

MEASUREMENTS OF WAVE-INDUCED STEADY CURRENTS OUTSIDE THE SURF ZONE

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In this paper the steady current induced by sea waves propagating over a sloping beach is studied experimentally in a large scale wave flume. The unwanted scale effects that characterize the experiments carried out in small installations are thus minimized. The results show that the steady streaming induced in the bottom boundary layer is offshore directed especially for waves characterized by a long period. This phenomenon has a significant influence on the steady velocity profiles which exhibit a qualitative trend that is different from that derived by the theory or by other experiments.

1. INTRODUCTION

A deep knowledge of the complex hydrodynamics induced by sea waves propagating towards the coast is important for several reasons and, in particular, in order to formulate reliable models for sediments transport and pollutants dispersion. As regards the transport processes, one of the most important characteristics of the flow is the steady current generated by nonlinear effects induced by the waves themselves. Indeed, even though the steady velocity component is small compared to the fluctuating one it can have an important influence on the transport phenomena.

The offshore current, called undertow, arises when a wave propagates towards the coast and its existence is necessary to compensate the onshore flux due to the Stokes drift.

The undertow is influenced by the shoreward current that arises in the bottom boundary layer (Putrevu & Svendsen, 1993), whose origin has been explained theoretically by Longuet-Higgins (1953) for the case of a laminar flow. The successive experimental work of Bijker, Kalkwijk & Picters (1974) have shown that the steady velocity at the edge of a turbulent boundary layer can be smaller than that determined by Longuet-Higgins (1953).

Although a significant number of experiments have been devoted to the analysis of the undertow velocity profile and of the steady streaming in the bottom boundary layer, in the author's knowledge no experiments have been performed by using waves characterized by a Reynolds number of the bottom boundary layer that falls inside the turbulent regime yet.

In the present study we have carried out several measurements along the water column, in a large scale wave flume, of the wave induced velocity offshore the breaker line, where in most of the wave conditions the bottom boundary layer was in the turbulent regime. The data have been elaborated in order to obtain information about the steady velocity profiles.

2. THE EXPERIMENTAL FACILITY AND THE INSTRUMENTATION

The experiments have been carried out in the CIEM large wave flume at the UPC (Universitat Politècnica de Catalunya, Spain). The wave flume is 100 m long, 3 m wide and 5 m deep. The bottom is covered by sand with $d_{50}=0.25$ mm. A slope 1:15 is present at the end of the flume which starts at about $x=42$ m.

The origin of the reference system (x, y) is placed in the middle of the stroke of the wave paddle and lies on the rigid bottom of the wave flume. The x axis is positive in the onshore direction, while the y axis is directed vertically and points upward.

The measurements have been carried out at four different stations along the channel ($x=33.93, 44.11, 55.33, 61.66$ m). The first station was in the horizontal part, the second station was close to the beginning of the slope and the other two stations along the slope. The water depth was equal to 2.5 m in front of the wave paddle for all the experiments.

The velocity have been measured by an array of eight ADV (Acoustic Doppler velocimeter) deployed along the same vertical direction. Close to the bottom the velocity was also measured by an UVP (ultrasonic velocimeter profiler). Here we discuss the data obtained by the ADV, those obtained by the UVP will be presented in a future paper. Several resistive and acoustic wave gauges were deployed in order to measure the free surface elevation. The position of the bottom was measured by a mechanical profiler placed on a carriage.

Fifteen different regular waves have been generated for each station by combining five different wave heights H ($H=0.2, 0.3, 0.4, 0.5, 0.6$ m) with three different wave periods T ($T=3, 4.25, 5.5$ s).

The waves have been generated according to the first order of the Stokes irrotational wave theory by a wedge wave paddle. However, during the propagation the waves became asymmetric especially those which were quite long with respect to the water depth.

During the experiments three-dimensional vortex ripples appeared on the sandy bottom, which were characterized by an average wavelength about equal to 20 cm and a wave height of 3-4 cm.

3. DISCUSSION OF THE RESULTS

As an example, in Figure 1 we have reported the time development of the velocity measured in the third station ($x=55.33$ m) by the ADV closest to the bottom (8 cm) for $H=0.5$ m and $T=5.5$ s. In the same figure it is also shown the time development of the free surface elevation measured by the wave gauge at the same position where the array of ADV is deployed.

