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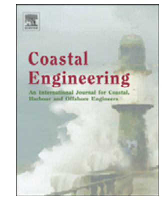

Turbulence based measurements of wave friction factors under irregular waves on a gravel bed

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ABSTRACT

Very few studies have quantified the wave friction factor, f_w, for coarse sediments at field-scale. To address this shortcoming, high-frequency measurements of turbulence obtained within the boundary layer of irregular waves over gravel in the Delta Flume, have been used to calculate values of f_w using different evaluation methods. In the field-scale laboratory experiments reported here, three velocimeters were deployed on the seaward side of a 4 m-high, 5 m-wide and 55 m-long gravel barrier subject to a JONSWAP spectrum of waves with significant wave heights ranging from 0.8 m to 1.3 m, and peak periods of 3.0 s to 10 s and offshore water depths ranging from 1.75 m to 3.75 m. The deployment area was essentially flat, with little or no predicted or observed sediment movement under the wave conditions investigated. The turbulent kinetic energy method was found to be the most suitable approach for calculating the bed shear stress, which can be related to f_w. Wave friction factor values under the conditions tested here fell in the range 0.01 and 0.27. Although f_w predicted by an existing equation agrees well with the mean measured f_w value, the application of a new predictor for f_w is recommended for improved parameterisation of skin friction over the range of relative roughness values encountered in this study. This approach combines the wave Reynolds number, wave steepness and relative depth to provide a simple expression to assist assessments of coarse sediment transport by waves for uses within a range of practical engineering applications.

1. Introduction

Close to the shore, and on the beach face, wave-induced bed shear stress dominates the mobilisation of sediment in moderate and storm conditions. For this reason, the accurate prediction of sediment transport by waves in these environments is required for many coastal engineering activities (e.g. beach nourishment, beach re-profiling, aggregate dredging and environmental impact assessments). In situations where the water depth is shallow in relation to the wavelength, wave energy is dissipated principally by bottom friction (Smyth and Hay, 2002) and the wave-only, skin friction bed shear stress, τ_w, responsible for sediment mobilisation and transport can be defined as

$$\tau_w = \frac{1}{2}\rho f_w U_w^2 \quad (1)$$

where ρ is the water density, f_w is a wave friction factor, and U_w is wave orbital velocity amplitude at the seabed. Because accurate estimates of τ_w are needed in a wide range of sediment transport formulae (e.g. Bakhtyara et al., 2009; Davies, 1985; Le Roux, 2003; Nielsen, 1992; Pedrozo-Acuna et al., 2006) there have been numerous studies undertaken to establish useful relationships between the physical roughness of the bed, τ_w and f_w. These have included: a) small-scale laboratory studies (e.g. Bagnold, 1946; Dixen et al., 2008; Jensen et al., 1989; Kamphuis, 1975; Kim, 2004; Smyth and Hay, 2002); and b) modelling and dimensional analyses (e.g. Christoffersen and Jonsson, 1985; Jonsson, 1966; Kajiura, 1968; Le Roux, 2003; Madsen, 1994; Myrhaug, 1995; Zhao and Anastasiou, 1993). However, published estimates of f_w from laboratory-based experiments vary significantly (Nielsen, 1992; Tolman, 1994) and few have examined coarse sediments such as those found on gravel beaches and barriers worldwide. Further, owing to the practical difficulties of obtaining accurate measurements in a frequently hostile environment, (Davies, 1986), field estimates of f_w are rare (Smyth and Hay, 2002), especially for coarse sediments. Recent reviews (e.g. Buscombe and Masselink, 2006) have highlighted that a present lack of knowledge of f_w limits our ability to predict accurately the short-term dynamic behaviour of coarse sediments comprising gravel barriers which in turn impacts on the design of some coastal defence schemes and related engineering activities. Obtaining accurate measurements or estimates of f_w

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therefore remains a challenge (Barnes and Baldock, 2007) and provides the primary motivation for the investigations reported here.

This paper first outlines details of an experiment designed to examine the hydrodynamics and coarse sediment transport processes in a region just seaward of the swash zone in the BARDEX experiments. It describes the use of high-frequency turbulence data to estimate τ_w and f_w in a broad range of different water depths and random wave conditions. Estimates of f_w are then compared with results from a number of widely-used predictive formulae. To overcome the significant data scatter a new simple expression for f_w is presented that combines the wave Reynolds number, wave steepness and relative depth to provide improved prediction of f_w for the present range of wave, bottom roughness and water depths.

