

ABSTRACT

Title of dissertation: ON THE IMPACT BETWEEN
 A WATER FREE SURFACE AND
 A RIGID STRUCTURE

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Dissertation directed by: Professor James H. Duncan
 Department of Mechanical Engineering

In this thesis, the impact between a water surface and a structure is addressed in two related experiments. In the first experiment, the impact of a plunging breaking wave on a partially submerged 2D structure is studied. The evolution of the water surface profiles are measured with a cinematic laser-induced fluorescence technique, while the pressure distribution on the wall is measured simultaneously with an array of fast-response pressure sensors. When the structure is placed at a particular streamwise location in the wave tank and the bottom surface of the structure is located 13.3 cm below the mean water level, a “flip-through” impact occurs. In this case, the water surface profile between the crest and the front face of the structure is found to shrink to a point as the wave approaches the structure without breaking. High acceleration of the contact point motion is observed in this case. When the bottom of the structure is located at the mean water level, high-frequency pressure oscillations are observed. These pressure oscillations are believed to be caused by air that is entrapped near the wave crest during the impact process.

When the bottom of the structure is sufficiently far above the mean water level, the first contact with the structure is the impact between the wave crest and the bottom corner of the structure. This latter condition, produces the largest impact pressures on the structure.

In the second experiment, the slamming of a flat plate on a quiescent water surface is studied. A two-axis high-speed carriage is used to slam a flat plate on the water surface with high horizontal and vertical velocity. The above-mentioned LIF system is used to measure the evolution of the free surface adjacent to the plate. Measurements are performed with the horizontal and vertical carriage speeds ranging from zero to 6 m/s and 0.6 to 1.2 m/s, respectively, and the plate oriented obliquely to horizontal. Two types of splash are found, a spray of droplets and ligaments that is ejected horizontally from under the plate in the beginning of the impact process and a highly sloped spray sheet that is ejected later when the high edge of the plate moves below the water surface. Detailed measurements of these features are presented and simple models are used to interpret the data.

ON THE IMPACT BETWEEN
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A RIGID STRUCTURE

by

An Wang

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Advisory Committee:

Professor James H. Duncan, Chair/Advisor

Professor Kenneth Kiger

Professor Johan Larsson

Professor Balakumar Balachandran

Professor Daniel Lathrop, Dean's representative

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List of Abbreviations

Fr	Froude number
We	Weber number
Re	Reynolds number
$\vec{u}$	velocity of the flow field
t	time
x	streamwise position
y	cross-stream position
z	vertical position
P	pressure
ρ	density
g	gravitational acceleration
σ	surface tension of water
η	free surface elevation
ϕ	velocity potential
$\hat{n}$	surface unit normal
$\bar{V}_s$	velocity at the surface of the structure
z_w	vertical position of the wave maker
x_b	streamwise location of maximum amplitude of the wave packet according to linear theory
w	window function
f_0	average frequency of the wave packet
λ_0	average wave length of the wave packet
k_0	average wave number of the wave packet
k_i	wave number of the i^{th} component in the wave packet
A	amplitude factor of the wave packet
$\bar{c}_g$	average group velocity of the wave packet
$\bar{c}_p$	average phase velocity of the wave packet
ω_i	angular frequency of the i^{th} component in the wave packet
$\bar{\omega}$	average angular frequency of the wave packet
q	parameter for adjusting energy distribution among components in the wave packet
ζ	constant that determines the rise rate of window function
τ_1	starting time the window function
τ_2	ending time the window function
X_I	horizontal coordinate of grid points in image reference frame
Z_I	vertical coordinate of grid points in image reference frame
X_L	horizontal coordinate of grid points in laboratory reference frame
Z_L	vertical coordinate of grid points in laboratory reference frame
ε_x	calibration error in horizontal direction
ε_z	calibration error in vertical direction
z_b	vertical coordinate of the bottom of the structure
H_m	maximum height of of the wave packet before breaking
P_{ieq}	pressure inside bubble at equilibrium state
R_0	bubble radius at equilibrium state
k	heat capacity ratio of air

f_n	natural frequency of air bubble
P_∞	ambient pressure of air bubble
R	radius of circle that fits the surface profile
z_c	vertical position of the center of the circle that fits the surface
V_n	water surface normal velocity
L	length scale: vertical distance from crest point to contact point
V_c	velocity scale: contact point velocity
Z_c	vertical position of the contact point
x_m	horizontal position of the crest point
z_m	vertical position of the crest point
t_s	the time when the wave maker motion starts
V_r	velocity of the ripple
V_{r_t}	tangential velocity of the ripple
V_{r_n}	normal velocity of the ripple
W_I	vertical velocity of the breaker's surface in open water at the fictitious position of the front face of the structure
δ	streamwise length of the ripple generated at $z_b/\lambda_0 = 0.0215$
B	width of the impact plate
L_p	length of the impact plate
L_H	horizontal distance from initial impact point to the surface of crater
L_V	vertical distance from initial impact point to the surface of crater
W_0	initial vertical impact velocity of the plate
β	deadrise (roll) angle of the impact plate
γ	pitch angle of the impact plate
v_d	horizontal velocity of the droplet
$L_c(t, \theta)$	distance from the initial impact point to the surface profile at t along the direction at an angle θ from the negative z -axis
V_0	ejection fluid speed at the spray root
θ	ejection angle at the spray root
X_0	streamwise position of lowest point on the impact plate when it reaches the mean water level
L_d	streamwise distance between the downstream and upstream edges of the impact plate

Chapter 1: Introduction

Water impact phenomena are common in nature and in several engineering fields. In ocean engineering applications, structures such as offshore platforms, seawalls, breakwaters, bridge piers, lighthouse, etc., frequently suffering impact from water waves and are damaged in extreme conditions. In naval architecture applications, slamming and “green water” caused by the interaction of ship and wave can cause extraordinary loads to the ship hull and onboard equipment. These impact events can often create very high local pressures on the structure and cause structural responses. In many situations, these impact events can also generate a water jet or spray carrying tremendous momentum. These highly energetic jets or spray can cause secondary damage to other surrounding structures. In addition, air entrainment can occur under certain conditions, depending on the geometry of the air-water interface immediately before the impact. The entrained air changes the compressibility of the flow, causing oscillations of the impact pressure. Therefore, in order to provide guidance for design, construction, operation and maintenance, it is important to understand the physics of this phenomenon. In spite of these important issues, very limited knowledge about the physics of water impact phenomenon has been achieved so far.

In order to understand the physics of water impact problems, two related topics are addressed in this thesis: (1) Deep-water breaking wave impact on 2D wall with finite vertical extent and (2) Spray formation during the slamming of a flat plate on quiescent water surface. Although the configurations are quite different, both of the studies explore the dynamic, transient characteristics of the water impact process.

The motion of an incompressible flow is described by the Navier-Stokes equations

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \vec{u} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{u} + \vec{g} \quad (1.1)$$

$$\nabla \cdot \vec{u} = 0 \quad (1.2)$$

Since the viscous effect is normally not important in the water impact problems, the bulk flow remains irrotational. Thus, the potential of the velocity field exists and satisfies Laplace's equation

$$\nabla^2 \phi = 0 \quad (1.3)$$

On the free surface, fluid particles on the free surface remain on free surface for all time. This can be represented by the kinematic boundary condition shown below

$$\frac{\partial \eta}{\partial t} + \frac{\partial \phi}{\partial x} \frac{\partial \eta}{\partial x} + \frac{\partial \phi}{\partial y} \frac{\partial \eta}{\partial y} - \frac{\partial \phi}{\partial z} = 0 \quad (1.4)$$

where $z = \eta(x, y, t)$ represents the water free surface. If the air has relatively little motion, then due to its small density one can assume that the air pressure on the water free surface should remain constant for all time. According to Bernoulli's equation, this condition can be represented by the dynamic boundary condition

shown below

$$\frac{\partial \phi}{\partial t} + \frac{1}{2} (\nabla \phi)^2 + gz + \frac{P_a}{\rho} + \frac{\sigma}{\rho} \left(\frac{1}{R_1} + \frac{1}{R_2} \right) = K \quad (1.5)$$

where P_a is the air pressure, σ is the surface tension of water, R_1 and R_2 is the radius of curvature of the water surface in $x - z$ and $y - z$ plane, respectively. At any point on the wet surface of the structure, the normal velocities of the fluid particles should equal to the normal velocities of the structure surface at this point, shown below

$$\frac{\partial \phi}{\partial n} = \hat{n} \cdot \vec{V}_s \quad (1.6)$$

where $\hat{n}$ is the unit normal at a point of the structure surface and $\vec{V}_s$ is the velocity of the structure surface at the same point.

Even though the governing equation (Laplace's equation) for the interior flow is linear, both kinematic and dynamic boundary conditions are nonlinear. In addition, both free surface nonlinear boundary conditions are satisfied on a unknown surface, which is part of the solution to the problem. In general, the water impact problems normally have the following characteristics:

1. Water impact is a nonlinear, transient phenomenon that occurs at the structure-air-water interface.
2. The impact process normally has a very short time scale. Therefore, viscosity does not have enough time to affect the bulk flow.
3. The rate of change of fluid inertial is normally high and the Reynolds number is large.
4. High impact pressures often occurs on the solid boundary.

5. Air can be entrained under certain conditions.

Wave impact on a vertical wall is a very difficult problem to tackle both theoretically and experimentally. Breaking wave phenomenon, which happens at the air-water interface, is nonlinear and transient. A wave breaking event involves a wide range of length scales, from as large as meters, such as the wavelength and the dimension of the structure, to as small as microns, such as the diameter of the air bubbles and water droplets. The wide range of length scales requires high spatial resolution and causes difficulty in both numerical and experimental studies. In many engineering applications, especially in deep water conditions, wave impact often occurs on structures whose “keel depth” is only a small fraction of the wave length and water depth. This type of impact has not been studied in detail in the past. According to our observations and measurements, variations of the keel depth of the structure can result in significant changes in the wave behavior and cause many interesting phenomena. The study of these types of impacts, including a detailed literature review, will be presented in Chapter 2, aiming at providing a detailed description of the discoveries and the interpretation of their physics.

The slamming of a ship with water waves is a critical issue that has drawn increased attention during the past decades. The slamming can cause extremely high loads on the ship structure, which will deform and even fail under certain conditions. The problem is very complex. Slamming occurs at the air-water interface and involves a moving solid boundary. The time scale of the slamming process is on the order of milliseconds. The physics of the slamming process is not well

understood, which makes the problem even more difficult to tackle mathematically. There has been significant progress during the past decades in studying the forces on the hull. The conventional method for studying the slamming force is the free-falling wedge test. However, the motion of the wedge is dependent on its mass and cannot be well-controlled during the nonlinear slamming process. Although the forces on a hull have been studied extensively, little attention has been given to the formation of the water sprays generated during slamming. In fact, parts of the spray carries high kinetic energy and can impinge on the surrounding structure, causing significant structural damage. In addition, these sprays increase the visibility of the vessel, which may be especially important for combatant planing vessels. Very little knowledge about the formation of the spray has been obtained so far. The second topic of this thesis will explore the spray formation during the slamming of a flat plate on quiescent water surface under prescribed plate motion. This study, along with a detailed review of the pertinent literature, will be presented in Chapter 3.

Chapter 2: Breaking Wave Impact on 2D Wall with Finite Vertical Extent

In this chapter, an experimental investigation of the impact of a plunging breaker on a partially submerged 2D wall is presented. This chapter is organized in the following five subsections: Overview and previous work, Experimental setup and techniques, Results, Discussions and Summary.

2.1 Overview and Previous Work

Wave impact on structures is an important problem in ocean engineering, coastal engineering and naval architecture applications. Extreme wave impact under certain conditions can cause serious damage to these structures, due to the extreme pressure or the tremendous momentum carried by high-speed water jets generated in the impact process. For years, many studies have been carried out aimed at understanding various aspects of the physics of the wave impact phenomenon.

One type of wave impact that is practically important and physically interesting is the impact of plunging breaking waves on a vertical wall. The following subsections will give an introduction of various aspects of this phenomenon: plunging breaking waves in open water, impact of plunging breaking wave on structures,

air entrainment during impact.

2.1.1 Breaking Waves in Open Water

Plunging breaking waves are commonly seen in both shallow water and deep water. Wave breaking happens when the slope of the wave satisfies certain criteria, causing energy conversion from kinetic and potential energy of the wave to kinetic energy of the turbulence, and the kinetic and gravitational and surface tension energy of the spray and droplets. In the process of breaking, the plunging breaker steepens and forms a growing plunging jet, which then turns over and impacts the water surface, generating turbulence, splashes, droplets and entraining air. The process is transient and nonlinear. Plunging breaking waves have been studied by many researchers in both experiments, see for example Rapp & Melville [66], Perlin *et al.* [63] and computations, Dommermuth *et al.* [25], Longuet-Higgins & Cokelet [48].

Breaking waves in deep water normally have two types. The first type is spilling breaker. As the wave crest of a spilling breaker steepens, surface structures (bulge, toe and capillary waves) form at the crest and the underlying flow eventually becomes unstable, leading to turbulent downslope flow near the free surface (Duncan *et al.* [27] [26], Liu & Duncan [46], Diorio *et al.* [22]).

The second type is plunging breaker. In this dissertation, deep-water plunging breakers will be discussed in detail and will be used in the experiments. Described by Battjes [2], a plunging breaker is characterized by the steepening and overturning of the front face of the crest and the formation of a jet that plunges into the water

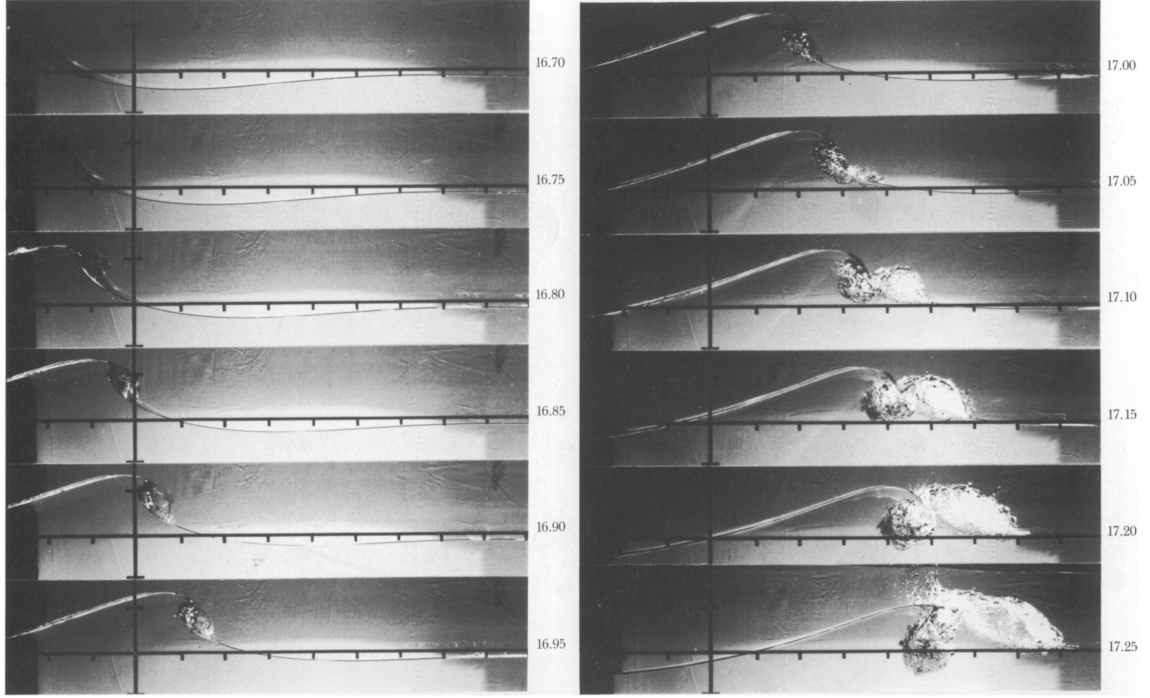


Figure 2.1: Photograph of plunging breaker in a wave tank by Rapp & Melville [66].

surface downstream of the crest. An air cavity is formed between the front face of crest and the plunging jet and some air is entrained when the jet plunges into water, which results in the collapse of the air cavity. The entrained air forms many little bubbles mixed with the turbulent water. The air-water mixture changes the compressibility of fluid and acoustic waves can be generated. In addition, droplets are ejected into the air during the jet impact and subsequent turbulent free surface flow (See Figure 2.1).

Plunging breaker have been simulated numerically by several researchers. Longuet-Higgins & Cokelet [48] proposed a mixed Eulerian-Lagrangian method to numerically simulate breaking waves up to the point of plunging jet impact. Dold & Peregrine [24] proposed a more accurate and more stable numerical method to simulate

plunging breakers up to the moment of jet impact.

The turbulent region and the mixing process in plunging breakers is also of great interest. Rapp & Melville [66] conducted a series of experiments and studied the turbulent mixing process and the turbulent flow field during the breaking process. They found the turbulent mixing depth linearly increases with time for 3 to 4 periods and follows a $t^{1/4}$ power law after that. The mixing region reaches a depth of two to three wave heights and horizontal length of one wave length within five periods of breaking. The turbulent RMS velocity is found to be $0.02C$ (where C is the characteristic phase speed) at the surface and remains significant at a depth of four to five wave heights. Ting & Kirby [73] experimentally studied the turbulence generated by plunging breaker in a surf zone for shoaling waves. They found that the turbulent intensity is highest under the wave front and decreases quickly after the crest passes. Okayasu [58] studied the velocity field under a plunging breaker by experiments. In their work, it is proposed that the velocity field can be divided into four components: the steady current, wave component, organized vortex motion and turbulence. Lubin *et al.* [51] simulated a plunging breaker by numerically using the Navier-Stokes equations for both the air and water, coupled with a LES turbulence model. Their model is able to simulate the interaction between the underwater vortices and the air pockets that are trapped during the breaking process.

Another important feature of plunging breakers is the air entrainment phenomenon, which is associated with the generation of acoustic waves. Chanson [10] studied the air entrainment process of pseudo-plunging breakers (a plunging water jet), including the comparison between fresh water and sea water. Melville [55]

points out that acoustic waves can be generated because the bubbles formed during breaking are not at equilibrium and oscillate in volume immediately after breaking. By measurements of the underwater acoustic field where a breaking wave passes, Deane [21] concluded that the turbulent region generated on the front face of the wave is acoustically active when air entrainment occurs. In his work, radiated noise ranging in frequency from 500 Hz to 5 kHz is correlated with the formation of bubbles.

2.1.2 Impact of Plunging Breaking Wave on Structures

In the presence of a structure, the behavior of a plunging breaker will be modified. Depending on the mechanism by which the plunging breaker is formed, this modification can be significant. For example, in deep water, plunging breakers are usually formed as a result of the focusing of different wave components. With the presence of the wall, these components can be reflected and the shape of the focused plunging breaker will be modified. The dimensions of the structure relative to the breaker wavelength is shown in this dissertation to be a critical parameter in the breaker behavior.

The impact of a two-dimensional plunging breaker on a wall with relatively large vertical extent and width compared to the wave height can be divided into several regimes based on the streamwise position of the wall relative to the location where the wave breaks in the absence of the wall (called “open water” herein), see for example Chan & Melville [9] and Peregrine [61]. However, since the presence of

the wall modifies the behavior of the undisturbed breaker, at the same streamwise location upstream of the wall, the water surface evolution during impact is different from that of the breaker in open water. Therefore, the regimes of impact cannot be accurately predicted only based on the behavior of the breaker in open water, although in some cases, this variation may not be extensive.

The changes in the water surface behavior as the streamwise position of the wall is varied have been studied extensively among many literature, especially with vertical wall in shallow water. Chan & Melville [9] did an experimental study of the deep-water breaking wave impact on a 2D wall that extended to the bottom of the tank. If the wall is located a wavelength or so downstream of the open-water breaker location, the plunging jet from the crest of the breaker overturns and plunges back into water before the breaking crest reaches the wall, see Figure 2.2(d)(e)(f). In this case, a significant amount of air can be entrained into the water and this can change the average compressibility of the fluid and the pressure distribution on the wall. According to Chan & Melville [9], double pressure peaks are possible at this condition in cases where the secondary jet that originates from the impact of the main plunging jet into the water can impact the wall before the turbulent breaking region of the wave. If the wall is located at a position far upstream of the breaking location, the breaker does not fully developed before reaching the wall and the impact phenomenon is relatively weak without violent impact pressure, see Figure 2.2(a)(b).

At a critical wall position in between the above two cases, see Figure 2.2(c), the breaker is just about to form a jet as it reaches the wall and at the same time the

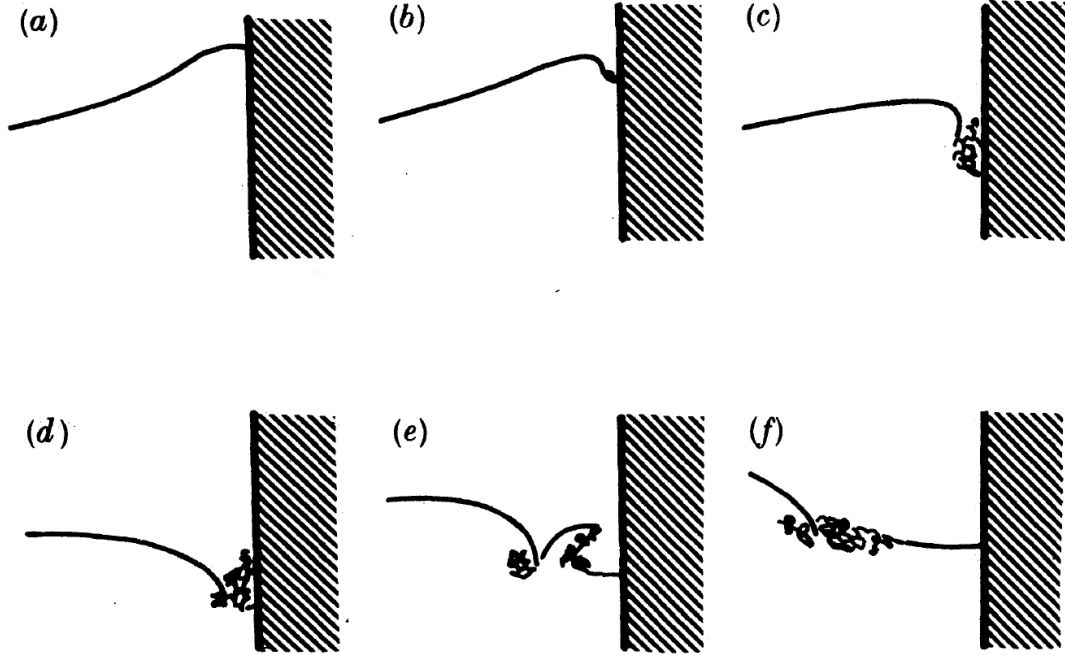


Figure 2.2: Regimes of impact of a plunging breaker on a wall based on the stream-wise location of the wall, by Chan & Melville [9].

contact point of the water surface on the wall is moving upwards and meets the crest. In this case, the impact does not involve breaking as the water surface profile undergoes a phenomenon called “Flip-through”, see Peregrine [61], in which a high-speed vertical jet is formed and very high wall pressures are developed. In this process, the fluid domain stays as a simply connected region without entraining air bubbles. The flip-through phenomena also occurs in some other free surface flow problems that involve the formation of a high-speed jet, such as standing wave (Longuet-Higgins [47], Zeff *et al.* [81]), capillary pinch-off of droplets (Day *et al.* [20], Lepinen & Lister [45]), collapsing cavitation bubble near a solid boundary (Longuet-Higgins & Oğuz [49], Zhang *et al.* [82]) and sloshing (Lugni *et al.* [52]). Flip-through involves a finite time singularity in potential flow formulations. However, the break-

down of the potential flow theory normally involves other new physics. For example, before the singularity occurs, small disturbances that are introduced from initial condition or at later times can accumulate over time and become dominant features on the water surface just before the moment of impact. At the moment of impact, these surface features invalidate the assumption of a continuous water surface which encloses a simply connected region, causing a small amount of air to be trapped. It is also possible that viscosity can play a role before the singularity occurs. Therefore, strictly speaking, it is not so clear whether a finite time singularity exists experimentally, if one examines the details of the flow with sufficiently high temporal and spatial resolution. Nevertheless, potential flow theory should hold for most of the period before the moment of impact.

With a potential flow formulation, flip-through phenomena have been investigated in several theoretical studies. Cooker [15] derived analytic models to describe several types of focusing flow with simplified boundary geometries. The models employ basic potential flow singularities to represent the flow field at one instant. It is mentioned with the absence of gravity, there exist a pressure peak just below the surface. Longuet-Higgins & Oğuz [50] used a single term solution to Laplace's equation with power-law temporal dependence as the velocity potential to model the unsteady flow field. In this model, the surface at far-field asymptotically approaches a constant slope, which is related to the order of the single term solution as well as the decay rate of the length scale (exponent of the power-law). However, the single term analytic solution can only qualitatively describes a free surface with the far field slope close to $\pi/2$. Longuet-Higgins [47] used model equations to study

the high-speed vertical jet produced by 2D standing waves under critical conditions. By properly choosing the initial shape of the standing wave, high acceleration of the surface is found to reach over $10g$. LH also studied the effect of small perturbations on the initial profiles on the acceleration of the jet. It is pointed out that maximum acceleration is sensitive to the initial shape of the surface and the small perturbations can further increase the maximum acceleration.

Extreme shock pressure during the impact process has been reported by many investigators, both in laboratory and field experiments. Bagnold [1] conducted an experimental study of the shock pressure generated during shallow water wave impact on a wall and developed a theoretical model to estimate the impact pressure. The wave was steepened to break by a sloped beach at the bottom of the tank. It is concluded the shock pressure is generated by the direct impact of a nearly vertical water surface on the wall along with an air cushion with some thickness between the wall and the wave front. The maximum pressure occurs when the thickness of the cushion is minimum. There are several other experimental studies on impact pressure. For example, Blackmore & Hewson [3] did full-scale field measurements of impact pressure on a seawall. Kirkgöz [39], Bullock *et al.* [7] measured wave impact pressure on vertical and sloping walls (reaching the tank bottom). Bagnold [1] and Chan & Melville [9] both reported the variability of the impact pressure even under very consistent experimental conditions. Besides this variability, due to the low resolution of these measurements, it is difficult to understand the detailed behavior of the impact pressure and its correlation with the evolution of wave.

Cooker & Peregrine [14] reported a numerical simulation of the flip-through

wave impact on a wall in shallow water using a boundary integral method. It is argued that a high-speed jet can form along with a high pressure just below surface, without direct impact of the wave front on the wall, see also in Cooker & Peregrine [?] and Figure 2.3. This is different from Bagnold [1]’s conclusion that the peak pressure is caused by the direct impact of a vertical wave front with the wall with some air trapped. Here, according to Cooker and Peregrine, although the wave front is nearly vertical, the contact point also rises up along the wall and meets the wave front which already converged to a very small region. It is found (probably the first time) that no direct impact of the water is necessary to produce a high pressure, which was similar to what is reported in several early experiments, although in these experiments, the event that causes the high pressure is not so clear due to the low measurement resolution. In this simulation, flow accelerations of more than $1000g$ were found just as the vertical jet forms. It is also mentioned that the behavior of wave impact is a local behavior in time and space, regardless of the broad geometry of the domain.

Cooker and Peregrine [19] indicated that the violent impact pressure in “Flip-through” impacts is caused by the rate of change of fluid inertial which is in turn caused by focusing of the free surface to a point. Viscosity is not important until after the impact. Surface tension is only important during the formation of a plunging jet which has a large curvature. However, it is mentioned that Froude scaling, which ignores the effects of the compressibility of trapped air, the areation level of the water and viscosity might overestimate the pressure. Theoretically, the focusing process can create infinitely large pressure, which is not true physically because

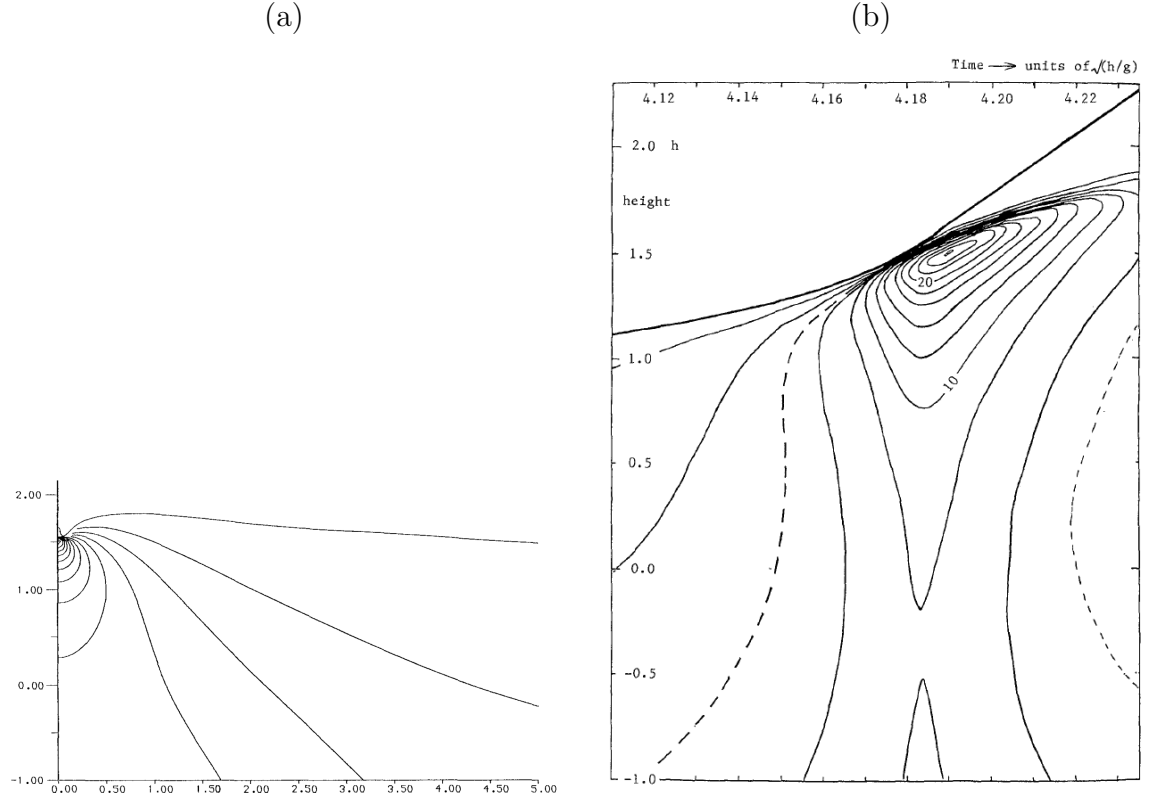


Figure 2.3: Impact pressure of a flip-through impact by numerical simulation from Cooker & Peregrine [19]. (a) Pressure distribution in flow field at a moment just before the jet forms. (b) temporal evolution of pressure on the wall.

when the surface profile shrinks to a small enough region, the surface roughness of the wall and the roughness of the free surface (small waves or ripples on free surface) can limit the impact pressure.

During the experimental study by Chan & Melville [8], the variability of the wall pressure distribution even under controllable wave conditions is shown to be significant. It is also indicated that the pressure fields found in between deep water and shallow water impact are very similar in behavior.

Kirkgöz [39] [40] measured the impact pressure by breaking waves on a bottom-

mounted wall (reaches bed) with various slopes. It was found that the impact pressure on a back-sloping wall is larger than that on a vertical wall. These experiments aimed at studying impact pressure at “perfect breaking”, which means the wave front face is almost parallel to the wall just before the moment of impact and the wave propagation direction is perpendicular to the wall. In this condition, the maximum impact pressure can be generated and no air is entrained. This is realized by adjusting the water depth of the impact region.

Cooker & Peregrine [16] studied the pressure and impulse acting on a body lying on the bottom during wave impact. Different shape of bodies are discussed. In this calculation, the water is assumed to be inviscid and incompressible (no air entrainment is considered).

Cooker & Peregrine [17] proposed a pressure-impulse theory for modeling the impact pressure and velocity field. Several impact examples are calculated with various geometries. It is concluded that the impulse is enhanced for impact in a confined space, such as sloshing. The pressure impulse is not sensitive to the shape of the wave. They suggested that the kinetic energy of the fluid is transferred into kinetic energy of the liquid jet generated during impact.

Wood & Peregrine [80] used the pressure-impulse theory (see also Cooker & Peregrine [18] [16] [17]) in studying three dimensional wave impact on vertical wall. They also concluded that the three dimensional effect is significant when the impact width is less than twice of the water depth. If the impact width is larger than the four times of the height of the wall, the two dimensional model can predict the pressure impulse.

Walkden [78] investigated the wave impact pressure on a caisson breakwater on both the front side and the back side during overtopping impact events. It is mentioned that the air trapped by plunging breaker can reduce the pressure impulse during an overtopping impact event.

Peregrine [61] mentioned that there are two high pressure maxima during each crest impact due to the acceleration and deceleration of the water jet and the impact pressure is very sensitive to the shape of the wave profile before impact.

Besides wave impact on walls, Wienke & Oumeraci [79], Repalle *et al.* [69], Ochi & Tsai [57] studied the wave impact on slender objects (vertical cylinders with circular and square cross sections). Easson & Greated [28] studied the velocity field under a breaking wave crest with laser-doppler anemometry technique and correlated the velocity field to the impact load on a cylinder. Wave impact on some other complicated structures, such as ship-hull shaped structures (Voogt *et al.* [76]), and gravel beaches (Pedrozo-Acuña *et al.* [60]) is explored in several papers.

