

Comparing field observations of sorting patterns along tidal sand waves with theoretical predictions

T. Van Oyen⁽¹⁾, P. Blondeaux⁽²⁾ and D. Van den Eynde⁽³⁾

1. Department of Civil Engineering, Ghent University, Technologiepark 904, B-9052, Ghent, Belgium

2. Department of Civil, Environmental and Architectural Engineering, University of Genoa, Via Montallegro 1, 16145 Genova, Italy

3. Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Gulledele 100, B-1200 Brussels, Belgium

Abstract

We present a site-by-site comparison between field observations and model predictions of grains size variations over tidal sand waves at six sites in the North Sea. To drive the model, at each location, local sediment characteristics are derived from the described field data, while hydrodynamic conditions are determined from a numerical model for tidal wave propagation in the North Sea. It is found that the theoretical model provides reasonable estimates of the occurring tidally generated bed forms. Moreover, at five of the six locations, the model describes a sorting pattern which concurs with the observed sediment grain size variation, indicating that the model provides a fair description of the processes governing the phenomenon.

1. INTRODUCTION

Tidal sand waves are prominent bed features observed in many coastal seas where an abundance of sand is present and tidal currents are dominant (macro-tidal conditions), e.g. the North Sea, San Francisco Bay, (Terwindt, 1971; Barnard *et al.* 2006). The bed features are characterized by a regularly undulating bottom profile, with crest-to-crest distances between 100 and 1000 m and with crest lines organized approximately orthogonal with the dominant direction of the tidal current. The amplitude of tidal sand waves can grow up to a few meters, and the bed forms are found to be able to migrate, with speeds up to tens of meters a year (van Dijk and Kleinhans, 2005). Consequently, the bed forms are hazardous for pipe lines and navigation channels such that a clear understanding of their dynamics is required to derive a long-term management strategy of the coastal zone.

The mechanism leading to the generation of tidal sand waves was first described by Hulscher (1996); and later on by Gerkema (2000), and Besio *et al.* (2006). These studies reveal that the formation of the bed forms is controlled by the interaction between the periodic tidal flow field and the wavy bottom topography which leads to a steady component of the flow directed from the troughs to the crests of the bed forms; dragging thus sediment from the bottom towards the top. Sediment, on the other hand, is transported down slope due to gravitational effects. The occurrence of the phenomenon is thus a balance between both mechanisms.

Field observations reveal striking sediment sorting patterns over tidal sand waves (Van Lancker and Jacobs, 2000; Roos *et al.*, 2007).

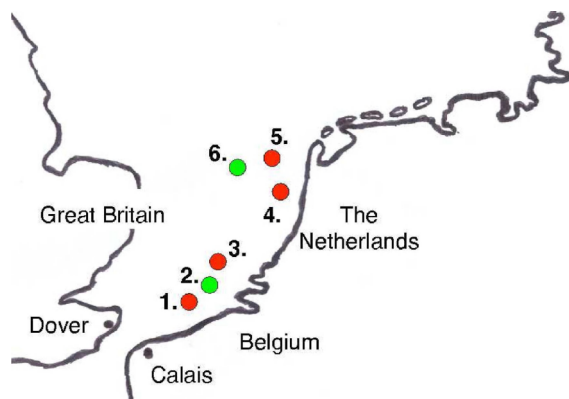


Figure 1. Illustration of the locations of the sites described by Van Lancker & Jacobs (2000) and Roos *et al.*, (2007), respectively number 1 and numbers 2 to 6. The green (red) dots indicate a site where a fining (coarsening) of the sediment towards the crest is observed.

Intriguing, however, these patterns are not persistent; i.e. at some locations, coarser grains are found at the crest while at others, measurements reveal a reverse pattern, see figure 1.