2. Experiments and equipment

The work described here was undertaken as part of the Barrier Dynamics Experiments (BARDEX: Williams et al., 2009, 2012). Briefly, this involved exposing a proto-type gravel barrier (4 m-high, 5 m-wide, 55 m-long, $D_{50}=11$ mm) to a range of wave conditions and water levels within the Delta flume (240 m-long, 5 m-wide, 7 m-deep). On the seaward side of the barrier, random waves were created using a wave paddle steered by a JONSWAP spectrum. Wave reflection was suppressed by the use of an Automated Reflection Compensator (ARC). A series of pumps allowed manipulation of the water levels on both sides of the barrier. A number of *wave runs*, each lasting approximately 10 min, was undertaken during each test series. In this paper data from test series B2 and B3, C3 and C4, D1 and E1 to E8 are used to investigate wave friction factors. Further details of the BARDEX experimental design are given by Williams et al. (2012).

Data analysed here were obtained using a rigid frame equipped with instruments to measure at high-frequency wave-induced flows, water depth and bed morphology at nearshore locations just seaward of the narrow swash zone (Fig. 1). Two autonomous imaging sonars, *Marine Electronics* Acoustic Bed Profilers (ABP), were used to measure detailed bed morphology (range and bearing), performing a 120° sweep of the bed at a rate of 1 Hz. Although data return from these instruments was incomplete, they provided valuable information on bed location and stability during some wave runs. Instruments to measure the flow included: a Sontek 10-MHz Hydra ADV Ocean Probe, measuring at approximately 0.06 m above the nominal bed level (i.e. 0.18 m below the probe tip); a Nortek Vectrino 10-MHz Velocimeter, fixed-stem, downwards looking probe, measuring at approximately 0.25 m above the bed (sampling volume 0.05 m below the probe tip); and a 10-MHz Nortek Vectrino$^+$ downward looking probe, measuring at approximately 0.5 m above the bed (0.05 m below the probe tip), (Fig. 1). These current meters measured at 25 Hz the three orthogonal turbulent flow components: along-flume, u; across-flume, v; and vertical, w. The Sontek ADV also housed a strain-gauge pressure sensor, providing high-resolution water level data at the measurement site. It was precisely time-synchronised to the Vectrino internal clock and ran in self-contained mode. The two Nortek Vectrinos were cable-synchronised and ran in real-time. They were manually

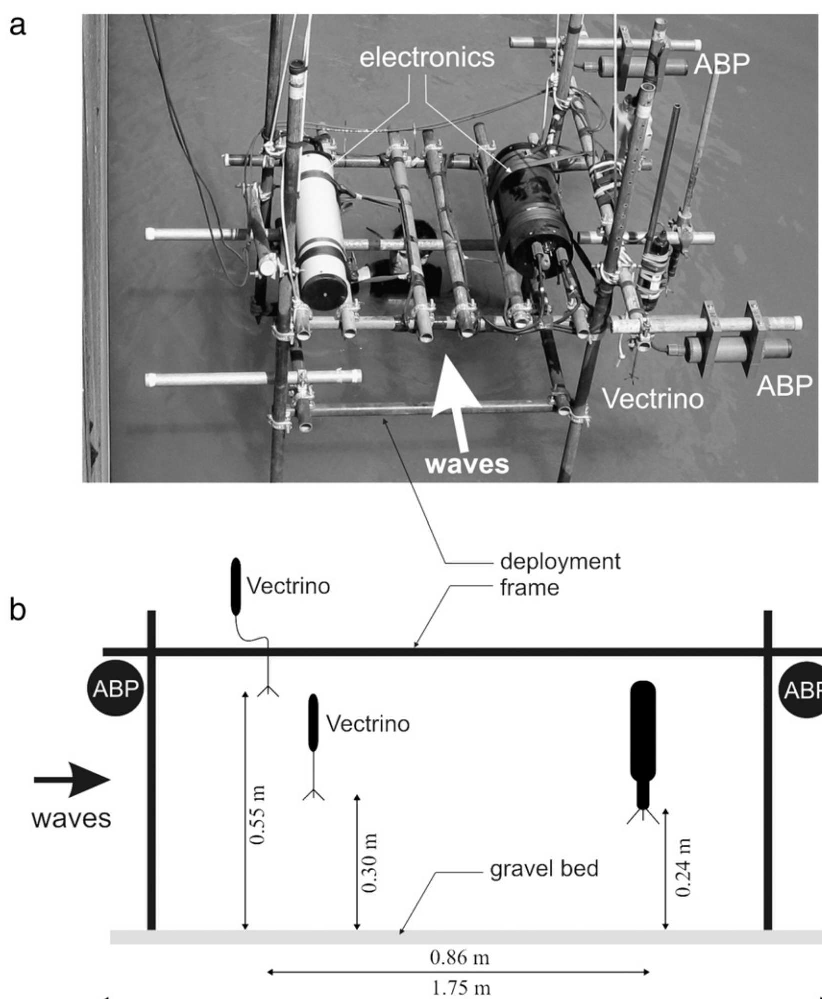

Fig. 1. Frame schematic (side elevation) showing instrument locations.