2.1.3 Air Entrainment during Wave Impact

As mentioned above, in some cases air entrainment occurs during or before the wave impact. During the wave impact, a large air pocket can be entrapped when the plunging jet directly hits the wall; the shape and volume of this air pocket depends on the shape of the wave crest at the moment just before impact on the wall. If the plunging jet falls back into the water before impacting the wall, the entrapped air pocket can break up into many small bubbles, forming an air-water

mixture that subsequently collides with the wall. The mixture has decreased density and increased compressibility, thus decreasing the speed of sound dramatically. In either of the above cases, the dynamics and compressibility of the air can influence the behavior of the fluid and the wall pressure.

Air entrainment during wave impact has been studied in experiments and theory. Bagnold [1] stated that the wave impact phenomenon is closely related to the compression of the air cushion and depends on the thickness of the air cushion. He also mentioned that the thickness of the air cushion is not well defined because of the irregularity of the wave front. The irregularity of the air cushion thickness could cause pressure variation over the impact region.

Peregrine & Thais [62] developed a method for estimating the effect of an air cushion on the wave impact pressure. In their work, the aerated water is assumed to be an incompressible liquid with a void fraction, representing homogeneously distributed small bubbles in water. Their results show that the Mach number of the incoming flow and the severity of the wave can affect the pressure reduction caused by the air cushion. It is also mentioned that even a small fraction of air dispersed as small bubbles in the flow can decrease the impact pressure significantly.

Bredmose *et al.* [5] studied the effect of air during wave impact by numerical simulations. Near the wall, a compressible aerated-flow model is developed by considering the aerated flow to be a homogeneous mixture of incompressible fluid and compressible air. The generation of a shock wave is considered by adding the conservation of energy to the governing equations. The outer flow is simulated by potential flow theory by using the boundary integral method. Similar to Bagnold [1],

the authors found that the pressure is maximum when only a small pocket of air is trapped. The trapped air tends to decrease the maximum pressure and increase the impulse and force because of an increase in the area of high pressure region and duration of the impact.

Gibson [34] measured the effect of air bubbles on the speed of sound in water. Their results indicate that the aeration has a dramatic effect on the sound speed in water (an air-water mixture with a void fraction of only 1% decreases the speed of sound by 90%).

Topliss [74] studied the pressure oscillation due to air entrainment during wave impact. In this analysis, it shows that the oscillation frequency is increasing as the aeration level decreases. Air bubbles close to the free surface tend to have higher resonant frequency than bubbles close to the bottom. Small air bubbles have higher resonant frequency than larger bubbles.

Bullock *et al.* [6] studied the effect of an air cushion on wave impact for both fresh water and sea water. Generally, the peak pressure is lower and the rise time is longer if the aeration is taken into consideration. Since bubble size in fresh water tends to be larger and coalescences occurs more readily than in seawater, the bubbles rise up to free surface and burst more quickly in fresh water. In other words, bubbles in seawater can persist for a much longer time. The aeration and void fraction in fresh water is much smaller than that in seawater during impact.

Air entrainment makes the wave impact phenomenon difficult to be scaled. Traditional Froude scaling can overestimate the impact pressure in cases with air entrainment, because the cushion effect of the air phase is not taken into account

(see Bullock *et al.* [6]). In the model proposed by [83], see above, the air phase oscillations are modeled as a spring-mass system, which can simulate the oscillation of the air packet. It is suggested when ρU^2 dominates over the initial pressure of the air pocket P_0 , i.e., $P_0/\rho U^2 \ll 1$, the scaling factor is a function of the geometry of the plunging jet. If $P_0/\rho U^2 \sim O(1)$, the scaling factor is a function of the geometry of both the plunging jet and the air pocket. Bredmose *et al.* [4] discussed the scale of the impact pressure in the presence of entrained air. For the aerated flow, the pressures lower and higher than 318 kPa are suggested to follow Froude scaling and Bagnold-Mitsuyasu scaling, respectively.

In many occasions, the distance between the bottom of the structure and the mean water level is small compared with the wave length and the water depth. This type of impact has not been studied in detail before. In fact, the impact process will be more complex in these occasions than that in the previous investigations of wave impact on walls with deep submergences. According to the discoveries that will be described in the following sections of this chapter, when the bottom of the structure is close to the mean free surface, it can be above the instantaneous free surface level for a short time during the impact process. When the water surface subsequently impacts the underside of the object, upstream propagating disturbances can be generated on the water surface. Even if the bottom of the wall remain submerged, the submergence of the wall also affect the evolution of the water surface. Also, as the wave approaches the structure, it is possible that vorticity can be generated at the edges of the structure and this vorticity can further influence the impact process. To further understand the physics of this type of impact, an experimental study of

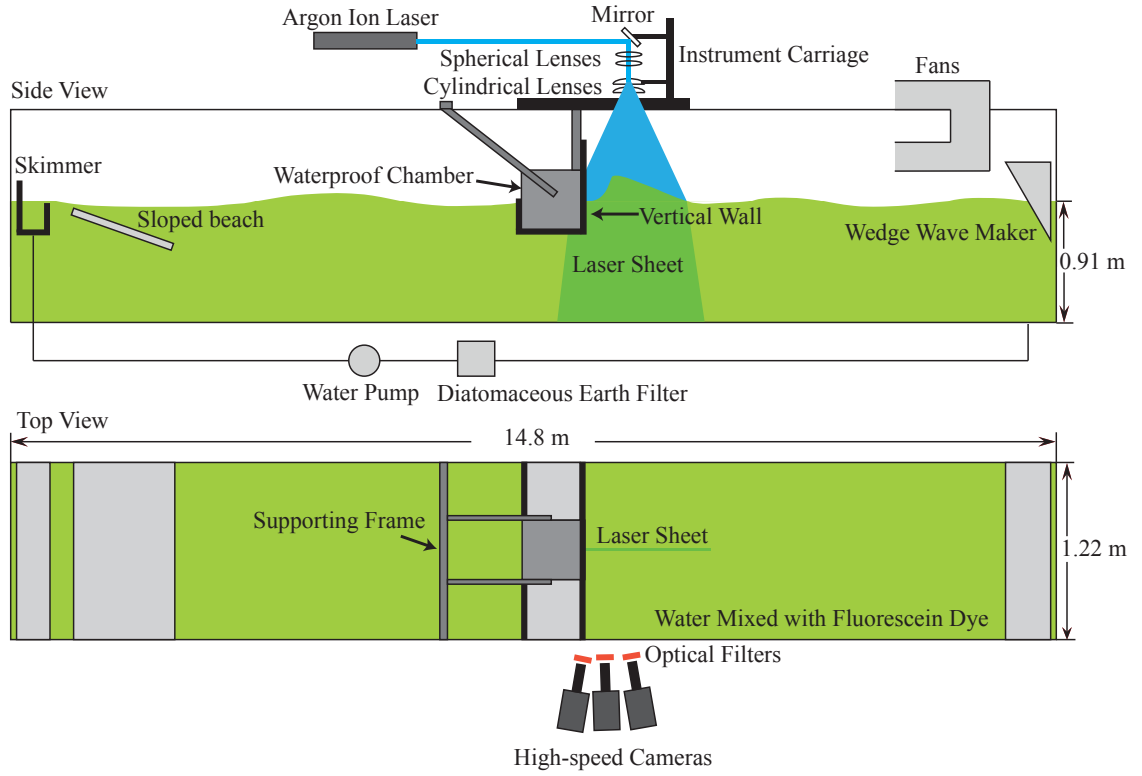


Figure 2.4: Schematic of the Wave Tank

wave impact on a structure with finite vertical extent is performed. Discoveries will be described and various aspects of the physics will be interpreted in the following sections.

2.2 Experimental Details

2.2.1 Experimental Facilities

The experiments were performed in a wave tank that is 14.8 m long, 1.2 m wide and 2.2 m tall, see Figure 2.4. The inside surface of the tank consists of a set of large flat panels which are in turn supported by an external superstructure

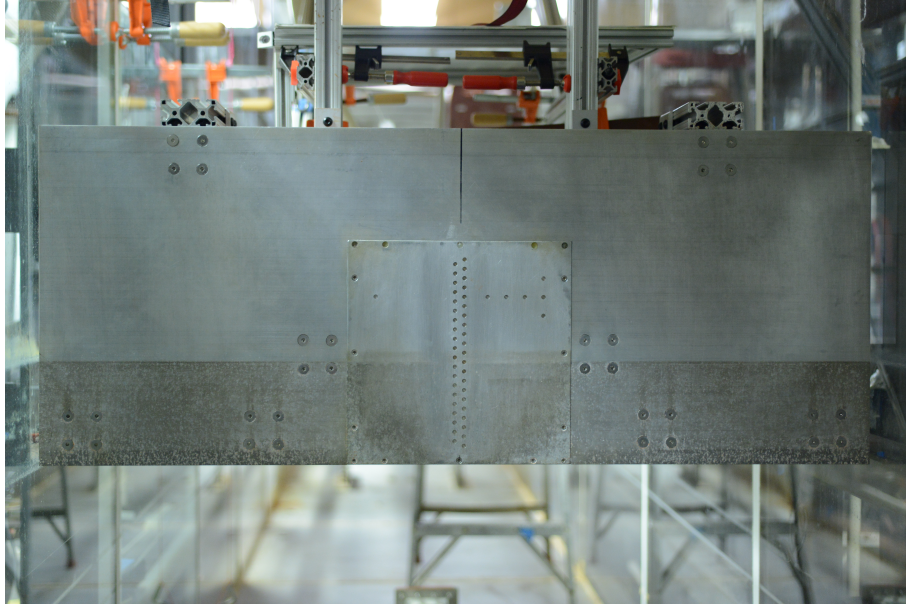


Figure 2.5: Photograph of the impact structure installed in the wave tank. The photo is taken from the upstream of the structure.

consisting of steel beams. All of the floor panels and the wall panels at the two ends of the tank are made of 0.635-cm-thick stainless steel plates while the panels on the long side walls of the tank are made of 3.5-cm-thick clear acrylic. The undisturbed water depth was 0.91 m for all experiments described herein.

The tank includes a programmable wave maker consisting of a vertically oscillating wedge that spans the width of the tank at one end. The side of the wedge closest to the end wall of the tank is vertical and the opposite side of the wedge is inclined at an angle of 30° from vertical. The wedge is driven by a ball-screw and linear-bearing mechanism that is in turn driven by a servo-motor. The servo motor is mounted rigidly on a frame isolated from the wave tank so that the undesired vibration of the wave maker frame cannot be transmitted to the water in the wave tank. A computer-based feedback control system is used with a position sensor and

a motor tachometer to provide precise control of the motion of the wedge. Repeated tests with the same wavemaker input parameters indicate only a $\pm 0.1\%$ root-mean-square error in wedge position at the time of peak displacement from the mean water level. In all experiments described herein, the wedge was oscillated about a mean level with the vertex of the wedge submerged 44.3 cm below the mean water level.

The wave impact occurs on a structure that interacts with the flow through three plane surfaces that span the width of the tank: a vertical forward face (45.7 cm tall), a vertical back face (15.2 cm tall) and a horizontal bottom face (30.4 cm wide), see Figure 2.4. The bottom centerpiece of the structure is a sealed 30.48 cm cube whose front, bottom and back faces are coplanar with the corresponding faces of the structure. The front face of the cube has mounting holes for pressure sensors as shown in Figure 2.6 and described in §2.2.2.3. The entire structure is rigidly mounted to the top of the wave tank and can be moved to a wide range of vertical and streamwise horizontal positions within the tank. A photograph of the impact structure is shown in Figure 2.5.

A fixed skimmer is located at the opposite end of the tank from the wave maker and a removable skimmer is placed just upstream of the structure during the time between experimental runs. Water from the skimmer is pumped through a diatomaceous earth filter and then back into the tank at the upstream end, i.e., near the wave maker. Two fans are used in the time between experimental runs to blow the surface layer toward the skimmer.

After each experimental run, the water filtration system will be turned on for about 15 minutes. Then the fans and water pumps are turned off and the skimmer

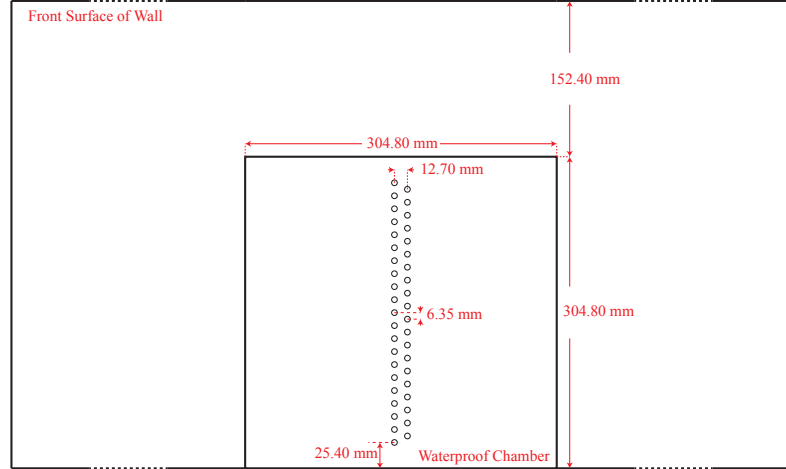


Figure 2.6: Pressure sensor layout on forward face of structure.

is removed. Then the wedge of the wave maker will be raised up to its equilibrium position about 45 minutes before the next experimental run. A sloped beach is installed on the downstream end of the tank to absorb the wave energy in order to reduce the time for water to recover its static state.

2.2.2 Experimental Techniques

2.2.2.1 Wave Generation: Dispersive Focusing Technique

The breaking waves are generated by using a dispersive focusing technique, which is also described by Rapp & Melville [66], Duncan *et al.* [26] and others. In this method, a packet of wave components with different frequencies (average frequency $f_0 = 1.15$ Hz) are generated and travel along the wave tank. According to linear wave theory, wave components with different frequencies travel with different phase speeds, so the wave components with a range of frequencies can be focused at a desire location, causing an increase of the amplitude of the focused wave. Eventually

a plunging breaker is formed in open water. In the present implementation of this technique, the wave maker motion is given by

$$z_w = w(t) \frac{2\pi}{N} A \sum_{i=1}^N \frac{1}{k_0} \left(\frac{k_0}{k_i} \right)^q \cos \left[x_b \left(\frac{\omega_i}{\bar{c}_g} - k_i \right) - \omega_i t + \phi \right] \quad (2.1)$$

where N is the number of wave components, A is a dimensionless constant representing the overall amplitude, x_b is the streamwise location of the maximum amplitude (by linear theory) to the back of the wave maker wedge, (k_i, ω_i) are the wavenumber and frequency of the i^{th} wave component (by linear theory, $k_i = \omega_i^2/g$), $k_0 = \bar{\omega}^2/g$ (where $\bar{\omega}$ is the average of the N frequencies), $\bar{c}_g$ is the averaged group velocity of the N wave components, ϕ is the phase shift, chosen to be $\pi/2$, $w(t)$ is a window function. q is an exponent chosen to distribute the wave amplitude among the various components. The radian frequency of each wave component $\omega_i = \bar{\omega} - \Delta\omega/2 + (i-1)\Delta\omega/(N-1)$ where $\bar{\omega}$ and $\Delta\omega$ are constants. The wave components are equally spaced in the frequency domain. The window function $w(t)$ is chosen to give the wave maker wedge zero motion when the summation of the wave components results in a very small motion:

$$w(t) = 0.25 (\tanh(\zeta f_0(t - \tau_1)) + 1) (1 - \tanh(\zeta f_0(t - \tau_2))) \quad (2.2)$$

where ζ is a constant which determines the rise rate of the window function, chosen as 5.0. The window function is nearly equal to 1.0 for most of the time between $t = \tau_1$ and $t = \tau_2$ and is zero at other times. The times τ_1 and τ_2 are chosen to allow the highest and lowest frequency components to travel to breaking location x_b :

$$\tau_1 = x_b (1/\bar{c}_g - 1/c_N) \quad (2.3)$$

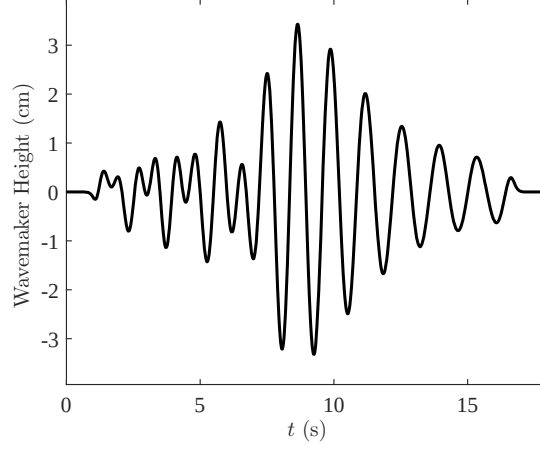


Figure 2.7: Time history of the vertical position of the wave maker wedge.

$$\tau_2 = x_b (1/\bar{c}_g - 1/c_1) + 6 \quad (2.4)$$

All of the experiments described herein were performed with the following set of wave maker motion parameters: $N = 32$, $A = 0.0688$, $q = 1.75$, $\Delta\omega = 0.77\bar{\omega}$, $\bar{\omega} = 7.226 \text{ s}^{-1}$ and $x_b = 7.15\lambda_0$, where $\lambda_0 = 2\pi g/\bar{\omega}^2 = 1.181 \text{ m}$. These parameters yield $f_0 = \bar{\omega}/(2\pi) = 1.15 \text{ Hz}$, $\bar{c}_g = 0.7138 \text{ m/s}$ and characteristic wave phase speed $\bar{c}_p = 2\bar{c}_g = 1.437 \text{ m/s}$. It should be noted that $x_b = 8.441 \text{ m}$ while the streamwise position of the front surface of the structure is 6.415 m from the vertical surface of the wedge. The time history of the wave maker position used in the current experiments is shown in Figure 2.7.

2.2.2.2 Wave Profile Measurement: Laser Induced Fluorescence Technique

The Laser Induced Fluorescence technique (LIF) is used to accurately measure the wave profile evolution during impact. In these measurements, the illumination is provided by a 6-Watt argon-ion laser operated at a 4-Watt power level. The laser

is operated in an all-lines mode with the majority of the power at wave lengths of 488 and 524 nm. The laser is located at one side of the wave tank close to the downstream end so that the laser beam travels along the length of the tank from the downstream end to the upstream end. Several mirrors are used to reflect the laser beam so that it travels on top and along the center plane of the tank. By adjusting the relative distance between two convex lenses mounted close to the outlet of the laser, fine adjustment on the laser beam can be undertaken so that the laser beam is collimated along its path. Another mirror is used to reflect the collimated horizontal laser beam to vertically downwards. A cylindrical lens is used to diverge the vertical laser beam into a laser sheet at the center plane of the tank. Two other convex lenses mounted between the last mirror and the cylindrical lens are used to focus the laser beam to a thin sheet at the water surface. It is very critical to create a thin laser light sheet in order to have sharp surface profiles in the images.

The water is mixed with fluorescent dye (Fluorescein sodium salt). When the fluorescent dye is exposed to the laser light, the electrons of the molecules at ground energy level absorb the laser light energy and are excited to some higher energy level. When those electrons transfer back to lower energy level, photons are emitted. The emitted light by the fluorescent dye has a different range of wavelength from that of the input laser light. The reemitted light from the fluorescent dye forms the illumination for the high-speed cameras. The light from the laser is prevented from entering the camera by placing a long-wavelength-pass optical filter in front of the camera lens. Consequently, only the light from the fluorescing water can form the image on the camera sensor. Since the excitation region of water is a

thin sheet, a sharp surface profile (air-water interface) can be recorded accurately. The fluorescent dye is injected into the water and mixed sufficiently by circulation system before experiments, so that the illuminated free surface has a uniform dye concentration.

Two Phantom V640 and one V641 high-speed cameras are used for recording the surface motion. Camera 1 is set with an image size of 2560 by 1580 pixels, a frame rate of 1500 pps and an exposure time 665 μs . Camera 1 is recording the wave profile in a relatively large field of view. Camera 2 is set with an image size of 1024 by 900 pixels, a frame rate of 4500 pps and an exposure time of 220 μs . Camera 2 records the surface profile around the impact region. Since the water is rising extremely fast around the impact region before impact, a high frame rate and sufficiently low exposure time is necessary for resolving this motion. An additional Phantom V641 camera (Camera 3) is operated at 13500 pps with a resolution of 512×452 pixels and exposure time of 72 μs , in order to capture the detailed motion of the surface profile at the flip-through condition.

A pulse-delay generator is used for the timing of the measurements. When the wave maker is triggered, a TTL signal is sent to a pulse-delay generator, which generates a TTL signal to different channels for triggering different instruments. The delay time between the triggering signals of different channels can be adjusted. Camera 1, 2, 3 and the pressure measurement A/D system are connected to different channels of the pulse-delay generator. The synchronization of the cameras and the A/D system is verified with a system with Helium Neon laser and the light detector. Initially, the Helium Neon laser light shines on the light detector, which

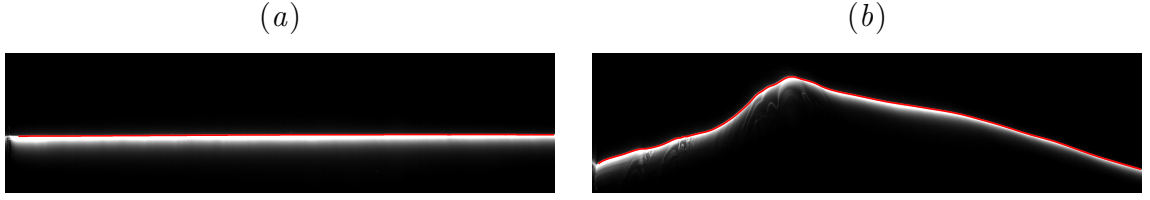


Figure 2.8: (a) Detected water surface position of the calm surface before an experimental run. (b) Detected water surface position of a wave.

outputs a electric signal and captured by the A/D system. Cameras capture the scattered laser light from the light detector. At some moment of time, the laser light is blocked quickly, which causes the electric signal output from the light detector drops sharply and the cameras capture the disappearance of the scattered light. The recorded electric signal by the A/D system and the recorded movies by the cameras are compared to ensure the accuracy of the synchronization.

With the cameras having downward viewing angles, the subsurface water within the light sheet serves as the background illumination for the surface features between the light sheet and the cameras. These features can be seen in the LIF images for observation purpose only. Within the plane of the light sheet, the water surface appears to be a sharp boundary where the intensity gradient reaches local maximum. The surface profiles were extracted from the LIF images based on a method described in Liu & Duncan [46]. A sample result is shown in Figure 2.8.

Since the optical axis of the camera-lens system is not exactly perpendicular to the light sheet and the lens has some curvature, the image taken by the camera is distorted from physical space and calibration is necessary. The calibration converts the pixel based coordinate system of the image into the physical coordinate system

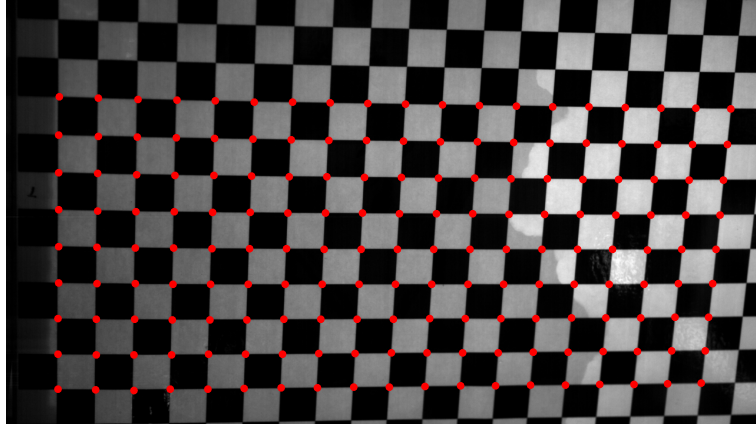


Figure 2.9: Extracted grid points from the calibration target.

and corrects the distortion over the field of view. A checker board is used for the purpose of calibration. The checker board is 61 cm×61 cm with 25.4 mm×25.4 mm black and white squares spaced alternately. The checkerboard is attached rigidly to a frame, which is mounted to the wall front face in a way that the checkerboard surface is always in the plane of the light sheet. Several images are taken for each experimental condition before and after the experiments. Each time after the calibration image is recorded, the calibration board is removed from the tank. Figure 2.9 shows a typical calibration image with all the detected corner points.

The coordinates of the grid points in the image reference frame (X_I, Z_I) are first extracted, see Figure 2.9. Since the coordinates of these grid points in the laboratory reference frame (X_L, Z_L) are known values, two bivariate cubic functions can be fitted for X_L and Z_L in the image reference frame (X_I, Z_I) , respectively. Then the coordinates of all the points in the image can be converted to coordinates in laboratory coordinate system by interpolation of these two functions.

$$X_L(X_I, Z_I) = \sum_{m=0}^3 \sum_{n=0}^3 A_{mn} X_I^m Z_I^n \quad (2.5)$$

$$Z_L(X_I, Z_I) = \sum_{m=0}^3 \sum_{n=0}^3 B_{mn} X_I^m Z_I^n \quad (2.6)$$

Before each experimental run, a LIF image of the still water surface was taken, as shown in Figure 2.8(a). The mean water line was extracted from this image.

The mean water line was first used in the above interpolation and a corrected mean water line was obtained. Then a linear function was fitted to the corrected water line to find its slope. Then the coordinate system was rotated to compensate this slope so that the mean water line after rotation is horizontal. Then the coordinates of contact point of the mean water line and the wall was found and the coordinate system was translated so that this contact point is at the origin.

The images from the high-speed movies are converted into binary images with a proper threshold value so that surface profile can be clearly distinguished. The surface profiles are then recorded in pixels using the coordinate system of the image. Figure 2.8(b) shows a typical surface profile detected from one image.

The error of this calibration is estimated at the checkerboard corners by the difference in values of the coordinates between the actual physical coordinates which are known and the fitted physical coordinates from the interpolation function 2.5.

$$\varepsilon_x = X_{CF} - X_{CP} \quad (2.7)$$

$$\varepsilon_z = Z_{CF} - Z_{CP} \quad (2.8)$$

Where X_{CF} and Z_{CF} denote coordinates of corners by fitting function, X_{CP} and

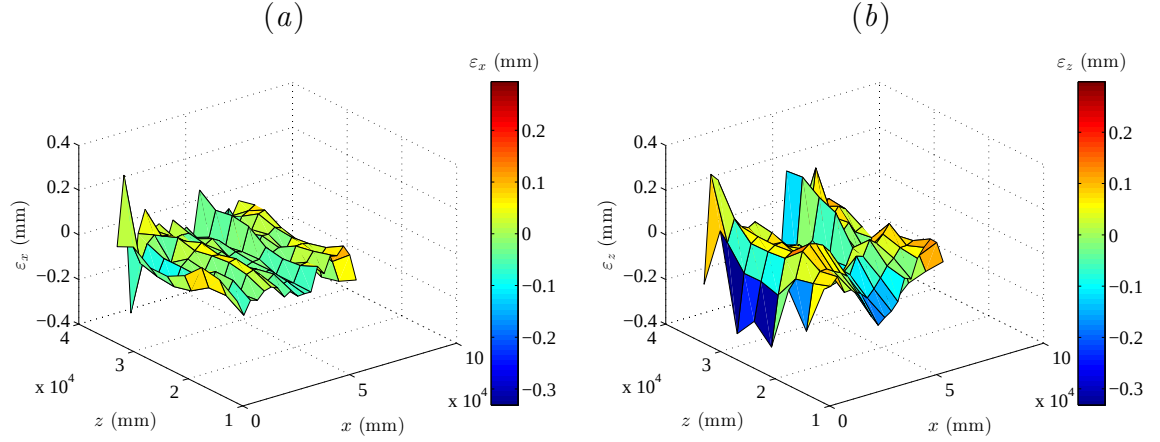


Figure 2.10: (a) Typical error map of corrected X coordinate. (b) Typical error map of corrected Z coordinate.

Z_{CP} denote actual coordinates of corners. A typical calibration error map is plotted in Figure 2.10, which shows the error is within ± 0.3 mm.

2.2.2.3 Pressure Measurement Technique

The impact pressure on the front face of the structure is measured. The major measurement positions are along two vertical lines which are symmetric about the vertical centerline of the front face, shown in Figure 2.6. The two vertical lines are 1.27 cm apart from each other. Similar to the experiments by Chan and Melville [9], the measurement positions on the two lines are staggered in order to achieve more spacial resolution in the vertical direction. The vertical distance between two adjacent positions on the same vertical line is 1.27 cm, so the effective vertical resolution is 0.635 cm. There are 21 positions on one vertical line and 20 position on the other, so that 41 different vertical positions can be measured. Since

the two lines of sensor positions are very close to the center line of the wall, these 41 sensor locations are called the center line locations.

A special hole profile for the pressure sensor is machined at each measurement position. The front plate of the water-proof chamber is 1.905 cm thick. The hole profile is designed in a way such that the measurement plane of the sensor is recessed from the front face of the wall by 0.508 mm. This recess space is filled with insulating grease, which transmits the impact pressure to the pressure sensor as well as delays the possible thermal effect of the generally cold tank water when it comes in contact with the sensors that are initially above the mean water level.

The wave impact pressure is measured by piezoelectric pressure sensors (Part Number: 113B28) supplied by PCB Piezotronic Inc.. The diameter of the sensor measurement face is 0.554 cm. The resolution, sensitivity and the measurement range of the pressure sensors are 0.007 kPa, 14.5 mV/kPa and ± 344.7 kPa, respectively. The rise time of the sensor is less than 1 μ s and its low frequency response frequency is 0.5 Hz.

When the pressure sensors sense pressure change, the piezoelectronic material in the sensor deforms and generates an electric signal. A signal conditioner is used to supply the input voltage to the pressure sensor. The output signal is sent to an analogue-to-digital data acquisition system supplied by National Instrument Corporation. The data acquisition system has four NI PXI-6133 DAQs, which have a 14-bit resolution and have 8 analogue input channels on each board. These DAQs can have a minimum full-scale input voltage range -1.25 V to 1.25 V, so that the resolution can reach as small as 0.1526 mV, which corresponds to about 0.01 kPa.

The sample rate used in the experiments is 500~900 kHz. The pressure measurement system is triggered by the same pulse-delay generator used for the high-speed cameras.

2.3 Results

The surface profile and pressure distribution measurements are presented below in three subsections. In the following subsection, §2.3.1, the profile history of the wave generated by the above-described wave maker motion operating in open water, i.e. with the structure removed from the wave tank, is presented. This is followed, in §2.3.2 and §2.3.3, by presentations of the water surface profile histories and surface pressure measurements during the wave impact on the structure, respectively.

2.3.1 Wave Behavior in Open Water

In order to show how the breaker is affected by the structure, the surface profile history of the breaker was first measured in open water. Images and surface profiles from an LIF movie of the open-water breaker are shown in Figure 2.11(*a*) and (*b*), respectively. In these images, the sharp boundary between the upper dark region and the lower bright region is the water surface profile in the plane of the light sheet. The lower bright region is illuminated by the fluorescing dye in the subsurface water within the light sheet. In the first image (i) and corresponding profile, the front (left) face of the wave near the crest is nearly vertical, indicating

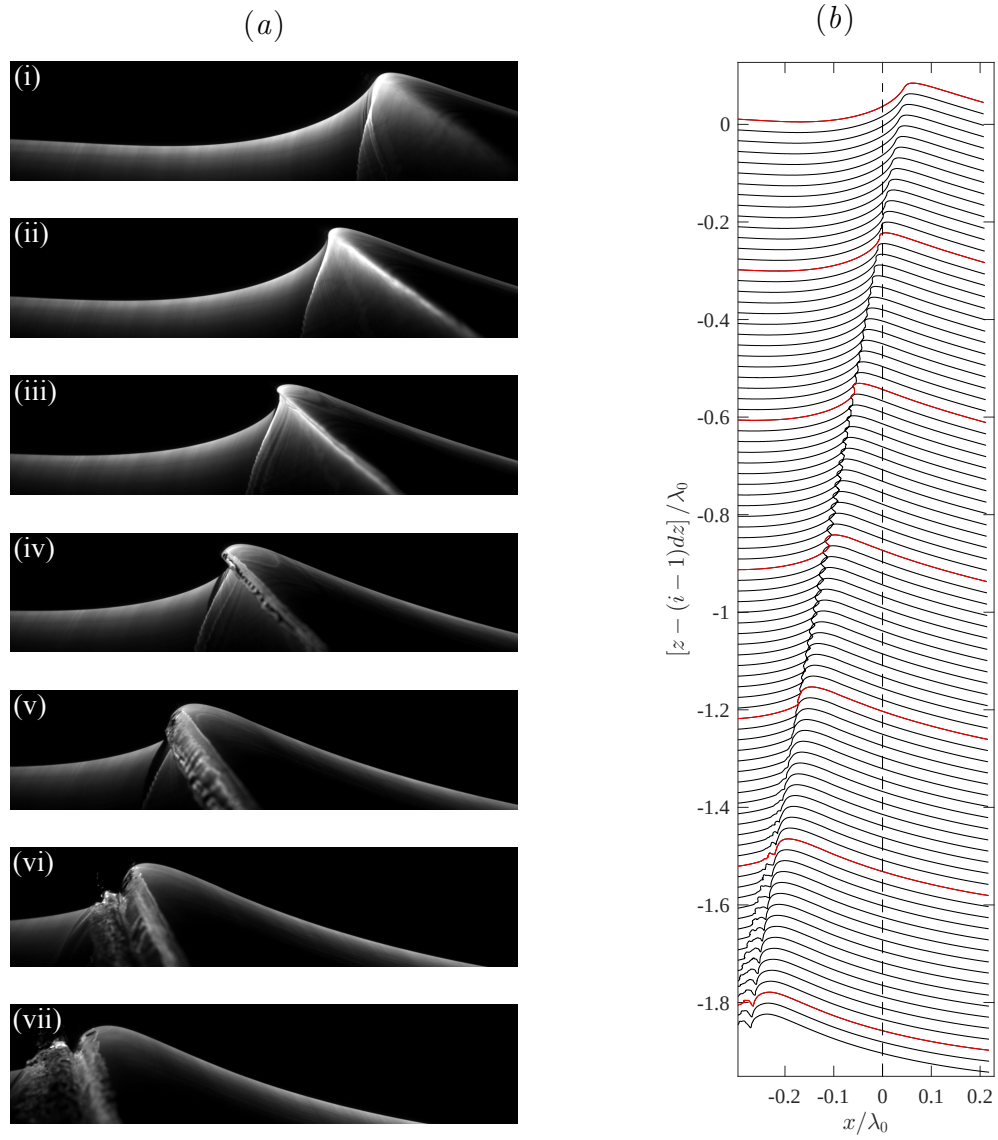


Figure 2.11: Images and profiles of the plunging breaker in the absence of the structure. The breaker is traveling from right to left. (a) Sequence of LIF images from a high-speed movie of the breaker. The imaged area is 65 cm by 38 cm and the time interval between successive images is 47 ms. (b) Surface profile history of the plunging breaker taken from the same movie as the images in (a). The time between profiles is 3.3 ms and each subsequent profile is plotted $dz = 0.022\lambda_0$ below the previous profile. The profiles corresponding to the images in (a) are plotted in red. The dashed line ($x/\lambda_0 = 0$) is the position of the front face of the structure in the experiments described in §2.3.2 and §2.3.3.

that the jet is about to form. Tracking the speed of the highest point of the crest region in this early phase of breaking yields a crest speed of 1.5 m/s which is a little greater than the average linear-theory phase speed of the 32 wave components of the packet, $\bar{c}_p = 1.437$ m/s. As the sequence progresses, the tip of the jet becomes visible and moves horizontally (ii and iii). The jet tip then falls downward (iv and v) and plunges into the water surface (vi) downstream (to the left) of the crest. This impact generates a zone of rough water surface downstream of the jet impact site (vii). The plunging breaker has a moderate strength in that, for a stronger breaker, the jet impact site would be farther downstream from the crest. The largest crest height during the breaking process was $H_m = 10.1$ cm as measured from the mean water level.