A first study on this phenomenon was conducted by Roos *et al.*, (2007), on the basis of a numerical model for sand wave evolution (van den Berg & van Damme, 2005), resulting in a coarsening of the crest of the bed form. Van Oyen & Blondeaux (2009a,b) also analyzed the process leading to the sorting of grain sizes, using the approach introduced by Besio *et al.* (2006). These studies suggest that the apparently conflicting observations could be the result of two mechanisms which, combined, govern the grain size distribution. The first mechanism follows from a balance between reduced mobility, favoring the transport of finer grains and prevailing for moderate tidal currents; and hiding/exposure effects which enhances the transport of coarse grains for strong tidal currents. The second mechanism occurs only for strong tidal currents and results from the different tidal excursion lengths for distinct grain sizes and can reverse the sorting process, see Van Oyen and Blondeaux (2009b).

To validate the theoretical model, Van Oyen and Blondeaux (2009b) compared model results with three locations in the North Sea. Here, we extend this comparison with three additional sites such that a more clear picture can be derived on the performance of the model.

In the next section, the model of Van Oyen and Blondeaux (2009b) is summarized for the self-consistency of the present work after which the data (Section 3) and the results (Section 4) are described. Conclusions are formulated in Section 5.

2. MODEL

A three-dimensional model (Blondeaux and Vittori, 2005a,b) is adopted to describe the tidally induced flow field related to the M2 component. The model is governed by continuity and momentum conservation, taking into account the Coriolis force. Reynold stresses are described by introducing a scalar eddy viscosity which is time-independent, though varies in the vertical as suggested by Dean (1974). The following boundary conditions are considered:

- (i) No-slip condition at the bottom boundary.
- (ii) Vanishing of shear stresses and kinematic boundary condition at the free surface.

Using the model introduced by Blondeaux and Vittori (2005a,b), the flow field is determined once the magnitude of the maximum depth averaged flow velocity during the tidal cycle u , the local depth h , the geometric mean grain size d and the eccentricity (i.e. the ratio between the minor and major axis of the tidal ellipse) is specified.

The heterogeneity of the bottom composition is described by considering a number of grain size classes, each with a certain probability of occurrence. Sediment fluxes, of each grain size class n , during the tidal cycle are evaluated by considering both sediment transport in suspension ($q_{s,n}$) and bedload transport ($q_{b,n}$). The latter is calculated following the empirical relation provided by van Rijn (1984a,b), modified to account for slope effects. Suspended sediment transport is evaluated by evaluating the flux of sediment concentration in suspension, which, in turn is governed by an advection –diffusion equation, see Van Oyen & Blondeaux (2009b) for details. Both the bedload and suspended load transport are adjusted to capture the influence of hiding effects, following Ashida and Michiue (1972), and reduced mobility effects.

To describe the evolution of the bed profile, we adopt the active layer approach, as proposed by Hirano (1971), which considers a top layer of the bed (with thickness L_a) in which the sediment is

well mixed and instantaneously available for transport. Hence, for each grain size class n it follows that

$$(1 - s) \left\{ -p_n \frac{\partial}{\partial t} (h + L_a) + \frac{\partial}{\partial t} (p_n L_a) \right\} = -\nabla \cdot \mathbf{q}_n. \quad (1)$$

Here, s denotes the sediment porosity and p_n the probability of occurrence of the grain size class n in the active layer. Summation of (1) over all the grain size classes then provides a relation which describes the evolution of the bed.

To evaluate the formation of sand waves and the related sorting pattern, the model considers a stability analyses; i.e. small wavy perturbations are imposed to a flat bed and their influence on the flow field, sediment transport and bottom evolution is evaluated. Considering observations and the results of Besio *et al.* (2006), the wavy perturbations are aligned orthogonal to the direction of the major axis of the tidal ellipse and are characterized by a wavenumber α_x . Only small perturbations are considered which has as advantage that the perturbed equations can be linearized. The drawback, however, is that, formally, the analysis is only valid for the initial formation of the bed forms.

