van and Van Bang, 2013). These constitutive relationships were critical to make reasonable predictions. Owing to the micro scale and inhomogeneity of the soil structure, they were generally formulated via (semi-)empirical functions which lacked a satisfactory theoretical base. Using various constitutive relations to simulate the same consolidation experiment, different researchers reported distinctively different

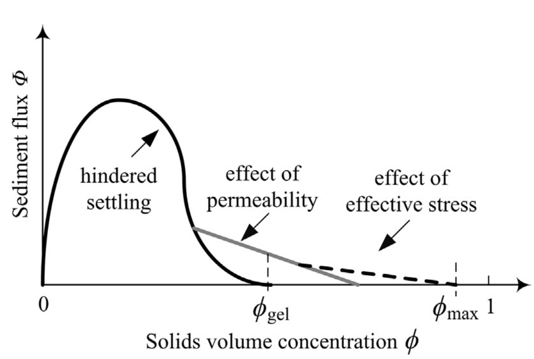

Fig. 1. Schematic view of the three main regimes in a sedimentation-consolidation experiment based on the relation between sediment flux Φ and volume concentration ϕ (see e.g., Kynch, 1952; Dankers and Winterwerp, 2007), modified from Dankers and Winterwerp (2007).

model results (Bartholomeeusen et al., 2002). In order to enhance the physical soundness, Merckelbach and Kranenburg (2004a) derived constitutive relations on the basis of a scale-invariant structure of the soil and a good agreement was reported for their validations against measured data.

Most of the existing approaches have only been implemented in a 1DV framework and only in sporadic cases they have been merged into morphodynamic models (Waeles et al., 2008; Villaret et al., 2010). Using a relaxation method towards a vertical equilibrium density profile (also adopted by Sanford, 2008), Waeles et al. (2008) was able to include the consolidation effect in a numerical model to simulate the morphological behaviours of the Seine estuary, France. The parametrised consolidation module was calibrated with the experimental consolidation tests using mud samples from the southern part of the Seine estuary and then merged into the morphodynamic model, but the effect of consolidation could not be clearly seen in the results since simulations without the consolidation module were not presented. In order to include the consolidation process into a finite element morphodynamic model (TELEMAC), Villaret et al. (2010) compared three potential 1DV consolidation modules from the perspective of physical soundness and numerical robustness, and suggested that the method of Thiebot et al. (2011) could be the most appropriate. Van (2012) applied the model to investigate the morphodynamics of the Gironde estuary, France. Model results of net bed erosion/deposition after one year of simulation differed considerably, with and without consolidation. The author suggested that both erosion and deposition might be over-estimated when the consolidation process was not included.

Though some preliminary results were shown, the above mentioned short-term simulations were not able to provide a comprehensive understanding of the consolidation effect on large-scale and long-time morphodynamic evolution of estuarine systems. Most of the existing state-of-the-art morphodynamic models do not take consolidation into account when treating bed dynamics. However, consolidation plays a role in morphodynamics of estuarine systems at least in two ways: (1) gradually increasing the bed resistance towards erosion, and (2) reducing the bed level. These effects can influence the flow field and the sediment transport processes which feedback into morphological evolution. Therefore, it remains elusive whether consolidation can be neglected or not, especially for long-term morphological simulations.

In this study, we develop a Gibson-type consolidation module extending the work of Merckelbach and Kranenburg (2004a) and merge it into a state-of-the-art morphodynamic model (Delft3D). The specific research questions we try to address include: (1) What are the parameters governing the mechanism of self-weight consolidation on intertidal mudflats? (2) How does consolidation affect the long-term morphodynamic evolution of intertidal mudflats? and (3) Can consolidation be neglected in morphodynamic models or under what conditions can it be neglected? By exploring these research questions, we aim to gain more in-depth knowledge of consolidation and its influence on estuarine morphodynamics. From a practical standpoint, insights obtained from this research can also assist the decision-making and long-term management of the intertidal mudflat reclamation and restoration.

2. Methods

The consolidation module is developed within the framework of an open-source morphodynamic model Delft3D (Lesser et al., 2004; van der Wegen and Roelvink, 2008). In the following section, we first briefly introduce the morphodynamic model (Delft3D) and then describe in detail how the consolidation module