In the wave impact experiments, the front face of the structure was placed at the position of the dashed line in Figure 2.11(b), which is 641.5 cm from the back face of the wave maker. At this position, in open water, the jet has just started to form and is moving horizontally. As is shown in the following subsection, this behavior is dramatically changed by the presence of the structure.

2.3.2 Water Surface Evolution during Impact

In this subsection, the water surface profile evolution during the wave impact on the structure is discussed. The presentation is organized into three subsections according to the general class of behavior of the water surface near the bottom of the structure: Cases where the bottom surface of the structure is below mean water

level and remains submerged during the impact are discussed in §2.3.2.1. Cases where the bottom of the structure is near the mean water level and the local water surface moves above and below the bottom surface during the impact are discussed in §2.3.2.2. Finally, cases where the bottom surface of the structure is well above the mean water level and only the wave crest hits the structure are discussed in §2.3.2.3.

2.3.2.1 Class I. The bottom of the structure remains submerged.

When the bottom of the structure is positioned at $z_b = -0.1129\lambda_0$, $-0.091\lambda_0$, $-0.065\lambda_0$ and $-0.038\lambda_0$, it remains submerged during the entire wave impact process. A flip-through response (defined below) occurs for the three deepest submergence cases and these will be discussed in this section. As the submergence $|z_b|$ is decreased, ripples generated at the contact line on the front face of the structure become stronger and seem to interfere with the flip-through process in the $z_b = -0.038\lambda_0$ case. For this reason the data from the $z_b = -0.038\lambda_0$ case is presented along with the Class II cases where the ripple effect is even stronger. In the following, the data from the condition with the largest submergence ($z_b = -0.1129\lambda_0$) are discussed in detail while selected quantities from all three data sets are compared to explore the effect of the submergence on this class of impact. LIF images and surface profiles from other conditions under this category are presented from Figure A.1 to A.4 in Appendix A.

Images from an LIF movie for $z_b = -0.1129\lambda_0$ are shown in Figure 2.12. As

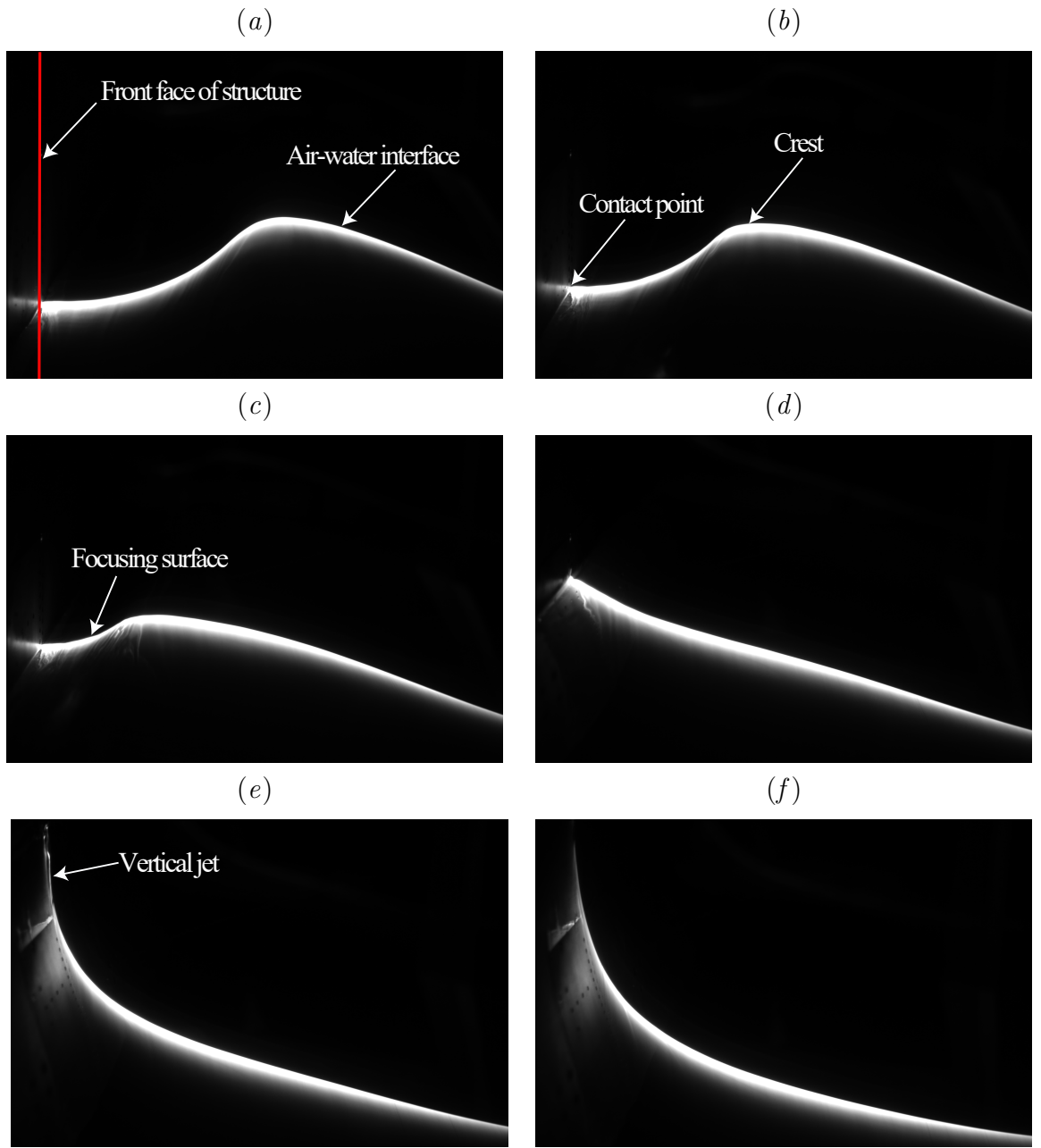


Figure 2.12: A sequence of images from a high-speed LIF movie of the evolution of the water surface profile for $z_b = -0.1129\lambda_0$. The contact point is located at the left of the images and is defined at the intersection of the instantaneous water surface in the plane of the laser light sheet and the front surface of the structure. The crest is defined as the instantaneous highest point on the water surface profile. From (a) to (f), the images were taken at $t = -200$ ms, -100 ms, -50 ms, 0 ms, 50 ms, 100 ms, respectively. $t = 0$ represents the moment of impact, defined as the time when the focusing surface is reduced the zero size, shown in (d).

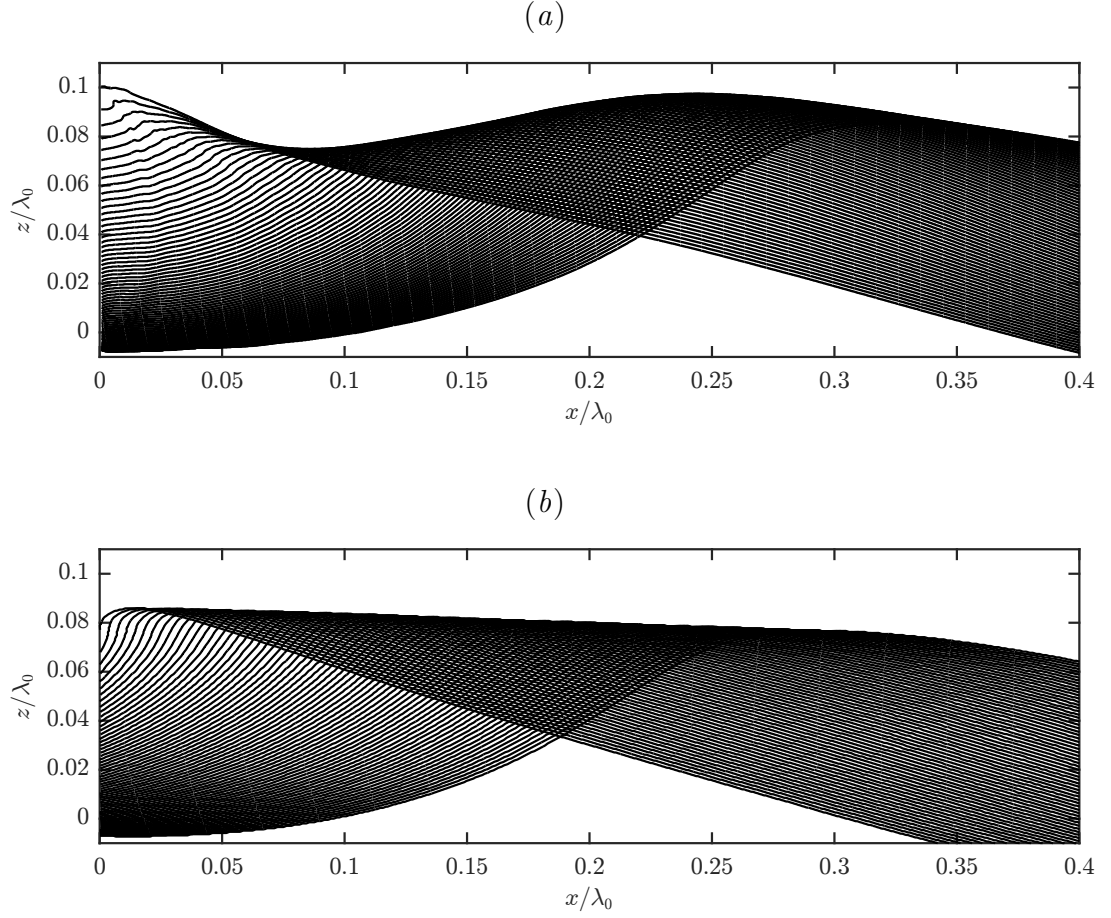


Figure 2.13: Surface profile history plotted in a reference frame fixed in laboratory for (a) condition $z_b = -0.1129\lambda_0$ and (b) the breaker in open water. The time between profiles is 3.3 ms. In (a), the last profile is at the time when the vertical surface of the plunging jet reaches the streamwise position of the wall, a total time of 264 ms before this time is covered. The front surface of the wall is located at $x/\lambda_0 = 0$. In (b), the profiles are plotted for a period of 264 ms before the moment of impact. The mean water level is at $z/\lambda_0 = 0$.

the crest approaches the wall, the water surface between the contact point of the water surface on the front face of the structure and a point just downstream (to the left) of the crest point forms an arc with upward curvature, see Figure 2.12(*a*). Further upstream, the crest region, which has downward curvature, merges to the back face of the wave, which forms a nearly straight line. As the impact continues, images (*b*) through (*e*), the crest moves downstream, the arc between the crest and the contact point shrinks and the slope of the back face of the wave remains nearly constant. In the final image (*f*), the arc between the contact point and the crest has focused to a point and the entire water surface has become a nearly straight line, except for a small portion upstream of the contact point which has a slightly larger slope than the rest of the surface. This instant in time is defined herein as the moment of impact. Shortly after the moment of impact, a high-speed thin vertical jet is initiated and grows upward along the surface of the structure under the effects of gravity and friction from the wall, not shown here. Following the nomenclature from Peregrine [61], we call this type of impact, flip-through.

A set of surface profiles taken from every fifth image of the movie from which the images in Figure 2.12 were taken is shown in Figure 2.13(*a*). The profile sequence is plotted in the laboratory reference frame and ends at the moment of impact. For comparison, a set of profiles of the wave in open water and plotted in the same reference frame is given in Figure 2.13(*b*). In the wave impact case, the profiles upstream of the crest are all parallel straight lines that are tilted clockwise by about $\theta_0 = 13.6^\circ$ from the horizontal. The parallel lines are nearly equally spaced by 0.0043 m horizontally, which indicates the back side of the surface is moving

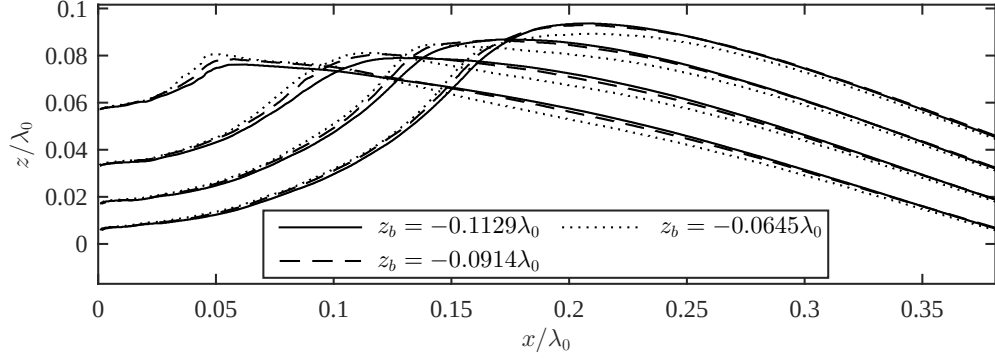


Figure 2.14: Surface profiles at four times for three submergences of the wall. The time interval between successive profiles is 33.3 ms. The mean water level is at $z/\lambda_0 = 0$.

horizontally at a nearly constant velocity of $0.9\bar{c}_p$. It can also be seen that as the crest point travels toward the structure, its absolute height first decreases and then increases as the moment of impact is approached. The wave in open water moves downstream at a nearly constant speed of $1.044\bar{c}_p$ and with a continually increasing amplitude at this position in the tank.

The flip-through behavior occurs at all three wall submergences in this response class, but there are quantitative differences in the profile histories. To illustrate these differences, a limited set of surface profiles for each of the three submergence conditions are shown in Figure 2.14. The four profiles for $z_b = -0.1129\lambda_0$ are taken at 33.3 ms intervals starting 130 ms before the moment of impact. In order to allow direct comparisons of the profile shapes, the profiles for the $-0.091\lambda_0$ and $-0.0645\lambda_0$ cases are at times when the contact points on the structure are at the same locations as in the profiles for the $z_b = -0.1129\lambda_0$ case. The time changes needed to match the contact point heights with the $z_b = -0.1129\lambda_0$ case are about

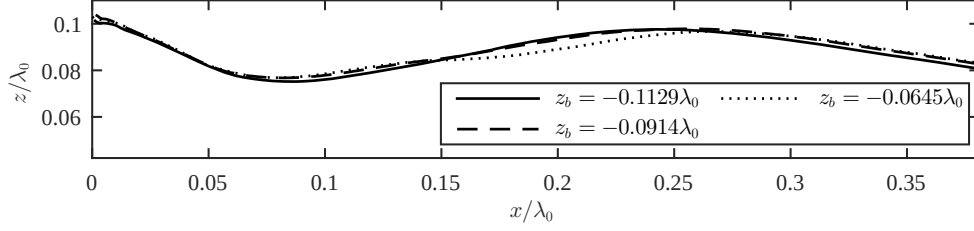


Figure 2.15: The top envelopes of the surface profiles at times before the moment of impact for three submergence cases with flip-through behavior.

2.7 ms (later) for the $z_b = -0.091\lambda_0$ case and 5.4 ms (later) for the $z_b = -0.0645\lambda_0$ case. As can be seen from the figure, the general behavior of the profiles at all three submergences is quite similar. In the region downstream of the crest, the water surface height at any streamwise position increases slightly as the submergence ($|z_b|$) decreases. However, on the upstream side of the crest, the opposite trend is found. It can also be seen that the crest point increases with height and shifts slightly downstream as the submergence decreases.

Another interesting aspect to compare the behavior of the wave surface evolution is the top envelope lines of all surface profiles at each submergence, as shown in Figure 2.15. At each streamwise position, a point above this line is always in the air while a point below this line is at least for a moment in the water. For all three conditions, the envelope lines show two peaks and two troughs within the range of measurements. From the upstream trough to the upstream peak (roughly $0.25 < x/\lambda_0 < 0.38$), the increase of the envelope indicates the increase of crest height when the crest travels within this range. From the upstream peak to the downstream trough (roughly $0.08 < x/\lambda_0 < 0.25$), the height of envelope indicates the decrease of the crest height within this range. The downstream peak is caused

by the rise of the contact point on the wall. For the small submergence case, the height variation of the envelope is smaller within the range between the upstream peak and the downstream trough. This indicates that for smaller submergence case, the crest height behaves more closely to a constant than the larger submergence case. This decrease in crest height as the breaker approaches the wall is discussed in relation to the surface shape in the discussion in §2.4.1.

2.3.2.2 Class II. Interaction between the Bottom of the Wall and the Water Surface

In this subsection, surface profile results are presented for conditions with $z_b = -0.038\lambda_0$, $z_b = -0.022\lambda_0$, $z_b = -0.014\lambda_0$, $z_b = 0$. At conditions $z_b = -0.022\lambda_0$, $z_b = -0.014\lambda_0$, $z_b = 0$, small amplitude waves that arrive at the structure before the main crest arrives cause the the bottom of the structure to be exposed to air and then reenter the water for one or more cycles. As described above, at the condition $z_b = -0.038\lambda_0$, the bottom of the wall remains submerged throughout the impact process; however, as in the other three cases, disturbances generated at the contact line on the front face of the structure propagate to the incoming main wave crest and affect its behavior in a similar way. In the following, the condition $z_b = 0$ will be discussed in detail and some comparisons of profile features will be made among all the four conditions. LIF images and surface profiles from other conditions under this category are presented from Figure A.5 to A.10 in Appendix A.

Figure 2.16 shows six images from a high-speed movie of the evolution of the

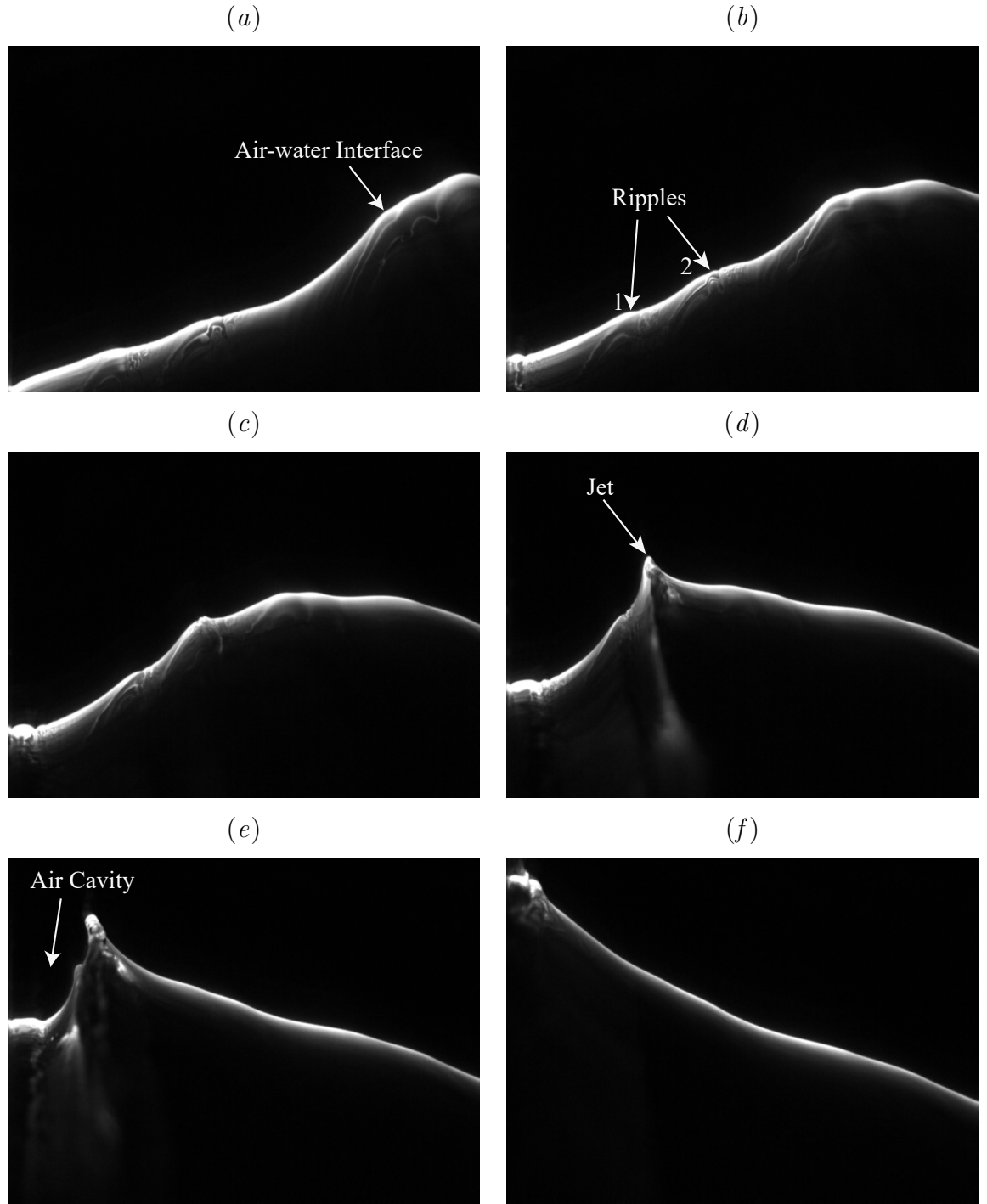


Figure 2.16: A sequence of images from the high-speed LIF movies showing the evolution of the water surface at the $z_b/\lambda_0 = 0$. The contact point is located at the left of the images. The time interval between two images is 21.3 ms. The field of view is roughly $17.8 \text{ cm} \times 15.7 \text{ cm}$.

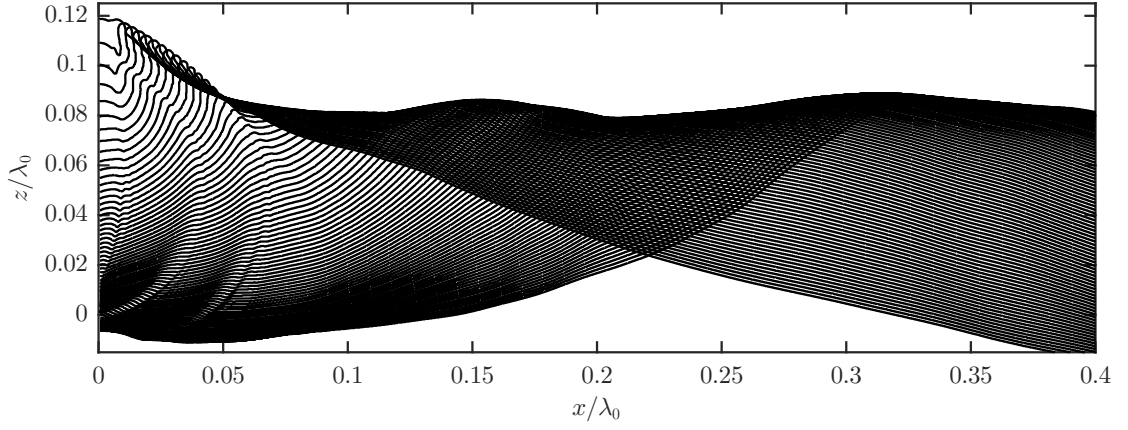


Figure 2.17: Surface profile history for condition $z_b = 0$ in a reference frame fixed in laboratory. The time between profiles is 3.3 ms. The profiles are plotted from $tf_0 = -0.3228$ (281 ms) to the moment of impact ($tf_0 = 0$). The mean water level is at $z/\lambda_0 = 0$. The front surface of the wall is located at $x/\lambda_0 = 0$.

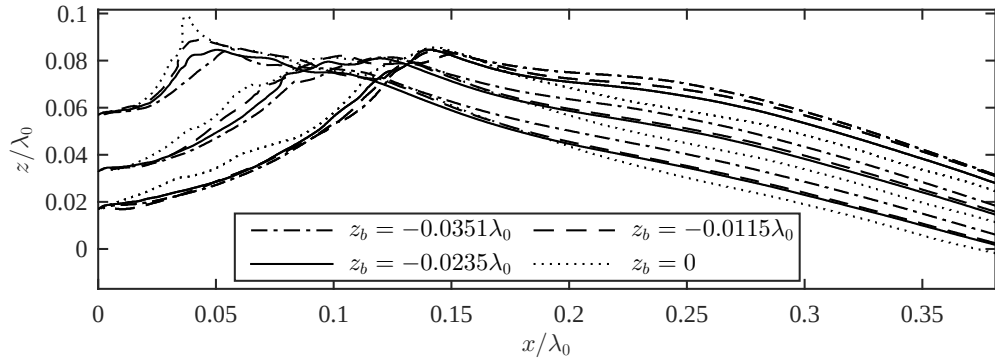


Figure 2.18: Surface profiles at three different times for four submergences of the wall. The time interval is 33.3 ms.

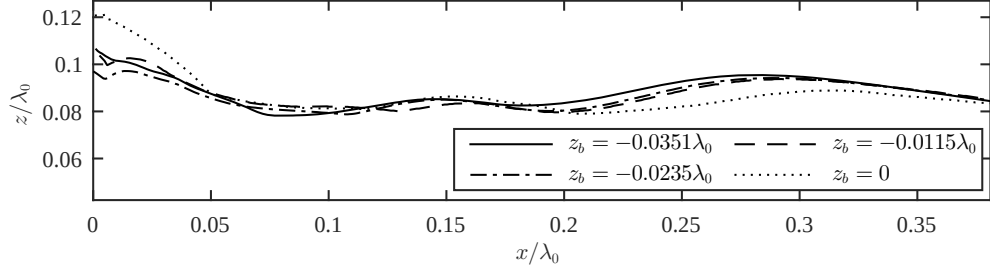


Figure 2.19: The top envelopes of the surface profiles at times before the moment of impact for four submergence cases when the bottom of the wall interacts with the water surface.

water surface for the $z_b/\lambda_0 = 0$ case and a set of surface profiles from the same movie are shown in Figure 2.17. Before the main crest arrives at the wall, small-amplitude wave components in the packet arrive and interact with the bottom of the wall. This interaction creates ripples at the free surface and these ripples propagate upstream, toward the wave maker. Two of these ripples are identified in image (b) of Figure 2.16. At the same time, the large-amplitude main crest approaches the wall and the small ripples are confined within the profile segment with upward curvature between the front surface of the structure and the crest. The ripples propagate along this curved surface and merge with each other as the surface segment shrinks. This process is most clearly seen in the profiles in Figure 2.17. The merged ripples grow in amplitude and turn into the jet that forms at the crest of the wave. As the process continues, the cavity between the jet and the wall shrinks in size and the contact point moves rapidly upward. The contact point reaches the height of the jet tip before the jet tip reaches the wall. Therefore, the jet impacts on a water column rather than the wall and appears to enclose an air cavity.

Surface profiles at three points in the impact process when the contact point height is nearly the same for all four submergence conditions compared in Figure 2.18. At the instants plotted, the surface height at the same streamwise position between the contact point and the crest is larger for conditions with smaller submergences and this difference is more significant at later time. The surface profiles become more rough for conditions with smaller submergences, indicating that the disturbances generated at the contact point are stronger. Compared with the flip-through conditions shown in Figure 2.14, the surface profile upstream the crest region in these four conditions is less straight. Also, unlike the flip-through conditions where the crest has one peak the crest regions in the present cases have a main peak and several nearby local maxima. From the corresponding movies, it can be seen that these local maxima are due to the evolution of upstream propagating disturbances as discussed in the §2.4.3. The multiple peaks of the crest region are also seen in top envelopes of the surface profiles in Figure 2.19, indicating that the local maxima are moving relative to the main crest. The envelope for the $z_b = 0$ condition has a steep rise in the range of $0 < x/\lambda_0 < 0.05$; this is caused by the jet generated at the crest as it merges with the ripples from the contact point.

2.3.2.3 Class III. Impact on Wall with Bottom above Mean Water Level

If the bottom of the structure is sufficiently above the mean water level to allow the small wave components that arrive before the main wave crest to pass

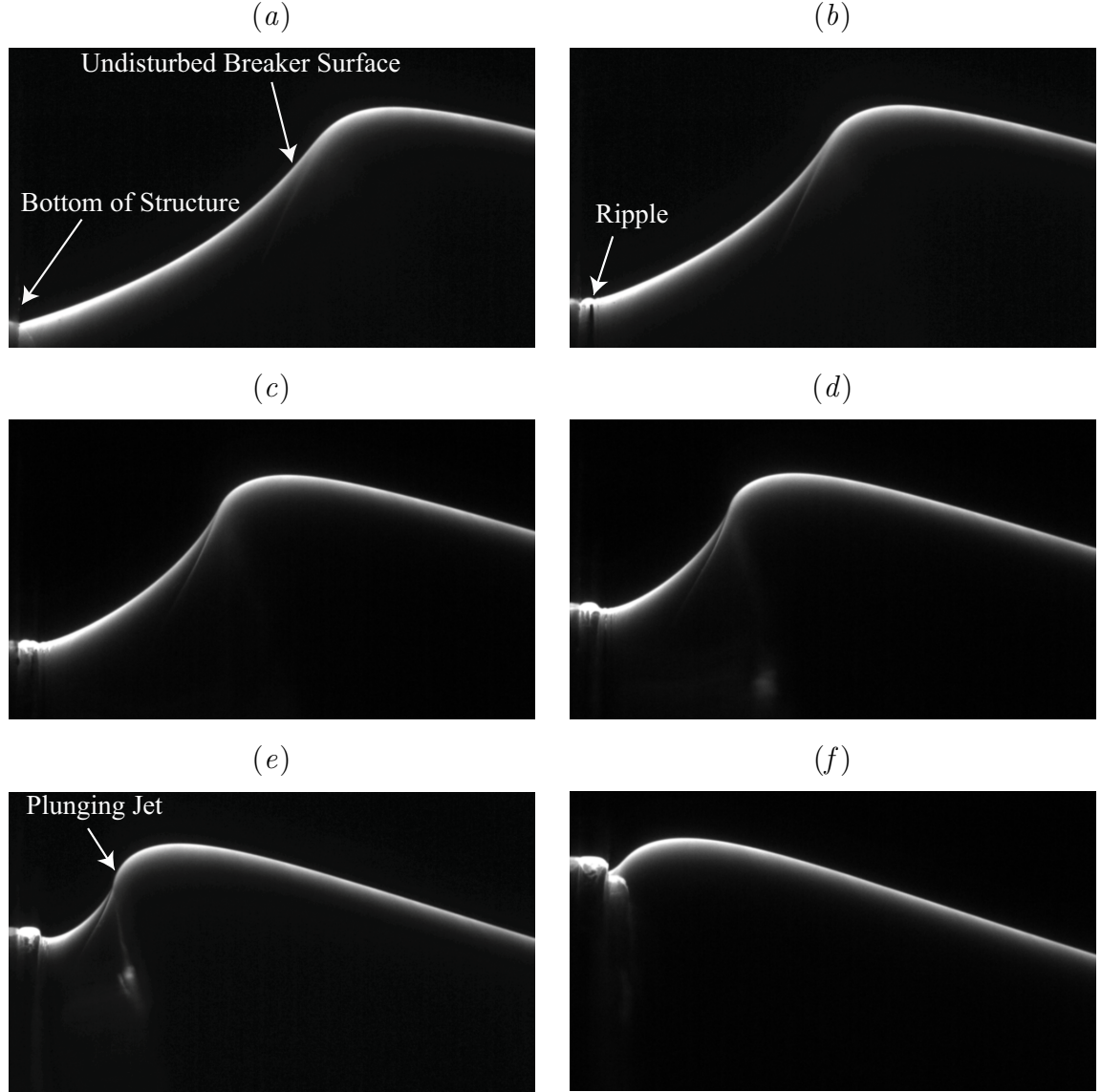


Figure 2.20: Sequence of LIF images of the water surface under condition $z_b/\lambda_0 = 0.0215$. The images are taken at frame rate of 4500 Hz. The time interval between two successive images is 13.33 ms. The field of view is roughly 18.1 cm $\times$ 10.6 cm.

