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Modelling the morphodynamic impact of offshore sandpit geometries

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ABSTRACT

We investigate the hydrodynamic effects and morphodynamic impact of large-scale offshore sand extraction, for a variety of pit designs. We use a process-based idealized model for flow, sediment transport and bed evolution in a tide-dominated environment. Legislation and other practical considerations motivate our assumption that sandpits are both wide (horizontal dimensions of the order of kilometres) and shallow (the ratio of pit depth to water depth being small). This results in a semi-analytical tool that, unlike previous studies, enables a quick and extensive study into the effects of varying the physical characteristics as well as the pit design parameters. These parameters include pit length, width, and orientation with respect to the tide.

The model results show that sandpits experience flow contraction, which is enhanced by friction–topography interactions and also affected by Coriolis effects. As a result, sandpits trigger the morphodynamic instability associated with the formation of large-scale bed features known as tidal sandbanks. It implies a gradual deepening and deformation of the pit itself, as well as the appearance of adjacent humps. The time scale of this behaviour is of the order of decades to centuries.

A sensitivity analysis is then carried out to determine the effects of pit geometry on the model results. The morphodynamic response is found to be strongest for sandpits elongated in the preferred direction of sandbank formation (giving the largest area of morphodynamic influence), and weakest for pits perpendicular to this direction. The migration of the pit is shown not to depend on the pit geometry, but rather on the ambient flow conditions.

1. Introduction

Shallow shelf seas like the North Sea are increasingly used as a source of sand (Hoogewoning and Boers, 2001; Harrison, 2003). For example, the land reclamation for the planned extension to Rotterdam Mainport in the Netherlands requires approximately 340 mm^3 sand, to be extracted from the Netherlands Continental Shelf. However, large-scale sand extraction may impact hydrodynamics, morphology, ecology and coastal safety. Potentially adverse effects are of concern to the authorities in charge of sand extraction policy and responsible for issuing the permits. In this study, we focus on the long-term impact of large-scale sand extraction on the morphology of the seabed, i.e. the pit itself as well as its surroundings. Such an intervention affects the dynamic interplay among hydrodynamics, sediment transport and seabed topography (known as the *morphological loop*).

Many aspects play a role in assigning locations for sand extraction. Recent legislation regarding sand extraction from the Netherlands Continental Shelf prohibits mining landward of the established 20 m depth contour (MSL), except for near-shore navigation channels, and defines a maximum pit depth of 2 m. For extraction projects exceeding 10 mm^3, the restriction on pit depth has recently been dropped, while additional legal constraints exist (Hommes et al., 2007). Other constraints deal with the availability of the desired type of sand, technical limitations of the dredging vessels and possible interference with other activities and values in the North Sea. Once the location has been fixed, there are still several degrees of freedom, related to the size and shape of the extraction area, as well as its orientation with respect to the flow.

Past research on the morphodynamic effects of large-scale sand extraction in tide-dominated offshore areas mainly consisted of process-based model studies, distinguishing between trenches and pits. Trenches (or navigation channels) are characterized by a length that is much larger than the width, justifying the assumption of spatial uniformity along the trench's longitudinal axis. For perpendicular tidal flow, continuity dominates the hydrodynamics (Van de Kreeke et al., 2002; Walstra et al., 2002b; Ribberink, 2004), whereas obliquely approaching flow experiences a refraction pattern over the trench (Jensen et al., 1999a). Morphodynamically, trenches at large angles to the flow are found to display migration rates of several metres per year, as well as damping and widening (alternatively referred to as infilling). In shallower areas, surface waves accelerate the morphodynamic process, without affecting the qualitative behaviour (Ribberink, 2004).

The geometry of a sandpit, on the other hand, is constrained in both horizontal directions, which gives rise to *flow contraction*, i.e. an

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increased water flux over the pit (Ribberink, 1989; Labeur, 1998; Klein, 1999; Walstra et al., 2002a). The morphodynamic evolution displays migration and a gradual deformation of the pit (Ribberink, 1989; Klein, 1999; Walstra et al., 2002a). It is recognized that both hydrodynamics and morphodynamics depend on the pit geometry. However, the large computational effort involved in conducting an extensive set of long-term runs for a variety of pit designs has so far prevented a detailed investigation of this topic.

Finally, the interaction between a sandpit and the morphodynamics of existing large-scale bed forms is a largely unexplored topic. De Swart and Calvete (2003) showed that, after dredging a shore-normal trench, shoreface-connected ridges tend to recover, a process which attracts sand from both the outer shelf and the near-shore zone. Roos and Hulscher (2007) showed that the recovery of tidal sandbanks after a local removal of sand attracts sediment from the surrounding banks. In the following, the presence of existing large-scale bed forms is ignored.