It turns out that (see Van Oyen and Blondeaux, 2009b), the amplitude $A(t)$ of each wavy perturbation with wavenumber α_x develops exponentially in time as

$$A(t) = A_0 \exp\{\Gamma t\}. \quad (2)$$

Hence, when Γ is positive (negative), the perturbation is amplified (suppressed) in time. Moreover, we consider that the wavenumber with the largest value of Γ will dominate the other wavelengths and corresponds to the bed forms observed in the field.

Concurrently, the sediment sorting pattern along the sand wave is evaluated. Considering two grain size classes to describe the mixture, it is found that the time development of the probability density (of class 1) is linear in time and controlled by the value of Π , i.e.

$$p_1(t) = \Pi t. \quad (3)$$

Taking class 1 to be related to the coarse grain size fraction, it follows from (3) that a positive

(negative) value of Π indicates that the coarse (fine) grains are found at the crests of the sand wave.

3. OBSERVATIONS

To evaluate the performance of the model, we compare field observations of sediment sorting patterns along tidal sand waves which are reported by Van Lancker & Jacobs (2000) and Roos *et al.* (2007).

Van Lancker & Jacobs (2000) describe echosounding and side-scan sonar measurements of the bottom profile at a sand wave field near the Baland Bank on the Belgian continental shelf (site number 1, figure 1, Blb). Sand waves with wavelengths of about 150 m and heights of approximately 1 m are observed in water depths between 3 and 15 m. Bottom samples reveal a sediment composition with mean grain sizes between 0.3 and 0.4 mm, and illustrate a coarsening of the sand wave crests. Sorting patterns over tidally generated bed forms at five locations in the North Sea are described by Roos *et al.* (2007). The first site is located on the Thornton Bank (location 2, Tnt). Based on measurements using a cylindrical box corer to analyse the bottom composition, Roos *et al.* (2007) describe that the mean grain size is finer at the crest (0.397 – 0.421 mm) of the bed forms than in the troughs (0.436 – 0.530 mm). In contrary, as reported by Roos *et al.* (2007), a coarsening of the grain size diameter at the crest is observed at three other sites in the southern North Sea:

- (i) west-southwest of Hoek van Holland (Hvh, location 3)
- (ii) a coastal site near Zandvoort (Znv, location 4)
- (iii) a site 50 km off shore of Egmond aan Zee (Egm, location 5).

The final site discussed by Roos *et al.* (2007) is located along the Brown bank (Bnb, site number 6 in figure 1). At this location, the grain size distribution over the tidal sand waves is only based on two measurements of the bottom composition and is not pronounced, i.e. the median grain size at the trough is only slightly higher (0.316 mm) than that at the crest (0.314 mm). A fining is thus observed, even though the measurements appear to be non-conclusive.

In order to describe the observed bottom composition with the model, the reported mean

grain size diameters (and sorting coefficients) are used to construct a cumulative probability curve of the grain sizes (in the Φ -scale), for each site respectively. Based on this distribution, we evaluate the values of Φ_{33} and Φ_{66} to fix the diameters of the coarse and fine grain size, respectively.

The hydrodynamic and bathymetric conditions used as input to compute the tidal flow field are obtained from numerical results computed by the Management Unit of the North Sea Mathematical Models (MUMM) as this information is not provided in the literature. Here, it is worth to note that the numerical grid for the sites Blb, Tnt and Hvh is much finer (750 m x 750 m) than for the other sites (4 km x 4 km).

4. RESULTS

Adopting the derived data and information provided by MUMM, we use the theoretical model to compute at each site the wavelength which is characterized by the largest value of Γ and thus is assumed to be dominant since it is the “fastest growing mode (*fgm*)”. For this wavelength, we then evaluate the value of Π in order to recognize the sorting process occurring concurrently with the formation of the bed forms.

For example, figure 2 illustrates the computed value of Γ for perturbations characterized by different wavenumbers α_x .