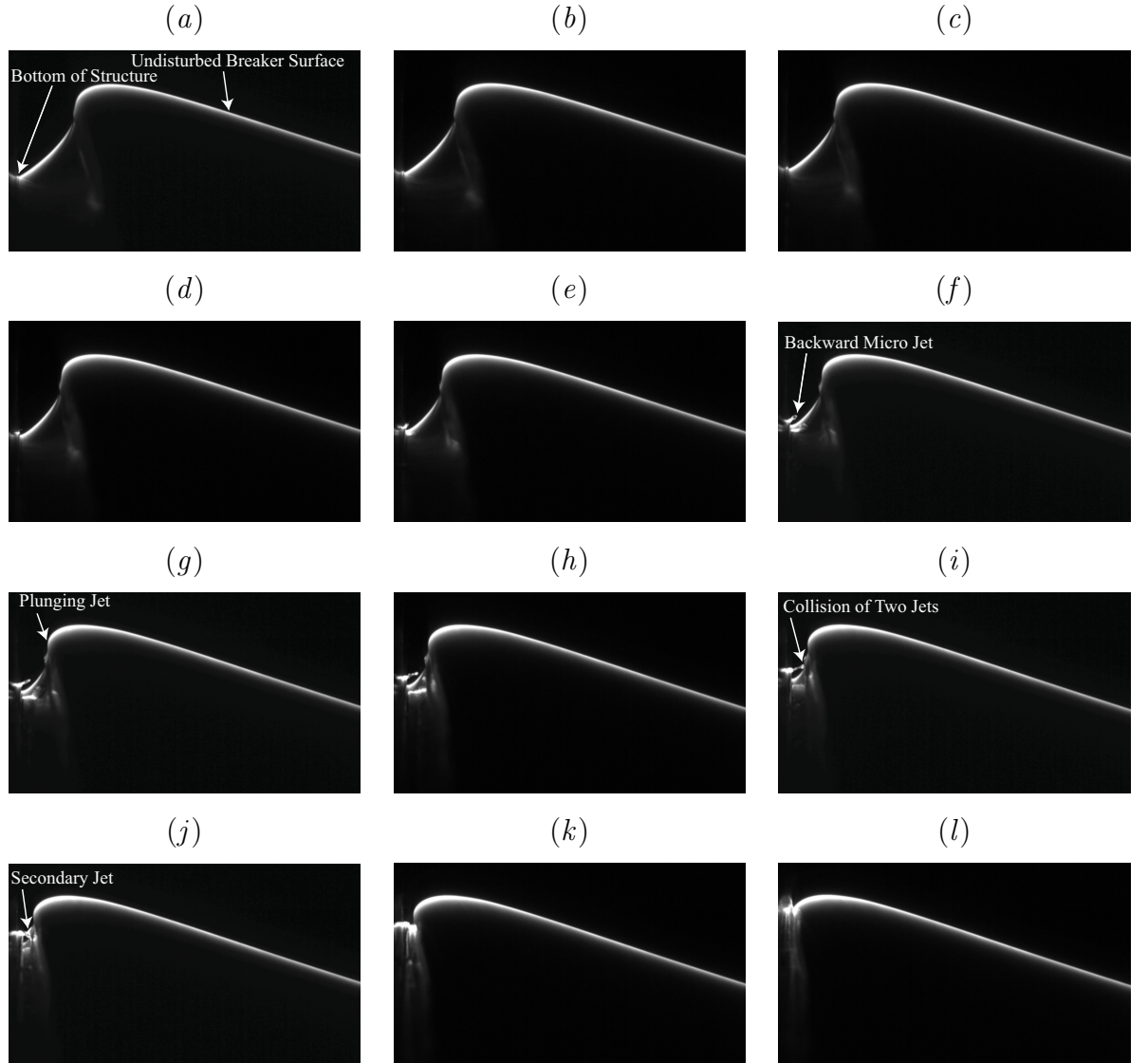


Figure 2.21: Sequence of LIF images of the water surface under condition $z_b/\lambda_0 = 0.043$. The images are taken at frame rate of 4500 Hz. The time interval between two successive images is 1.78 ms. The field of view is roughly $18.1 \text{ cm} \times 10.6 \text{ cm}$.

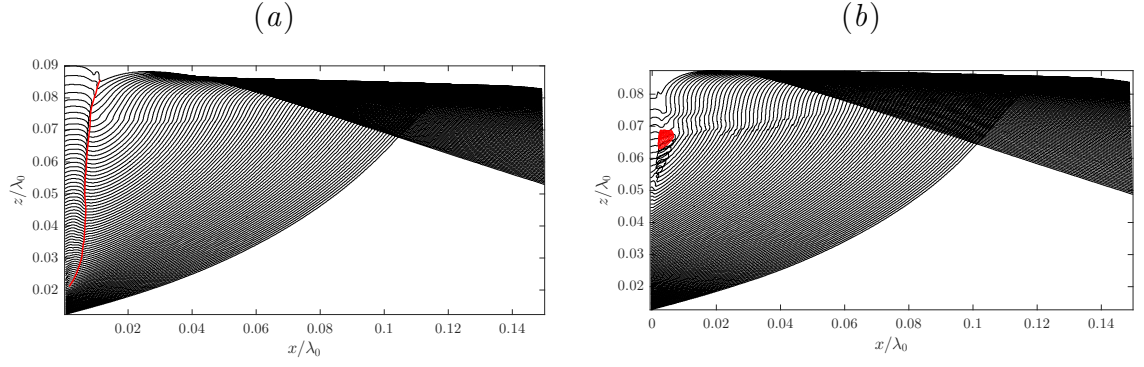


Figure 2.22: Surface profile history plotted in a reference frame fixed in laboratory for (a) condition $z_b = 0.0215\lambda_0$ and (b) condition $z_b = 0.043\lambda_0$. The time interval between two successive profiles is 1.11 ms. In (a), the red solid line represents the upstream trough of the ripple. In (b), the red solid lines represent the boundaries of the air cavity in light sheet at different time after the micro-jet meets the plunging jet.

undisturbed under the structure, only the main crest interacts with the front face of the structure. Two conditions ($z_b/\lambda_0 = 0.0215$ and $z_b/\lambda_0 = 0.043$) in this category are discussed below.

Figure 2.20 shows a sequence of LIF images of the water surface evolution of the case $z_b/\lambda_0 = 0.0215$ and a set of surface profiles from the same high-speed movie are shown in Figure 2.22(a). In the first image in Figure 2.20, the water surface is about to make first contact with the structure and this “undisturbed” profile is the same as in the open water case. As the process continues, the downstream side of the breaking crest of the breaker first hits the front lower corner of the structure, see image (b). The the bottom and front face of the structure block the motion of the water and cause the formation of a ripple. As the process continues, the ripple

grows in size, see images (c) and (d). Eventually the ripple grows into a thick water column that moves upward. It is noted that even though the structure blocks some of the flow, the plunging jet begins to form, see image (e), as it would in open water. However, in the present case the jet formation is blocked by the large water column on the front face of the structure. These features are shown clearly in the profile history in Figure 2.22(a).

Images from a high-speed movie of the wave impact for the highest position of the structure ($z_b/\lambda_0 = 0.043$) are shown in Figure 2.21 and set of surface profiles from the same movie are shown in Figure 2.22(b). Before the downstream side of the crest region of the breaker hits the front lower corner of the structure, the breaker is undisturbed as shown in Figure 2.21 (a)(b)(c). Because bottom surface of the structure is higher than in the $z_b/\lambda_0 = 0.0215$ case, the breaker has more time to propagate in an open water condition and the plunging jet is more pronounced just before impact in image (c). As the impact process begins (image (d)), a micro jet forms near the contact point, rather than the large ripple formed in the $z_b/\lambda_0 = 0.0215$ case. The micro jet grows toward the upstream direction within the small space between the front face of the structure and the breaker's plunging jet (images (e), (f), (g) and (h)). Once the micro jet reaches the plunging jet, the collision between the two jets creates a secondary jet that moves downstream. The secondary jet hits the rising water column along the front face of the wall. Finally, the breaker's plunging jet hits the water column rising along the wall, making it highly likely that air is entrained during this process.

2.3.3 Impact Pressure

The temporal evolution of the wall pressure distribution for wave impacts when the bottom of the structure is located at $z_b = -0.1129\lambda_0$, 0 , $0.0215\lambda_0$ and $0.043\lambda_0$ are presented in this subsection. For each value of z_b , the pressure is displayed as a contour plot on a z - t plane, see Figure 2.23. The time history of the pressure measured by each sensor is an alternative way to present the data and is shown in Figure B.1 in Appendix B. As discussed in the previous subsection, in the $z_b = -0.1129\lambda_0$ case, the water surface focuses to a point on the wall without breaking, as shown in Figure 2.12. The wall pressure evolution for this condition is shown in Figure 2.23(a). At each instant in time, the boundary between the upper dark blue region and the region below is the approximate location of the water surface. The free surface height and the vertical pressure gradient just below the free surface increase with time. The step-like structure of the boundary at the free surface is due to the finite size and discrete locations of the pressure sensors. At about $tf_0 = -0.002$, double pressure spikes of magnitudes near $1.1\rho\bar{c}_p^2$ and $2.7\rho\bar{c}_p^2$ appears just under the free surface. Each spike lasts for about $0.001tf_0$ and has a vertical extent of $0.01\lambda_0$. The behavior of the impact pressure under this condition will be further discussed in §2.4.2.

At $z_b = 0$, as shown in Figure 2.23(b), the high-pressure region along the wall spans over a much wider range of height than in 2.23(a). The spatial and temporal range where the pressure exceeds $1.0\rho\bar{c}_p^2$ reaches about $0.03\lambda_0$ and $0.009f_0^{-1}$, respectively. The peak pressure is about $2.0\rho\bar{c}_p^2$. Pressure oscillation is observed at

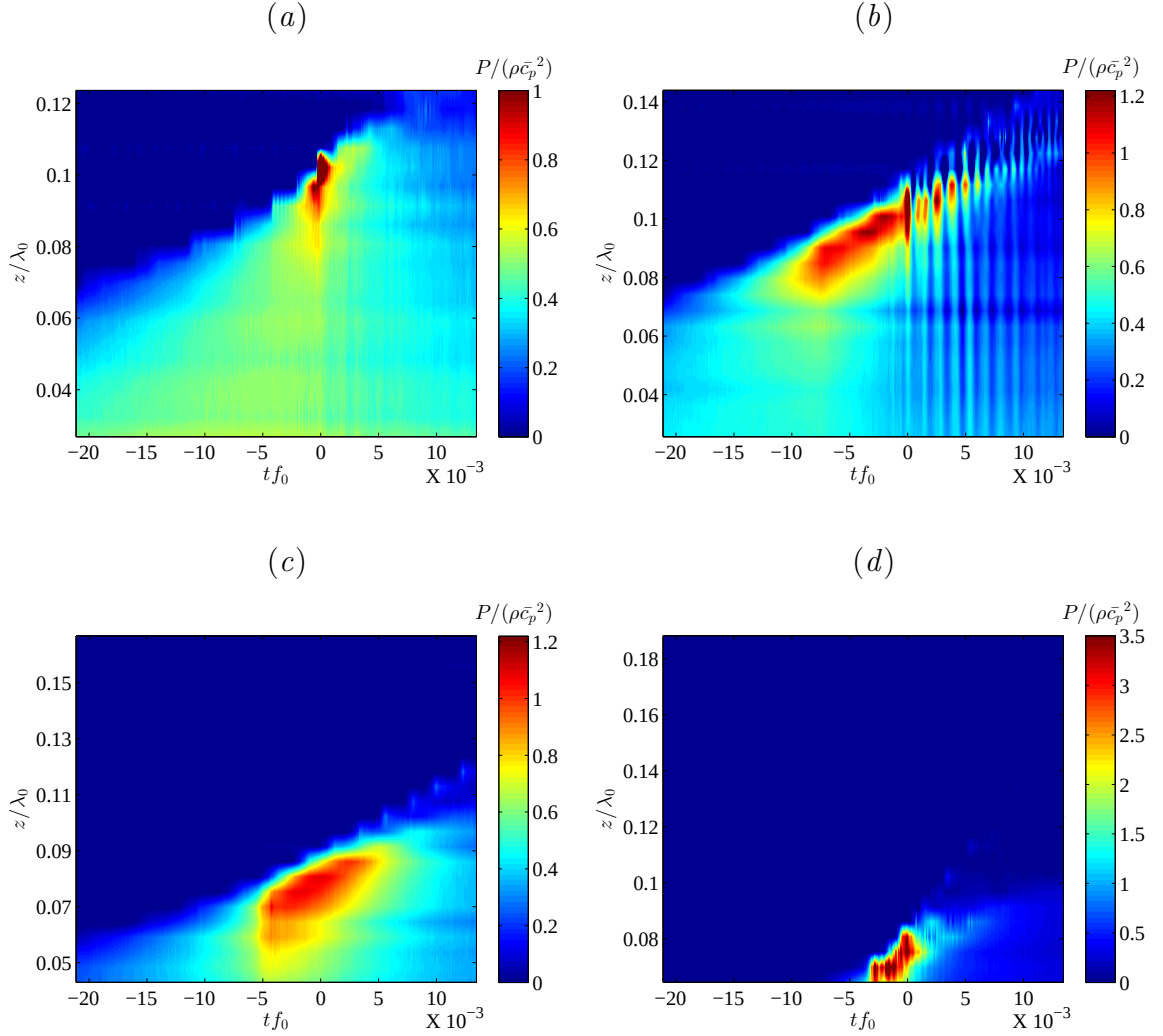


Figure 2.23: (a)(b)(c)(d) represent the evolution of the impact pressure on the wall with the bottom of the wall at $z_b = -0.1129\lambda_0$, $z_b = 0$, $z_b = 0.0215\lambda_0$, $z_b = 0.043\lambda_0$, respectively. Each plot is the measurement from one typical run at this condition. The scale of the color bar is varied because the range of impact pressure is different at different conditions. $t f_0 = 0$ represents the time when the pressure reaches the maximum value at all heights. $z/\lambda_0 = 0$ is the height of the mean water level. The magnitude of the pressure is scaled by the nominal dynamic pressure $\rho \bar{c}_p^2$, where $\bar{c}_p$ is the averaged phase velocity of the wave packet. The pressures vs time of each sensor at these four cases are shown in Figure B.1 in Appendix B.

this condition. At a particular time, the oscillation of impact pressure occurs over the whole measurement range below the contact point of the wave. At earlier times, the sensors of all height have similar oscillation frequency of about 1000 Hz.

The natural frequency of a spherical bubble in water can be estimated by

$$f_n = \frac{1}{2\pi R_0} \sqrt{\frac{3kP_{ieq}}{\rho} - \frac{2\sigma}{\rho R_0}} \quad (2.9)$$

where R_0 is the radius of the spherical bubble at equilibrium state, ρ is the density of water, k is the heat capacity ratio of air and $k = 1.4$, σ is the surface tension of water and $\sigma = 71.97$ mN/m, P_{ieq} is the pressure inside the bubble at equilibrium state and

$$P_{ieq} = P_\infty + \frac{2\sigma}{R_0} \quad (2.10)$$

According to Equation (2.9), the 1000-Hz oscillation frequency of pressure corresponds to the natural frequency of a spherical air bubble with a radius of 3.28 mm under ambient pressure of 1 atm. At later times, the oscillation frequency increases with time at pressure sensors with higher positions, while the oscillation amplitude of these high-frequency components attenuates rapidly. At later times, the oscillation frequency measured by the top 5 sensors can reach as high as 2800 Hz. However, these high-frequency oscillation at later times is not picked up by pressure sensors at lower positions. The lower frequency components (about 1000 Hz) last for a longer time at lower positions, even though the amplitude of this oscillation also damps over time. As shown in Figure 2.16, there is probably an air cavity between the jet and the front face of the structure. As the jet moves downstream and the contact point rises along the wall, the cavity shrinks and eventually encloses. During the

process, it is highly likely that a large amount of air is entrained into the flow, causing the pressure to oscillate. In the computational work by Bredmose *et al.* [4,5], in the case of air entrainment, similar behavior of pressure oscillation is found. In their simulation, the fluid has some initial aeration level, which lowers the propagation speed of the acoustic waves. In our measurements, for the low-frequency component of the oscillation, there is nearly no visible phase delay at different heights. This indicates that the acoustic waves generated during the process transmit through the fluid at very high speed.

At $z/\lambda_0 = 0.0215$, the high-pressure region also spans over a wide range of height and time, as shown in Figure 2.23(c). The spacial and temporal range where the pressure exceeds $0.8\rho\bar{c}_p^2$ reaches about $0.03\lambda_0$ and $0.01f_0^{-1}$, respectively. The peak pressure with the value of about $1.1\rho\bar{c}_p^2$ is measured by multiple pressure sensors. No obvious pressure oscillation is found, which indicates there is little air entrained into the flow. As shown in Figure 2.20, the ripple generated at the corner of the wall developed into a rising water column along the wall. At the same time, the plunging jet of the breaker plunges toward the downstream direction. The water surface between the water column and the plunging jet changes its curvature and shrinks over time as it rushes upward. Eventually the water column merges with the jet. The merging process is smooth without direct collision and air does not seem to be entrained.

At $z_b = 0.043\lambda_0$, very high impact pressure is observed along with some extent of pressure oscillation, as shown in Figure 2.23(d). The peak pressure of this condition reaches as high as $4.5\rho\bar{c}_p^2$. The oscillation frequency of pressure is found to be

higher than 3000 Hz, which is higher than that in the $z_b = 0$ condition. According to Equation (2.9), the oscillation frequencies of the pressure observed for this condition correspond to the natural frequencies of spherical bubbles with radius smaller than 1.09 mm at 1-atm ambient pressure. The amplitude of the oscillation is also significantly smaller than that in case $z_b = 0$. As shown in Figure 2.21, the water column along the wall at this condition has a smaller thickness compared with the case $z/\lambda_0 = 0.0215$, because there is less time for the water column to develop along the wall before the plunging jet arrives the water column. Therefore, the horizontal momentum carried by the plunging jet is probably less attenuated by the water column. This behavior might be the reason that a higher pressure on the wall is created during the collision. When the micro jet impinges on the plunging jet, it is likely that a small air cavity is trapped between the two jets. It is believed that the entrained air causes the pressure oscillation in Figure 2.23(*d*).

2.4 Discussion

2.4.1 Properties of the Focusing Flow in Flip-through Impact

In this subsection, some properties of flip-through impact will be explored in detail. Since the backsides of the profiles are equally spaced nearly parallel nearly straight lines, this portion of the profiles collapse on a single straight line in a reference frame moving downward with a constant speed, which equals to the vertical speed of the back face of the surface. Since this is an inertial reference frame the dynamical equations governing this fluid motion are unchanged. The origin of

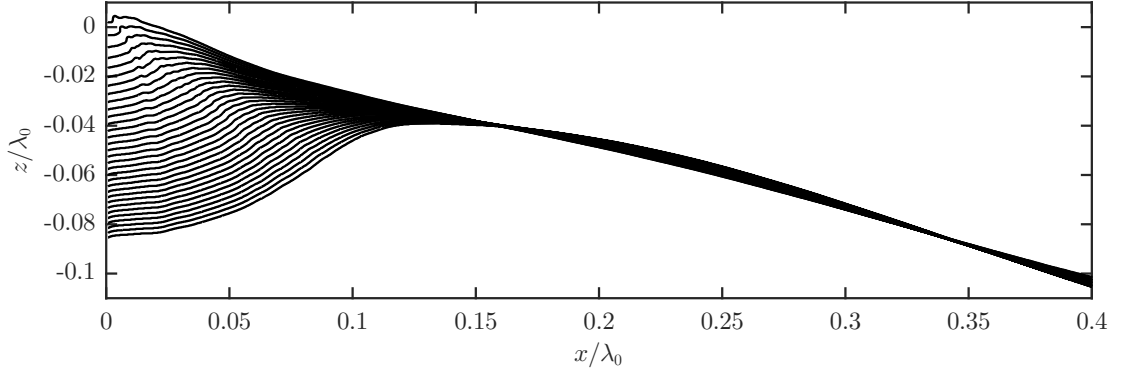


Figure 2.24: Surface profile history for condition $z_b = -0.1129\lambda_0$ in a reference frame moving vertically at velocity of $V_r = -0.33\bar{c}_p$. The time between profiles is 2 ms. The profiles are plotted from $tf_0 = -0.0736$ (64 ms) to the moment of impact ($tf_0 = 0$). The wall is located at $x/\lambda_0 = 0$.

the new reference frame is redefined as the intersection of the extended front face of the wall and the extended straight line fitted to the backside of the surface. The profiles in the new reference frame is shown in Figure 2.24. The backside of the profiles now nearly collapse on a thin band of lines. In the moving reference frame, the only variation of the profiles at different times is the portion between the contact point and the crest. This portion of the profiles forms a focusing surface as the crest approaches the wall.

The profiles between the contact point and the crest can be divided to two portions according to the sign of the local surface curvature. The point of local curvature transition from positive to negative curvature, which is determined by fitting a 20th order polynomial to the surface profiles and finding the maximum of its first order derivative, is shown in Figure 2.28(a). The surface profiles between the contact point and the curvature transition point have positive second order

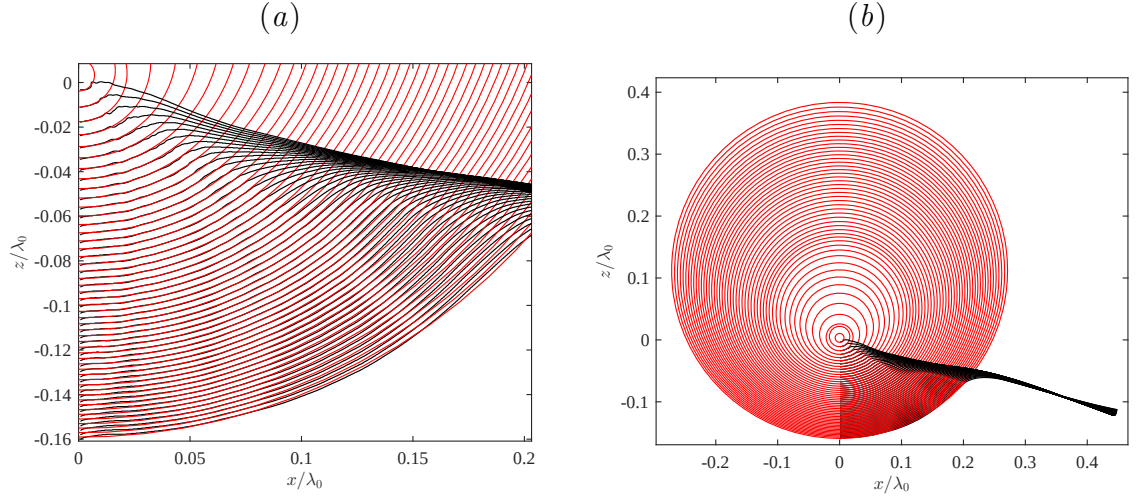


Figure 2.25: The circles fitted to a portion of the profiles between the contact point and the point before the crest where the slope of the profile reaches maximum, according to a 20th order polynomial fit to the profiles at each time. The center of the fitted circles are constrained at the vertical line that passes the contact points. The fitting is a least square minimization process. (a) The closeup view of the circles (red) fitted to the profiles (black). (b) The expanded view of the fitted circles and the profiles. The circle fit is shown in a moving reference frame with a vertical velocity of $V_r = -0.33\bar{c}_p$.

derivatives and appear to be nearly circular arcs. To test this hypothesis, circles with their centers constrained to be on the vertical plane of the front face of the structure were fit to the upward curvature portions of the surface profiles by using a least squares error minimization method. The results for one experimental run are shown in Figure 2.25. Upstream of the curvature transition points, the free surface profiles have negative second order derivatives and deviate from the circle fit gradually with increasing distance from the curvature transition point.

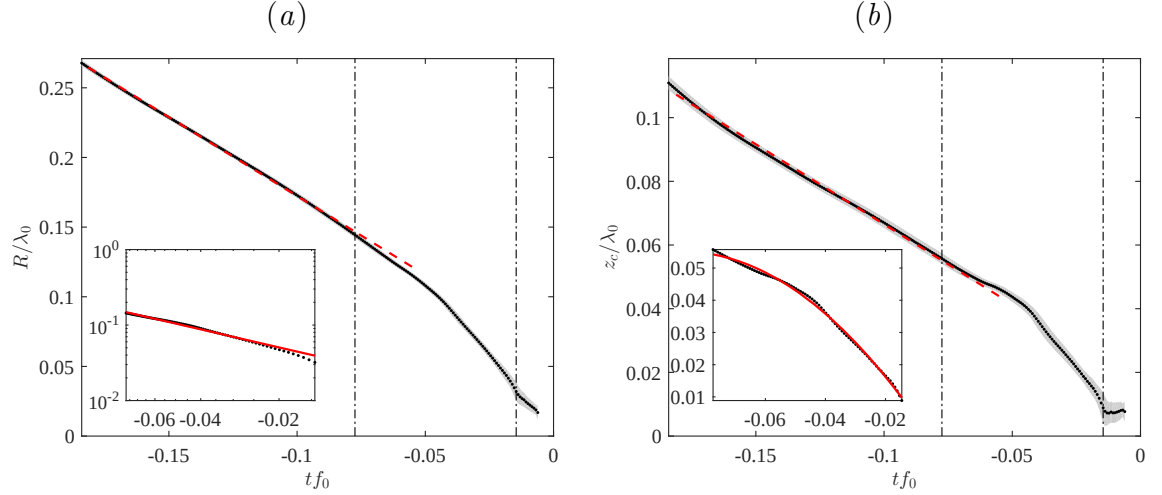


Figure 2.26: The geometrical parameters of the circles shown in Figure 2.25 at $z_b/\lambda_0 = -0.1129$. The data points at each time are the average of four experimental runs under identical experimental condition. The gray band around the data points represents the uncertainty range with one standard deviation above and below the data points. The data between the two vertical lines is replotted in the inset figure. The left vertical line represents the time when the curvature of the curve in (a) starts to become negative according to a 11th order polynomial fitting function. The second vertical line represents the time after which the profiles are not well fitted by circles. The red dashed lines in the main figure in both (a) and (b) are the fitted straight lines to the portion of the two curves earlier than the time represented by the left vertical line. (a) The radius of the fitted circles vs time. In the inset figure, the red line is the power law fit of the radius vs time curve within the two vertical lines in the main figure. The inset figure in (a) is plotted in logarithmic scale. (b) The vertical position of the center of the circles vs time. In the inset figure, the red line represents the 2nd order polynomial fit to the portion of the curve within the two vertical lines. The inset figure is plotted in linear scale. The data is shown in a moving reference frame with a vertical velocity of $V_r = -0.33\bar{c}_p$.

The geometrical properties of the circles for case $z_b = -0.1129\lambda_0$ are shown in Figure 2.26. As can be seen in Figure 2.26(a), the radius of the circles decay as the time approaches $tf_0 = 0$. The decaying process can be divided into two periods. During the first period $tf_0 < -0.077$, when the radius of the circles decay as a linear function of time. The slope of the function gives a radius decay rate of 1.54 m/s, which is very close to the average phase velocity of the wave packet $\bar{c}_p = 1.44$ m/s. The second period, $-0.077 < tf_0 < -0.014$, the radii of the circles decay more rapidly following a power law function of time $R \propto t^{0.824}$. When $-0.014 < tf_0 < 0$, the circle is not a satisfactory representation of the surface any more due to the lack of spatial resolution under this data set, when the surface shrinks to a very small size.

Figure 2.26(b) shows the time evolution of the position of the center of the circles. Similar to the trend of radius vs time curve, the vertical position of the center z_c moves downward following a linear function of time for the first period. It seems the z_c vs t curve follows the linear function slightly longer than the first period. In the second period, curves resembles a parabolic function to some degree.

The surface normal velocity was computed according to the approximation illustrated in Figure 2.27. The surface profile at each time was first smoothed and interpolated at equally spaced x grid points by cubic spline function. The surface normal vector is found numerically at each grid point (i.e. point P_1) along the surface profile at each time (i.e. $t = t_1$). The intersection point (P'_2) of the surface normal direction at point P at $t = t_1$ and the surface profile at $t = t_2$ is found by spline interpolation. The distance between P_1 and P'_2 yields the approximated

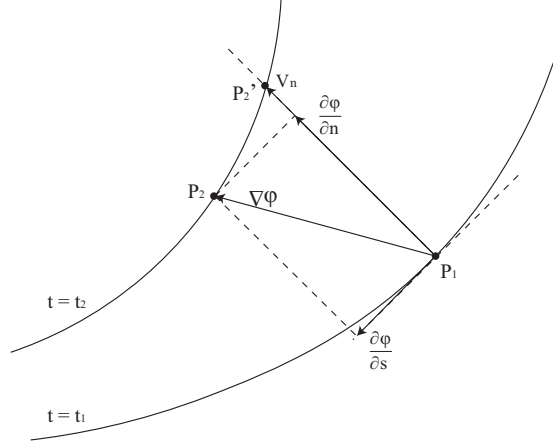


Figure 2.27: The approximation of surface normal velocity.

surface normal velocity V_n at $t = t_1$. Therefore, since Δt is small, V_n is a reasonable approximation of the surface normal velocity $\partial\phi/\partial n$. With this approximation, the surface normal velocity along the free surface at each time can be computed.

In the moving reference frame, since the surface profiles at different times on the backside of the breaker collapse on a thin band of nearly straight lines, the surface normal velocity on the backside of the wave is close to zero. Figure 2.28(b) shows the V_n vs t for the contact point and curvature transition point. The curvature transition point has a larger magnitude of V_n than the contact point at the same time. However, both V_n seem to follow a power law with $V_n \propto |t|^{-0.42}$ at the contact point and $V_n \propto |t|^{-0.36}$ at the curvature transition point. The increasing magnitude of the surface normal velocity with position away from the contact point provides another way of interpretation of the circle fits in Figure 2.25. Since V_n is larger near the transition point, the fluid particle near the transition point travels along the radial direction at this time at a higher rate than the particles near the contact point. Therefore, after the same amount of time, particles near the transition point

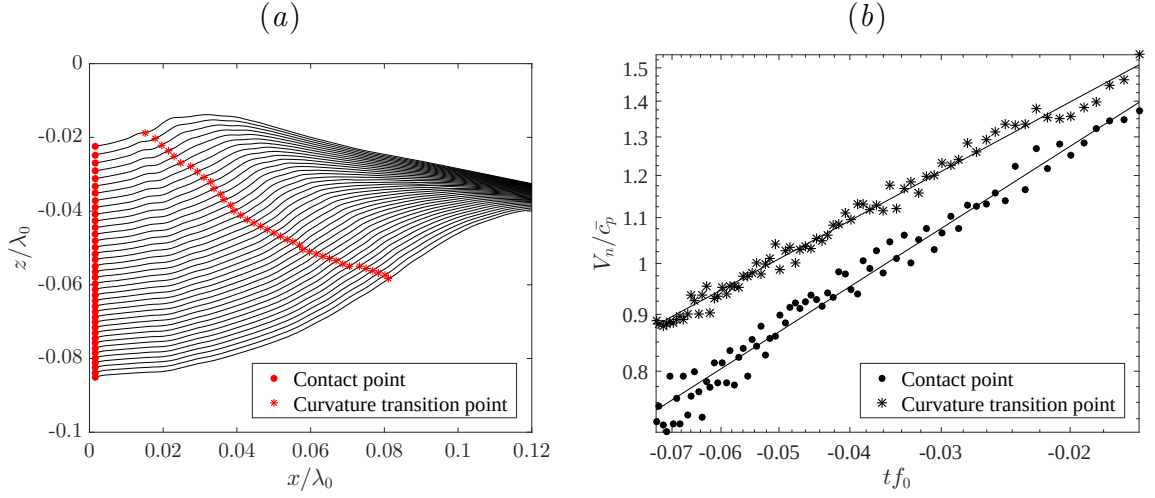


Figure 2.28: (a) The position of the transition points and contact points on the profiles at different times. (b) The surface normal velocity at different times. Asteris represents V_n at the curvature transition points. Dot represents V_n at the contact points. The solid line is the power law fit to the data point. Data is taken from condition $z_b/\lambda_0 = -0.1129$ and is shown in a moving reference frame with a vertical velocity of $V_r = -0.33\bar{c}_p$.

have larger displacement than the particles near the contact point. The particles on surface stay on surface at all times, so the surface formed by these particles at the next time bends toward the wall, which creates the downward moving shrinking circles.