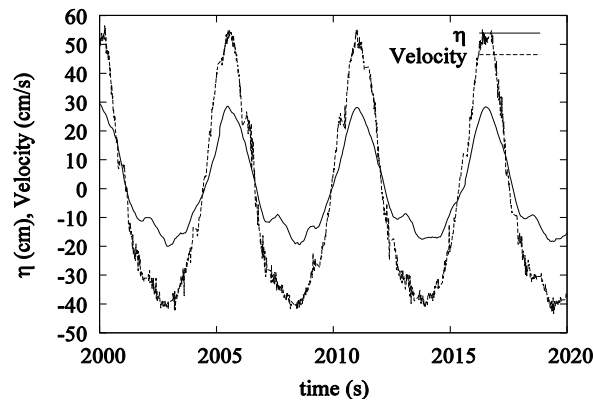


Figure 1. Time development of the free surface elevation η and of the velocity measured by the ADV closest to the bed in the third station ($x=55.33$ m) for $H=0.5$ m and $T=5.5$ s.

We observe that the wave amplitudes at the crests are larger than those at the troughs, i.e. the wave is asymmetric. It can be also noted that such asymmetry is also exhibited by the time development of the velocity. How we will explain in the following, such characteristic plays an important role in determining the distribution of the steady velocity along the vertical.

The steady velocity profiles have been computed by averaging the velocity time series over an integer number n of periods. One of the requirements to get reliable information on the steady velocity is that the averaged velocity converges to a constant value as n increases. However, it has been observed that such requirements could not be rigorously satisfied all the times even though every test lasted 600 wave periods.

Generally the measurements were taken below the trough level but, for large waves and close to the shoreline, it happened that the upper ADV probe was outside the water during the passage of the wave trough. For sake of clarity we highlight that the velocity profiles shown in the following figures are pertinent to the region outside the bottom boundary layer.

The trend of the steady velocity profiles along the channel are shown in Figure 2 for $H=0.5$ m and $T=5.5$ s. These profiles are considerably different from that derived from the theory of Longuet-Higgins (1953) under the assumption of a laminar flow or from other experimental works where the boundary layer was in the laminar regime (Bijker, Kalkwijk & Picters, 1974). The most apparent difference is that while in the previous studies the convex part of the velocity profiles is turned towards offshore, in the present experiments more often the convex part is turned towards onshore.

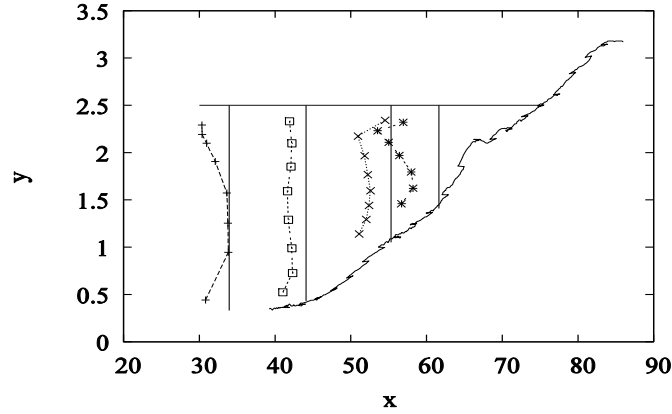


Figure 2. Trend of the steady velocity profiles along the channel for $H=0.5\text{m}$ and $T=5.5\text{ s}$.

This result can be partially explained if we first note that close to the bottom (at the edge of the bottom boundary layer) the steady velocity is offshore directed. This finding, which is in contrast with the results of Longuet-Higgins (1953), is due to the asymmetry of the waves. Indeed, when a water wave is asymmetric the different intensity of the turbulence during the seaward and the landward half cycles causes an offshore directed steady streaming (Ribberink & Al-Salem, 1995; Scandura, 2007).

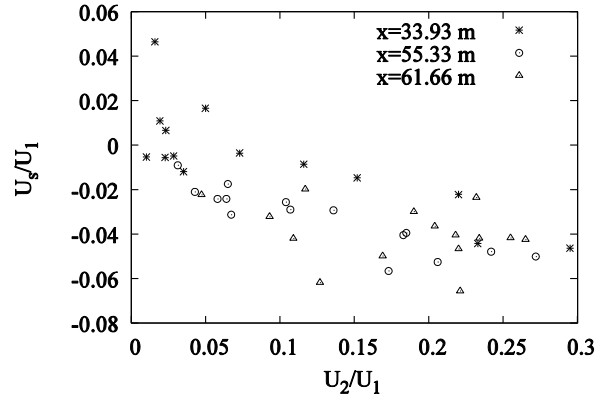


Figure 3. Dimensionless steady velocity close to the bottom versus the ratio U_2/U_1 .

