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Modelling and measurement of sand transport processes over full-scale ripples in oscillatory flow

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Abstract

A new series of laboratory experiments was performed in the Aberdeen Oscillatory Flow Tunnel (AOFT) and the Large Oscillating Water Tunnel (LOWT) to investigate time-averaged suspended sand concentrations and transport rates over rippled beds in regular and irregular oscillatory flow. The wave-induced oscillatory near-bed flows were simulated at full-scale. Five series of experiments were carried out. During the two AOFT experimental series, ripple dimensions, ripple migration rates and net sand transport rates were measured under regular and irregular asymmetric flow for two different sand types. The three LOWT experimental series focussed on measurements of the ripple dimensions, ripple migration rates, time-averaged suspended sand concentrations and net sand transport rates under regular asymmetric and irregular weakly asymmetric flow for two different sand types. From analysis of new and other full-scale data, it is concluded that the lower part of the time- and bed-averaged concentration profile (up to two times the ripple height above the ripple crest level) has an exponential profile. A new reference concentration formula is proposed based on the formula of Bosman and Steetzel [Bosman, J.J., Steetzel, H.J., 1986. Time- and bed-averaged concentration under waves. Proc. 20th ICCE Taipei, ASCE, pp. 986–1000], which includes the grain-size influence. Furthermore, it is shown that the concentration decay length is strongly related to the ripple height and that the simple formula $R_c = 1.27\eta$ gives good agreement with the data. A new transport model is proposed for the wave-related net transport over full-scale ripples based on a modified half wave cycle concept of Dibajnia and Watanabe [Dibajnia, M., Watanabe, A., 1992. Sheet flow under nonlinear waves and currents. Proc. 23rd ICCE Venice, ASCE, pp. 2015–2028; Dibajnia, M., Watanabe, A., 1996. A transport rate formula for mixed sands. Proc. 25th ICCE Orlando, ASCE, pp. 3791–3804]. The magnitudes of the half wave cycle transport contributions are related to the grain-related Shields parameter, the degree of wave asymmetry and a newly defined vortex suspension parameter P, which is the ratio between the ripple height and the median grain-size. The new model has been calibrated using transport data from the new regular flow experiments and has subsequently been validated using other data, including measurements from irregular flow experiments. The new model is seen to perform better overall than existing practical models for ripple regime net sand transport.
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1. Introduction

For the prediction of seabed changes, coastal evolution and the morphological impact of human interference in the coastal system such as large-scale sand mining, a reliable sand transport model is of crucial importance. However, large gaps remain in our knowledge of sand transport processes and there is a continuing need for models which are well validated with reliable measurements of the relevant processes under controlled conditions. One of these knowledge gaps is the wave-related component of suspended sand transport over rippled beds (Davies et al., 2002).

Except under storm conditions, when the seabed is flat and sheet-flow dominates the transport process, wave-generated ripples generally cover a large part of the shoreface bed (depths

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of 8 to 20 m). These ripples typically have heights of 0.01–0.1 m, lengths of 0.1–1 m and migration rates of 1.0–20 mm/min. Ripples strongly influence the boundary layer structure and turbulence intensity near the bed and have a great influence on the sand transport. The transport mechanisms are not well understood due to the complexity of the interaction processes between the wave-induced oscillatory flow, the bedforms and the suspended sand.

Fundamentally different physical processes determine sand transport rates above plane and rippled sand beds. Above rippled beds, momentum transfer and the associated sand dynamics in the near-bed layer are dominated by coherent motions, specifically by the process of vortex formation above ripple slopes and the shedding of these vortices around flow reversal. Above steep long-crested ripples, this well-organized vortex process is highly effective in entraining sand into suspension. In a near-bed layer with a thickness of 1–2 times the ripple height, the flow dynamics are dominated by these coherent periodic vortex structures, whereas above this layer the coherent motions break down and are replaced by random turbulence (Davies and Villaret, 1997). This leads to the entrainment of sand into suspension to considerably greater heights than above plane beds.

