Coastal Engineering 76 (2013) 26–42

Contents lists available at SciVerse ScienceDirect

Coastal Engineering

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

Practical sand transport formula for non-breaking waves and currents

Dominic A. van der A [a,*], Jan S. Ribberink [b], Jebbe J. van der Werf [b,c], Tom O'Donoghue [a], René H. Buijsrogge [b], Wouter M. Kranenburg [b]

[a] University of Aberdeen, School of Engineering, King's College, Aberdeen, AB24 3UE, United Kingdom
[b] Water Engineering and Management, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands
[c] Marine and Coastal Systems, Deltares, P.O. Box 177, 2600 MH, Delft, The Netherlands

ARTICLE INFO

Article history:
Received 22 November 2012
Received in revised form 22 January 2013
Accepted 24 January 2013
Available online 28 January 2013

Keywords:
Sediment transport formula
Sheet flow
Ripples
Bed shear stress
Phase lag effects
Advection effects

ABSTRACT

Many existing practical sand transport formulae for the coastal marine environment are restricted to a limited range of hydrodynamic and sand conditions. This paper presents a new practical formula for net sand transport induced by non-breaking waves and currents. The formula is especially developed for cross-shore sand transport under wave-dominated conditions and is based on the semi-unsteady, half wave-cycle concept, with bed shear stress as the main forcing parameter. Unsteady phase-lag effects between velocities and concentrations, which are especially important for rippled bed and fine sand sheet-flow conditions, are accounted for through parameterisations. Recently-recognised effects on the net transport rate related to flow acceleration skewness and progressive surface waves are also included. To account for the latter, the formula includes the effects of boundary layer streaming and advection effects which occur under real waves, but not in oscillatory tunnel flows. The formula is developed using a database of 226 net transport rate measurements from large-scale oscillatory flow tunnels and a large wave flume, covering a wide range of full-scale flow conditions and uniform and graded sands with median diameter ranging from 0.13 mm to 0.54 mm. Good overall agreement is obtained between observed and predicted net transport rates with 78% of the predictions falling within a factor 2 of the measurements. For several distinctly different conditions, the behaviour of the net transport with increasing flow strength agrees well with observations, indicating that the most important transport processes in both the rippled bed and sheet flow regime are well captured by the formula. However, for some flow conditions good quantitative agreement could only be obtained by introducing separate calibration parameters. The new formula has been validated against independent net transport rate data for oscillatory flow conditions and steady flow conditions.

1. Introduction

In recent years a substantial body of field- and laboratory-based research has been devoted to measuring sand transport processes induced by waves and currents, and predictive approaches for the net, wave-averaged sand transport have been developed. Generally, these approaches can be classified as process-based numerical models or parameterised (engineering) formulae. Process-based models represent many of the detailed physical processes involved in sand transport by waves and currents, and resolve the vertical and sometimes also the horizontal structure of the time-dependent, intra-wave velocity and sand concentration fields. Such models (see e.g. Henderson et al., 2004; Holmedal and Myrhaug, 2009; Hassan and Ribberink, 2010) are often restricted to specific flow and sand conditions, require relatively long computation times and are therefore generally not implemented in coastal morphodynamic models. Parameterised sand transport formulae on the other hand, consist of a set of relatively simple equations often covering a wide range of flow and sand conditions, require short computation times and can be implemented easily in coastal morphodynamic models.

Practical sand transport formulae for the coastal marine environment are generally semi-empirical formulae which can be classified as time-averaged, quasi-steady or semi-unsteady. Based on approaches used for fluvial sediment transport, time-averaged formulae predict sand transport at a timescale that is much longer than the wave period, using wave-averaged values of velocity and sand concentration. The Bijker (1971) formula is an example of a widely-used time-averaged transport formula, in which waves act as stirring agent for the current-related transport (suspended load and bed load). In time-averaged formulae, the total net transport is always in the direction of the mean current and the wave-related transport component is not taken into account.