The goal of this paper is to investigate the initial morphodynamic effects of large-scale sand extraction, with a particular focus on the role of pit geometry. Motivated by legislation and other practical considerations mentioned above, we consider sandpits of a few metres depth with horizontal dimensions of the order of kilometres, created in an offshore and tide-dominated environment. In terms of dimensions and environment, the pits resemble inverted tidal sandbanks, suggesting that the hydrodynamic and morphodynamic processes around these large-scale bed forms (Zimmerman, 1981; Huthnance, 1982a,b; De Vriend, 1990; Hulscher et al., 1993) may apply to sandpits, as well (Roos and Hulscher, 2003). We follow an idealized process-based modelling approach based on Hulscher et al. (1993), linearizing with respect to the ratio of pit depth and water depth. The resulting semi-analytical tool enables a quick and extensive study into the effects of varying the physical characteristics as well as the pit design parameters. To facilitate the quantitative comparison among the different settings, we introduce the following pit indicators:

- degree of flow contraction
- pit migration
- area of morphodynamic influence.

This approach is closely linked to the concept of Coastal State Indicators (Van Koningsveld et al., 2005; Hommes et al., 2007).

This paper is organized as follows. In Section 2, the morphodynamic model is introduced, paying particular attention to the pit geometry, the physical mechanisms and the solution method. Section 3 contains the results, in which we present the qualitative behaviour, define the three pit indicators and investigate the sensitivity to pit design parameters. Finally, Sections 4 and 5 contain the discussion and conclusions, respectively.

2. Morphodynamic model

2.1. Pit geometry

Consider an offshore part of a shallow sea, far away from coastal boundaries, with a typical water depth H of about 25 m, dominated by M2-tidal flow conditions with a typical maximum depth-averaged velocity U=1 m s^{-1} (and an angular frequency $\sigma\sim 1.41\cdot 10^{-4}$ rad s^{-1}). We define a coordinate system with horizontal coordinates $\boldsymbol{x}=(x, y)$, in which the x-direction coincides with the principal direction of the tidal flow. The z-axis points upward from mean sea level, with the free surface located at $z=\zeta$.

We consider a sandpit as a local perturbation of an otherwise flat seabed of uniform depth H. As depicted in Fig. 1, the pit shape is modelled roughly as a rectangular box of length L, width B (of the order of kilometres) and depth $H_{\rm pit}$, assumed small compared to the

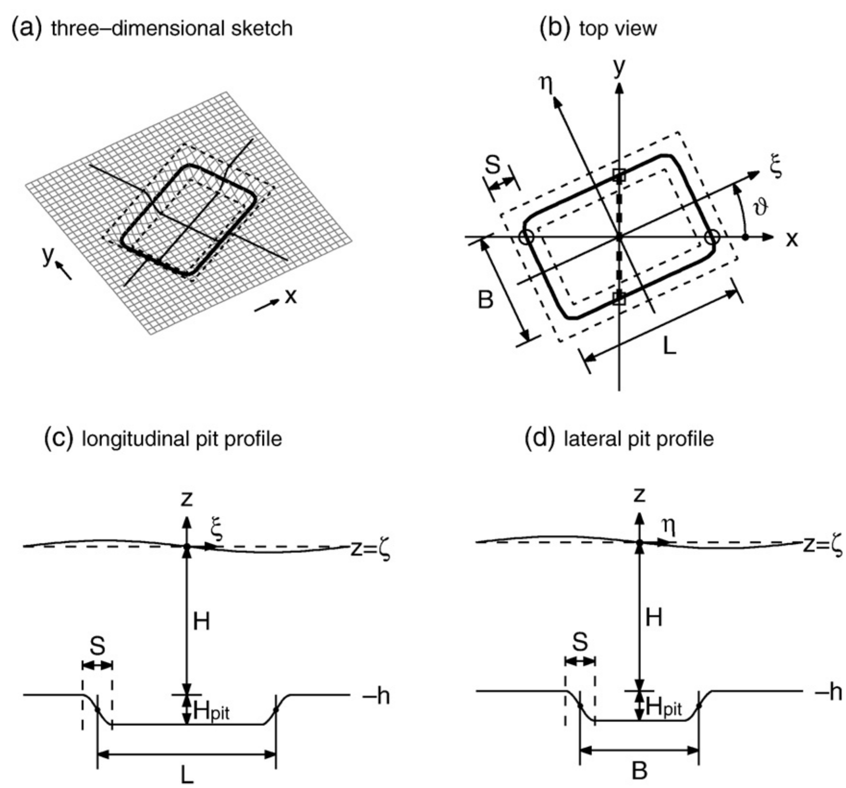

Fig. 1. Pit geometry: (a) three-dimensional sketch, (b) top view, (c) longitudinal pit profile along ξ-axis, (d) lateral pit profile along η-axis. The pit has length L, width B, depth $H_{\rm pit}$, orientation ϑ and a horizontal slope length S. The thick solid line is the contour where the pit depth equals $\frac{1}{2}H_{\rm pit}$. The flux across the thick dashed line in b will be used to quantify the degree of flow contraction. Note: the vertical scale has been strongly exaggerated with respect to the horizontal scale.