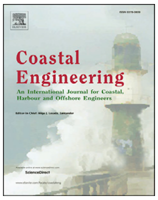
Coastal Engineering 136 (2018) 56–64

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng



Modelling the effect of suspended load transport and tidal asymmetry on the equilibrium tidal sand wave height

W. van Gerwen [a,b,*], B.W. Borsje [a], J.H. Damveld [a], S.J.M.H. Hulscher [a]

[a] *Water Engineering and Management, University of Twente, Enschede, The Netherlands*
[b] *Hoogheemraadschap Hollands Noorderkwartier, Heerhugowaard, The Netherlands*

ARTICLE INFO

Keywords:
Morphodynamic modelling
Tidal sand waves
Equilibrium height
Delft3D
North Sea

ABSTRACT

Tidal sand waves are rhythmic bed forms found in shallow sandy coastal seas, reaching heights up to ten meters and migration rates of several meters per year. Because of their dynamic behaviour, unravelling the physical processes behind the growth of these bed forms is of particular interest to science and offshore industries. Various modelling efforts have given a good description of the initial stages of sand wave formation by adopting a linear stability analysis on the coupled system of water movement and the sandy seabed. However, the physical processes causing sand waves to grow towards equilibrium are far from understood. We adopt a numerical shallow water model (Delft3D) to study the growth of sand waves towards a stable equilibrium.

It is shown that both suspended load transport and tidal asymmetry reduce the equilibrium sand wave height. A residual current results in asymmetrical bed forms that migrate in the direction of the residual current. The combination of suspended load transport and tidal asymmetry results in predicted equilibrium wave heights comparable to wave heights found in the field.

1. Introduction

The bed of shallow shelf seas inhabits regular bed forms of various sizes. The largest of these bed forms are tidal sand waves and tidal sand banks, with wave lengths in the order of hundreds of meters to several kilometers, respectively. Sand banks are up to tens of meters in height. They are less dynamic than sand waves; the migration rate of sand banks is an order of magnitude smaller than the migration rate of sand waves (Dyer and Huntley, 1999). This makes them of less interest to offshore operations. Sand waves are observed in many tide-dominated sandy shallow shelf seas like the North Sea, Bisanseto Sea, Irish Sea, the shelves off the coast of Spain and Argentina, and in many straits and tidal inlets around the world (Van Santen et al., 2011). Typical migration rates for sand waves are in the order of 1–10 m/year, and can go up to tens of meters in areas with strong tidal currents (Knaapen, 2005). The height of sand waves is in the order of meters (typically 1–10 m), and the typical growth rate is in the order of 0.1 m/year. See Table 1 for an overview of sand wave characteristics. Examples of several sand wave fields at different locations in the North Sea are shown in Fig. 1.

The dimensions and migration of sand waves makes understanding their dynamic behaviour of particular importance to offshore activities. For instance, sand waves can affect the navigation depth as well as the stability of offshore platforms, pipelines and wind turbines, as pointed out by Németh et al. (2003). Knowledge about seabed dynamics could improve the design and increase the interval between surveys, so costs are reduced (Dorst et al., 2013). Therefore, coastal managers are in need for tools to formulate design criteria for offshore operations.

The formation of sand waves is explained as follows (Hulscher, 1996): sand waves are generated by small perturbations of the seabed that cause flow alterations. Considering continuity, the flow on the stoss side of the perturbation accelerates as a result of decreasing water depths, whereas on the lee side the flow decelerates as a result of increasing water depths. Because of the oscillating behaviour of the tide, this happens in both directions, causing residual circulation cells when looking at tide-averaged flow values. This results in a net transport of sediment towards the crest. Gravity causes transport from crest to trough, and acts as opposing factor. It is the balance between these two processes that determines the preferred wave length.

Various modelling studies have increased our understanding of sand wave dynamics, where a clear distinction can be made between linear and non-linear models. Linear stability models are used to predict the initial stages of formation of small-amplitude sand waves. The model approach introduced by Hulscher (1996) was later extended by Gerkema (2000); Komarova and Hulscher (2000); Besio et al. (2003). Tidal

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* Corresponding author. Water Engineering and Management, University of Twente, Enschede, The Netherlands.
E-mail address: wietsevangerwen@gmail.com (W. van Gerwen).

https://doi.org/10.1016/j.coastaleng.2018.01.006
Received 15 March 2017; Received in revised form 15 December 2017; Accepted 21 January 2018

Table 1
Tidal sand wave characteristics from field measurements.

Source	Location	Wave length [m]	Wave height [m]	Growth rate [m/year]	Migration rate [m/year]
McCave (1971)	North Sea	200–500	2–7	–	–
Besio et al. (2004)	North Sea	120–500	2–10	–	1–8
Németh et al. (2007)	Gulf of Cadiz	150–300	2–4	–	–
Cherlet et al. (2007)	North Sea	240–860	2–6	–	–
Van Santen (2009)	North Sea	150–800	1–9	–	–
Dorst et al. (2011)	North Sea	400–700	–	–	0–7
Van Dijk et al. (2011)	North Sea	100–800	1–10	0.16	0–40
Van Oyen et al. (2013)	North Sea	100–760	0.5–5	–	–

asymmetry was investigated by Németh et al. (2002); Besio et al. (2004) and a depth dependent eddy viscosity with a no-slip condition at the bed was introduced by Blondeaux and Vittori (2005a, b); Besio et al. (2006). Roos et al. (2007) and Van Oyen and Blondeaux (2009) looked into grain sorting and Borsje et al. (2009) investigated the effect of benthic species on the preferred sand wave length. These models predict the stability of small perturbations superimposed on a flat bed, looking at different wave lengths. The perturbations that show positive growth rates are unstable, whereas the perturbations that decay are stable. The perturbation with the largest positive growth rate is titled the fastest growing mode (L_{FGM}). This mode is assumed to prevail due to the weak non-linearity of the system (Dodd et al., 2003). These modelling studies show fair agreement with field data on wave length, migration rate and crest orientation.

