Laboratory observations of turbulence and bed shear stress in the swash zone

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DISSERTATION SUMMARY

LABORATORY OBSERVATIONS OF TURBULENCE AND BED SHEAR STRESS IN THE SWASH ZONE

Doctoral Course of Applied Marine Environmental Studies

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DEJUN FENG

Research background

The swash zone on most beaches is readily accessible, but this accessibility does not translate into a wide knowledge of the underlying physical processes. This zone exhibits some of the most challenging attributes in the coastal ocean with regard to measurement and modeling campaigns. Flows in the swash zone reverse direction with the reversal timing varying across the foreshore extent. Flows are rapid and contain large sediment loads and void fraction. Turbulence is acknowledged as important for energy considerations and sediment mobility but quantification is hampered through non-stationarity and signal discontinuity (for instance due to intermittent submergence of instrumentation and/or to flows laden with bubbles and sediment). Fluid and sediment processes are further complicated by a highly variable sea bed with elevation variability occurring across a wide range of frequencies. More investigations from many aspects are needed to reach a comprehensive understanding of the swash zone hydrodynamics

Research objectives

1. To evaluate the turbulence level by using ensemble average and moving average decomposition methods. Results of the Turbulent Kinetic Energy (TKE) from the two methods will be compared so as to decide a more robust estimation of TKE in the swash zone. And the TKE evolution within the swash zone especially in the upper shallow locations will be extensively analyzed.

2. To resolve the velocity field close to the bottom so as to clarify the importance and necessary of obtaining high-resolution measurements. The bed shear stress and the corresponding friction coefficient values can be different greatly when estimated using high-resolution and coarse-resolution velocity profiles.

3. To estimate bed shear stress by using available methods. Advantages and limitations of each method are seriously discussed. The applicability of these methods will be assessed. Especially the criteria used to decide the top elevation of the log fitting will be discussed extensively.

4. To clarify the dependences of hydrodynamics on the measurement locations. All the variables will be estimated at different locations along the swash

Research methodology

For the small-scale experiment the experiments were carried out using an updated version of the open channel flume at Tokyo University of Marine Science and Technology. It consisites of a water reservior bulit into one end of a 7.1 m long, 0.3 m wide and 0.7 m high, glass-sided flume. The reservior is fronted by a gate which can be raised to produce a pluning wave leading to a bore which propagates towards an impermeable slope located downstream. The dimensions of the reservior are shown in figure 4-1. The reservior exit is streamlined to ensure a smooth transition for the flow from reservior to the flume. A 1/6 transparent sloping bottom made of acylics with a thickness of 8 mm was constructed at the other end of the flume. The slope was mounted to the side-wall of the flume to increase its rigidity. The measurements were done at two locations: L1 (120 cm from the toe of the slope), L2 (140 cm from the toe of the slope).

For the larger-scale experiment, laboratory experiments were conducted using a dam-break flume (15 m x 1.8 m x 1 m) with a reservoir in one end and a 1/10 transparent slope in the other end. The slope is designed to be 10 m long so as to increase the duration of swash flow making the longer measurements possible. By quick releasing the gate, a great plunging wave was generated towards the slope leading to a swash bore. The experiments were conducted under the following condition: the initial water depth in the reservoir and on the flume floor is 750 mm and 50 mm, respectively. Five wave gauges were installed as shown in Figure 5-1 to measure the water depth. PIV measures were conducted in 3 locations and every location 100 repeats: first 50 repeats with small Field Of View (FOV) for bottom boundary layer velocity measurement and the second 50 repeats with large FOV capturing the whole water for whole field velocity measurement.

The repeatability of the facility was shown to be satisfactory by comparing the 50 water depths measured by the wave gauges. A high speed camera was used to obtain PIV image pairs with the following setting: 1280 x 1024 pixels, 100 fps time delay between image pairs 100 μs. High-performance double heads Nd:YAG laser with maximum repetition rate up to 100 Hz together with a series of optical elements was used to illuminate the measuring section upward from the under of the slope to avoid free surface disturbances.