Despite the slight variation in the shape of the profiles at the three conditions with different submergences discussed in §2.3.2.1, the portion of profiles between the contact point and the curvature transition point for all three conditions can be well represented by circular arcs with center constrained to be on the vertical axis that goes through the contact point, similar to condition $z_b = -0.1129\lambda_0$. At the three

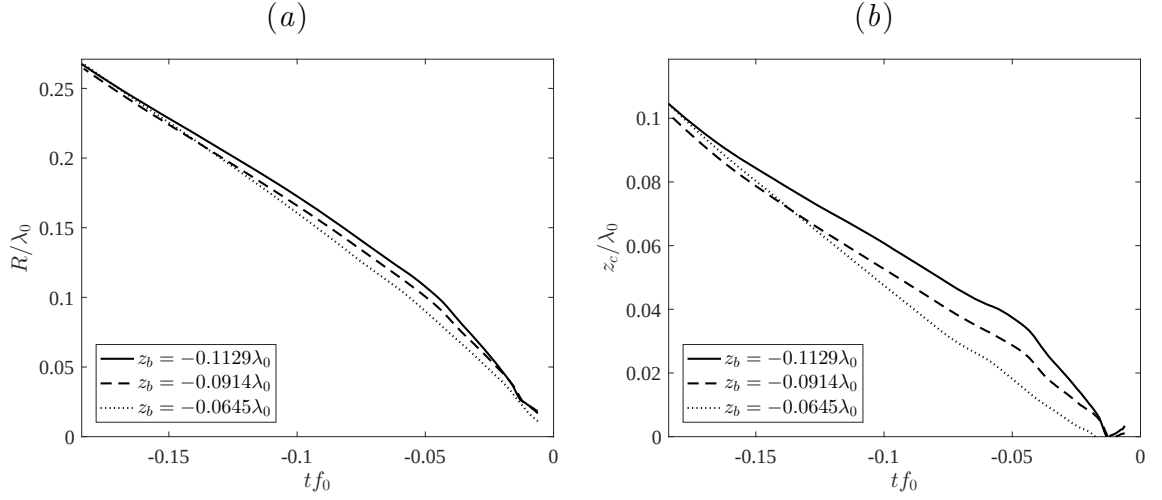


Figure 2.29: The evolution of geometrical features of the fitted circles at different submergences of the wall. (a) Radius of the circles vs time at different submergence. (b) Height of the circles vs time at different submergence. Each curve in (a) and (b) are averaged over at least three runs. $tf_0 = 0$ is the moment when the surface profiles collapse at a point on the front face of the structure. The data is shown in a moving reference frame with a vertical velocity of $V_r = -0.33\bar{c}_p$.

conditions, in a reference frame moving downward with velocity $V_r = -0.33\bar{c}_p$, the surface profiles upstream of the crests nearly collapse on three straight lines with slightly different slopes. Thus, analysis at condition $z_b = -0.1129\lambda_0$ can be applied to the other two conditions. Figure 2.29 shows the time evolution of the geometrical features of the fitted circles for the three different submergences of the wall in the moving reference frame.

At all submergences, the radius and center height of the circles show similar decreasing trends over time. At roughly $-0.18 < tf_0 < -0.15$, the radii of the circles at different submergences have nearly the same value at the same time relative to

the moments of impact. As discussed previously, for the larger submergence case $z_b = -0.1129\lambda_0$, the radius decays almost linearly for early times and transitions to an exponential decay after some time. However, the decay rate of the radius for $z_b = -0.0645\lambda_0$ is more uniform over time. However, the value of the radius for the smaller submergence case is smaller than that of the larger submergence case at the same time before the moment of impact. This is caused by the fact that the steepness of the profile between the contact point and the transition point is larger for cases with smaller submergences. The case $z_b = -0.0914\lambda_0$ behaves between the other two submergence cases.

The heights of the circle center vs time for different submergences are shown in Figure 2.29(b). At early times before the moment of impact, roughly $-0.18 < tf_0 < -0.15$, the variation of the center heights between conditions is small. The center height vs time at different submergences deviates from each other as time approaches the moment of impact. As discussed in the previous section, the center height motion for case $z_b = -0.1129\lambda_0$ has two different periods, while the two-period classification is not so obvious for the other two cases. When $tf_0 > -0.13$, the center heights are smaller for conditions with smaller submergences at the same time before the moment of impact.

2.4.2 Effect of Froude Number on the Flip-through Impact

The impact pressure on the wall is found to be extremely sensitive to the detailed geometry of the water surface just before the moment of impact. As described

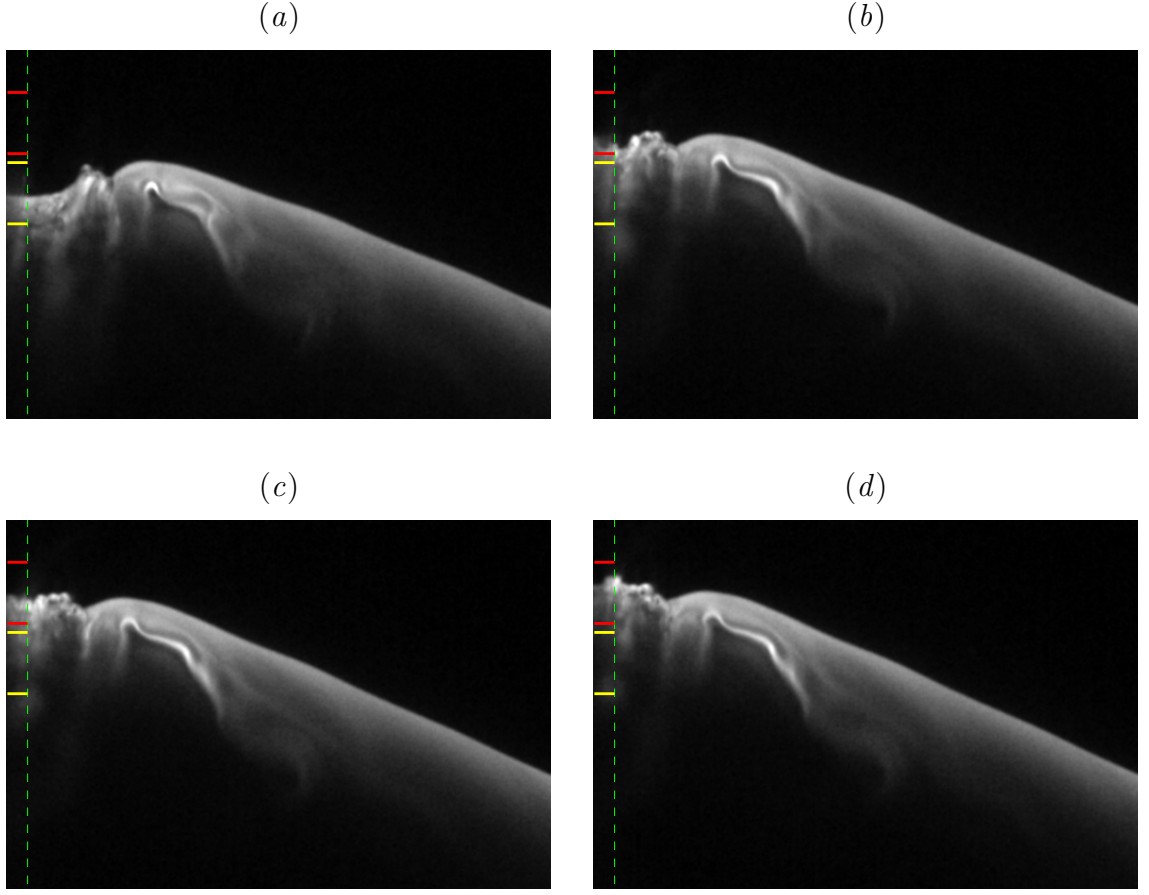


Figure 2.30: (a), (b), (c), (d) are snapshots of the water surface ($z_b = -0.1129\lambda_0$) at -1.926 ms, -0.593 ms, -0.296 ms, 0 ms before the moment of impact, respectively. The green dashed lines represent the position of the vertical wall. The two red lines and two yellow lines represent the boundaries of the pressure sensors No. 20 and No. 19, respectively. The field of view of the images is 4.8×4.3 cm.

in the §2.4.1, for $z_b = -0.1129\lambda_0$, a strong flip-through impact occurs. In the pressure measurements shown in Figure 2.23(a), a double pressure peak is found. In order to understand the double peak phenomenon, LIF movies with higher temporal resolution (13.5 kHz) and a field of view of only $4.8 \text{ cm} \times 4.3 \text{ cm}$, focused at the zone of impact were taken during the impact. Four images from one of these movies are

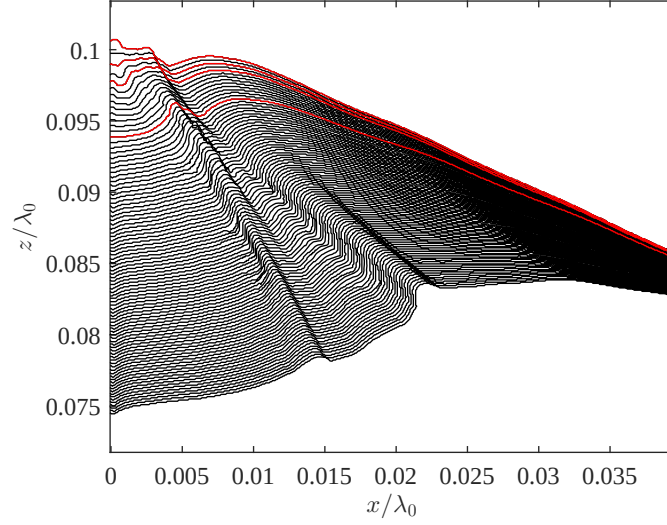


Figure 2.31: Surface profiles near the impact zone before the moment of impact at condition $z_b = -0.1129\lambda_0$. Time interval between each line is 0.149 ms. The profiles shown in red are the profiles from image shown in Figure 2.30(a), (b), (c), (d).

shown in Figure 2.30. The surface profiles from the movie and the pressure measurements are shown in Figure 2.31, 2.32, respectively. The instants when the images in Figure 2.30(a), (b), (c), (d) are taken are called t_a , t_b , t_c and t_d , respectively. These four instants are shown by the four vertical white dashed lines in Figure 2.32(a) and the four vertical red dashed lines in Figure 2.32(b). Again, Figure 2.32(b) shows the double peak phenomenon. The magnitude of the two pressure peaks are significantly larger than the pressures measured at the other heights over all time. The earlier peak and later peak were measured by two adjacent pressure sensors, No. 19 and No. 20, respectively. t_a is the instant when the earlier pressure peak starts to rise from zero, according to Figure 2.32(b). Figure 2.30(a) shows at $t = t_a$, the contact point just slightly exceeded the lower boundary of the No. 19 sensor. At $t = t_b$, the earlier peak reaches its maximum value, see Figure 2.32(b). As shown in

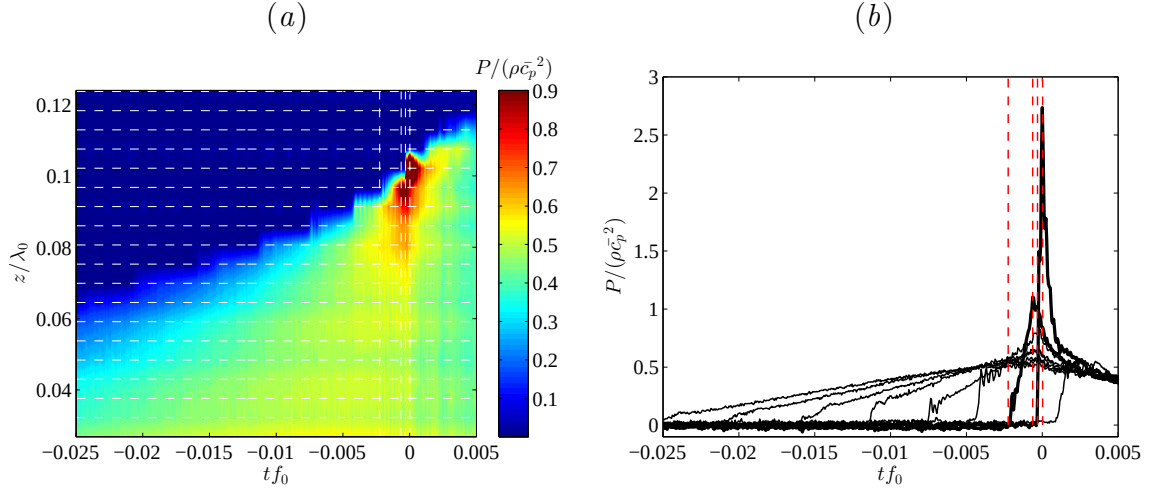


Figure 2.32: (a) The evolution of impact pressure on the wall at $z_b = -0.1129\lambda_0$. The horizontal lines represent the center line of the position sensors. The four vertical white dashed lines represent the time corresponding to the images shown in Figure 2.30(a), (b), (c), (d). (b) The time history of the pressure measured by the No.14 ~ No.20 sensors. The four red dashed lines represents the time corresponding to the images shown in Figure 2.30(a), (b), (c), (d).

Figure 2.30(b), at $t = t_b$, the contact point almost reaches the higher boundary of the No. 19 sensor. At this instant, the tip of a small jet formed at the crest is still upstream of the wall. This indicates there has not yet been direct impact of the jet with the wall. Therefore, the earlier pressure peak is probably caused by the focusing of the surface. The later peak has higher maximum than the earlier peak and is measured by pressure sensor No. 20. As shown in Figure 2.30(c), at $t = t_c$, when the later peak starts to rise, the small jet on the surface just impinges on pressure sensor No. 20. This indicates the later peak with highest magnitude may caused by the direct impact of a small jet on the wall. The later peak reaches its maximum at

$t = t_d$ when the small jet has already impinged on the wall, see Figure 2.30. These synchronized images and pressure records provide strong evidence that the earlier pressure peak on the wall is the unique feature for flip-through impact problems, as described in some previous theoretical work.

In the process of flip-through wave impact, since the time scale is too short for viscous diffusion to affect the outer flow, the outer flow can be well described by potential flow theory. According to Bernoulli's equation, the pressure on the wall consists of two parts: the dynamic pressure $(\rho \partial \phi / \partial t + 0.5 \rho (\nabla \phi)^2)$, and the hydrostatic pressure $(\rho g z)$. With part of the free surface indented with a circular shape, the normal component of the velocity at the free surface focuses the free surface toward its center of curvature at any instant. The effect of the dynamic pressure term can create a pressure maximum inside the flow adjacent to the wall, if gravitational force are neglected, see Cooker [15]. The gravitational term diminishes the pressure peak below surface. The balance of these two effect determines the existence of a pressure maximum on the wall below free surface, if the viscous effect and surface tension are not considered.

The potential flow model proposed by Cooker [15] describes a particular type of focusing flow with an indented free surface, similar to that found in the present experiments. In particular, the model assumes a horizontal surface with a semicircular indentation with radius R , see Figure 2.33(a). At time $t = t_0$, the flow is described by a line sink placed at the center of the semicircle. The instantaneous normal velocity of any point on the circular arc is V and the normal velocity on the surrounding flat free surface is zero. Given R and V at any instant in time, the

theory predicts the pressure field in the flow as

$$P = \rho g \left(r - \frac{R^2}{r} \right) \cos \theta - \frac{\rho V^2}{2} \left(\frac{R^2}{r^2} (1 + \cos 2\theta) + \sum_{n=1}^{\infty} a_n \left(\frac{R}{r} \right)^{2n-1} \cos [2n-1]\theta \right) \quad (2.11)$$

where

$$a_n = \frac{16}{\pi} \frac{(-1)^{n+1}}{(4n^2 - 1)(2n - 3)} \quad (2.12)$$

On the line of symmetry at $\theta = 0^\circ$ (the front face of the structure in the present experiments), Equation (2.11) reduces to

$$P = \rho g \left(r - \frac{R^2}{r} \right) - \frac{\rho V^2}{2} \left(\frac{2R^2}{r^2} + \sum_{n=1}^{\infty} a_n \left(\frac{R}{r} \right)^{2n-1} \right) \quad (2.13)$$

In dimensionless form, Equation (2.11) and (2.13) can be written as

$$\begin{aligned} \frac{P(r, \theta)}{\rho V^2} = & \frac{1}{Fr^2} \cos \theta \left(\frac{R}{r} \right)^{-1} + \left(\frac{8}{3\pi} - \frac{1}{Fr^2} \right) \cos \theta \left(\frac{R}{r} \right) \\ & - \frac{1}{2} (1 + \cos 2\theta) \left(\frac{R}{r} \right)^2 - \frac{1}{2} \sum_{n=2}^{\infty} a_n \cos [2n-1]\theta \left(\frac{R}{r} \right)^{2n-1} \end{aligned} \quad (2.14)$$

$$\frac{P_w(r)}{\rho V^2} = \frac{1}{Fr^2} \left(\frac{R}{r} \right)^{-1} + \left(\frac{8}{3\pi} - \frac{1}{Fr^2} \right) \left(\frac{R}{r} \right) - \left(\frac{R}{r} \right)^2 - \frac{1}{2} \sum_{n=2}^{\infty} a_n \left(\frac{R}{r} \right)^{2n-1} \quad (2.15)$$

respectively. In these equations, Fr is the Froude number defined as

$$Fr = \frac{V}{\sqrt{gR}} \quad (2.16)$$

The first term in Equation (2.14) and (2.15) is the hydrostatic term, which, of course, produces linearly increasing pressure with depth. The remaining terms are the dynamic pressure field and produce pressure contours with a subsurface maximum as shown in Figure 2.35(c). Since V increases and R decreases during the flip-through impact, Fr increases with time. During the beginning of the impact,

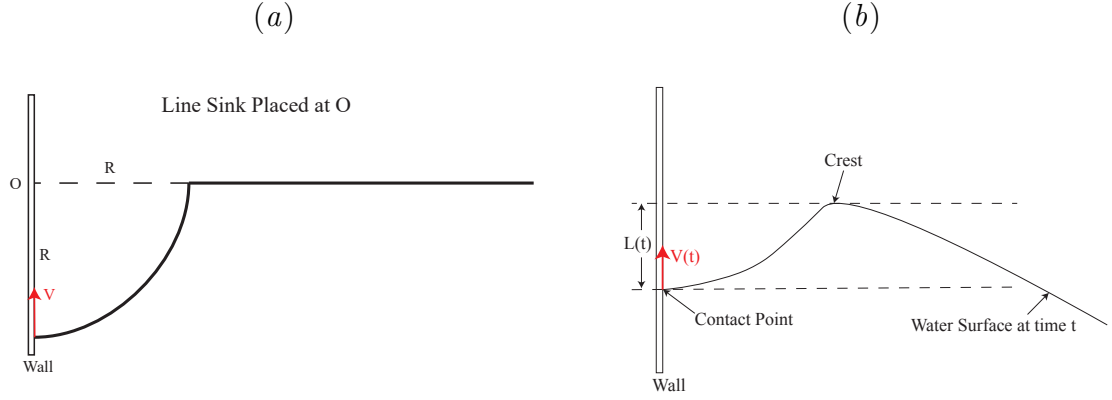


Figure 2.33: (a) Geometry described in the model by Cooker [15]. (b) Definition of $L(t)$ and $V(t)$ at surface profiles from measurements.

Fr is small and the hydrostatic terms dominate so there is no localized subsurface maximum pressure. The local pressure maximum occurs for $Fr_m > 7$.

Though Cooker's model is not directly applicable to the present experiments, it can be used to gain some insight into the flow dynamics. The difference between the two flows include the boundary shape outside the circular arc and the distribution of normal velocity along the circular arc. Thus, in order to apply the model to the experiments, we need to make some choices forced by the differences in the surface shapes and motions. An alternative choice for the radius in the experiments is the length scale $L(t)$ defined as the height difference between the contact point and the crest, as shown in Figure 2.33(b). Since the averaged surface normal velocity on the circular arc is difficult to obtain, particularly when the surface shrinks to be sufficiently small, the contact point velocity V_c will be chosen as the velocity scale $V(t)$. These definitions of the length scale and velocity scale is shown in Figure 2.33(b).

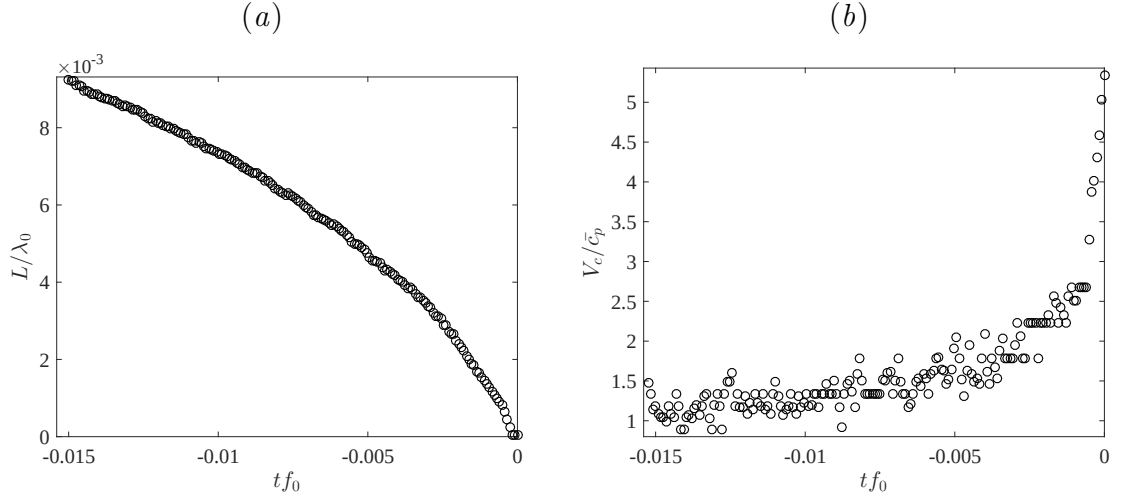


Figure 2.34: (a) and (b) show the measured temporal evolution of length scale L and velocity scale V at the final stage before the moment of impact at $z_b = -0.1129\lambda_0$, according to the definition shown in Figure 2.33(b). In (a), the circles represent the measured vertical distance from the crest point to the contact point. In (b), the circles represent the velocity value computed from finite difference of the contact point position vs time data from experiments. The data is obtained from an LIF movie with a frame rate of 13.5 kHz.

With these definitions, the length scale and velocity scale vs time are shown in Figure 2.34. It is found that both the length scale and velocity scale have increasing rates of change as the time approaches the moment of impact.

By using the length scale L and velocity scale V from Figure 2.34, Cooker's model can give the pressure distribution at each time, see Figure 2.35. In Figure 2.35(a) ($L = 0.0085\lambda_0$, $V = 1.039\bar{c}_p$, $Fr = 4.75$), the pressure increases as height decreases: the hydrostatic pressure dominates. In Figure 2.35(b) ($L = 0.0072\lambda_0$, $V = 1.292\bar{c}_p$, $Fr = 6.43$), a pressure maximum is about to form just below the

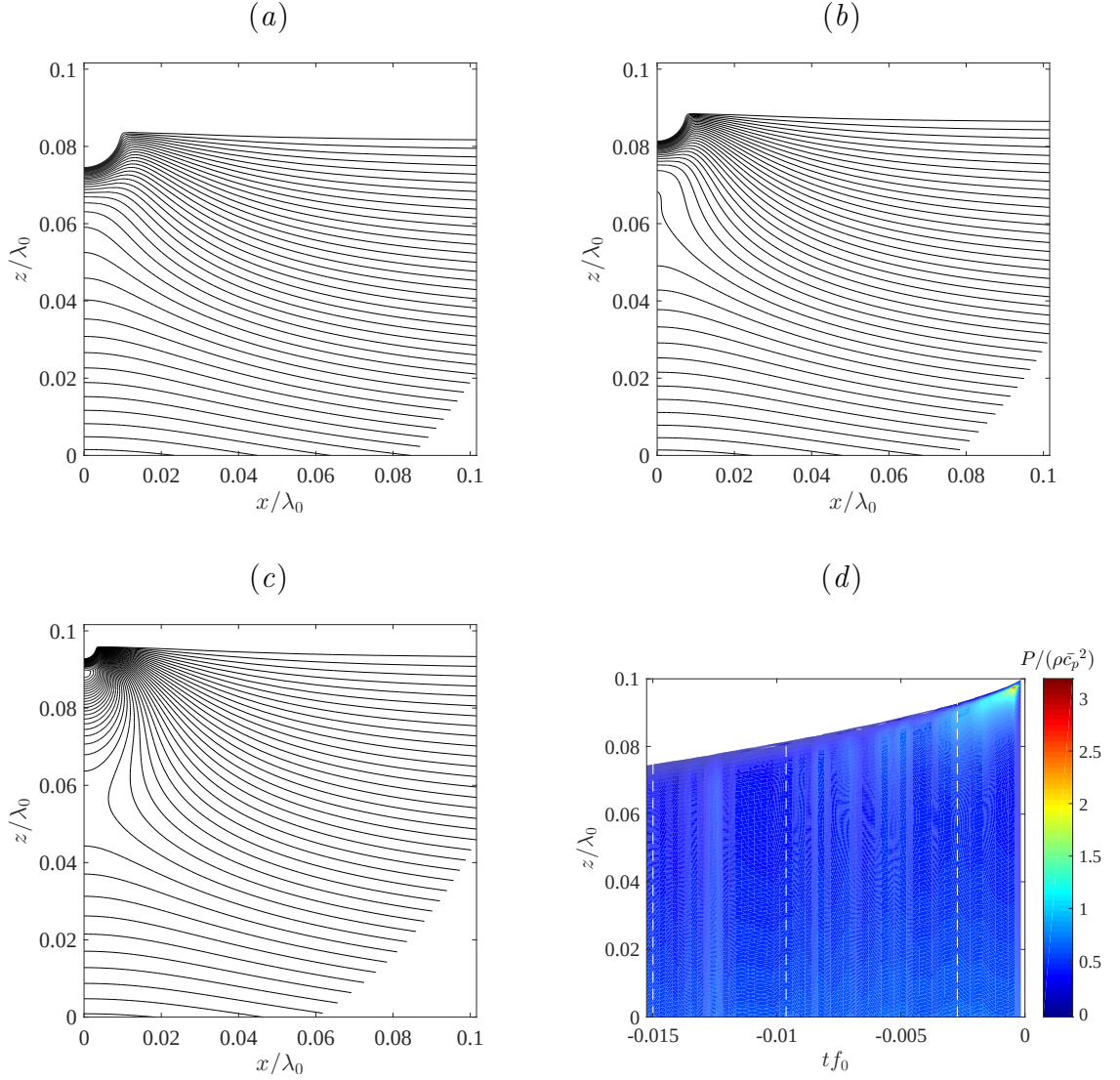


Figure 2.35: (a), (b), (c) represents the pressure distribution in the flow field computed by the Equation (2.11) at $t = -13.0$ ms, $t = -8.4$ ms, $t = -2.4$ ms, respectively. The calculation uses the L and V from experiments at different times shown in Figure 2.34. (d) shows the temporal evolution of the pressure distribution on the wall computed from Equation 2.11. The three vertical white dashed lines represent the time of the pressure field corresponding to (a), (b) and (c).

free surface, which indicates the inertial effect becomes important and starts to balance the hydrostatic effect. As the velocity of the surface keeps increasing and the size of the indentation decreases dramatically at the final time before the moment of impact, the inertial effect becomes dominate and a pressure maximum appears just below the free surface, as shown in Figure 2.35(c) ($L = 0.0055\lambda_0$, $V = 1.38\bar{c}_p$, $Fr = 7.83$). The temporal evolution of the pressure on the wall is shown in Figure 2.35(d). It shows the spatial pressure maximum on the wall only appears after about $tf_0 = -0.008$.

In the experiments, we can define the Froude number by

$$Fr(t) = \frac{V(t)}{\sqrt{gL(t)}} \quad (2.17)$$

With this definition, the evolution of the Froude number vs time is shown in Figure 2.36. The spread of the data points mostly comes from the numerical error when taking derivatives of the contact point position to obtain $V(t)$. Starting from $tf_0 = -0.015$, the Fr gradually increases following a nearly linear curve. After about $tf_0 = -0.008$, the Fr increases rapidly over time. From the pressure record shown in Figure 2.32, when $tf_0 > -0.00225$ (shown by the first dash vertical line), at a fixed instant, the pressure measured by the pressure sensor just below the free surface is larger than the pressures measured by all the lower sensors. This indicates the pressure maximum starts to occur after this instant. In Figure 2.36, this time is labeled as t_e . $Fr = Fr_e = 15.38$ at this critical time. At later times, Fr exceeds Fr_e and the pressure maximum always occurs below the contact point. At early times ($tf_0 < t_e f_0$), Fr is smaller than this critical value Fr_e and the gravitational effect

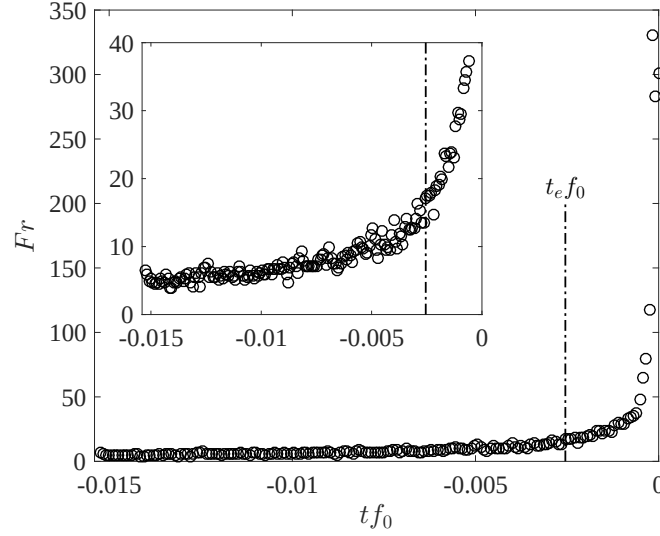


Figure 2.36: Froude number vs time at $z_b = -0.1129\lambda_0$. Froude number is defined as $Fr = V(t)/\sqrt{gL(t)}$, where $V(t)$ is the velocity of the contact point from experiments, $L(t)$ is the vertical distance from the crest point of the wave to the contact point and is determined from experiments, g is the gravitational acceleration. t_e is the moment when the subsurface local pressure maximum starts to appear in experiments. The inset figure is a closeup view of the curve with the last 7 points excluded.

dominates the distribution of pressure on the wall; as a result, no pressure maximum is observed. With the definition of Fr defined in Equation (2.16), Cooker's model suggests a critical value for $Fr_m = 7$, which is smaller than the value suggested by our measurements. The difference could be caused by several reasons. First of all, Cooker's model considers the instantaneous focusing flow field as a line sink, which may not be an exact solution to the flow field of the wave impact problem. Second, in Cooker's model, the free surface is a semicircle combined with a horizontal line that extends to infinity. In the wave impact experiments, the free surface is observed

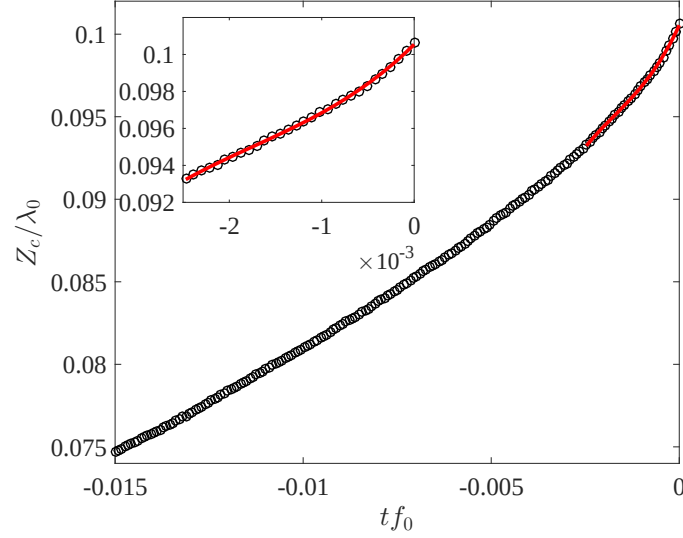


Figure 2.37: The vertical position of the contact point vs time for $z_b = -0.1129\lambda_0$. The circles are the data points measured from one experimental run. The sample rate of the data is 13.5 kHz. The red line is the third order polynomial fitting function to the data when $-0.0026 < tf_0 < 0$. The polynomial fitting function is $Z_c/\lambda_0 = c_3(tf_0)^3 + c_2(tf_0)^2 + c_1(tf_0) + c_0$, where the value for $[c_3, c_2, c_1, c_0]$ is $[289950, 1510.2, 4.9175, 0.1005]$. The inset figure is the detailed view of the polynomial fitting. $tf_0 = 0$ is the moment of impact. Z_c is measured from the mean water level.

to be a circular arc combined with a transitional curve and a straight line with about 75° slope. The straight line only extends to the trough of the wave, instead of reaching infinity.

Bredmose *et al.* [5] reported results from numerical simulations of flip-through wave impact for a shallow water wave on a wall that extends to the bottom of the tank. Their results (Figure 12 in the paper) also shows similar trends. At early times before impact, the pressure on the wall is dominated by gravity and increases as the

height decreases. From about 10 ms before the impact, a pressure peak appears just below the free surface. The pressure peak only lasts for about 15 ms.

The pressure maximum below the free surface creates a high pressure gradient between the location of the maximum and the free surface. This high pressure gradient creates a high acceleration and drives the flow to form a high-speed vertical jet. The vertical position of the contact point vs time is shown in Figure 2.37. According to the third order polynomial fitting function to the data points shown in Figure 2.37, the acceleration of the contact point can be estimated by the second order derivative of this fitting function, see caption of Figure 2.37. At the moment of impact, the acceleration of the contact point reaches $481g$.

When $tf_0 < 0$, the temporal evolution of length scale $L(t)$ and velocity scale $V_c(t)$ can be represented by power law, as shown in Figure 2.38(a) and (b), respectively. The velocity scale V_c is computed from the Z_c vs t data (shown in Figure 2.37) by central finite difference for all interior points and one-side difference at the end points.

The Weber number is defined as the following

$$We = \frac{\rho V_c(t)^2 L(t)}{\sigma} \quad (2.18)$$

The temporal evolution of We is shown in Figure 2.39. Unlike the increasing trend of Fr , We vs t spreads around a constant level about $We = 400$ for most of the time. At the last few frames just before $tf_0 = 0$, We decreases from the constant level and eventually becomes nearly zero.

