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Velocity characteristics in boundary layer flow caused by solitary wave traveling over horizontal bottom

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ABSTRACT

The characteristics of horizontal velocity in the bottom boundary-layer flow induced by a solitary wave propagating over a horizontal bottom are presented experimentally, using high-speed particle image velocimetry (HSPIV). The ratio of wave height to water depth varies from 0.096 to 0.386 and the flow inside the boundary layer is laminar. The results show that the horizontal velocity profiles can be mainly classified into two categories with respect to the passing of the solitary wave-crest at the measuring section: the pre-passing (or acceleration) phases under favorable pressure gradient and post-passing (or deceleration) phases under adverse pressure gradient. For the velocity distributions obtained during the pre-passing phases, a nonlinear regression analysis was used to precisely determine the time-dependent characteristic length and velocity scales underlying these profiles. A similarity profile of the horizontal velocity is established first using the time-dependent free-stream velocity and boundary layer thickness as the characteristic velocity and length scales, respectively. In addition, the displacement thickness, the momentum thickness, and the energy thickness are also considered as alternative length scales. All these four representative thicknesses are closely related to each other, demonstrating that any one amongst them can be regarded as the characteristic length scale. The forms of similarity profiles for the non-dimensional velocity distributions are somewhat analogous to the results of steady boundary layer flow over a thin plate under with pressure gradient, but with different coefficients or powers. While during the post-passing phases, flow reversal which acts like an unsteady wall jet and moves in the opposite direction against the wave propagation occurs after the passage of solitary wave-crest. The thickness of flow reversal layer increases with time. A similarity profile is proposed for the velocity distributions corresponding to occurrence of the extreme value in the maximum negative velocity of flow reversal. Variations of the maximum negative velocity and the thickness of flow reversal with the time right after the start of flow reversal are also discussed in detail. Moreover, the non-dimensional time leads of the horizontal velocities at different heights in the boundary layer over the free-stream velocity are evidenced to be more noticeable toward the bottom, and also in lower ratio of wave height to water depth. A similarity profile for the non-dimensional time lead versus the non-dimensional height above the bottom surface is also presented.

1. Introduction

The observation of movement of solitary waves over large distances, exhibiting the property of stable state of motion, was initially reported by Russell [33]. The solitary waves propagate steadily neither steepening their wave height nor widening their wave length, but maintaining constant wave length and wave height without loosing their energy considerably. The solitary waves to some extent resembles to long waves because of shallow water depth, before they undergo changes as they approach the shores. Therefore, the study on solitary waves is of continued interest due to their simple and permanent wave form. Further, their study can help in simulating the run-up and shoreward inundation [10].

As a long wave transverses the ocean and reaches the nearshore region, the influence from sea bed becomes more profound due to shallow water depth. Consequently, bottom friction, the

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Nomenclature

b_m	height of negative maximum velocity (L)
$(b_m)_M$	height of negative maximum velocity when $U_m = (U_m)_{max}$ at $T = T_M$ (L)
b_0	thickness of flow reversal (L)
$(b_0)_M$	thickness of flow reversal when $U_m = (U_m)_{max}$ at $T = T_M$ (L)
c_0	wave celerity (L T^{-1})
g	gravitational acceleration (L T^{-2})
H_0	solitary wave height (L)
h_0	water depth (L)
K	a parameter, $K = \sqrt{3H_0/4h_0^3}$ (L)
Re	Reynolds number defined by the water depth h_0, $(u_\infty)_{max}h_0/\nu$ (–)
Re^*	Reynolds number defined by half of the water particle displacement a, $(u_\infty)_{max}a/\nu$ (–)
T	non-dimensional time, $t(g/h_0)^{1/2}$
T_{fr}	non-dimensional time for occurrence of flow reversal (–)
T_L	non-dimensional time lead at different heights with respect to $T = 0$ (–)
T_{Lb}	non-dimensional maximum time lead at bottom boundary with respect to $T = 0$ (–)
T_M	non-dimensional time when $U_m = (U_m)_{max}$ occurs (–)
t	time defining relative position of wave crest from measuring section at $x = 0$ (T)
t_{fr}	time for start of flow reversal in boundary layer (T)
t_p	period of solitary wave motion (T)
U_m	maximum negative velocity of flow reversal (<0) after $T > T_{fr}$ (L T^{-1})
$(U_m)_{max}$	extreme value of U_m (<0) occurring at $T = T_M$ (L T^{-1})
u	(ensemble-averaged) horizontal velocity (L T^{-1})
$(u_\infty)_{max}$	maximum free-stream velocity (>0) occurring at $T = 0$ (L T^{-1})
u_∞	free-stream velocity at the edge of bottom boundary layer (L T^{-1})
x	horizontal distance with $x = 0$ at measuring section (L)
y	vertical height or distance from bottom surface (L)
δ	boundary layer thickness (L)
δ_0	boundary layer thickness at $T = 0$ (L)
δ_e	energy thickness (L)
δ_*	displacement thickness (L)
η	free surface elevation above still water level (L)
θ	momentum thickness (L)
ν	kinematic viscosity (L^2 T^{-1})
ξ	non-dimensional parameter, $\xi = Kc_0t$ (–)
Φ_f	phase lead of maximum bed shear stress over that of maximum free-stream velocity (deg)
Φ_r	phase difference between maximum free-stream velocity and maximum negative bed shear stress (deg)