In the small FOV case, the camera was positioned very close to the laser sheet to increase the magnification (12 μm/pixel) to measure the boundary layer velocities. In the large FOV case, the distance between the laser sheet and the camera depends on the measurement location for just capturing the whole water. Glass hollow sphere with a diameter of 10 μm were used as tracer particles. The specific gravity of the particle is slightly larger than unity and thus it follows the water flow well. The timing $t = 0$ was defined as the timing of gate releasing and simultaneously a TTL signal was generated and sent to trigger a DG645 digital delay generator that used to achieve the synchronization of all the instruments. To achieve this synchronization, a laser displacement meter was installed parallel to the gate, when the gated is opened, the laser displacement meter will send out a TTL signal to the delay generator and then the entire instrument will work simultaneously.

A high-resolution Particle Image Velocimetry (PIV) technique was specially developed for processing these PIV recordings. Based on the fact that large vertical velocity gradients and small bed-normal velocities characterize the bottom boundary layer flow, a rectangle interrogation window with a longer dimension in the stream-wise direction and a smaller dimension in the span-wise direction compared with that used in previous studies were adopted to give a dense spatial resolution. The accuracy was improved by applying an iteration cross-correlation scheme based on adaptive Fast Fourier Transformation (FFT) algorithm which can accelerate the computation and overcome the circularity limitation of the normal FFT. With the aid of the spatial-temporal-resolved PIV system, velocity field in the aforementioned complicated flow conditions was successfully measured for the first time. No previous studies were done in such shallow swash zone because of the technique limitations.

Conclusions

The objectives of the work were to gain a better understanding of the flow of (bore) waves on (plane, impermeable, smooth) beaches, including the spatiotemporal distribution of velocity, turbulence and bed shear stress to improve the knowledge of the hydrodynamic processes occurring in the shallow swash zone. The work is divided into three separate parts: development of advanced PIV technique, the small-scale swash experiment and large-scale swash experiment.

Firstly, by recognizing the limitations of the commercial and open-source PIV software, an advanced PIV program was successfully developed by using modified FFT method to overcome the circular effects caused by normal FFT method and keep the high computation speed as that in the direct cross correlation method. Considering the fact that in the swash zone, the bed-parallel velocity is much larger than the bed-normal velocity in almost all the swash duration, except during the flow reversal, where magnitudes of velocities of the two directions are both very small, and the vertical velocity gradient is relatively large. Considering the above mentioned fact and with the aim to improve the measurement resolution in the bed-normal direction, in this study, the interrogation window size was set to be rectangle with a relative larger dimension in the bed-parallel direction and a smaller dimension in the bed-normal direction. By using the advanced PIV technique, the velocity field within the bottom boundary layer is successfully resolved. The calculated velocity vectors were then post-processed by using the statistical method of Grubbs Test.

Secondly, with the main aim of comparing the TKE results estimated using the ensemble average and moving average methods, the experiment was conducted in the small-scale dam-break flume so as to make high temporal resolution PIV measurements by using the continuous wave laser as light source to illuminate the seeding particles and use the high speed CCD camera (2000 frames per second) to record the illuminated seeding particles. It is almost impossible to apply the continuous wave laser in the large-scale dam-break flume of high incident bore velocity since the relative low energy output of the laser are not high enough to be sensed by the high speed CCD camera within a very short shutter speed.

The velocity profiles show a typical forward leaning shape during the uprush and then become to be depth-uniform close to the flow reversal, at which the flow close to the bottom changes direction firstly compared with that in the upper layer. After that, during the flow reversal, the phase lead is formed and lasts for almost the entire backwash duration, which is different from the previous studies that measurements were done in inner swash zone, where the phase lead only exists for a short time after flow reversal. This may be caused by the less swash duration in the shallow swash zone, where there is not enough time for the backwash flow to reestablish the velocity profiles. The velocity profiles in the uprush show the peak value just below the surface, which is caused by the opposite direction of vorticities in the upper layer and lower layer of the bore front. Consistent with the previous studies, the measured maximum uprush is larger than the measured maximum backwash velocity, although the actual maximum uprush and backwash velocities should be larger than the measured one. The uprush duration is less than the backwash duration, indicating the asymmetry of the swash flow in time.

