EVOLUTION OF A SPILLING BREAKER: AN EXPERIMENTAL STUDY OF THE GEOMETRICAL AND KINEMATIC FEATURES.

Lucarelli, A.*,1,2, Falchi, M.1, Felli, M.1, Lugni, C.1,3, Colicchio, G.1,3, Brocchini, M.2

1 CNR-INSEAN, Rome, Italy
2 Univ. Politecnica delle Marche, Ancona, Italy
3 AMOS, NTNU, Trondheim, Norway
e-mail:
  alessia.lucarelli@insean.cnr.it
  massimo.falchi@cnr.it
  mario.felli@cnr.it
  claudio.lugni@cnr.it
  giuseppina.colicchio@cnr.it
  m.brocchini@univpm.it

ABSTRACT

We here describe an experimental study of a spilling breaker finalized to the comprehension of the physics and on the development of a simplified mathematical model for the motion of the breaker. Such a model is based on the three-layer structure already proposed by the authors: an underlying potential flow, a thin, turbulent single-phase layer in the middle and a turbulent two-phase layer (air-water) on the upper part. Laboratory experiments have been specifically designed and carried out to investigate the physical mechanisms involved in the interaction among the mentioned three layers. A sloshing wave has been selected for the generation of the breaker. A 3m long, 0.6m deep and 0.10m wide tank has been built in Plexiglas and forced through an hexapode system, which allows a high accuracy of the motion. To ensure repeatability of the phenomenon, a suitable breaker event has been generated to occur during the first two oscillation cycles of the tank. The tank motion has been suitably designed using a potential and a Navier-Stokes solver. A PIV system has been set-up to measure both mean and turbulent kinematic quantities. The analysis of the experimental data will provide information on possible links of the geometrical quantities that characterize the individual layers, and the kinematic quantities measurable in the single-phase turbulent layer.

1. INTRODUCTION

The evolution of a spilling breaker is a complex physical phenomenon that involves multiphase flows, compressibility effects, water spraying and jetting. The numerical and theoretical modeling, along with a comprehensive physical investigation of the mechanisms involved, is still a challenge for the hydrodynamic research.

Spilling breaker is part of a wider class of breaking wave where the waveform changes relatively slowly. Together with the bore, it forms the class of the quasi-steady breakers. In a spilling breaker the turbulence is confined in a region near the crest of the wave, with white water spilling down the front face starting from the wave crest.

Based on the physical observation that the time scale for the evolution of a breaker is longer than the one relative to the transport of the fluid elements through it, Peregrine [1] defined a spilling
breaker as a quasi-steady breaker in the frame moving with the wave. However, it is unsteady when compared to the motion of the underlying wave, with a longer time scale of evolution.

For a quasi-steady, fully-formed spilling breaker, which is the focus of this work, there are many analytical studies; the most interesting for us are briefly described in the follow.

Longuet-Higgins & Turner [2] presented an entraining plume model where the spilling breaker is approximated as a turbulent gravity current riding down the forward slope of a wave while laminar flow entrains from below. The entrainment is modeled by a finite tangential stress at the boundary between the turbulent and laminar flows. For the first time, the role of the air-water mixing and the unsteady motion of the toe front is included; however, the turbulence is confined within the surface roller.

In [3] the turbulent region of a bore is modeled as a liquid wedge spreading from the toe front downward in the water body. They used a depth-integrated equation and a simplified k-ε turbulence model to properly describe the local hydrodynamics. Although the turbulence generated at the toe front is realistic, the model does not take into account for the air phase, flow unsteadiness, flow rotation and local curvature. Further, an infinite cross-flow velocity gradient at the toe front induces a foot singularity.

In [4], the authors proposed a theory where the spilling breaker is approximated as a stationary vortex placed on the forward face of the wave. The turbulence generated at the toe resembles the one of a mixing layer and the pressure is hydrostatic. This simple model provides a reasonable description of the incipient breaking conditions; however it does not consider the influence of the cross flow and is valid only for quasi-steady breakers.

More recently, Peregrine & Broccini ([5],[6]) and Broccini [7] focused on the effects of the strong turbulence at the free surface, with the aim of improving the modelling of breaking waves and applying to a wider range of flow conditions.

The main finding consists in simplifying the surface boundary conditions for the turbulent air-water mixture at the front and on the crest of a spilling breaker. The boundary conditions (kinematic and dynamic) are achieved by considering first the Reynolds ensemble averages and integrating then across the surface layer (in the region where air and water are present).