If We is independent of t , the decay rate of length scale and the increasing

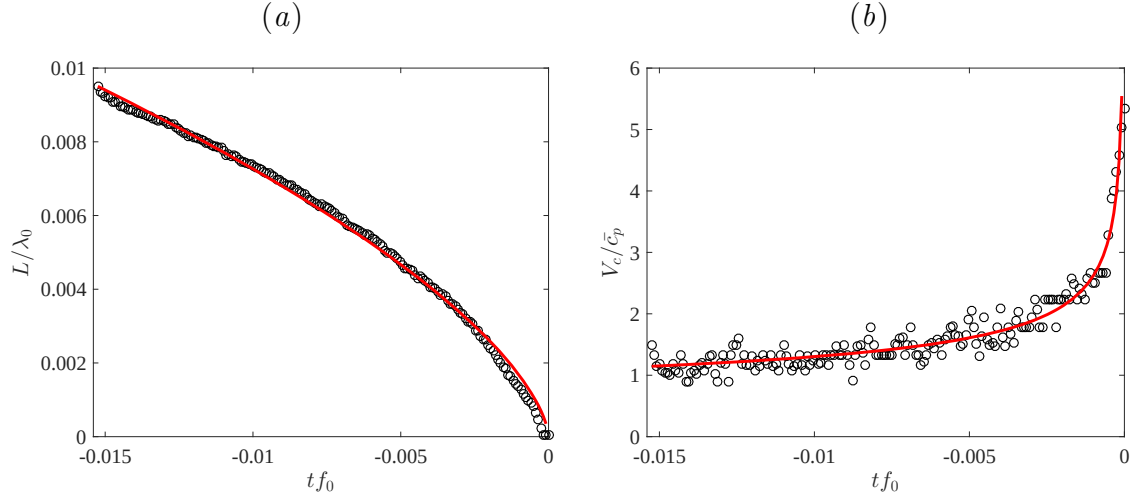


Figure 2.38: The power law fitting to the length scale vs time (shown in (a)) and velocity scale vs time (shown in (b)) at the final stage before the moment of impact. The circles have the same definition as described in Figure 2.34. The red lines are the power law fitting function to the data points represented by the circles. In (a), the fitting function is $L/\lambda_0 = 0.1366 |tf_0|^{0.6372}$. In (b), the fitting function is $V_c/\bar{c}_p = 0.3214 |tf_0|^{-0.3039}$.

rate of velocity scale have to satisfy specific relations. If the length scale is assumed to decay following a power law, i.e., $|t|^\xi$, by dimensional analysis, the velocity scale should follow the power law $|t|^{\xi-1}$. As a result, the We follows the power law $|t|^{3\xi-2}$. Therefore, We is independent of time when $\xi = 2/3$.

From Figure 2.38, it is found the length scale $L \propto |t|^{0.6372}$ and the velocity scale $V_c \propto |t|^{-0.3039}$. The power law fitting agrees with the dimensional analysis in previous paragraph and explains the fact that We is nearly independent of time for most of the time before the moment of impact. However, according to the power law, V_c should go to infinity at $tf_0 = 0$. This is an unphysical prediction for the velocity.

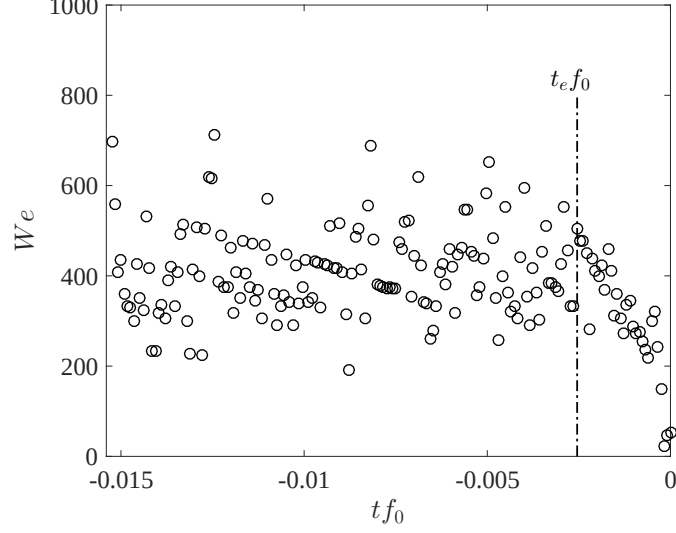


Figure 2.39: Weber number vs time at $z_b = -0.1129\lambda_0$. Weber number is defined as $We = \rho V(t)^2 L(t) / \sigma$, where $V(t)$ is the velocity of the contact point from experiments, $L(t)$ is the vertical distance from the crest point of the wave to the contact point and is determined from experiments, σ is the surface tension of water, ρ is the density of water. t_e is the moment when the subsurface local pressure maximum starts to appear in experiments.

At the last few frames just before $tf_0 = 0$, since L is nearly zero and V_c has finite value, We becomes nearly zero. During this very short time before the moment of impact, the power law fails to describe the flow and further understanding of the physics is needed.

2.4.3 The generation of upstream propagation waves

§2.3.2.1 shows the different behaviors of the surface profile evolution among the four conditions in Class I. To further examine the mechanisms causing the differences, the horizontal and vertical positions of the crest point are plotted versus time

in Figures 2.40(a) and (b), respectively. Data for the wave in open water is shown along with data taken with the structure positioned at the three submergences. As mentioned above, in the open water case the plot of x_m versus t is essentially a straight line indicating that the crest speed is nearly constant. Also, the height of the crest point, z_m , increases at first but then reaches a maximum at about the time that it passes the approximate location the front face of the structure, when installed. With the wall installed in the tank, x_m decreases in time with an overall slope (horizontal crest speed, c_x) less than the open water case; however, the slope is not constant. For the $z_b = -0.1129\lambda_0$ case, c_x is relatively constant at $0.71\bar{c}_p$ for $16.17 < (t - t_s)f_0 < 16.42$. At $(t - t_s)f_0 = 16.42$, c_x suddenly increases dramatically and then settles down to a relatively constant value of $1.71\bar{c}_p$ until the crest point meets the wall at the moment of impact. This behavior is nearly identical for all three values of z_b . Similar transient increases in c_x also occur at $(t - t_s)f_0 = 16.38$ and $(t - t_s)f_0 = 16.34$ for $z_b = -0.0914\lambda_0$ and $z_b = -0.0645\lambda_0$, respectively.

In the presence of the wall, the vertical position of the crest point z_m also varies significantly compared with the undisturbed breaker, as shown in Figure 2.40(b). The behavior of z_m over time is similar for cases $z_b = -0.1129\lambda_0$ and $z_b = -0.0914\lambda_0$. At the same time, z_m reaches maximum at about $(t - t_s)f_0 = 16.27$ with a value of $0.098\lambda_0$, larger than the z_m of undisturbed breaker at this instant with a value of $0.082\lambda_0$. z_m starts to decrease between $16.26 < (t - t_s)f_0 < 16.42$. At $(t - t_s)f_0 = 16.42$, z_m reaches the minimum with a value of $0.075\lambda_0$, smaller than the z_m of the undisturbed breaker at this instant with a value of $0.087\lambda_0$. At $z_b = -0.0645\lambda_0$, the behavior of z_m over time is slightly different from the other two cases with deeper

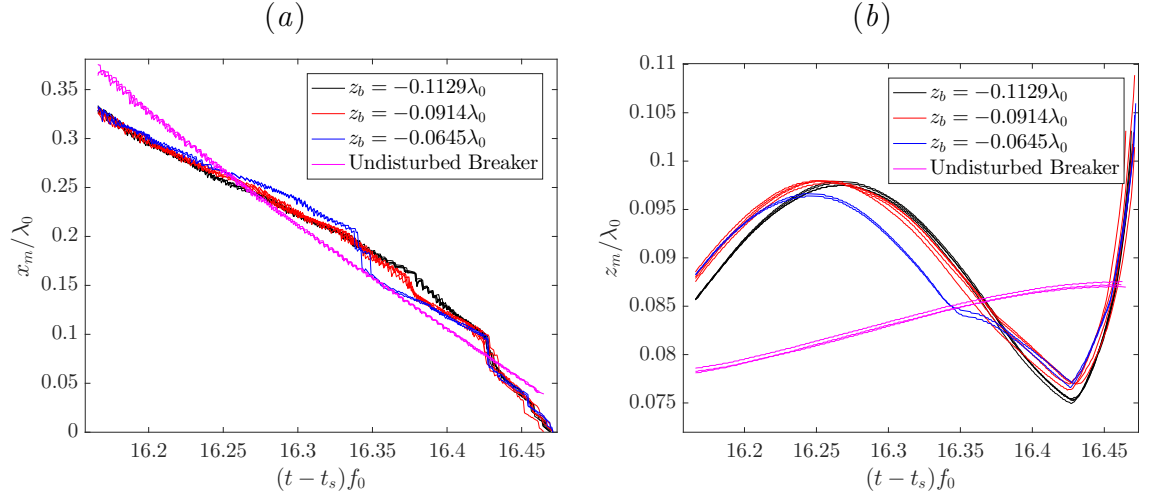


Figure 2.40: Behavior of the wave crest point. The horizontal and vertical coordinates of the wave crest point are plotted versus time in subplots (a) and (b), respectively, for three values of the structure submergence, z_b/λ_0 . The coordinate origin is located at the intersection of the mean water level and the front surface of the structure ($5.43\lambda_0$ from the back face of the wave maker) and the time when the motion of the wave maker starts is taken as t_s . Each line with the same color represents the data from one experimental run at the same condition. The horizontal crest position data is a little noisier than the vertical position data because the relatively flat shape of the wave crest, see Figure 2.14, makes the horizontal location of the maximum height sensitive to small imperfections in the profile data.

submergence. The maximum value of z_m for $z_b = -0.0645\lambda_0$ is slightly smaller while its minimum value is slightly larger than the former two cases. There is an extra plateau for $z_b = -0.0645\lambda_0$ case between the maximum and minimum of z_m . The starting time of this plateau is the same as the first drop in the x_m vs t curve in Figure 2.40(a). For all three cases with the presence of the wall, after z_m reaches

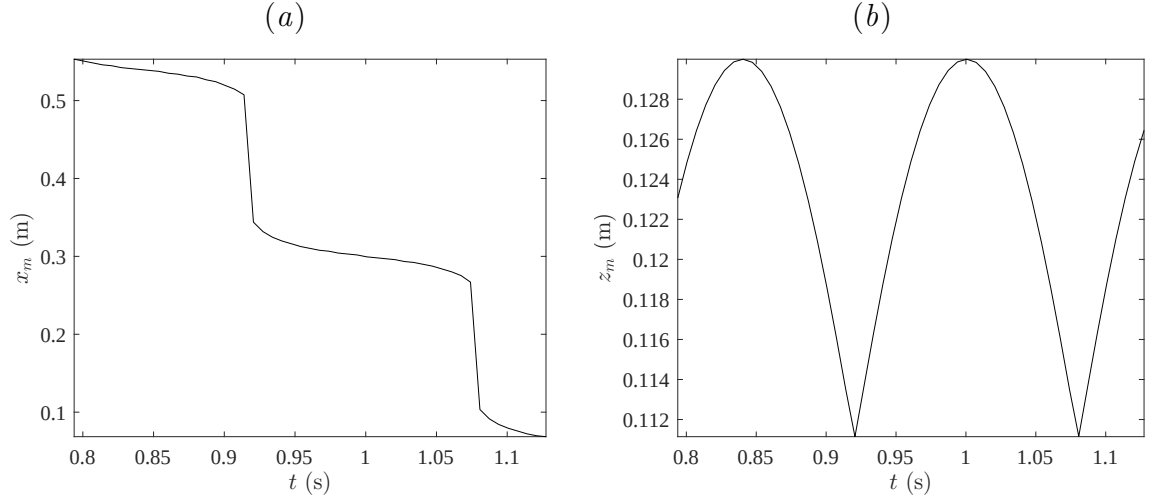


Figure 2.41: The evolution of the horizontal and vertical coordinates of wave crest point of a left moving sine wave of angular frequency ω_1 added to that of a right moving sine wave of frequency $\omega_2 = 2\omega_1$ are shown in subplots (a) and (b), respectively, according to Equation (2.19)(2.20)(2.21). The left propagating wave has amplitude $A_1 = 0.12$ m and angular frequency $\omega_1 = 6.54$ Hz. The right propagating wave has amplitude of $A_2 = 0.01$ m and angular frequency $\omega_2 = 13.08$ Hz.

its minimum value at about $(t - t_s)f_0 = 16.42$, z_m increases rapidly until the crest point meets the wall.

It is hypothesized that the above-described behaviors of the crest point are caused by a small amplitude wave that is generated at the structure and propagates upstream before the main crest impacts the structure. In order to explore the formation of these small waves, two sine waves with different frequencies are superimposed. The two sinusoidal waves are described as the following equations

$$z_1 = A_1 \sin(k_1 x + \omega_1 t) \quad (2.19)$$

$$z_2 = A_2 \sin(k_2 x - \omega_2 t + \pi) \quad (2.20)$$

The overall amplitude of the wave is the superposition of the two waves

$$z = z_1 + z_2 \quad (2.21)$$

The left propagating wave has larger amplitude than the right-propagating wave. The angular frequencies of the two waves satisfy the relation $\omega_2 = 2\omega_1$. The value of the wave number is determined according to the dispersion relation of gravity wave in deep water, $k_1 = \omega_1^2/g$, $k_2 = \omega_2^2/g$. The values of the parameters used in this simulation is as following: $A_1 = 0.12$ m, $A_2 = 0.01$ m, $\omega_1 = 6.54$ Hz, $\omega_2 = 2\omega_1 = 13.08$ Hz, $k_1 = 4.36$ m⁻¹, $k_2 = 4k_1 = 17.44$ m⁻¹. The coordinates of the crest point are plotted versus time in Figure 2.41. As can be seen in the figure, the behavior of the crest point in the model is very similar to that in the experiments, thus giving some support to the generation of a second harmonic upstream propagating wave during the impact.

To further examine the above described second harmonic effect, water surface profiles for conditions $z_b = -0.1129\lambda_0$, $z_b = -0.0914\lambda_0$, $z_b = -0.0645\lambda_0$, and $z_b = 0.0$ are plotted in a moving reference frame with horizontal speed equal to the crest speed of the breaker in open water, 1.5 m/s, see Figure 2.42. In order to observe the small waves propagating upstream, the i^{th} profile is shifted upward by $(i-1) \times 0.6$ cm. At early times, for all four conditions, the crest point moves upstream in moving reference frame because their crest speed is slower than that of the breaker in open water. The crest point moves in steps. This behavior is more obvious for smaller z_b . The upstream propagating waves forms “ridges” between the contact point and the crest. At $z_b = -0.0645\lambda_0$, two ridges are found. At $z_b = 0$, at least three ridges

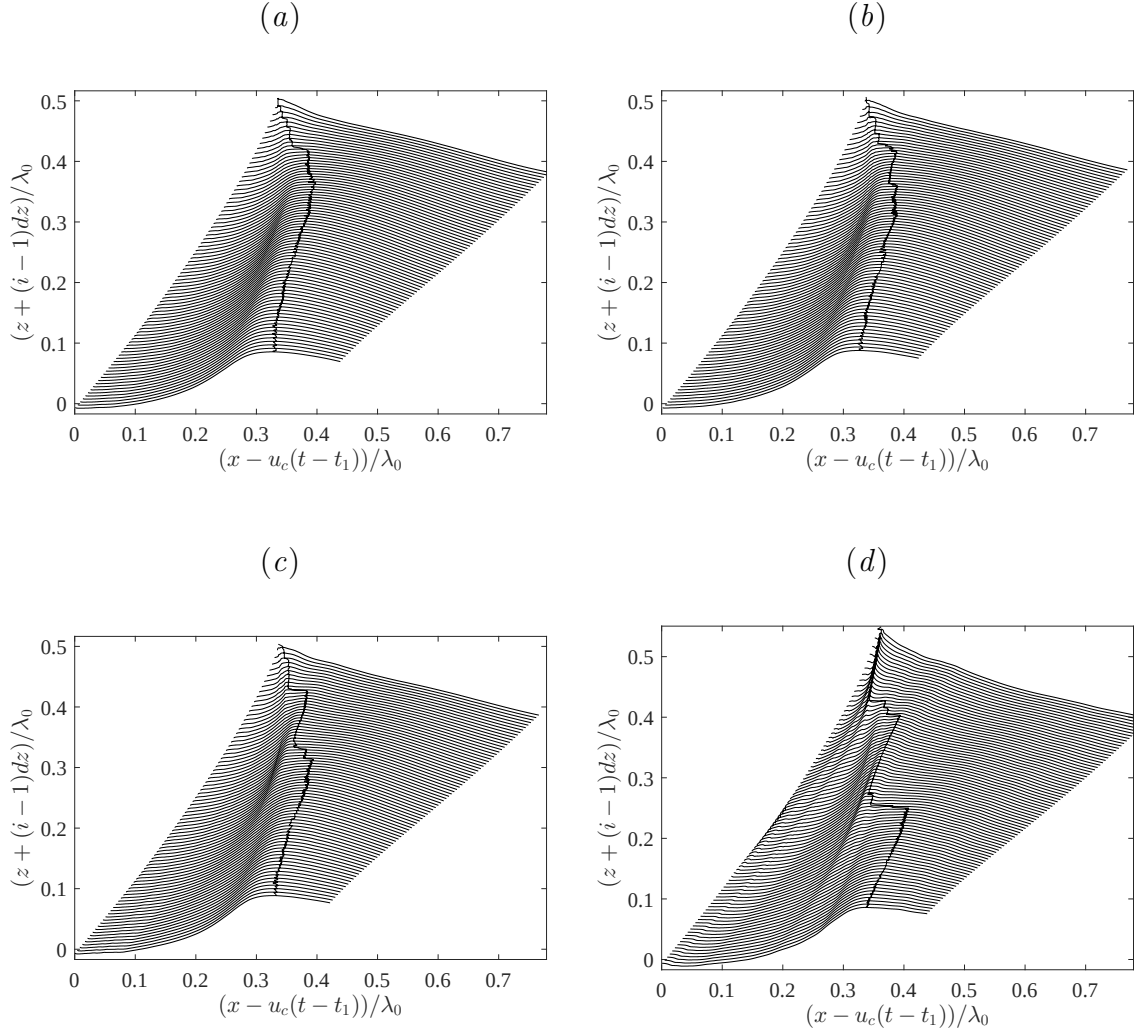


Figure 2.42: The water surface profiles for cases $z_b = -0.1129\lambda_0$, $z_b = -0.0914\lambda_0$, $z_b = -0.0645\lambda_0$, and $z_b = 0.0$, respectively. The profiles are plotted in a reference frame moving horizontally with the speed of the crest point of the breaker in open water, $u_c = 1.5$ m/s. The i^{th} profile is shifted upward by $(i - 1)dy$ cm, where $dy = 0.6$ cm. The time interval between subsequent profiles is 3.33 ms. The bold solid lines represents the position of the crest point in each cases.

can be clearly identified. For $z_b = -0.1129\lambda_0$ and $z_b = -0.0914\lambda_0$, the ridges are not clearly formed. A similar plot of the profiles from the above-described linear

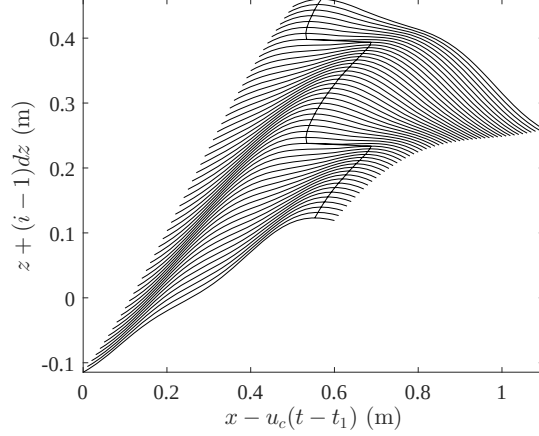


Figure 2.43: The surface profile from the superposition of two sine waves. according to Equation (2.19)(2.20)(2.21). The left propagating wave has amplitude $A_1 = 0.12$ m and angular frequency $\omega_1 = 6.54$ Hz. The right propagating wave has amplitude of $A_2 = 0.01$ m and angular frequency $\omega_2 = 13.08$ Hz. The profiles are plotted in a reference frame moving horizontally with the speed $w_1/k_1 = 1.5$ m/s, where $k_1 = \omega_1^2/g = 4.36$ m⁻¹. The i^{th} profile is shifted upward by $(i - 1)dy$ cm, where $dy = 0.67$ cm. The time interval between subsequent profiles is 6.7 ms.

model are shown in Figure 2.43. The profile behavior is quite similar to that from the experiments.

Another interesting property of the water surface is the slope. Figure 2.44 shows the temporal evolution of the surface slope for condition $z_b = -0.1129\lambda_0$ and $z_b = 0$. In this figure, the “streaks” represents the evolution of features with sharp variation of surface slope. In Figure 2.44(a), the wide bright region represents the evolution of the main crest, which has a flat surface and zero slope at the crest point. In Figure 2.44(b), at a fixed time, the main crest has multiple stream-wise positions where the slope equals zero. Downstream of the main crest point, three “streaks”

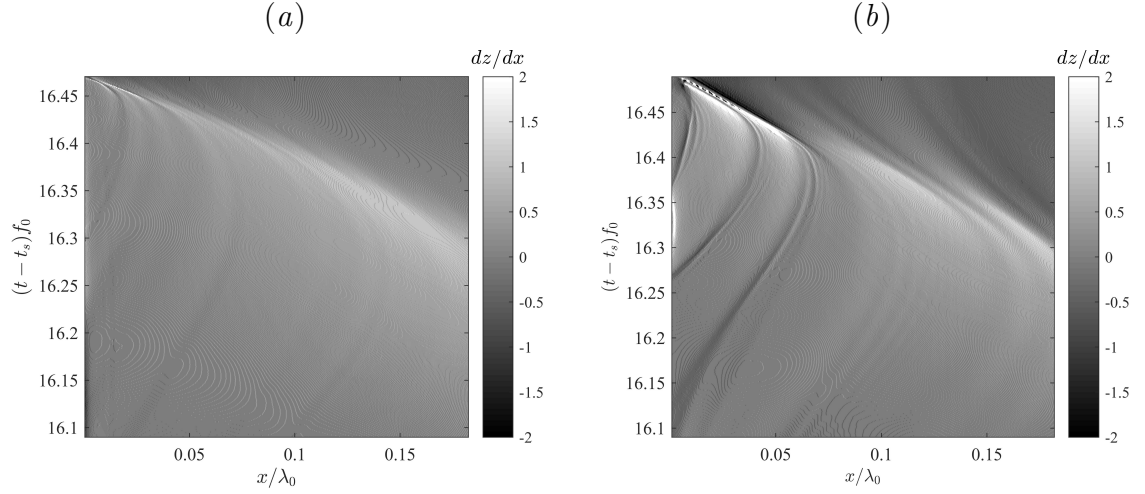


Figure 2.44: The evolution of water surface slope along streamwise direction for (a) $z_b/\lambda_0 = -0.1129$, (b) $z_b/\lambda_0 = 0$. t_s is the time when the wave maker motion starts.

appears. These “streaks” represents the propagation of the ripples generated at the bottom of the structure. These ripples propagates upstream and eventually merges into the jet, which impacts on the structure.

To further explore the process of the propagation of the ripples on the water surface, the normal and tangential velocities of the ripples (labeled as Ripple 1 and 2 in Figure 2.16(b)) are tracked over time, as shown in Figure 2.45. The normal velocities of the two ripples increase with increasing rate of change as the wave crest approaches the structure. This trend seems to be exponential and similar to the trend of the surface normal velocity in the flip-through case, see Figure 2.28(b). The increase of normal velocity of the ripple is probably caused by the focusing of water surface between the crest and the contact point. The tangential velocity varies around a nearly constant (about $0.3\bar{c}_p$) over time for both ripple 1 and ripple 2. This

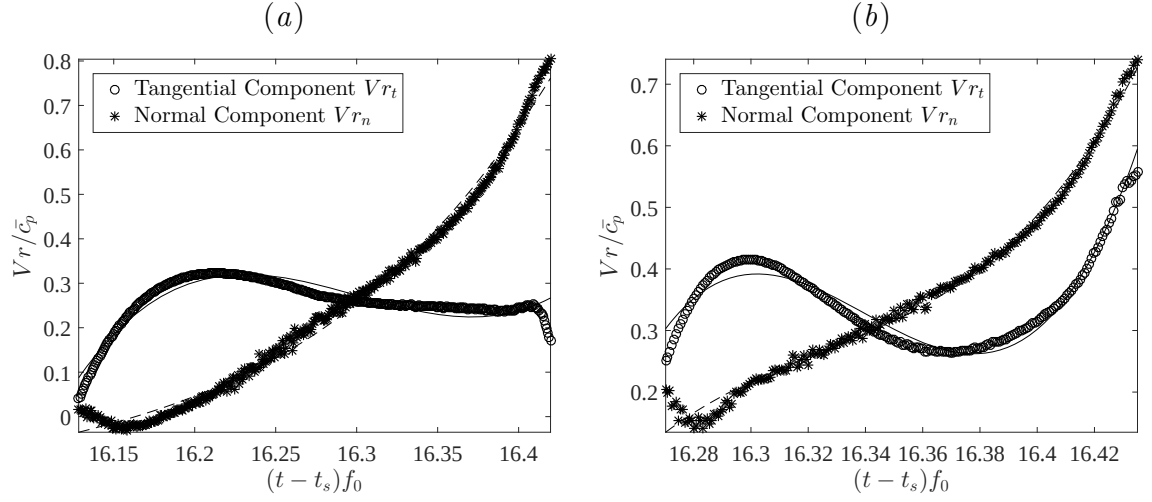


Figure 2.45: The tangential and normal component of the velocity of a surface ripple vs time for case $z_b/\lambda_0 = 0$. The positions of the ripple are represented by the its upstream trough point, where the slope of the surface reaches local extrema. The velocity of those ripples are computed by numerically differentiate the position data of these points. The tangential and normal vector of the surface at these points are computed by the derivative of the spline function that fits the water surface. The computed velocity of the ripples are then decomposed in tangential and normal direction. (a) velocity of ripple 1. (b) velocity of ripple 2.

tangential speed is much slower than the speed of the crest point of the breaker in open water (1.5 m/s) and larger than the minimum phase speed of gravity-capillary waves (23 cm/s).

2.4.4 The formation of ripples at $z_b/\lambda_0 = 0.0215$ and micro-jets at

$$z_b/\lambda_0 = 0.043$$

At both $z_b = 0.0215\lambda_0$ and $z_b/\lambda_0 = 0.043$, the breaker is undisturbed before the moment the water surface touches the bottom of the structure. After the bottom of the structure is reached by the water surface, the phenomena are different between the two conditions. At $z_b/\lambda_0 = 0.0215$, a ripple is generated immediately after the water surface touches the bottom of the structure. This ripple grows in size while moving upward on a column of water, see Figure 2.20. At $z_b/\lambda_0 = 0.043$, instead of a ripple, a micro-jet is generated when the water surface touches the bottom of the structure. The micro-jet grows toward the upstream and collides with the plunging jet. In the latter case, the collision of the micro-jet and the plunging jet can possibly cause air entrainment. In order to further explore the criteria for the generation of the micro-jet, the temporal evolution of the vertical velocity (W_I) of the breaker's surface in open water at the fictitious position of the front face of the structure is shown in Figure 2.46. The vertical velocity of the breaker is computed by finite difference on the vertical coordinates of the breaker's profile in open water at the fictitious position of the front face of the structure. With the structure installed, when the breaker first touches the bottom of the structure, the instantaneous vertical velocity of the breaker's surface can be found by interpolation on the polynomial fitting function of the numerically differentiated velocity vs time data. It is found that $W_I = 0.25\bar{c}_p$ at $z_b/\lambda_0 = 0.0215$ and $W_I = 0.70\bar{c}_p$ at $z_b/\lambda_0 = 0.043$. Therefore, the water surface has a much higher momentum at the latter condition when the

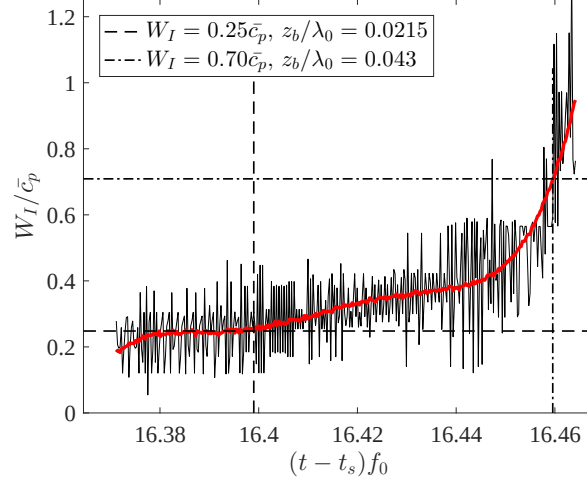


Figure 2.46: Vertical velocity at the surface of the undisturbed breaker at the same streamwise position ($x = 0$) as the front surface of the structure vs time. t_s is the time when the motion of the wave maker starts. The vertical line on the left (dashed) represents the time $((t - t_s)f_0 = 16.40)$ when the breaker surface touches the lower front corner of the wall at condition $z_b/\lambda_0 = 0.0215$. The vertical line on the right (dash-dot) represents the time $((t - t_s)f_0 = 16.46)$ when the breaker surface touches the lower front corner of the wall at condition $z_b/\lambda_0 = 0.043$. The red solid line is the polynomial fit to the velocity data. The values of W_I at the above two times are found by interpolation on this polynomial.

bottom of the structure is first touched. This more energetic surface can create a micro-jet instead of a ripple. Since the micro-jet increases the chance of air-entrainment, there might exist a boundary for the occurrence of air entrainment in the range $0.0215 < z_b/\lambda_0 < 0.043$. In other words, for triggering the formation of micro-jet, the instantaneous vertical velocity of the water surface when the surface touches the structure should be between $0.250\bar{c}_p$ and $0.70\bar{c}_p$.

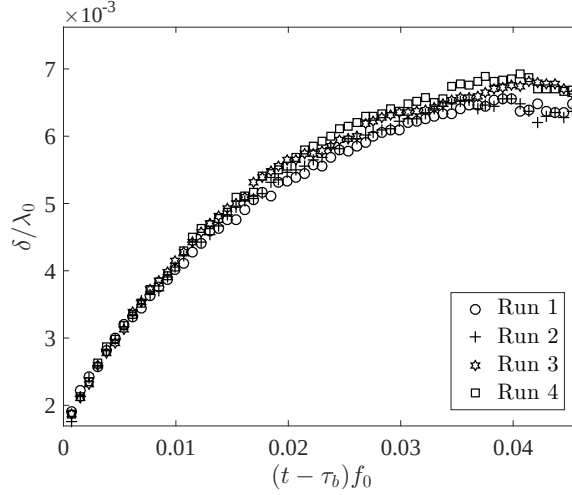


Figure 2.47: The streamwise length of the ripple versus time at four repeated experimental runs under condition $z_b/\lambda_0 = 0.0215$. The streamwise length of the ripple is defined as the distance from the wall to the trough of the ripple, which can be clearly defined from the image for this range of time. τ_b is the moment when the local water surface first touches the bottom of the structure.

The streamwise length of the ripple at condition $z_b/\lambda_0 = 0.0215$ is another interesting parameter to explore. By tracking the position of the trough of the ripple, the streamwise length of the ripple can be represented in an consistent and well defined manner. It is found that the streamwise length of the ripple increase nearly linearly for early times. The rate of increasing of the streamwise length slows down and seems to become a constant at later times, as shown in Figure 2.47.

2.5 Summary

In this chapter, the wave impact on a structure with different “keel depths” is explored experimentally. The structure consists of two vertical flat plates on the

two faces perpendicular to the direction of wave propagation and one horizontal flat plate on the bottom face. The middle of the front face has a square cutout to allow the installation of a box with pressure sensors on its front surface. The height of the bottom surface of the structure (z_b) is adjusted along the vertical direction from $-0.1129\lambda_0$ to $0.043\lambda_0$, where λ_0 is the averaged wave length of the wave packet and the $z_b = 0$ is at the mean water level. Based on the dispersive focusing technique, the experiments use a single wave maker motion, which generates a plunging breaker in open water. A cinematic laser induced fluorescent technique is used for measurements of the evolution of water surface profiles. Piezoelectric pressure sensors are used to measure the impact pressure on the front face of the structure. The wave maker motion, surface profile measurements and impact pressure measurements are synchronized.

The water surface evolution of the breaker in open water was first measured. From the surface evolution of the breaker, the stream-wise position of the structure is chosen so that the front face of the structure is located at the position where the plunging jet just forms. At this single streamwise position, conditions with 9 different z_b/λ_0 values are explored. Three classes of impact can be categorized.

The Class I impact includes condition with $z_b = -0.1129\lambda_0, -0.091\lambda_0, -0.065\lambda_0$ and $-0.038\lambda_0$. In this class, the bottom surface of the structure remains submerged during the entire impact process. At $z_b = -0.1129\lambda_0, -0.091\lambda_0$ and $-0.065\lambda_0$, a “Flip-through” phenomenon occurs. In the process of the flip-through impact, the water surface upstream of the crest merges to a nearly straight line with the angle of about 13.6° from horizontal. The profiles of the back face of the wave are almost

equally spaced and parallel. The water surface between the contact point and the crest forms circular arcs with decaying radius over time. The center of the circles is moving downward. This process is called “focusing”. During the focusing process, the evolution of the circles fitted to the wave profiles near the structure behave differently as time proceeds for $z_b = -0.1129\lambda_0$. When $tf_0 < -0.077$, the radius decays as a linear function of time with a decay rate of 1.54 m/s. The center of the circle also moves downward following a linear function of time in the first period. When $tf_0 > -0.077$, the radius decays following an exponential function of time $R \propto t^{0.824}$. The vertical position of the circle moves downward following a parabolic function of time in the second period. The other two z_b values do not create the two obvious time periods with different behaviors.