Although the moving average method can reveal the local characteristics of the turbulence, it is still difficult to decide the moving window size (cut-off frequency). In this study, with the aim to find the tendency of the TKE in the swash zone rather than the actual magnitude, the TKE is estimated by using 4 cut-off frequencies. All of the results show similar tendency that the uprush TKE is larger than the backwash TKE with less TKE level close to the surface, indicating that in the shallow swash zone the main source of TKE is from the bottom rather than the surface. This is easy to understand when considering the distance between the measurement in the shallow swash zone and the location of bore collapse. However, it is found that the TKE level estimated using ensemble average is one order of magnitude higher than that estimated using moving average, showing the uncertainty of the results from ensemble average because of the difficulty in achieving perfect repeatability in practice.

Bed shear stress results from momentum integral method and linear fitting method show that these two methods are not suitable for the shallow swash zone. To make direct comparisons between previous studies easily, log-law is adopted to estimate the bed shear stress. The upper limit of the log fitting is decided by taking the following parameters into consideration: the correlation coefficient, the non-dimensional wall unit and the fitting error. Results show that the measured peak uprush bed shear stress is larger than the measured peak backwash bed shear stress, which is contrast to that in the inner swash zone, where the measured peak uprush bed shear stress is larger than the measured peak backwash bed shear stress. Consistent with the tendency of the bed shear stress, the measured non-dimensional bed shear stress, friction coefficient, is larger in the backwash.

Thirdly, although the small-scale swash experiment already reveals the main hydrodynamics in the shallow swash zone and the distinct parts compared with the previous studies, the comparisons between results estimated using high resolution and coarse resolution data are still not easy to be made. Also the scale should have effect on the results. With the main aim to compare the results estimated using different resolution velocity data, the large-scale swash experiment using high performance YAG laser and CCD camera mounted with large magnification lens and small magnification lens was done at three measurement locations in the shallow swash zone to investigate the bottom boundary layer characteristics and compare the results estimated using high/coarse resolution velocity data.

The velocity profiles show a similar tendency to that of the small-scale experiment. However, the measurement resolution is improved with lowest measurement location being resolved to 0.126 mm from the bottom and 20 measurements points were successfully obtained within the lowest 1 mm. At location 3, the mini bore-collapse phenomenon, which was firstly detected by the numerical simulation study, was observed and the velocity field under the mini bore-collapse was measured for the first time in the laboratory. Due to the difficulty in determining accurately the free surface, the velocities in the vicinity of the surface are not taken into consideration, leading to the less obvious phenomenon, which is very apparent in the small-scale experiment that the uprush velocity peaks just below the free surface. The TKE was estimated using ensemble average method because that the less high pulse laser rate prohibit the application of moving average method to estimate TKE. The results show that from the lower location to the upper location, the TKE is decreasing with the dissipation of surface-related turbulence and decreased velocity magnitude. In the lower location, the uprush TKE is 2 times larger than that in the backwash. However, in the upper location, the uprush and backwash TKE have similar magnitude, implying that the effect of surface-related turbulence has decreased to the minimum. At all locations, the TKE results estimated using high resolution velocity data give larger value, revealing that the high resolution data can resolve the small scale turbulence well. Bed shear stress estimated by log-law shows similar tendency with that in the small-scale experiment with the peak backwash bed shear stress is similar or larger than the peak uprush bed shear stress. However, the results estimated by fitting the velocity profile from the lowest point 0.126 mm to the 0.46 mm to the log profile using high resolution is 2-3 times larger than that estimated by fitting the velocity profile from the lowest point 0.98 mm to the 2.836 mm to the log profile using coarse resolution data. This is the first time that comparisons like this were made and no previous studies can estimate shear stress within this thin layer because of the difficulty in measuring the velocity in such shallow area. The magnitudes of friction coefficient largely depend on the choice of free stream velocity. Dramatic difference can be obtained when different free stream velocities are used since the friction coefficient is in inverse proportion to the square of the free stream velocity. But the general tendency is similar for the three measurement locations with a slight larger value in the backwash than that in the uprush.