To reach an equilibrium height, sand wave growth needs to reduce in time, for which non-linear terms need to be introduced. This is done in non-linear models, which are an add-on to the linear models (e.g. Németh et al., 2006, 2007; Van den Berg et al., 2012). Calculations in these models are done on a domain with the length equal to the L_{FGM}, this is done to prevent the growth of very long sand waves that would otherwise fill the domain, which is physically incorrect (Van den Berg et al., 2012). With this restriction, these type of models can predict growth towards a stable equilibrium. Sterlini et al. (2009) found that a residual current decreased the height significantly. However, these equilibrium heights were still larger than field observations.

Recently, a numerical shallow water model (Delft3D) has been used to predict the initial stages of sand wave formation (Borsje et al., 2013, 2014). This model enables the investigation of sand wave growth without the restriction of a domain with the length of the fastest growing mode, because the growth of very long sand waves is suppressed. This is achieved by the combination of an advanced turbulence model and suspended load transport (Borsje et al., 2014).

Despite all these studies, so far no model was able to reconstruct realistic equilibrium heights for sand waves. Therefore, the aim of this paper is to uncover the physical processes influencing the growth and equilibrium height of sand wave fields. This is done by using the numerical shallow water model (Delft3D) as presented in Borsje et al. (2013), running it for long periods of time and adding complexity in transport processes (including suspended load transport) and hydrodynamics (including tidal asymmetry via imposing a residual current to the symmetrical tide).

Section 2 describes the model set-up. The modelled influence of suspended load sediment transport and residual current strength on the equilibrium height are then presented in section 3. The model set-up and results are discussed in section 4, followed by the conclusions in section 5.

2. Sand wave model description

The growth of sand waves is modelled using the numerical shallow water model Delft3D (Lesser et al., 2004). Using this model, Borsje et al. (2013) modelled the initial stages of sand wave formation, which they later extended by including suspended load transport in Borsje et al. (2014). Here, we limit ourselves to a summarized model description and refer the interested reader to Borsje et al. (2013, 2014) for a more detailed model description.

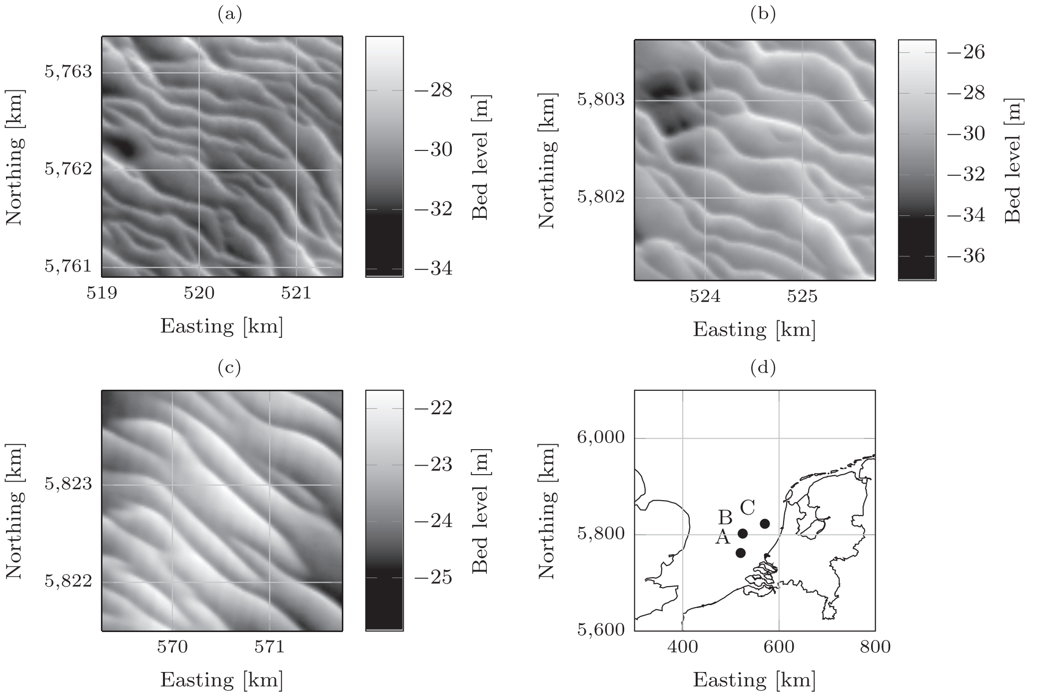

Fig. 1. Examples of sand wave fields (a, b, c) with its geographical location in the North Sea (d).