Quasi-steady formulae calculate intra-wave sand transport, with the assumption that the instantaneous sand transport relates only to the instantaneous forcing parameter, either the flow velocity or bed shear stress. Commonly-used quasi-steady formulae predict non-zero net transport resulting from velocity skewness, as occurs under Stokes-type

* Corresponding author. Tel.: +44 1224 272806; fax: +44 1224 272497.
E-mail address: d.a.vandera@abdn.ac.uk (D.A. van der A).

0378-3839/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coastaleng.2013.01.007

waves (e.g. Bailard, 1981; Ribberink, 1998; Soulsby and Damgaard, 2005; Wang, 2007), but most do not account for transport resulting from acceleration skewness, as occurs under sawtooth-shaped waves (Van der A et al., 2010; Watanabe and Sato, 2004). Formulae that do account for both velocity and acceleration skewness have mostly been developed for sheet-flow conditions (e.g. Gonzalez-Rodriguez and Madsen, 2007; Nielsen, 2006; Suntoyo et al., 2008) and do not apply to lower energy conditions when the bed is generally covered with ripples.

The assumption of quasi-steadiness only holds for conditions for which the reaction time of sand particles is short relative to the wave period. In other words, the pick-up and settling of sand particles must take place in a much shorter time than the wave period. This assumption is not the case for fine sand sheet-flow conditions (Dohmen-Janssen et al., 2002; O'Donoghue and Wright, 2004; Van der A et al., 2009) and rippled bed conditions (Van der Werf et al., 2007), where phase lag effects can significantly affect the magnitude and sometimes even the direction of the net transport rate. Semi-unsteady formulae have been developed to account for phase lag effects in sheet-flow conditions (Camenen and Larson, 2007; Dibajnia and Watanabe, 1992), rippled bed conditions (Nielsen, 1988; Van der Werf et al., 2006) and for both sheet-flow and ripple conditions (Silva et al., 2006; Van Rijn, 2007a,b,c).

Existing transport formulae are based for the most part on experimental data from oscillatory flow tunnels, in which the flow is horizontal and horizontally uniform. However, net transport rate experiments carried out in large wave flumes (Dohmen-Janssen and Hanes, 2002; Ribberink et al., 2000; Schretlen et al., 2011) indicate that the added complexities in the hydrodynamics of surface waves compared to tunnel flows can be important in determining the net sand transport. Kranenburg et al. (2013) use a detailed advection–diffusion boundary layer sand transport model and the above mentioned tunnel and flume data to quantify the importance of progressive wave, streaming-related, bed shear stress (wave Reynolds stress) and, at least for fine sand, of vertical advection of sand by vertical orbital velocities and horizontal advection of sand by gradients in the horizontal sediment flux. Existing transport models do not account for these real wave effects, although Nielsen (2006) does incorporate a streaming-related bed shear stress in his formulation, while Van Rijn (2007a) incorporates streaming by adding a small steady current at the edge of the wave boundary layer. Nielsen (2006) has shown that the net transport of medium sand is better predicted when a streaming-related mean bed shear stress is added to the instantaneous oscillatory bed shear stress in a 'quasi-steady' Meyer-Peter and Müller type sand transport formula.

This paper presents a new semi-unsteady formula for predicting net sand transport under waves and currents. Based on an extensive dataset of measurements of net sand transport rates from large-scale laboratory experiments, covering a wide range of hydraulic conditions and transport regimes, the formula can be applied to rippled bed and sheet-flow conditions, incorporates phase lag and flow acceleration effects, and can be applied to both oscillatory flow and surface wave conditions. The new sand transport formula is presented in Section 2 of the paper. Section 3 presents a comparison of calculated net transport rates with measured transport rates from the large scale-experiments. The general behaviour of predicted net transport rates across a range of flow conditions is examined in Section 4. Section 5 presents the results of validation tests against independent data for oscillatory flow and steady flow conditions. A discussion of results and conclusions from the paper are presented in Sections 6 and 7 respectively.