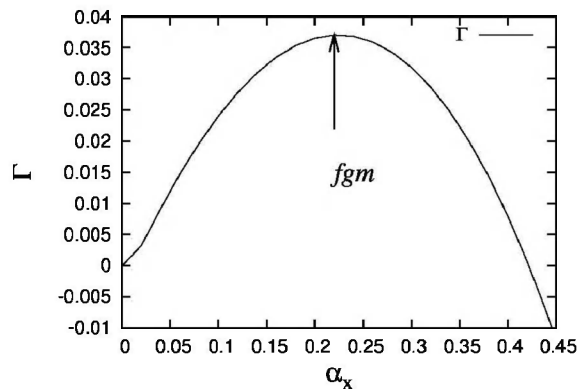


Figure 2. The value of Γ for bed forms with different wavelengths (wavenumbers α_x). Hydrodynamic, bathymetric and bottom characteristics representative for the conditions at Egmond aan de Zee are considered.

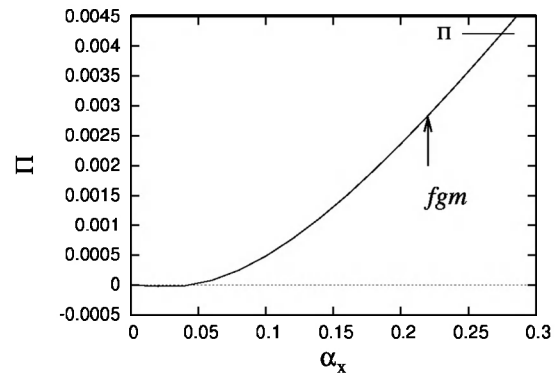


Figure 3. Plot of the value of Π as function of the wavenumber α_x . Hydrodynamic, bathymetric and bottom characteristics representative for the conditions at Egmond aan de Zee are considered.

Table 1. Summary of the observed and predicted wavelength at each site.

Location	Obs. λ [m]	Pred. λ [m]
1. Blb	150	329
2. Tnt	145	173
3. Hvh	350	435
4. Znv	760	327
5. Egm	203	685
6. Bnb	206	556

which allows to evaluate the fastest growing mode (here, $\alpha_{x,max}$ is equal to 0.22). The corresponding wavelength is then computed as $\lambda = 2\pi h/\alpha_{x,max}$. The model, in addition, can compute the value of Π for different wavenumbers, as shown in figure 3. Considering the value of Π for the fastest growing mode, it follows that a coarsening of the crest is predicted since Π_{max} is positive.

For each site, the fastest growing wavelength and the concurrently occurring sorting process is evaluated. Table 1 summarizes the observed (obs. λ) and predicted (pred. λ) wavelength for the six locations. It appears that the model provides reliable wavelengths for the locations Tnt and Hvh, while leading to a fair estimate at the other locations.

In addition, by evaluating the value of Π for the fastest growing mode, the predicted sorting patterns are found; i.e. a positive (negative) value of Π for the fastest growing mode corresponds to a coarsening (fining) of the crest. In Table 2 the observed trends are compared with the obtained results.

Table 2. Comparison of the observed sorting trends with the predicted grain size distribution.

Location	Observed	Value of H	
1. Blb	Coarsening	pos.	✓
2. Tnt	Fining	neg.	✓
3. Hvh	Coarsening	pos.	✓
4. Znv	Coarsening	pos.	✓
5. Egm	Coarsening	pos.	✓
6. Bnb	Fining	pos.	✗

It is found that for five out of the six locations the theoretical model correctly reproduces the qualitative sorting pattern.

The results thus indicate that the model provides (at least) a fair estimate of the occurring wavelength. Moreover, the comparison between the observed and predicted sorting pattern suggests that the model describes adequately the governing processes controlling the grain size distribution along the tidally generated bed forms; especially taking into account the non-conclusive field data obtained at Bnb.