Although similar to [3], the analytical model in [1] and [2], then supported by the data from [8], is not limited to shallow water conditions. Further, major improvements exist in representing the mean flow unsteadiness, stretching, local curvature and rotations. In this theory, the spilling breaker is represented through a three-layers system (fig.1): a top layer, called two-phase flow, which is an air-water mixture; a middle layer characterized by a turbulent, single-phase water flow, which rides on the underlying irrotational potential wave body (low layer).

It is to be noted that our present analysis and the overall conceptual structure of the model are valid even in the case the lowest layer is characterized by a rotational flow, and can be easily adapted to that condition.

As a continuation of these seminal works, present research activity is part of the PhD project by Lucarelli.

The aim of the PhD activity is the definition of the geometric features of the three layers, the kinematic and dynamic quantities which characterize their mutual relationship, and the equations governing the motion of the foot of the breaker. A detailed and accurate physical investigation of the evolution of the spilling breaker becomes then a priority of the study.

Unfortunately, few experimental studies are available in literature. They provide detailed spatial descriptions and a fundamental understanding of the temporal evolution of the mean and turbulence flow in the breaker.

In [10], [11] and [12], the authors performed an experimental study of mechanically generated focusing waves in deep water and revealed interesting details of the dynamic of the turbulent incipient spilling breaker. The turbulent phase of the breaking process begins when the toe starts to move down the wave face; the toe is quickly accelerated to a constant velocity. This finding contradicts the theoretical model in [2], which predicts constant acceleration of the toe. The
discrepancy might be due to the dominance of surface tension effect in the experiment, which is not included in the model. Another difference is that physically the wave face slope changes in time, while the theoretical model assumes constant slope.

Flow field measurements using PIV during this process showed a quick growth of the circulation as a vortical region convected and spread along the breaker, starting at the toe and extending back to the crest. However, the limited measurement field does not allow further speculations on the flow field behind the wave crest. In [13] a weakly turbulent hydraulic jump with breaking and air entrainment is generated. The authors found that the effects of non-uniform velocities and non-hydrostatic pressure are important for mass and momentum conservation. Little attention was focused on the intermittency of the surface and its influence on the flow structure. Recently Misra [9] has proposed an experimental study on the estimation of the instantaneous air-water interface directly from particle image velocimetry (PIV) images of a laboratory generated air entraining turbulent hydraulic jump. Because of the above considerations, the present paper shows the preliminary results of an accurate and reliable experiment on the kinematical field of a spilling breaker in a sloshing tank. The main aim is the fully physical comprehension of the breaker as well as the validation and completion of the analytical model mentioned above. The paper is structured as follows: section 2 describes the experimental set-up and the techniques of analysis of the data; section 3 presents the experimental results and the discussion of the physical phenomena involved. Finally, conclusions and future perspectives are given in Section 4.

2. EXPERIMENTAL SET-UP AND ANALYSIS

The experimental study of a spilling breaker requires the tackling of several challenges. First, a reliable measurement of the turbulent flow field, which characterizes the breaker in the region surrounding the wave crest, requires a statistical analysis, i.e. a large number of independent events, each given by a single sloshing run. The capability to generate a spilling breaker with high repeatability becomes, then, a crucial issue for the reliability of the statistical analysis. According to previous studies on the evolution of breaking waves induced by shallow sloshing flows ([14], [15]), a suitable spilling breaker has been designed to evolve in a sloshing tank by means of a combination of numerical solutions.
Assuming irrotational flow conditions, an efficient HPC solver [16] has been first used to reproduce the flow evolving in a 3 m long, 0.6 m deep and 0.1 m wide tank. To ensure high repeatability, the motion of the tank has been designed to force the first breaking event during the first oscillation with a filling depth of 0.2 m (see figure 4, left column).

Figure 3 shows, from top to bottom respectively, the time history of the designed motion along with the velocity and acceleration of the tank. To avoid vibrations and mechanical noise, the motion has been generated as smoothly as possible, at least during the acquisition time (indicated by the red and blue line in figure 3) of the kinematic flow field.

Fig. 2 Experimental set-up

Fig. 3 Time history of the motion (top panel), velocity (middle panel) and acceleration (bottom panel) of the tank
Once the general motion parameters have been fixed and the incipient breaking event numerically realized, a Navier-Stokes solver [17] has been used to follow the spilling breaker evolution with the aim to optimize the arrangement of the PIV setup (cameras + laser source, see the top panel of figure 2) necessary for the measurement of the kinematical field.

