

Turbulent Solitary Wave Boundary Layer

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ABSTRACT

This paper summarizes the results of an experimental investigation of turbulent solitary wave boundary layers. The wave induced flow has been simulated by a solitary motion in an oscillating tunnel. The experiments show that the boundary layer flow remains laminar for Re numbers smaller than $Re=5 \times 10^5$. The experiments further show that the bed shear stress reverses during the deceleration stage of the free-stream flow. In a narrow sub-range of Re number ($2 \times 10^5 \leq Re < 5 \times 10^5$) in the laminar regime, the boundary layer flow experiences a regular array of vortices near the bed over a short period of time during the deceleration stage. The transition-to-turbulence at $Re=5 \times 10^5$ is associated with the emergence of turbulent spots, revealed by single/multiple, or, sometimes, quite dense spikes in the bed shear stress variations. Flow resistance in terms of wave friction coefficient including the phase information has also been worked out for both the acceleration and deceleration stages of the free-stream flow of the wave.

KEY WORDS: bed shear stress; boundary layers; sediment transport; solitary waves; waves

INTRODUCTION

Although much research has been done on boundary layers under harmonic progressive waves (Lundgren and Jonsson, 1961, Hino et al., 1983, Sleath, 1987, Jensen et al., 1989, Lodahl et al., 1998, Diken et al., 2008, on the experimental side, and Fredsøe, 1984, Spalart and Baldwin, 1987, Justesen, 1988, Lohmann et al., 2006, on the theoretical side, to give but a few examples), to the authors' knowledge, Liu et al. (2007) were the first to study boundary layer flows under solitary waves in details. They derived analytical solutions, based on (1) those of Liu and Orfilla (2004) for viscous boundary layer flows under transient long waves, and (2) the solutions for the nonlinear boundary layer equations. They also carried out laboratory measurements that include the free-surface displacement, PIV-resolved velocity fields of the boundary layer, and the bottom shear stress. Liu et al. (2007) gave a detailed account of the existing work prior to their study, notably Keulegan (1948) and Mei (1983). Tanaka et al. (1998), in their work on laminar boundary layers under cnoidal waves, derived equations for the

time variations of the velocity and the bottom shear stress for solitary waves (which they viewed as the asymptotic case of cnoidal waves as the Ursell parameter goes to infinity), using Keulegan's (1948) analytical solution. In an earlier study, Liu (2006) developed analytical solutions for the wave damping due to a turbulent boundary layer.

It appears that no study is yet available, investigating turbulent, solitary wave boundary layer flows. The objective of the present study is to examine these boundary layer flows. To this end, the solitary wave boundary layer flow is simulated in the laboratory in an oscillating water tunnel. With this, the wave-induced velocities can be increased quite substantially, up to 1.2 m/s in the present facility, resulting in Re numbers up to 2×10^6 , the Reynolds numbers which cannot be achieved in ordinary, small- or medium-scale wave-flume facilities. Here Re is defined by

$$Re = \frac{aU_{0m}}{\nu} \quad (1)$$

in which U_{0m} is the maximum value of the free-stream velocity outside the boundary layer, and a is the half of the stroke of the water particle displacement in the free-stream region under the solitary wave, and ν is the kinematic viscosity coefficient. It turns out that the boundary layer flow experiences tremendous changes (laminar, laminar with transverse vortex tubes near the bed, laminar-to-turbulence transition, and turbulence), as Re is increased.

EXPERIMENTAL FACILITY

The experiments were carried out in a U-shaped water tunnel, the same as that used in Jensen et al., 1989), Fig. 1. The solitary motion in the tunnel was driven by a pneumatic system. The piston of the pneumatic system was driven such that the free-stream velocity in the tunnel satisfied

$$U_0 = U_{0m} \sec h^2(\omega t) \quad (2)$$

the variation of the particle velocity at the bed at a given location under a small-amplitude solitary wave. Here ω is the angular frequency,