The surface normal velocity at the contact point and the curvature transition point both increase following an exponential function of time. The velocity at the curvature transition point is always higher than the velocity of the contact point at the same instant.

The double pressure peak phenomenon is found in the flip-through impact when $z_b = -0.1129\lambda_0$. The early peak is probably caused by the focusing of the flow and the second peak is caused by the impact of a small jet. The behavior of the wall pressure is closely related to the instantaneous Froude number. When $tf_0 < -0.00225$ which corresponds to $Fr < 15.38$, the pressure on the structure is dominated by gravitational effects. In this case, the pressure increases as height decreases and no pressure maximum exists on the wall. With the rapidly increasing velocity scale (contact point velocity) and the decreasing length scale (vertical distance

from crest to contact point), the inertial effect is starting to become important and eventually dominates. At $tf_0 = -0.00225$ which corresponds to $Fr = Fr_e = 15.38$, a pressure maximum is measured just below the free surface. When $tf_0 > -0.00225$ and $Fr > 15.38$, the pressure maximum is found on the wall. The analytic model by Cooker [15] shows similar behavior and gives a value of critical Froude number of $Fr_m = 7$. The pressure maximum only appears for a very short time (about 2 ms) before the moment of impact. This pressure maximum creates a very high pressure gradient between its location and the free surface. This pressure gradient causes very high acceleration of the flow just before the moment of impact. The contact point acceleration from experiments reaches 481 times of gravitational acceleration just before the moment of impact.

Small waves are generated in Class I impact. These waves propagate upstream and modify the behavior of the water surface evolution. The smaller $|z_b|$ the stronger the upstream propagating waves. These upstream propagating waves cause the sharp change of crest position vs time curve. These effects of the upstream propagating waves can be well represented by superposing two sinusoidal waves with frequencies f_0 and $2f_0$. It is hypothesized that these waves are generated by interaction of the incoming wave flow field with the bottom corner of the structure such that a wave is generated at the phase of both the downward and upward flow past the corner.

Class II includes the conditions $z_b = -0.022\lambda_0$, $z_b = -0.014\lambda_0$, $z_b = 0$. In Class II, the bottom of the structure exits and reenters the water flow at least one time before the main crest arrives at the structure. Small disturbances generated

at the contact line propagate upstream and modify the behavior of the main crest significantly.

In the case $z_b = 0$, disturbance ripples eventually merges into jet of the incoming wave crest. These ripples move along the curved surface between the crest and the contact line with increasing normal velocities and their tangential velocities vary around $0.3\bar{c}_p$. An air crater forms between the jet and the structure. Just before the jet meets the rising contact point, it is likely that air gets entrained when the crater closes. Pressure oscillation is observed at this condition. Oscillation with lower frequency occurs for all heights nearly at the same phase. Oscillations with higher frequency only occur at high positions and damps out quickly over time.

Class III includes the condition $z_b/\lambda_0 = 0.0215$ and $z_b/\lambda_0 = 0.043$. The water surface remains undisturbed before the water surface first touches the bottom of the structure. At $z_b/\lambda_0 = 0.0215$, a ripple forms when the bottom first touches the water surface. The ripple's length along the stream-wise direction increases over time and approaches a constant. No pressure oscillation is observed at this condition.

At $z_b/\lambda_0 = 0.043$, a micro-jet forms when the bottom first touches the water surface. This micro-jet collides with the plunging jet and air is possibly entrained during the process. The pressure on the structure oscillates at this condition with high frequency. The fact that the surface normal velocity is only $0.25\bar{c}_p$ in the $z_b = 0.0215\lambda_0$ case and as high as $0.70\bar{c}_p$ for the $z_b = 0.043\lambda_0$ case just before the waves hit the structure, may explain the more violent behavior of the flow in the $z_b = 0.043\lambda_0$ case. There possibly exists a boundary between the two conditions for triggering air entrainment.

Chapter 3: Flat Plate Slamming on a Free Surface

In this chapter, the experimental study of a flat plate slamming on a free surface will be presented. This chapter will be organized in the following four sections. An introduction to slamming phenomenon will be presented in §3.1. The details of the experimental setup will be presented in §3.2. Results and discussion of two types of impact will be presented in §3.3. Finally, a summary will be given in §3.4.

3.1 Overview and Previous Work

When planing vessels travel in rough sea conditions, the impact between the hull and the water surface is an important issue that requires further understanding. During the past decades, the pressures and forces on the hull have been studied extensively; however, the formation of the spray during the impact has drawn less attention. The spray is important for a number of reasons. First, the spray carries a significant amount of kinetic energy and part of the spray can easily get above the deck. Second, the formation of the spray causes changes in the topology of the air-water interface and in some cases, air bubbles are entrained. Third, the cloud of spray significantly increases the visibility of the vessel. Another important

motivation for studying the spray formation is safety concerns during the landing of a seaplane on a water surface. When a seaplane is landing, the spray generated during the impact of the seaplane and the water surface can impinge on the wings and cause significant structural damage (Savitsky & Breslin [71]).

In the traditional theoretical analysis of the slamming problem, potential theory is usually used, which assumes the surrounding flow field is incompressible, irrotational and inviscid. This assumption is reasonable in most of the cases for the following reasons. First of all, the time scale of slamming phenomenon is very short, on the order of milliseconds, which is too short for viscous effect to diffuse away from the boundary of the body. In other words, the viscous boundary layer does not have enough time to grow sufficiently to dominate the flow field. Therefore, the flow field can be assumed inviscid. Second, it is assumed that no motion exists in the flow initially, so the flow should stay irrotational all the time under the assumption of inviscid fluid. Third, if no air bubbles or air pockets are trapped in the water, which is generally true if the impact angle is relatively large, there is no compressible effect on the flow. Although surface tension might be important for the detailed geometry of the slamming splash structures and droplets generation, it is not expected to play an important role in determining the slamming load. Surface tension is usually neglected in traditional slamming analysis.

There are some typical features associated with slamming phenomenon. One of the important features is the localized high pressure, both temporally and spatially. In addition, similar to the wave impact pressure, the slamming pressure has a very short time duration, on the order of several milliseconds. The severity of

the slamming load is also related to the impact angle, which is the angle between the solid surface and the free water surface. Generally, the smaller the impact angle, the larger the slamming load. The localized high slamming pressure can cause significant damage to the structure.

During the slamming process, air can be trapped into the flow, resulting in a change in the acoustic properties of water and the generation of acoustic waves. In this case, the compressibility of air has to be taken into account. Especially in cases when the impact angle is very small, such as the impact of a flat-bottom body on water surface, the air flow causes the water to rise at the edge of the body. As a result, an air cushion is trapped (Faltinsen [30]). Although the air cushion could reduce the local slamming pressure, it still might cause a hydroelastic response of the structure. In addition, at the free surface, due to the low hydrostatic pressure (equal to atmosphere pressure) and the excitation of the hydroelastic oscillation, the pressure could oscillate around atmosphere pressure, resulting in the local pressure being lower than the vapor pressure of water. Consequently, cavitation can occur. In all these cases with air entrainment or cavitation, the flow becomes very complicated. If the structure is not rigid, which is usually true in engineering applications, the hydroelastic response of the structure is coupled with the water flow and air flow motion. The hydrodynamic pressure, the shape and position of free surface, the rigid body motion of the structure, the deformation and vibration of the structure, and the wetted area have to be calculated simultaneously.

A detailed literature review will be given in the following subsections. §3.1.1 reviews previous studies on the slamming of rigid bodies on water surface. Hydroe-

lastic effects in slamming will be reviewed in §3.1.2. Finally, air entrainment during slamming will be reviewed in §3.1.3.

3.1.1 Slamming of Rigid Body on the Water Surface

In order to explore the physics of hull/water-surface impact, the problem is usually simplified to the impact of a vertically moving wedge with a quiescent water surface. There have been many theoretical studies of this problem. In most of these studies, potential flow is assumed.

In one of the earliest of these theoretical works, von Kármán [75] proposed a simplified model for calculating the impact load on a sea plane when landing on water surface. This model solves the problem by conservation of momentum, which assumes the initial momentum MV_0 is transmitted to the momentum of the water M_aV and the remaining momentum on the body MV , where M_a is the added mass from the water. The impact load is determined by the wedge deadrise angle, the penetration depth and the initial velocity. In the case of flat bottom (zero deadrise angle) slamming, this model gives infinite load. In order to achieve a finite load, it is assumed that the momentum is transferred to the water at the speed of sound. Von Kármán's model does not consider the deformation of the free surface or the water rising, so the wetted area is only a function of the geometry of the body, resulting in the underestimation of the wetted area.

Wagner [77] made improvements to the model of von Kármán by taking into account the rising water line during impact. This gives a larger wetted area com-

pared with von Kármán’s model. Wagner assumed that the body is blunt and the flow velocity normal to the body surface is approximately equal to the vertical slamming velocity of the body. Wagner’s model gives the upper limit of the wetted area estimation.

There have been many methods proposed for computing this type of impact. Based on Wagner’s blunt body theory, Pierson [65] proposed a method to calculate the free surface shape, velocity and potential distribution at bigger deadrise angles. It is mentioned that the impact load correlates with the spray thickness, which is defined as the distance from the wedge surface to the intersection of the extension of the straight portion of the spray to the half-width of the spray. Dobrovol’skaya [23] derived a similarity solution based on Wagner’s method and applied it to the water entry problem of a symmetric wedge. Zhao & Faltinsen [84] extended this method to give the numerical solution with deadrise angle ranging from 4° to 81° , by using a nonlinear boundary element method. In both Dobrovol’skaya and Zhao’s approaches, it is assumed that no air pocket is trapped between the body and the free surface. Howison *et al.* [36] extended Wagner’s method and applied it to several 2D and 3D impact problems with different geometries of the impacting body, whose bottom was nearly parallel to the undisturbed water surface. Oliver [59] extended the Wagner’s theory to second order. Moore *et al.* [56] extended Wagner’s theory to 3-D with oblique impact velocity. Additional theoretical studies of wedge slamming include Faltinsen & Semenov [32], Moore *et al.* [56], Garabedian [33], Mackie [53], Cointe [13]. A review has been given by Korobkin [43].

Some early experimental investigations on wedge impact were reported by

Chuang & Milne [11], Chuang [12], Greenhow & Lin [35] and others. Chuang [12] performed a series of experiments of slamming a wedge model with combined horizontal and free falling motions. Both rigid and elastic models with various deadrise angles were used and the deflection, pressure distribution and acceleration of the model were measured. These early experiments did not have sufficient resolution to study the detailed geometry of the spray.

In several more recent studies, the spray generated during impact also was examined. Peters *et al.* [64] performed an experimental and numerical study of the splash generated by the impact of a circular disk on a quiescent water surface with the disk oriented horizontally. It was found that the length and velocity scales follow a power law in time and that the scaled profiles of the splash at different times collapse to a single curve. Marston & Thoroddsen [54] studied the impact of a solid cone with various angles into different liquids. The shape of the ejecta was observed to be self-similar at all speeds for low surface tension liquids or at high impact speeds for high surface tension liquids. In these axisymmetric experiments, the angle between the cone surface and the still water surface was relatively large. Iafrati & Korobkin [37] did a numerical study on the vertical impact of a flat plate on water surface. It was found that the initial water surface profiles were self-similar at leading order. In addition, it was predicted that the thickness of the spray jet decays as $O(R^{-5})$ where R is the distance measured from the plate edge. Surface tension was not included in these simulations.

Droplets can break up from the continuous spray sheet when the sheet becomes thin and therefore unstable. Peters *et al.* [64] pointed out that droplets break up

from the rim of the splash because of a Rayleigh–Taylor instability. The diameter of the droplets were found to be nearly independent of the impact Weber number. Guillaume Riboux & Gordillo [70] studied drop impact on a solid surface and, in particular, the tiny droplets that are generated from the rim of the splash formed during the impact. During this process, surface tension tries to slow down the rim of the splash, which is moving outward with high speed due to the momentum carried by the impinging droplet. Due to instability, ridges form at the edge of the rim during the deceleration process. These ridges break up into droplets when their amplitudes become sufficiently large. The stability of the rim was studied in detail by Krechetnikov [44].

3.1.2 Effect of Hydroelasticity

Faltinsen [29] divided the ship wetdeck slamming process into two time phases. The first phase is called the structural inertial phase, which generates high acceleration with a very short time scale. The second phase is called the free vibration phase which has a relatively large time scale and its initial condition is obtained from the first phase. An Euler’s beam model is used for the structure in this study. The effect of horizontal speed is considered in this theoretical part of this study. In the experimental part of the study, a steel plate is dropped and hits an incoming wave crest. The results indicate that the maximum strain is proportional to the drop velocity but not sensitive to the wave crest radius and the position where the crest hits the plate. The experiments are also reported in Faltinsen *et al.* [31].

Reinhard *et al.* [68] studied theoretically the water entry problem of a flat elastic plate moving with constant horizontal velocity which is much larger than its vertical velocity. The water is infinitely deep and 2-D Euler Beam theory is used to model the elastic part of the problem. The jet formation in the front of the plate and the wake region behind the plate is included in the calculation. The coupled problem with rigid body motion, elastic deformation, the pressure field and the free surface shape are solved simultaneously without considering an the air cavity under the plate. It is indicated that the elastic plate can have a higher contact point speed than in rigid plate impact and that the impact load is also higher compared with a rigid plate. In addition, some other features of elastic plate slamming such as a relatively vibrant jet in the wake region is also reported. A similar study can be found in Reinhard *et al.* [67]

Some other studies of hydroelasticity during slamming can be found in Korobkin & Khabakhpasheva [42] and Korobkin [41].

3.1.3 Air Entrainment and the Effect of Compressibility

During the impact of a flat plate or a wedge on a water surface, air can be entrained in several scenarios. When the deadrise angle of the wedge is small or in the case of zero deadrise angle, the water surface can rise at the edge of the plate and trap an air pocket Faltinsen [30]. Semenov & Yoon [72] reported, based on numerical calculations, that a negative pressure region can occur along a wedge in cases with oblique impact velocity. This low pressure region might cause ventilation, cavitation

or flow separation. Negative pressures were also found by Reinhard *et al.* [68] in a study of the oblique impact of an elastic plate. The authors indicated that regions of negative pressure and cavitation are more likely to happen for elastic plate impact because of the vibration of the plate. It was found that the entrained air changed the behavior of the impact pressure significantly. Iafrati & Korobkin [38] suggested that the existence of entrained air can reduce the peak pressure but increase the loading period, which results in a large pressure impulse.

Faltinsen [29] indicated the existence of cavitation and ventilation due to the local low pressure and the oscillation of the structure, during the second half of the first wet natural period. Semenov & Yoon [72] found by calculation that there is a negative pressure region along the wedge side, which might result in ventilation and flow separation (fluid detaches from solid surface). Reinhard *et al.* [68] also found by calculation a low pressure region for rigid plate slamming. Reinhard *et al.* also suggested that for elastic plate slamming, due to the elastic vibration of the plate, the pressure could be even lower, which can cause cavitation and flow separation.

Most of the previous studies on slamming focus on the forces while the spray formation has not been examined in detail. Although some theoretical work solves for the water surface evolution in simplified models, detailed experimental measurements of the geometry and behavior of the sprays have been very rare. In this dissertation, the slamming of a flat nearly rigid plate on a quiescent water surface is studied by experiments. The spray generation during the vertical and oblique impact at a range of impact velocities are studied.

3.2 Experimental Details

In this section, a description of the experimental setup will be presented with the following organizations. A detailed description of the experimental facilities, including the towing tank and high-speed carriage in §3.2.1, and the hydraulic power system and control scheme in §3.2.2. Then, the scheme of synchronization and triggering will be introduced in §3.2.3. Finally, the setup for the laser induced fluorescence measurements of the spray profile will be presented in §3.2.4.

3.2.1 Towing Tank and Two-axis High-speed Carriage

The experiments were performed in a newly-constructed towing tank which is 13.4 m long by 2.44 m wide by 1.35 m tall. The towing tank is constructed with a steel frame supporting a system of clear Acrylic plastic panels on all the four sides and bottom. Along one side of the towing tank, there is a steel supporting frame made of 11 equally spaced vertical H-beams, which are mounted to the floor, and two long horizontal box-beams which are mounted to the H-beams. The frame is 2.97 m tall. The top of the H-beams are also supported by horizontal steel bars mounted into the nearby laboratory wall so that the frame has enough stiffness during high-speed impacts. One precision rail is mounted along each of the two box-beams. On each end of the steel frame, a hydraulic servomotor is mounted on a steel panel which is mounted between two of the H-beam columns. The two hydraulic motors drive a belt through overhung loaded adapters and pulleys. The belt is connected to a two-axis high-speed carriage which can travel along the rails

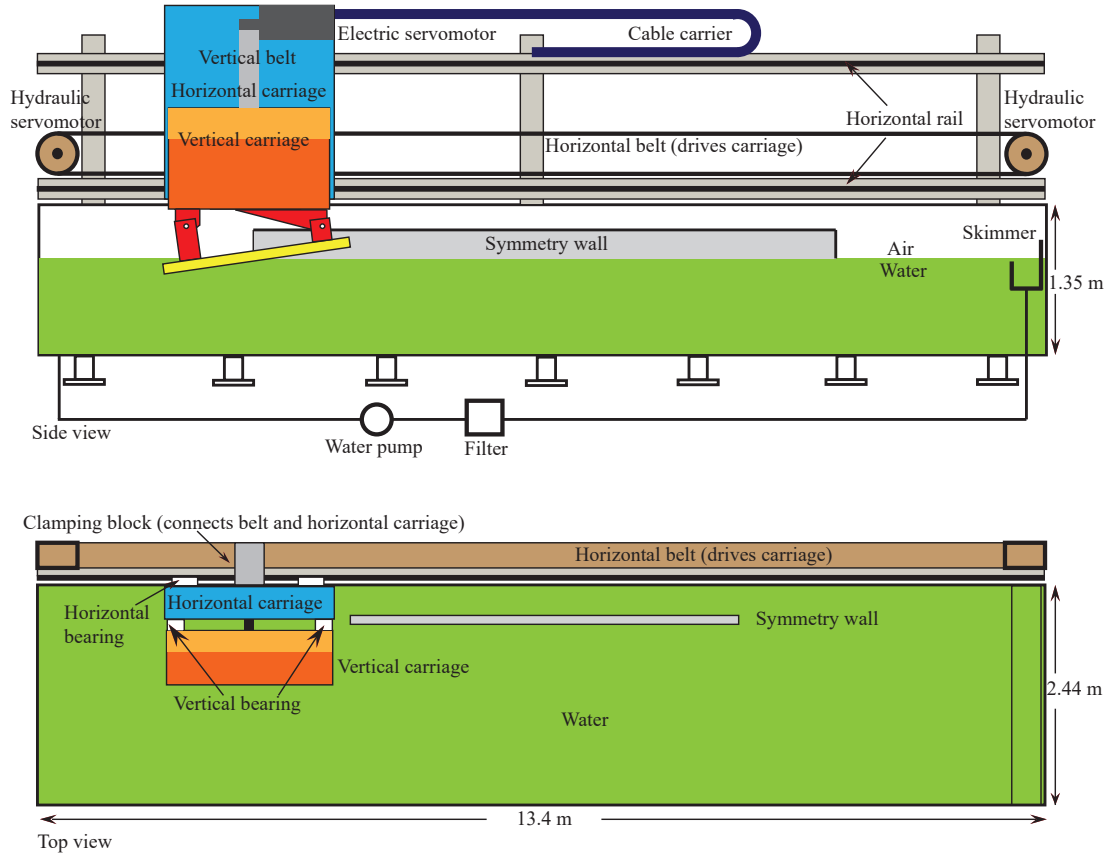


Figure 3.1: Schematic of the high-speed towing tank.

in the horizontal direction. The carriage, which will be introduced in detail in the following paragraphs, has its own electric servomotor which drives a traverser (called vertical carriage) in the vertical direction. A structure with a flat impact plate is attached to the traverser. A schematic diagram of the towing tank and carriage system is shown in Figure 3.1.

The two-axis carriage is made of stainless steel sheet metal (See Figure 3.2). A rectangular box (horizontal carriage), which is made of two horizontal and two vertical I-beams riveted to the sheet metal shell, is connected to the horizontal belt by a clamping structure on its backside, see Figure 3.3. The I-beams, which are also constructed from stainless steel sheets, form the frame for the horizontal carriage

so that it can remain stiff during the impact. Four bearings are installed on the backside of the box. The linear motion of the belt drives the box horizontally along the two rails, on which the four bearings can slide. Each of the two bearings sliding on the top rail is connected to the horizontal carriage through a flexible adapter, which consists of two blocks clamped on the top horizontal I-beam of the carriage. Therefore, even if the rails are not precisely straight, the flexible adapters give the top bearings some flexibility. The two rails are aligned with a laser alignment system. By using a beam-profile camera mounted on a dummy carriage and a 5-mW HeNe laser mounted at one end of the tank, the variation of the center of the laser beam on the image is recorded when carriage is moved along the rails. The variation of the two rails is adjusted to be within 0.5 mm from a straight horizontal line along the full length of the track. Therefore, the carriage motion is smooth and precise.

An electric servo motor is mounted inside the horizontal carriage box structure (See Figure 3.3). A gearbox with 7:1 gear ratio is installed with the motor. Through a pulley on the shaft, the electric motor drives a vertical belt, which rotates an idler pulley fixed on the bottom of the box. A trapezoidal sheet-metal box (vertical carriage) is connected to the vertical belt by clamping plates. Four bearings are mounted on the back of the vertical carriage and these bearings slide on two vertical rails which are mounted on the front side of the horizontal carriage.

A structure for mounting the impacting plate is installed at the bottom of the vertical carriage. The flat plate is bolted to several aluminum stiffeners at its upper side to keep the plate rigid during impact. The dimension of the plate is $122\text{ cm}(L_p) \times 38\text{ cm}(B) \times 1.27\text{ cm}$. The plate can rotate against the stream-wise axis

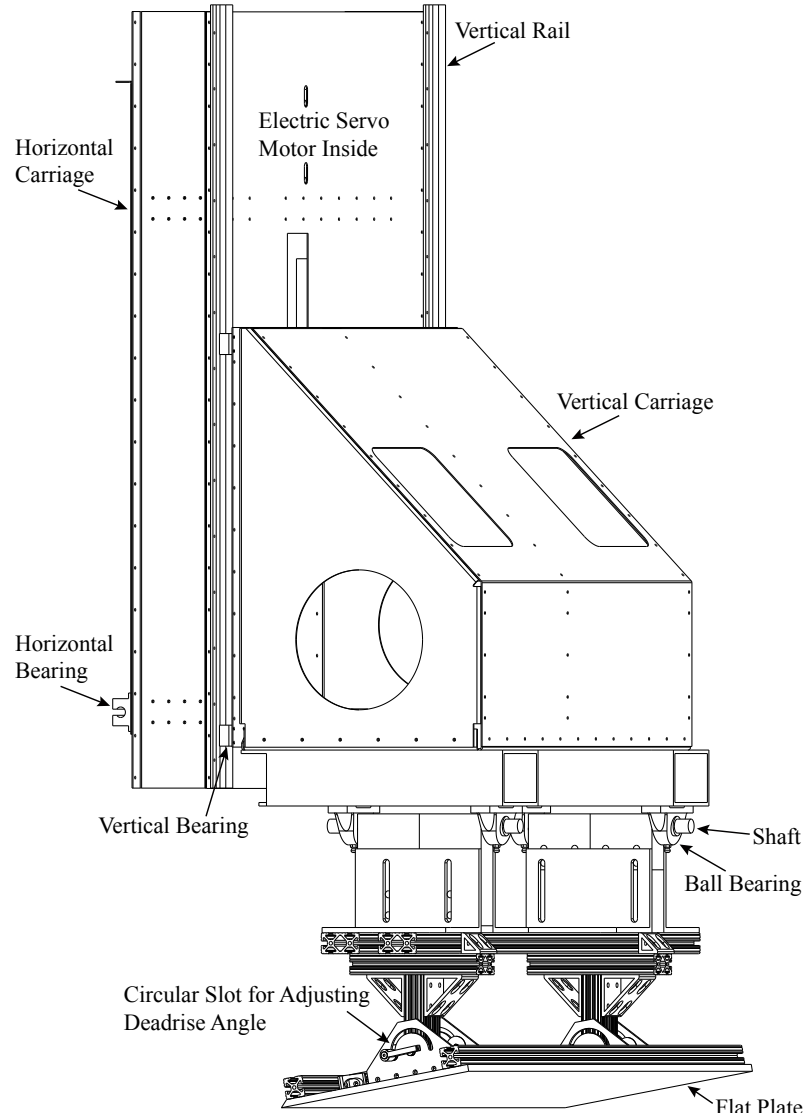


Figure 3.2: Carriage structure.

through the circular slots on several brackets. Therefore, the roll angle of the plate can be adjusted. In addition, the mounting structure of the impact plate is attached on two cross-stream shafts, which are fixed on the vertical carriage by pillow blocks. The shafts go through two aluminum blocks which attach to several right angle brackets with straight slots. The shafts and the slots on the angle brackets allow the adjustments of the pitch angle of the plate. The angle brackets can slide along

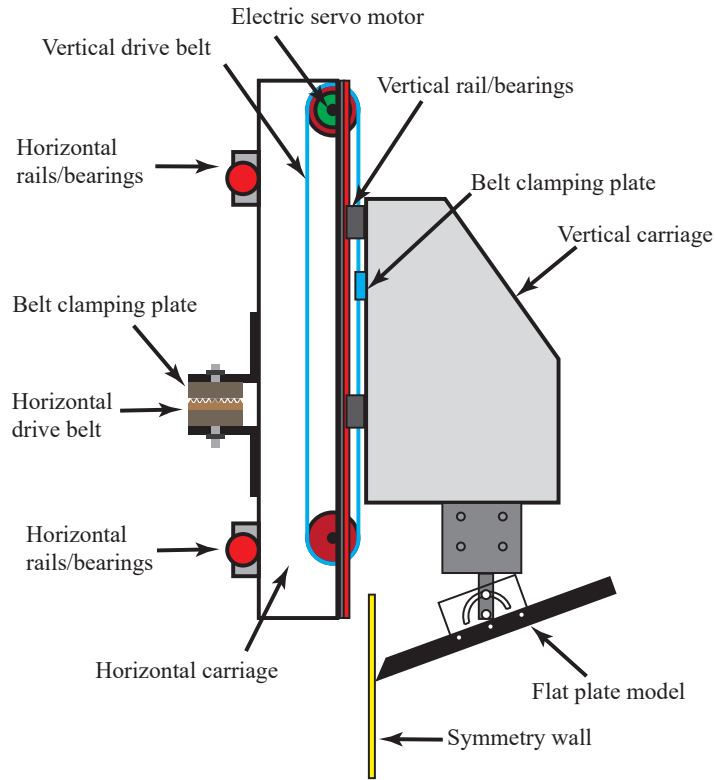


Figure 3.3: End view of two-axis high-speed carriage with flat plate model attached.

two longitudinal aluminum beams. This configuration makes the distance between the two mounting points on the longitudinal beam adjustable when the pitch angle is changed, see Figure 3.2.

A vertical “symmetry wall” that is 6.1 m long and 1.1 m tall is installed inside the towing tank. The symmetry wall is parallel to the horizontal rails of the carriage. Several rails are installed along the cross-stream direction at the bottom of the towing tank. These rails support the symmetry wall from its bottom and allow the symmetry wall to slide on them when the cross-stream position of the symmetry wall needs to be adjusted. The wall is connected into the side wall by 18 brackets distributed into 3 rows around the mean water level. These brackets

give the symmetry wall extra strength during slamming. In addition, these brackets have the mechanism to allow the symmetry wall to change its cross-stream position. During the current experiments, the position of the symmetry wall is adjusted so that it is aligned with the lower edge of the impact plate. The gap between the surface of the symmetry wall and the lower edge of the plate is less than 3 mm. The symmetry wall is made of a 1.27-cm polycarbonate plate bolted into a frame which is a combination of aluminum and stainless steel stiffeners. These stiffeners can ensure that the symmetry wall nearly does not deform during the slamming. The position of the symmetry wall is illustrated in Figure 3.1, 3.3.

3.2.2 Hydraulic Power System and Carriage Motion Control

In order to reach high impact velocity within a limited travel length, high acceleration is required to overcome the carriage system inertia when initiating and stopping the motion. Therefore, a large force is required. The horizontal motion of the carriage is driven by a hydraulic system supplied by MTS Systems Corp.. Hydraulic oil is driven by a 3000-Psi 60-horsepower hydraulic power unit and stored in three accumulators before an experimental run. The hydraulic oil is distributed to the two hydraulic motors driving the horizontal carriage by a manifold. The manifold includes a system of on-off valves and a 3-stage servo valve to regulate the oil flow into the two motors.

The horizontal position of the carriage is measured by an absolute encoder with 30-bit resolution and position sampling time less than 1 μ s. The encoder is

mounted rigidly on the pulley of one hydraulic motor and rotates at the same rate as the pulley. The feedback displacement signal from the encoder and the displacement command form the outer loop (position control) of the PID control scheme. The 3-stage servo valve in the manifold determines the flow rate of hydraulic oil flowing to the hydraulic motors. The flow direction and flow rate correspond to the direction and magnitude of the carriage horizontal velocity. The inner loop (velocity control) of the system controls the position of the spool in the servo valve, which determines the flow rate and therefore the velocity of the carriage. When an electric command from the controller is received by the valve, a flapper inside the valve blocks one side of a nozzle so that hydraulic fluid flows to one end of the spool and pushes the spool in one direction. Once the spool reaches the desired position where the spring force created by the off-center spool position and magnetic force created by command current balance each other, the spool stays at a stable position, which gives the motor constant rotation speed, leading to constant carriage horizontal velocity. The control scheme of the horizontal carriage is also shown in Figure 3.4.

A Temposonic position sensor (MTS Systems Corp.) is mounted on the horizontal carriage in order to measure the vertical position of the vertical carriage. Since the vertical motion system is an electric system, only one stage of control (position control) is needed. The servovalve in the hydraulic system, the servomotor in the electric system and the PID controller ensures the accuracy of motion.

Several defensive strategies are adopted to prevent overtravel of the horizontal carriage, as illustrated in Figure 3.5. The overtravel limits are set in the control program as the first stage of defense. In the second stage of defense, a spring loaded

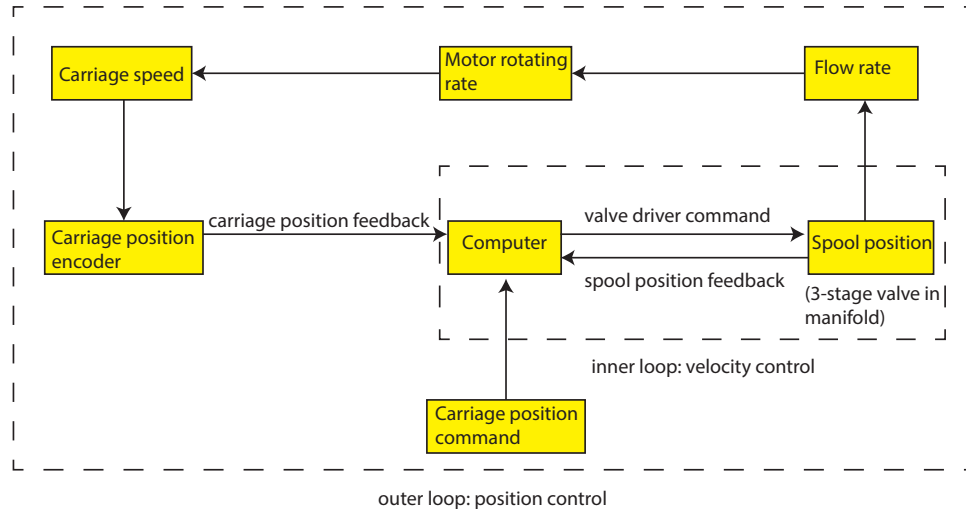


Figure 3.4: The control scheme of the horizontal carriage.

electric switch is installed on the horizontal carriage and in contact with a track along the tank within the range of horizontal motion. Once the carriage overtravels the track, the spring pushes off the switch which deenergizes a solenoid valve. The solenoid valve opens and dumps the flow in the pilot pressure line of the hydraulic manifold so that no pilot pressure is supplied to the servo valve and the flow to the hydraulic motors stops. In the third stage of defense, another two hydraulic valves are used on either end of the tank to stop the pilot pressure flow to the servovalve once the carriage overtravels and pushes on them. This valve includes an adjustable flow resistor and the value of this resistance determines how fast the motors stop. On the vertical carriage, besides the overtravel limit in the control program, two proximity switches are installed on either end of the travel range to stop the servomotor.