In particular, the Navier-Stokes solver (see the right column of Figure 4) allowed the estimate of the size of the area where the breaking wave arose and developed, which corresponded to a length of about 1.80 m and to a height variable according to the evolution of the breaker, but with a maximum extension of about 0.35 m.

The large extent of the region of interest and the need to undertake detailed flow measurements with a spatial and temporal resolution suitable to accurately resolve the evolution of the turbulent flow structures in the spilling breaker, required the implementation of ad-hoc camera arrangement and acquisition strategies.

More specifically, a multi-camera recording system with 4 cameras arranged side by side was used to simultaneously acquire a large flow extent at a spatial resolution adequate to resolve flow eddies as small as 2mm. With this arrangement, the field of view of the camera system allowed to cover about half of the region of interest and thus created the need to split it in two regions as shown in figure 2 (bottom). Namely:

- A region upstream, indicated with the blue rectangles in the bottom panel of figure 2, which covers the formation and the evolution of the breaker during its maximum vertical variation, i.e. until an almost steady horizontal evolution.
- A region downstream, indicated by the red rectangles in the bottom panel of figure 2, which covers the rest of the breaker evolution. Correspondently, the evolution of the wave profile required to arrange the cameras at different vertical positions. This was achieved inclining the cameras by 7 deg in the vertical plane (see right panel of figure 2).

For each region, PIV recording was performed in two phases shifting image sampling times by 0.5dt, dt being the sampling period of the PIV system. This implies that PIV snapshots were recorded at the instants \( t_i = t_0 + i \cdot dt \) during the first phase and at \( t_i = t_0 + 0.5 \cdot dt + i \cdot dt \) during the second phase, with \( i = 1, \ldots, T/dt \), and \( T \) indicating the acquisition time. In particular, the sampling period \( dt \) was 1/8 s and the acquisition time was \( T = 1.5 \) sec.

It is worth noting that the aforementioned acquisition strategies claim for a high repeatability of the breaker evolution. To this aim, a preliminary set of 32 flow visualization tests was undertaken using a simplified configuration with a single digital camera (frame rate = 25 fps and resolution 1920x1080) and diffused light. The repeatability analysis, based on the position of the wave crest, returned an error estimated within 10 mm, which is of the same order of magnitude of the camera resolution. Finally, a Hexapode system ‘Symetrie Mistral’ forces the motion of the tank and ensures a high accuracy of the motion with a resolution of the order of 0.1 mm.

The 4 cameras used for PIV image recording were Imager sCMOS models by LaVision (i.e. 16 bits, 2560 × 2160 pixel resolution, 6.5 µm pixel size, 50 frames/s maximum frame rate). Each camera was equipped with a 50 mm lens which gives a magnification factor of about 9 pix/mm at the distance of 800 mm from the laser sheet.

The illumination was provided by a double cavity Nd-Yag laser (2 x 200 mJ/pulse @ 12.5 Hz by Quantel). The laser beam was expanded through a set of one cylindrical (i.e. 15mm focal length) and one spherical (i.e. 1000 mm focal length) lenses to obtain an illumination domain extended over the whole region of interest and 1mm thick.

Facility water was seeded with hollow glass particles of 10 µm diameter.

The whole experimental campaign consisted of more than 2048 runs (i.e. two camera positions and two recording phases), which correspond to a statistical population of 512 events.

The PIV images are processed by the La Vision software DaVIS 8.2, which uses a multi-pass cross-correlation image algorithm with windows deformation [18]. PIV images were pre-processed masking the image region over the water surface and subtracting the minimum
background value. The final size of the interrogation windows was 24x24 pixels with an overlap of 75%.

Fig. 4  Evolution of the free surface before (left column: HPC solver) and after the breaker generation (right column: NS solver)

3. RESULTS
Through the visualization of the air-water interface at different time instants, Figure 5 shows the main stages governing the generation and the evolution of the spilling breaker in a frame of reference fixed with respect to the sloshing tank. The time is increasing from top to bottom and from left to right. The formation of the breaker is dominated by the steepening of the wave crest (from A to B). When the velocity of the water particles at the wave crest becomes higher than the velocity of the underlying flow (B), the toe is generated and starts to move downward.

Fig. 5  Image sequence of the generation and evolution of the spilling breaker in the sloshing tank. The time is increasing from A to F

In this time interval the wave changes quickly its shape, leading to the generation of a breaker, characterized by an evident two-phase flow (air-water mixture) in the front of the wave. Conversely to the findings of other literature experiments on spilling breakers (e.g. generated...
through hydraulic jump [9] or behind a steady hydrofoil close to the free-surface [12]), here the first stage of the evolution, i.e. from B to D, is governed by the mean flow unsteadiness and stretching, as well as variation of the local curvature and rotation of the local reference system fixed to the wave front.