Nevertheless, caution should be taken upon considering this model as a conclusive prediction model since (i) the approach is not able to describe correctly the hydrodynamics and related sediment transport for tidal sand waves of finite amplitude (due to the linear stability approach) and (ii) the model omits hydrodynamic processes which, surely, also effect the wavelength and sorting trend such as wind waves, other components of the tidal wave and wind-induced currents. Moreover, further comparison with more sites based on better quality input data seems required.

5. CONCLUSIONS

A comparison between field observations of grain size segregation along tidal sand waves and a theoretical model is performed for six locations in the southern North Sea. The predicted wavelength compares reasonably with the observed crest-to-crest distances for all the sites. For five out the six sites, the model is found to correctly predict the qualitative sediment distribution along the sand waves (i.e. coarsening or fining of the crests). The results thus indicate that the model provides a fair description of the dynamics leading to the formation of the bed forms. However, care should

be taken to adopt the model as a predictive model for coastal management due to the inherent limitation of the model (being based on a linear stability analysis) and since the model, presently, omits important processes such wind wave induced sediment transport, interactions between several tidal components, etc.

6. ACKNOWLEDGMENT

The first author is grateful to the Ghent University (Special Research Fund) for his post-doctoral grant. T.A.G.P. van Dijk is gratefully acknowledged for accommodating the coordinates of the sites described by Roos *et al.* (2007).

7. REFERENCES

- Ashida, K. & Michiue, M. 1972 Study on hydraulic resistance and bedload transport rate in alluvial streams. Trans. Japan Soc. Civil Eng. 206
- Barnard, P.L., Hanes, D.M., Rubin, D.M. & Kvitek, R.G. 2006 Giant sand waves at the Mouth of the San Francisco Bay. Eos. Trans. AGU 87 (29)
- Besio, G., Blondeaux, P. & Vittori, G. 2006 On the formation of sand waves and sand banks. J. Fluid Mech. 557
- Blondeaux, P. & Vittori, G. 2005a Flow and sediment transport induced by tide propagation. Part1: The flat bottom case. J. Geophys. Res. 110
- Blondeaux, P. & Vittori, G. 2005b Flow and sediment transport induced by tide propagation. Part2: The wavy bottom case. J. Geophys. Res. 110
- Dean R. D. 1974 Aero report 74 – 11. Tech. rep., Imperial College, London.
- Gerkema, T. 2000. A linear stability analysis of tidally generated sand waves. J. Fluid Mech. 417
- Hirano, M. 1971 On river bed degradation with armouring. Trans. Japan. Soc. Of Civil Eng. 3
- Hulscher, S.J.M.H. 1996. Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model. J. Geophys. Res. 101
- Roos, P, Hulscher, S., van der Meer, F., van Dijk, T.A.G.P., Wientjes, I. G.M., van den Berg, J. 2000. Grain size sorting over offshore sand waves: Observations and modelling. In: Dohmen-Janssens, C., Hulscher, S.
- Terwindt, J.H.J. 1971. Sand waves in the southern bight of the North Sea. Mar. Geol. 10, 51 - 67.
- van Dijk, T.A.G.P & Kleinhans, M.G. 2005 Processes controlling the dynamics of compound sand waves

- in the North Sea, The Netherlands, J. of Geophys. Res. 110
- Van Lancker, V., & Jacobs, P., 2000 The dynamical behaviour of shallow marine dunes. In: Trentesaux, A., Garlan, T. (Eds.), Int. Workshop on Marine Sandwave Dynamics. University of Lille 1, France.
- Van Oyen T., & Blondeaux, P., 2009a Grain sorting effects on the formation of tidal sand waves. J. Fluid Mech. 629
- Van Oyen T., & Blondeaux, P. 2009b Tidal sand wave formation: Influence of graded suspended sediment transport. J. Geophys. Res. 114
- van Rijn, L.C. 1984a Sediment transport, part 1: bed load transport. J. Hydraul. Engineering 110
- van Rijn, L.C. 1984a Sediment transport, part 2: suspended load transport. J. Hydraul. Engineering 110