2. Sand transport formula for oscillatory flows and progressive waves

The new transport formula is based on a modified version of the semi-unsteady "half-cycle" concept originally proposed by Dibajnia and Watanabe (1992). In this concept the wave-averaged total net sand transport rate (bedload and suspended load) as taking place in the oscillatory boundary layer is essentially described as the difference between the two gross amounts of sand transported during the positive "crest" half-cycle and during the negative "trough" half-cycle. Unsteady phase lag effects are taken into account via two contributions to the amount of sand transported during each half-cycle: sand entrained and transported during the present half-cycle and sand entrained during the previous half-cycle which is transported during the present half-cycle; the latter is the phase lag contribution. The present formula differs from Dibajnia and Watanabe (1992) in the following ways: (i) bed shear stress rather than near-bed velocity is used as the main forcing parameter; (ii) the effects of flow unsteadiness (phase lag effects) are incorporated in a different way; (iii) the effects of acceleration skewness are incorporated; (iv) it covers graded sands and (v) the formula distinguishes between oscillatory flows and progressive surface waves. The present formula distinguishes itself from other half-cycle-type formulae (Dibajnia and Watanabe, 1996, 1998; Silva et al., 2006; Watanabe and Sato, 2004) through (v), as well as through the calculation of the detailed sub-processes and the extent of experimental data used to inform formula development and calibration.

In the new formula, the non-dimensional net transport rate is given by the following "velocity–load" equation:

$$\vec{\Phi} = \frac{\vec{q}_s}{\sqrt{(s-1)gd_{50}^3}} = \frac{\sqrt{|\theta_c|}T_c\left(\Omega_{cc} + \frac{T_c}{2T_{cu}}\Omega_{tc}\right)\frac{\vec{\theta}_c}{|\theta_c|} + \sqrt{|\theta_t|}T_t\left(\Omega_{tt} + \frac{T_t}{2T_{tu}}\Omega_{ct}\right)\frac{\vec{\theta}_t}{|\theta_t|}}{T} \quad (1)$$

where $\vec{q}_s$ is the volumetric net transport rate per unit width, $s = (\rho_s - \rho)/\rho$ where ρ_s and ρ are the densities of sand and water respectively, g is acceleration due to gravity and d_{50} is the sand median diameter; $\vec{\theta}$ is the non-dimensional bed shear stress (Shields parameter), with subscripts "c" and "t" implying "crest" and "trough" half cycle respectively; T is wave period; T_c is the duration of the crest (positive) half cycle and T_{cu} is the duration of accelerating flow within the crest half cycle (Fig. 1); similarly T_t is the duration of the trough (negative) half cycle and T_{tu} the period of accelerating flow within the trough half cycle.

There are four contributions to the net sand transport:

- Ω_{cc} represents the sand load that is entrained during the wave crest period and transported during the crest period;
- Ω_{ct} represents the sand load that is entrained during the wave crest period and transported during the trough period;
- Ω_{tt} represents the sand load that is entrained during the wave trough period and transported during the trough period;
- Ω_{tc} represents the sand load that is entrained during the wave trough period and transported during the crest period.

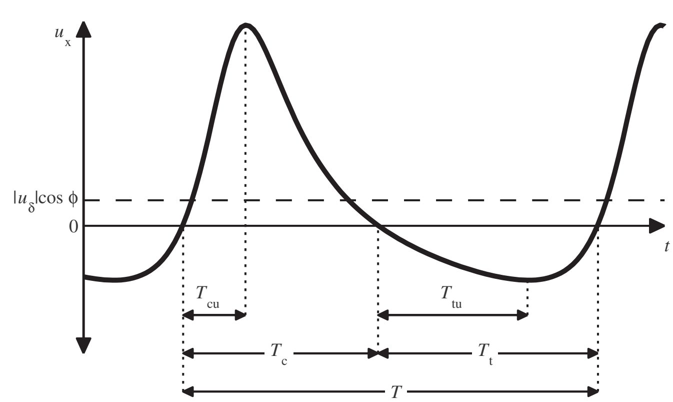

Fig. 1. Definition sketch of near-bed velocity time-series in wave direction. The parameters T_c and T_c are the positive (crest) and negative (trough) flow durations. Similarly, T_{cu} and T_{tu} are the durations of flow acceleration in positive and negative x-directions.