consequential momentum exchange, and energy dissipation are all intensified within the very thin bottom boundary layer. The anticipated changes in wave shape and celerity have been reported by many investigations and studies. Research on the boundary layer flow under a solitary wave has been largely progressed since Keulegan [13], in which the analytical equations dealing with damping by viscous effects of solitary waves was derived. Ott and Sudan [30] modified the KdV (Korteweg-de Vries) equation to include energy dissipation in which a linear dissipation rate was added. The analytical equation was re-derived using perturbation method by Mei [29] and the results obtained were similar to Keulegan [13]. Liu and Orfila [26] presented a prominent study in which sets of Boussinesq-type depth-integrated equations for long-wave propagation were derived which include viscous effects. The equations are able to estimate the damping rates for both harmonic progressive waves and a solitary wave. The influence of turbulent bottom boundary layer were considered by Liu [25], in which the eddy viscosity in the turbulence closure model was assumed to be a power function of the vertical elevation. Phase shift between the bottom stress and the depth-averaged velocity for simple harmonic progressive waves, and the damping rate of a solitary wave were both analyzed. Liu et al. [28] further extended the Liu and Orfila [26] formulation from constant depth to slowly varying depth and used experimental data for testing solitary wave damping and shoaling to validate the resulting formulation. Good agreement was found between the numerical results and the experimental data. In addition, bottom shear stress was also reported in the study and compared with conventional empirical model.

To the best knowledge of the authors, the laminar boundary layer flow under a solitary wave was first examined by Liu et al. [27], in which the occurrences of negative velocity inside the laminar boundary layer and reverse direction of the bed shear stress with time lead were reported when the solitary wave decelerates. Nevertheless, very few laboratory measurements were conducted in Liu et al. [27] to check the theoretical results. In addition, Sumer et al. [37] presented velocity profiles in the boundary layer and bed shear stress, using laser Doppler velocimetry (LDV) and hot film probe, respectively. Prescribed time-dependent velocity outside the bottom boundary layer was generated in a large U-tube to simulate the free-stream velocity of a small-amplitude solitary wave, whilst without producing the free surface of a solitary wave. A thin-layered milk tracer was employed in flow visualization to facilitate in identification of flow characteristics in different flow regimes. Important finding of the occurrences of negative velocity inside (both laminar and turbulent) boundary layers and reverse motion of bed shear stresses with time leads was indicated by Sumer et al. [37] for a larger range of Reynolds number.

The invention in non-intrusive measurement techniques, such as LDV and particle image velocimetry (PIV) have assisted in precise measurements for the studies of boundary layer flow. Several applications of these techniques in the studies of laminar and turbulent boundary layer flows of progressive, standing, or solitary waves are reported, e.g., Sleath [35], Jensen et al. [12], Lin et al. [19], Lin and Hwung [17], Lin et al. [18], Lin et al. [20], Carstensen et al. [4] and Sumer et al. [37]. The LDV has the advantages such as higher spatial and velocity resolution, no calibration required, and measuring very near boundaries. However, its point-measurement nature creates measurement uncertainties and thus limits its use to some applications. On the other hand, PIV provides a whole-view velocity measurement, largely reducing the ensemble error required by the point-measurement algorithm. Moreover, due to the rapid development of optical apparatus and technologies, the image grabbing tool has transformed from traditional film or video cameras to high-speed digital cameras. High time-resolved, high-speed PIV (HSPIV) having time resolution over 1/200 s makes various boundary layer flow measurements more accurate and has become the main stream in the research community, e.g. Lin et al. [24,22,21,23].