In order to quantify the phenomenon of the steady streaming, in Figure 3 it is reported the dimensionless steady velocity close to the bottom U_s/U_1 versus the ratio U_2/U_1 , where U_s is the steady velocity, U_1 and U_2 are the amplitudes of the harmonic components of period T and $2T$ respectively of the velocity time spectrum. The ratio U_2/U_1 can be assumed as a measure of the wave asymmetry and generally it increases with the period T . Although in Figure 3 the data are rather dispersed, it is quite clear that as the wave asymmetry increases the steady velocity increases becoming more negative. For small asymmetries the intensity of the turbulence between two consecutive half cycles is similar, therefore the mechanism described by Longuet-Higgins (1953) prevails and the steady streaming can be positive.

The effect the steady streaming on the velocity profile can be understood with the help of Figure 4, where the steady velocity profiles for $H=0.5\text{ m}$ are reported. In the previous Figure we observe that the offshore steady velocity close to the bottom increases with the wave period. This phenomenon makes the steady velocity profiles for small and large periods qualitatively different among them. Indeed, for small periods the steady velocity at the bottom is small, therefore a large part of the flow takes place in the upper part of the fluid column. On the other hand for large periods the steady velocity at the bottom is larger and this allows a significant part of the flow to take place close to the bottom, making the steady velocity more constant along the vertical. The sudden variation of the velocity in the last point along the vertical is due to the fact that the probe was slightly above the trough level.

In Figure 5, where the velocity profiles for $T=5.5\text{ s}$ are shown, we observe that both the steady velocity along the water column and the steady streaming close to the bottom increase with H .

It is also clear that in order to match the no slip condition on the bed, the steady streaming in the bottom boundary layer must develop a very strong gradient.

A more rigorous discussion about the shape of the velocity profiles is no trivial as it would involve complex mechanisms such as the non linear interaction between the wave velocity and the steady velocity fields. However, further analysis are in progress aimed at improving the understanding of the observed phenomena.

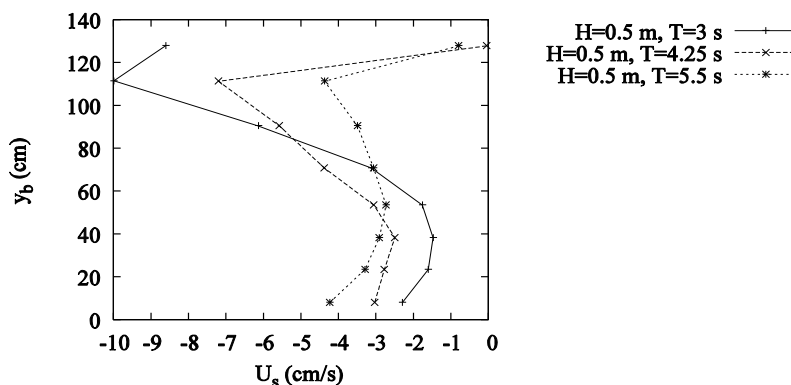


Figure 4. Steady velocity U_s versus the distance from the sandy bottom y_b in the third station ($x=55.33$) for $H=0.5$ m.

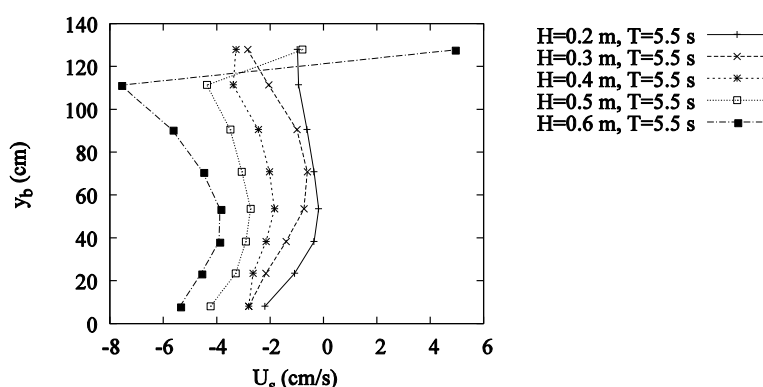


Figure 5. Steady velocity U_s versus the distance from the sandy bottom y_b in the third station ($x=55.33$) for $T=5.5$ s.

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