In connection with sand transport, the phase of sand pick-up from the bottom during the wave cycle is also significantly different above rippled beds with pick-up being linked to the phase of vortex shedding. This has potentially important consequences for the net sand transport rate beneath asymmetrical waves, which can be negative ('offshore') despite higher positive ('onshore') orbital velocities. The underlying mechanism of this wave-related transport opposing the direction of wave propagation in the case of asymmetrical waves is the existence of phase differences between the peak concentrations and peak velocities related to the generation of vortices on the lee-side of steep ripples. Due to the time needed for sand settling, phase lags are generally more important for finer sand and shorter wave periods.

Experimental results are important to understand the complex nature of ripple regime sand transport. Numerous experimental studies into the wave-related sand transport processes over ripples have been carried out in the past, both in the field and in the laboratory. For example, Sato (1987) studied the geometry of sand ripples and the net sand transport rate over ripples under different flow conditions in an oscillating flow tunnel. However, due to limitations of the experimental facility, these experiments were carried out under small-scale conditions, i.e., relatively short wave periods ($T<5.0$ s) and fine sand ($D_{50}=0.18$ mm). More recently, Clubb (2001) performed experiments in a large oscillating water tunnel under field-scale conditions with oscillating periods between 2.0 and 10.0 s. Although Clubb measured the ripple dimensions under a wide range of flow and sand conditions, he only measured suspended sand concentrations and net sand transport rates under four different conditions. Furthermore, he did not investigate the effect of flow irregularity.

Field experiments into sand transport processes over rippled beds have been conducted by, e.g., Hanes et al. (2001), Grasmeijer (2002) and Williams et al. (2005). However, at this moment, it is not yet possible to measure the total net sand transport rate in the field. Furthermore, there is in general a large uncertainty about the position of the different measuring instruments relative to the local bed level, resulting in relatively large uncertainty in the measured quantities.

Many investigators have attempted to model the wave-related sand transport over ripples. These models can be divided into *research* and *practical* models (see Davies et al., 2002). Research models represent many of the detailed physical processes involved in sand transport by waves and currents over rippled beds, and resolve the vertical and sometimes also the horizontal structure of the time-dependent (intra-wave) velocity and sand concentration fields, e.g., the 1DV turbulence closure model of Davies and Thorne (2005), the 2DV discrete vortex models of Hansen et al. (1994) and Malarkey and Davies (2002), the 2DV k–ω turbulence closure model of Andersen (1999) and the 2DV k–ε turbulence closure model of Eidsvik (2004). Such models are complex, require long computation times and are therefore generally not implemented in coastal morphological models.

The present paper focuses on practical modelling of sand transport processes over rippled beds. By comparison with research models, practical models require short computation times and can be implemented easily in coastal morphological models. However, they do not resolve the spatial and temporal structure of the velocity and sand concentration fields. Practical models may be 'quasi-steady' or 'semi-unsteady' (Dohmen-Janssen, 1999). The transport models of Bailard (1981), Van Rijn (1993) and Ribberink (1998) are quasi-steady and are based on the assumption that the instantaneous transport rate is related to the instantaneous velocity or bed shear stress. Semi-unsteady models account for phase lags in the time-dependent flow, suspended sand concentration and sand flux. Examples of semi-unsteady transport models for application to ripple regime conditions include the 'grab-and-dump' model of Nielsen (1988) and the model of Dibajnia and Watanabe (1992, 1996). Practical models have a more empirical character than research models and are, in general, well-validated covering a wide range of conditions. It should be realised that their application is generally limited to these ranges of conditions.

A new extensive experimental study was carried out in the Aberdeen Oscillatory Flow Tunnel (AOFT) at the University of Aberdeen and in the Large Oscillating Water Tunnel (LOWT) at WL|Delft Hydraulics. In these facilities, the oscillatory near-bed flow conditions as induced by moderate (non-breaking) waves can be simulated at full-scale for a wide range of relevant coastal conditions. The main objective of the experiments was to gain more insight into and data on the time-averaged wave-related sand transport processes in the ripple regime under full-scale conditions. The ripple dimensions, the ripple migration rates, the time-averaged concentration profiles and the net sand transport rates were measured for 20 regular symmetric and 15 irregular asymmetric flow conditions with a wide range of grain-sizes, orbital velocities and flow periods.

The aim of this paper is to present and analyse the new data and to use this new data set and existing full-scale data sets (1) to assess existing formulas for the prediction of the time-averaged

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