The curvature of the crest progressively decreases and the toe motion becomes parallel to the bottom (panel D). Starting from this instant, the breaker becomes closer to the typical condition of a hydraulic jump: the curvature is small, the rotation is almost null and it advances in steady condition (from D to F).

With the aim to understand the physical mechanisms governing the turbulent flow field below the wave crest, hereafter we discuss the spatial variation of the kinematic statistical quantities. In the present preliminary analysis of the data, we focus on the stage corresponding to panel E of figure 5, that is when the breaker is fully developed and is approaching the steady-state condition.

The curvature of the crest progressively decreases and the toe motion becomes parallel to the bottom (panel D). Starting from this instant, the breaker becomes closer to the typical condition of a hydraulic jump: the curvature is small, the rotation is almost null and it advances in steady condition (from D to F).

With the aim to understand the physical mechanisms governing the turbulent flow field below the wave crest, hereafter we discuss the spatial variation of the kinematic statistical quantities. In the present preliminary analysis of the data, we focus on the stage corresponding to panel E of figure 5, that is when the breaker is fully developed and is approaching the steady-state condition.

More in detail, figure 6 shows the mean Galilean velocity field below the air-water interface. The Galilean reference system is defined as fixed with the wave crest velocity. In this case, the image corresponding to the mean of 512 repetitions of the same condition is used as background, which justifies the smoothness of the air-water interface.

An anticlockwise vorticity is evident at the toe region, as a consequence of the breaking wave inception.

Because of the unsteadiness of the local flow injected at the toe, a rotational and turbulent flow is expected in the region upstream. This is also the consequence of the separation of the flow injected: the fluid particles, indeed are unable to follow the sharp curvature at the toe.

This implies that the vorticity is expected to be injected and advected upstream and then diffused and dissipated on the smaller spatial scales.

This mechanism is confirmed by looking at the turbulent kinetic energy and vorticity field shown in figure 7 and 8, respectively. The strong turbulent motion (see fig.7) is responsible for the air-water mixing region (localized in the white region of the wave front), characterized by an enhanced heat and mass transfer, as well as dissipation of mechanical energy. From the spatial variation of the turbulent kinetic energy (Fig.7) we can then identify a turbulent layer, which is bounded by the black dash-dotted line. This layer, with a fully turbulent flow, was already experimentally observed in [9] and modeled theoretically in [1,2].

Interesting is also the evolution of the vorticity field shown in figure 8.

As expected, the vorticity injected at the toe, is advected and diffused upstream.
Also in this case, we can define a limiting curve which bounds from below the layer of rotational flow and separates the vortical flow region in the upper part from the lower irrotational flow region; this is represented by the black dashed line in Fig. 8.

In order to further highlight the difference between the turbulent and rotational flow, figure 9 shows the Reynolds stresses distribution at the same instant used in figures 6-8. The two limiting curves previously identified have been superimposed. As expected, the Reynolds stresses dominate in the turbulent flow (delimited by the dash-dotted line), while are quite small in the rotational (no turbulent) region.
Fig. 9 Reynolds stress field at the instant corresponding to panel E of Fig. 5

4. CONCLUSIONS
An accurate and reliable experimental investigation has been performed for the kinematic field that characterizes the evolution of a spilling breaker occurring in a sloshing tank. To ensure high repeatability, a suitable tank motion has been numerically designed to realize a breaker during the first oscillation of the tank. A PIV technique has been used to measure the mean and turbulent velocity field. More than 2000 runs have been realized with the aim to give a reliable estimation of the turbulent statistical quantities.

The present preliminary results are only a first step towards a full understanding of the physical mechanisms governing the spilling breaker evolution.

The physical investigation enabled the identification of four different regions which characterize the flow below a spilling breaker:
- a. two-phase turbulent flow, in a small region near the toe and characterized by air-water mixture and then easily identified from fig 5.;
- b. one-phase turbulent flow, in the region between a., the free-surface and the limiting curve of the turbulent kinetic energy (see fig. 7). This is characterized by a fully turbulent water flow;
- c. rotational flow (see fig. 8), characterized by advection and diffusion of the vorticity.
- d. irrotational flow, where the fluid kinematics is described by means a potential flow approximation.

5. REFERENCES