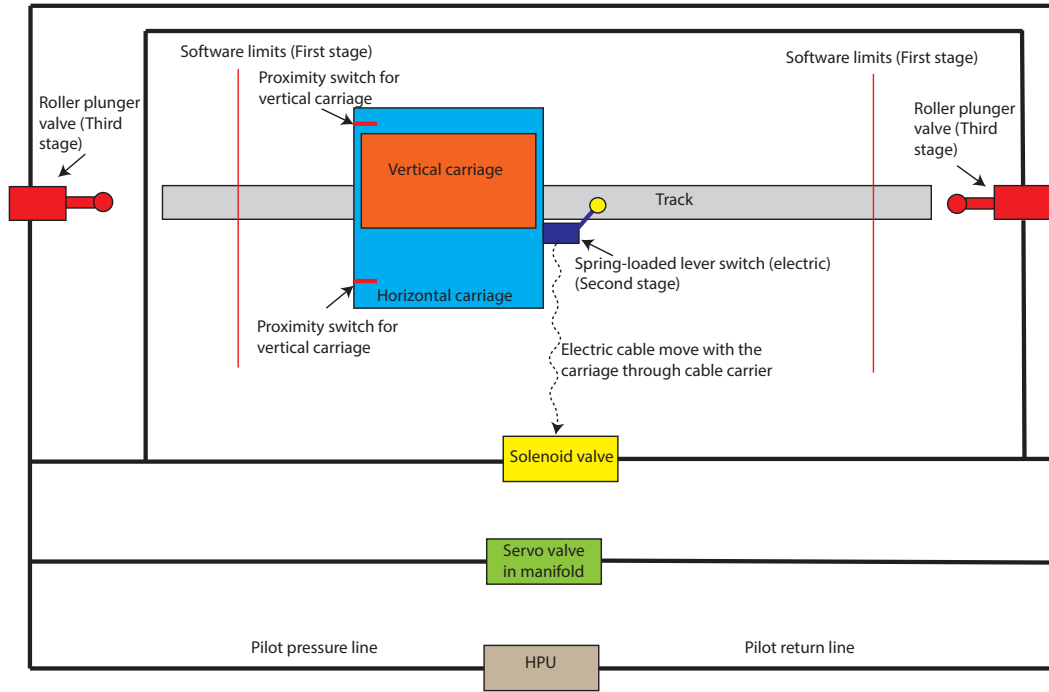


Figure 3.5: The scheme for the prevention of carriage over travel.

3.2.3 Synchronization and Triggering

The hydraulic motors which drive the horizontal carriage have a minimum smooth rotating speed below which the motors turn in steps. Therefore, the starting point of the horizontal motion has uncertainty within about 3 cm. In order to achieve highly repeatable motion in laboratory spatial coordinate system, a laser trigger system is used to initiate the vertical motion when the horizontal carriage reaches constant velocity. In the trigger system, a HeNe laser with 1 mW continuous power output shoots a laser beam across the towing tank at a position where the horizontal carriage has reached a constant velocity. A light detector is mounted at the other side of the towing tank to receive the laser light, which makes the detector

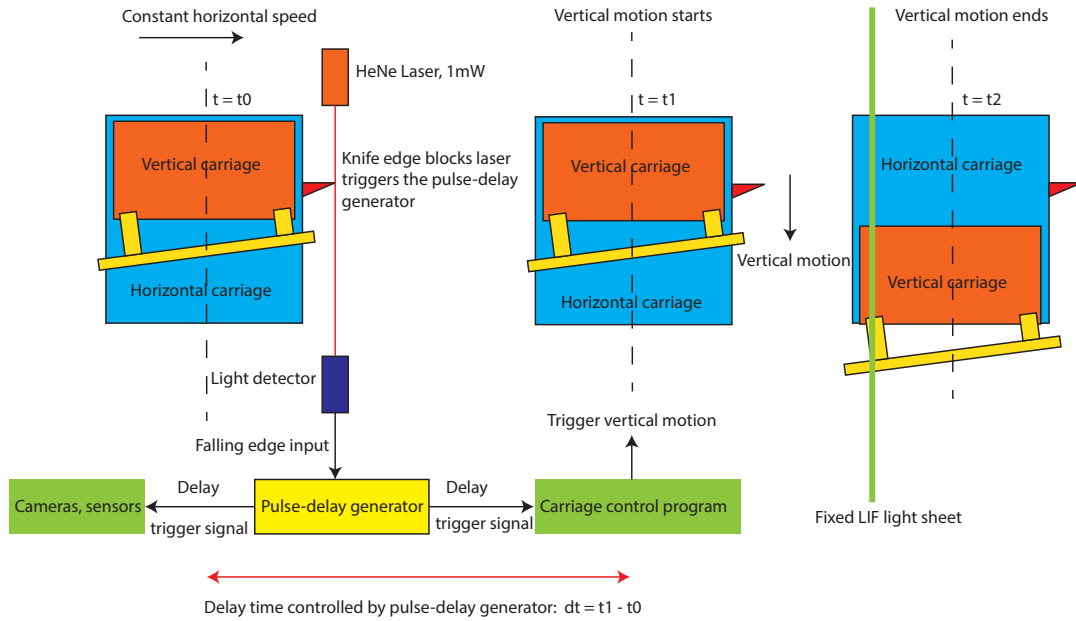


Figure 3.6: The scheme for synchronization of the measurement system with the carriage motion.

generate a 5 V output. A knife edge mounted on the carriage blocks the laser beam when the horizontal carriage travels by the laser beam. At the same moment, the output of the detector drops from 5 V to 0 V. The falling edge of the voltage signal is detected by a pulse-delay generator, which produces a TTL signal to initiate the vertical carriage motion. The delay time between the trigger event and the starting moment of the vertical motion can be adjusted so that different horizontal carriage positions can be achieved in a controllable manner when the vertical carriage is at the same height, for example the height when the trailing edge of the plate first reaches the undisturbed water surface. The spatial coordinates of the carriage at the same moment after the trigger is highly consistent from run to run (when the vertical carriage is at the same height, the run-to-run variation of horizontal carriage

position is on the order of 1 mm). The synchronization scheme is illustrated in Figure 3.6.

3.2.4 Spray Measurements: Laser Induced Fluorescence

The water surface profiles are measured with a laser induced fluorescent technique. Similar to the setup of the wave impact experiments described in §2.2.2.2, a set of optics are mounted on the ceiling above the tank to create a thin laser sheet in the vertical plane perpendicular to the path of the horizontal motion of the carriage. The orientation of the laser sheet is shown in Figure 3.7.

By using two convex lenses, The light sheet is focused at a line which is inclined relative to the horizontal plane. The inclined angle is similar to the angle between the spray sheet and the mean water level. Therefore, the surface profile of the entire spray sheet stays as a sharp boundary in LIF images. Two Phantom V641 cameras and one Phantom V640 camera (Vision Research Inc.) are mounted at the upstream side of the laser sheet (the end of the tank where the carriage starts its horizontal motion), see Figure 3.7. The cameras are tilted from the horizontal plane by about 15° . Two of the cameras with smaller frame rate and larger resolution are used to measure the surface profiles of the Type II spray. The third camera with high frame rate and smaller image size is used to measure the velocity of the droplets in the Type I spray. The definition of Type I and Type II spray will be introduced in §3.3.1.2. The water is mixed with fluorescent dye at a concentration of about 5 ppm so that the profile of the intersection of the laser light sheet and the

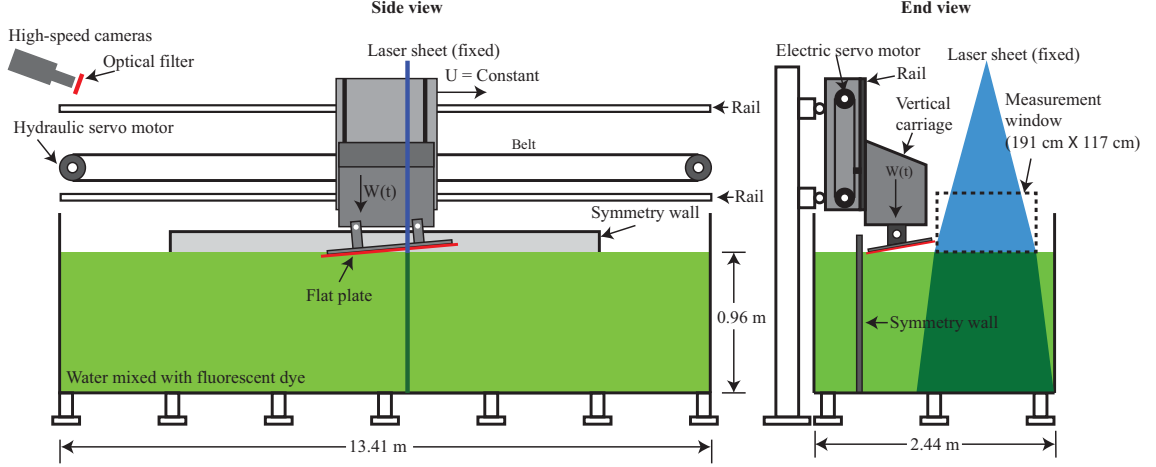


Figure 3.7: The schematic of the measurements of the spray by laser induced fluorescence technique.

instantaneous water surface can be captured by cameras. Similar to the wave impact experiments, optical filters are installed in front of the camera lenses. During the experiments, the light sheet stays at the same streamwise position. In the oblique impact experiments, the plate impacts the water surface with both horizontal and vertical motion. The measurement plane relative to the impact plate is varied by varying the delay time between the trigger event and the starting time of the vertical motion by adjusting the pulse-delay generator. Therefore, the profiles of the spray can be measured at cross-stream planes with different streamwise coordinates at the moment when, say, the trailing edge of the plate first touches the undisturbed water surface. As a result, the temporal evolution of the three-dimensional geometry of the spray can be reconstructed.

Similar to the wave impact experiments, a calibration board is used for correcting the distortions in the LIF images. The LIF images are processed using the same scheme described in §2.2.2.2.

3.3 Results and Discussion

In this section, two types of impact will be presented. In the first type of impact, the horizontal carriage is held stationary and only the vertical carriage is in motion. In these experiments, the impact plate has a deadrise (roll) angle of $\beta = 10^\circ$ and a pitch angle of $\gamma = 0^\circ$. This type of impact is called “vertical impact”. In the second type of impact, the horizontal carriage accelerates to a constant velocity and then the vertical carriage starts its vertical motion. In this type of experiments, plate has a roll angle of $\beta = 10^\circ$ and a pitch angle of $\gamma = 5^\circ$. This type of impact is called “oblique impact”. The vertical impact case is discussed in detail below in §3.3.1 and preliminary results for the oblique impact case are presented in §3.3.2.

3.3.1 Vertical Impact

In this subsection, vertical impact will be explored. The vertical motions used in this set of experiments will be introduced in §3.3.1.1 and the general behavior of the spray generated during vertical impact will be presented in §3.3.1.2. Based on the observations, the spray can be categorized into two types. The first type of spray will be introduced in §3.3.1.3. In the subsequent subsections §3.3.1.4, §3.3.1.5, §3.3.1.6, the various features of the second type of spray will be explored.

3.3.1.1 Vertical Motion

To generate the motion of the vertical carriage, an acceleration vs time curve is first created. The accelerations for the accelerating and decelerating periods are

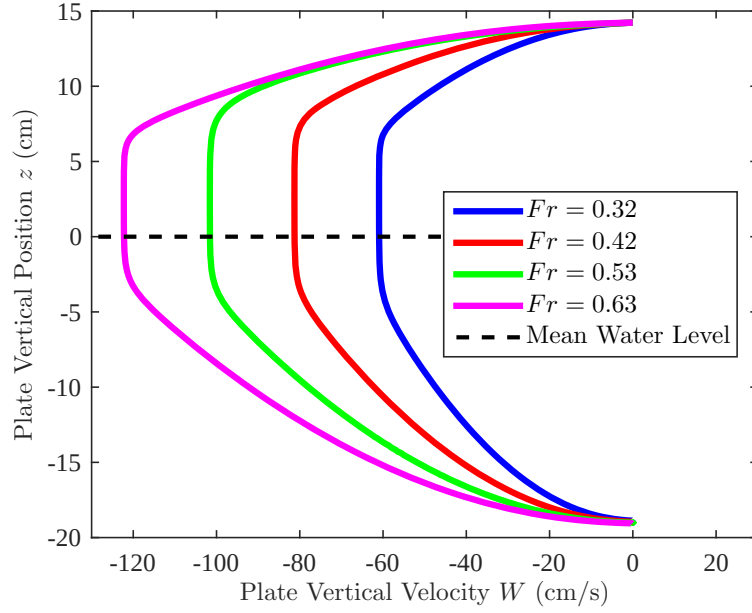


Figure 3.8: The velocity of the vertical carriage vs the position of the lowest point on the impact plate, which is called the leading edge. The mean water level is at $z = 0$.

a positive and negative constant for most of the period, respectively. The starting and ending portions of the two acceleration periods were smoothed with a hyperbolic tangent function to avoid sudden changes in the temporal derivative of the acceleration. The resulting acceleration vs time function was then integrated twice to get the position vs time functions which were used as the input to the control system. The vertical motion is designed in a way such that the velocity accelerates to a constant, W_0 , before the leading edge of the plate touches the still water surface and then starts to decelerate once the leading edge touches water surface, as shown in Figure 3.8. Since at the moment when the leading edge touches the water surface, the deceleration is nearly zero and starts to increase gradually following

a hyperbolic tangent function, the decrease in velocity during this transitional period is small and not easily visible in Figure 3.8. The experiments were performed with four different vertical motions. If we define the Froude number based on the initial impact velocity W_0 and the width of the plate B , $Fr = W_0/\sqrt{gB}$, the four experimental condition can be represented by $Fr = 0.32, 0.42, 0.53, 0.63$, which corresponds to $W_0 = 0.61, 0.81, 1.01, 1.22$ m/s, respectively.

3.3.1.2 General Behavior of the Spray

A sequence of images from the high-speed LIF movie for $Fr = 0.42$ are shown in Figure 3.9. The field of view is roughly $106\text{ cm} \times 68\text{ cm}$. The time interval between each image is 0.1 s. The trailing (high) edge of the plate is at the left of the image. Figure 3.9(a) shows a moment shortly after the trailing edge of the plate touches the local water surface. A cloud of droplets and ligaments moves with high horizontal velocity across the tank. This spray is defined as Type I spray, which is originated from the leading (low) edge of the plate when it first impacts the water surface. Shortly after the leading edge enters the water surface (before Figure 3.9(a)), there is a rise of the local water level near the trailing edge of the plate, due to the water entry effect under the plate. Then, as the plate continues to move down, the trailing edge of the plate first touches the local water surface and produces the Type II spray as shown in Figure 3.9(a). A schematic diagram showing various features of the water surface profile for the Type II spray is given in Figure 3.10. The Type II spray consists of a thin continuous spray sheet of water that originates from a

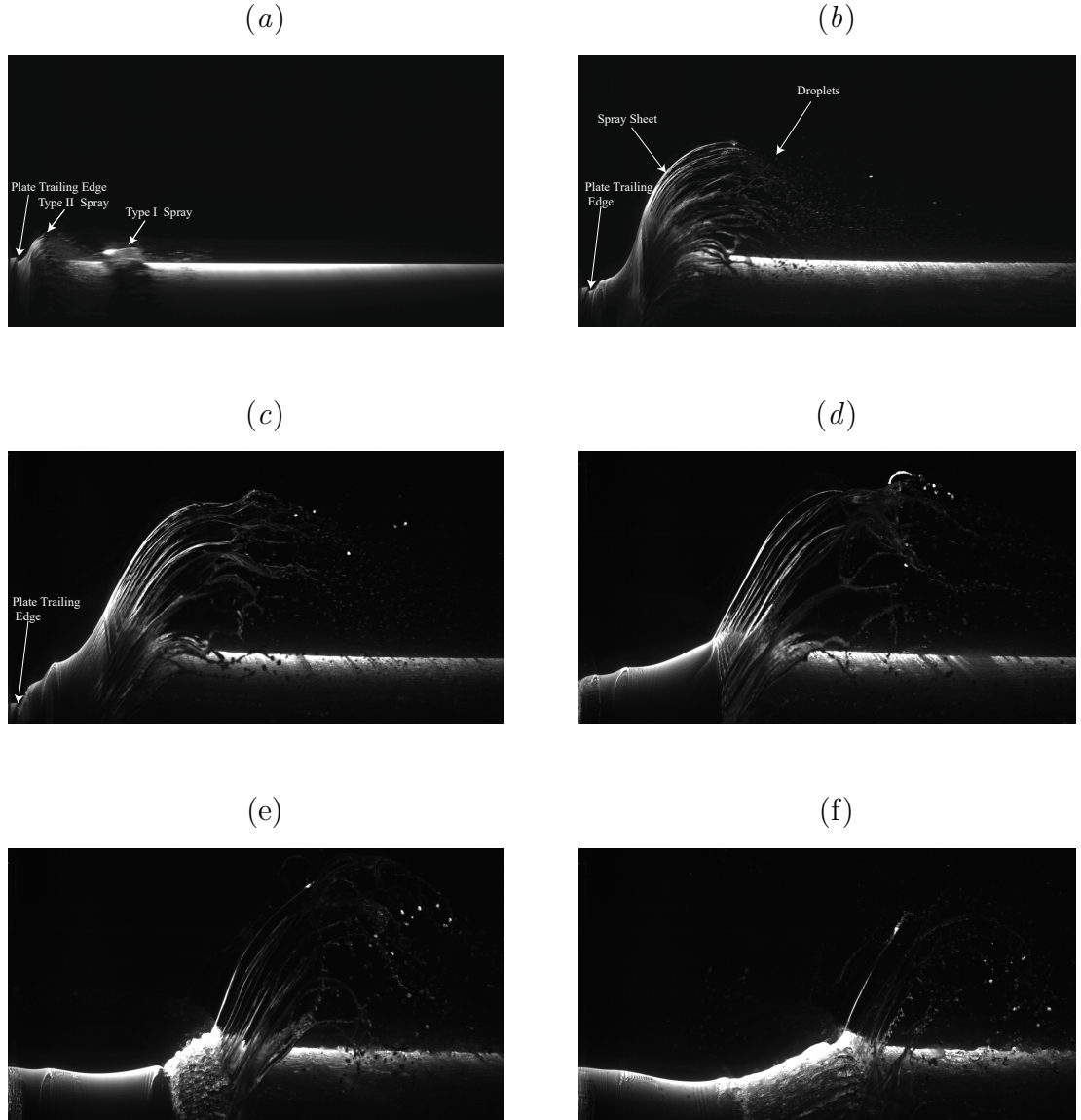


Figure 3.9: Sequence of LIF images of the spray formation for $Fr = 0.42$. The field of view is $106 \text{ cm} \times 68 \text{ cm}$. The time interval between successive images is 0.1 s . In the LIF images, the sharp boundary between the dark region and bright region represents the air-water interface. The trailing edge of the plate is located at the left side of the images. Type I spray, which consists of a cloud of droplets and ligaments, is shown in (a). Type II spray is a spray sheet originated from the spray root. Evolution of Type II spray is shown from (a) to (f).

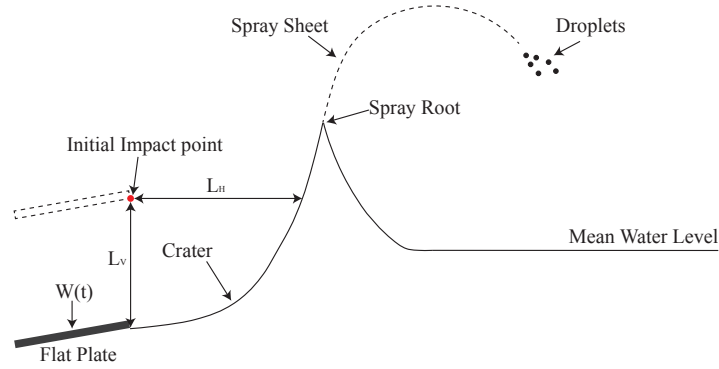


Figure 3.10: A schematic diagram showing various features of the free surface shape during plate impact. The initial impact point is the point where the trailing edge of the plate first touches the local water level. L_H and L_V are the horizontal and vertical distance from the initial impact point to the surface of crater, respectively. spray root point. The overall scale of the spray sheet at first grows in time. At the far end of the spray sheet, the sheet becomes unstable and breaks up into droplets, as shown in Figure 3.9(b)(c)(d). Eventually the spray sheet falls down under the effect of gravity and collapses on the free surface, forming a free surface turbulent splash zone, as shown in Figure 3.9(e)(f).

The surface profiles extracted from the high-speed LIF movies for four different Froude numbers are shown in Figure 3.13. The profiles are measured from the trailing edge of the plate to a point on the profile where the surface becomes ill defined due to breakup of the Type II spray sheet. The first profile is the surface profile just after the trailing edge of the plate impacts on the local water surface and the time interval between successive profiles is 7.5 ms. After the trailing edge

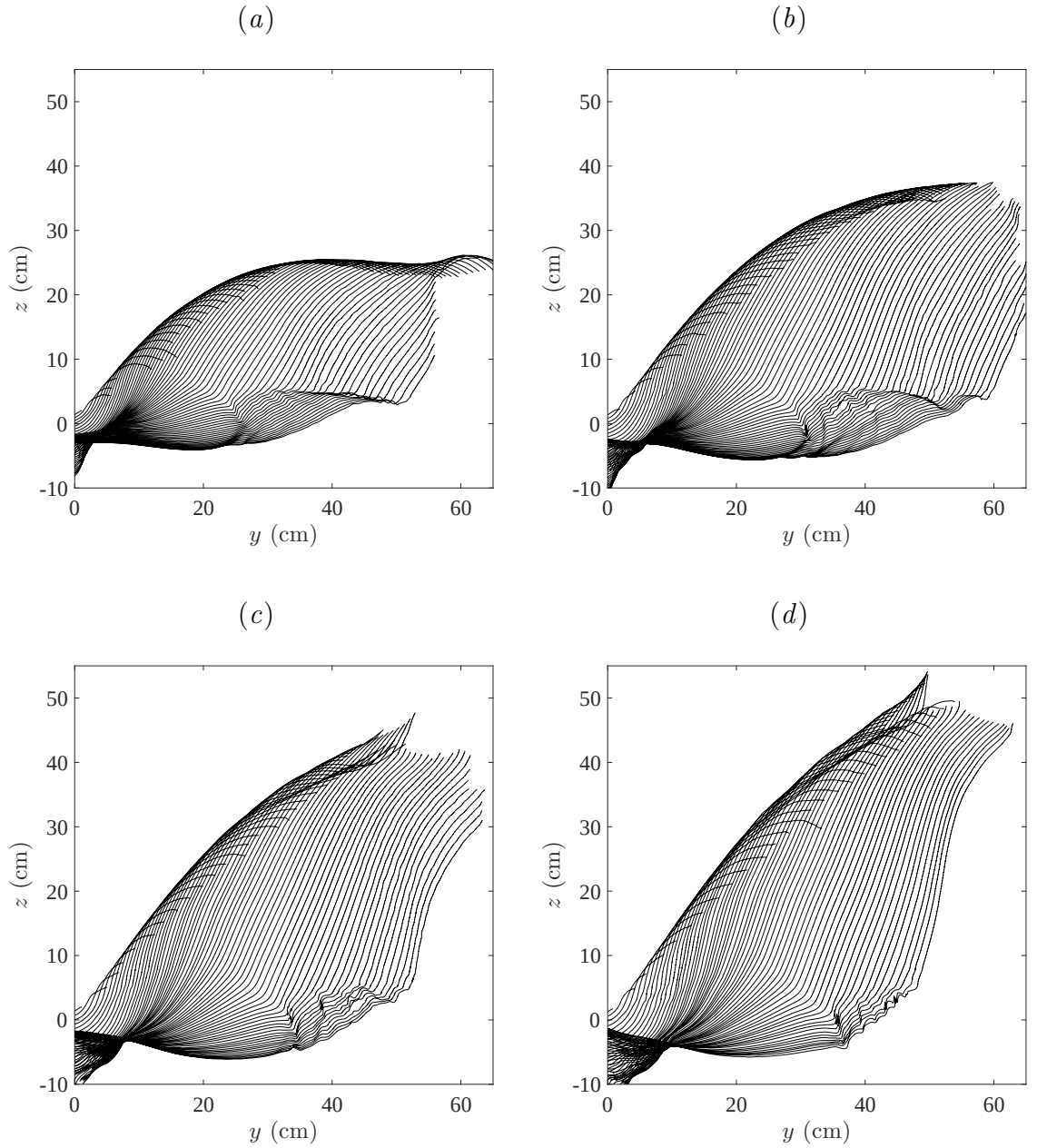


Figure 3.11: Surface profiles at different velocities. The profiles are plotted in a reference frame fixed with the laboratory. $z = 0$ is at the mean water level. $y = 0$ is at the trailing edge of the impact plate. The profile is plotted from the trailing edge of the plate to a point where the spray sheet is still well defined in the LIF images. From (a) to (d), the profiles are measured from $Fr = 0.32, 0.42, 0.53, 0.63$, respectively.

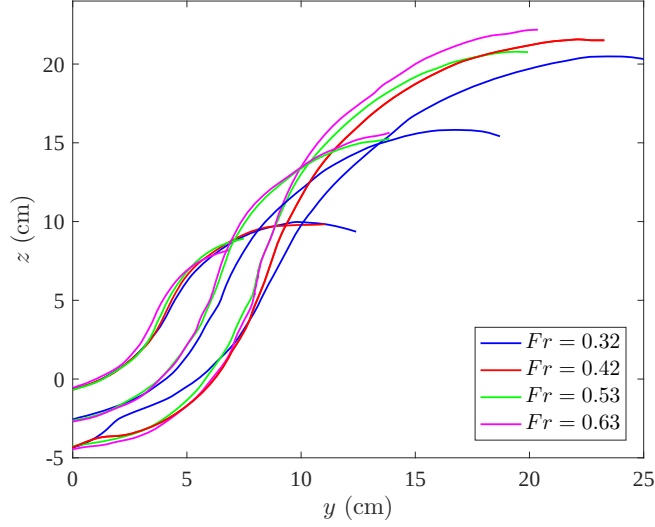


Figure 3.12: Surface profiles at different Fr at three plate penetration depths. At the three penetration depth, the trailing edge of the impact plate is at $z = -0.7$ cm, $z = -2.7$ cm and $z = -4.4$ cm, respectively. $z = 0$ is at the mean water level.

initially touches the local water surface, the crater deepens over time for all four Froude numbers. The spray sheets at different times are nearly parallel to each other with the spacing between successive profiles increases with time. The slope of the spray sheet increases with the Froude number. The maximum height the spray sheet reaches is higher with larger Froude numbers, probably because faster carriage motion at larger Froude numbers inputs more kinetic energy into the flow.

In order to compare the geometry of the profiles, the profiles at the same plate penetration depth for different Froude numbers are shown in Figure 3.12. Three different penetration depths are chosen. It is found that near the trailing edge of the plate, the profiles at different Froude number nearly collapse on each other, except for $Fr = 0.32$ at the deepest height, because at this height, the water surface at the crater forms a backward plunging breaker at $Fr = 0.32$. The profiles start

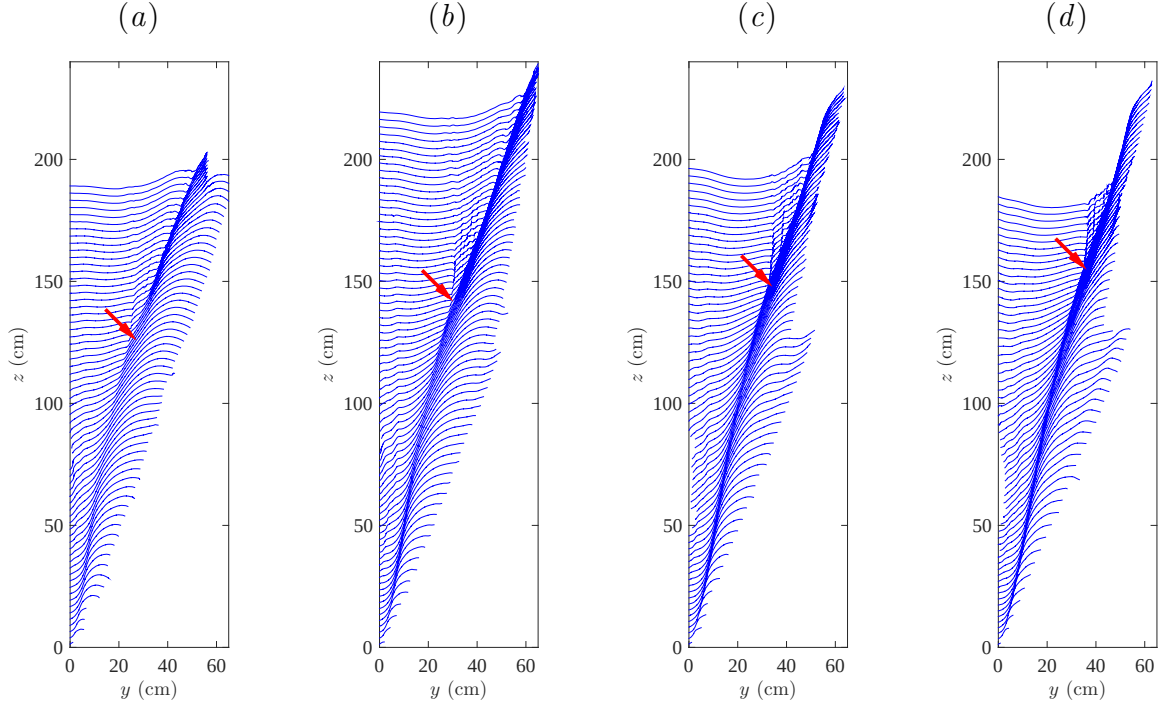


Figure 3.13: Surface profiles at different impact velocities. Each subsequent profile is shifted upward by 1.5 cm from the previous profile. The trailing edge of the plate is located at $y = 0$. From (a) to (d), the profiles are measured from $Fr = 0.32, 0.42, 0.53, 0.63$, respectively. The red arrow in each figure points to the spray root point of the frame when the turbulent splash zone starts to form.

to deviate from each other some distance y_{dev} away from the trailing edge of the impact plate. This point of deviation is different at different penetration depths. The larger the penetration depth, the further the deviation point is away from the trailing edge of the impact plate. For $y > y_{dev}$, the profiles at higher Froude number is steeper for all penetration depth. The larger the penetration depth, the larger the difference in steepness between cases with different Froude number.

As a set of water surface profiles for each Froude number is shown in Fig-

ure 3.13. In these plots, each profile is shifted upward by 1.5 cm from the pervious profile in the physical plane for clarity of the presentation. The profiles around the spray root form a region with high line density because of the high curvature of this portion on each profile. This region with high line density qualitatively shows the evolution of the horizontal position of the spray root. The trajectory of the spray root seems to be similar qualitatively for the four values of Fr . The free surface turbulent splash zone (seen to the left of the spray root at about 150 mm on the vertical axis) starts progressively earlier in time with decreasing Fr , which is consistent with the fact that the higher Fr cases generate larger spray, which takes a longer time to collapse.

An interesting measure of the spray is its envelope, defined here as the curve of the highest positions that the spray ever reaches at each cross-stream, y , location. This envelope is shown as the red line in Figure 3.14(a) where the set of profiles for the $Fr = 0.42$ case is shown in the laboratory reference frame. Figure 3.14(b) shows the envelopes for each of the four values of Fr . In the region close to the trailing edge of the plate, the envelopes have nearly the same slope for all Fr . At $y/B = 0.3$, the envelopes at different Fr start to deviate from each other while the slope starts to decrease as y/B increases for all four cases. The spray for higher Fr reaches a larger height.

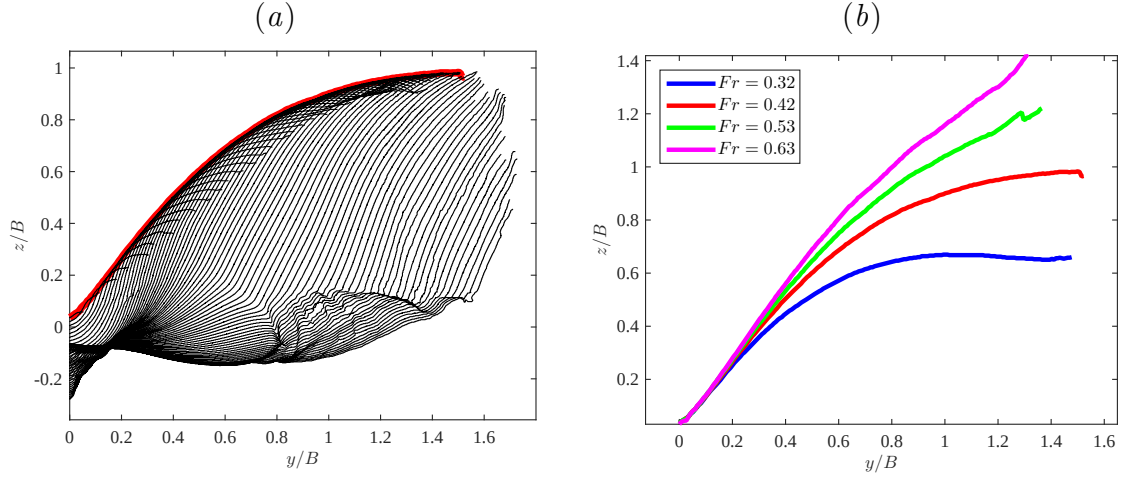


Figure 3.14: Envelopes of the profiles at different Froude number. (a) The envelope (red) of the profiles (black) at $Fr = 0.42$. The Envelope is a line that consists of the highest points the spray ever reaches. (b) Envelopes of profiles at $Fr = 0.32, 0.42, 0.53, 0.63$.

3.3.1.3 Behavior of the Droplets in Type I Spray

The velocity (v_d) of the droplets in the Type I spray were measured from the LIF image sequences and the resulting data for each of the four values of Fr are plotted in Figure 3.16(a). The velocities of the droplets are computed based on the change in position of individual droplets from frame to frame in the movies as the droplets move within the plane of the light sheet. A given data point is the velocity of a droplet at a given cross-stream position (y). The spread in the droplet velocities for each Froude number is the result of the difficulty in determining the position of the droplets and the numerical error when taking derivatives of position vs time data, as well as the fact that the droplets slow down as they move away from the plate. The solid line is a linear fit to the averaged velocity of the droplets

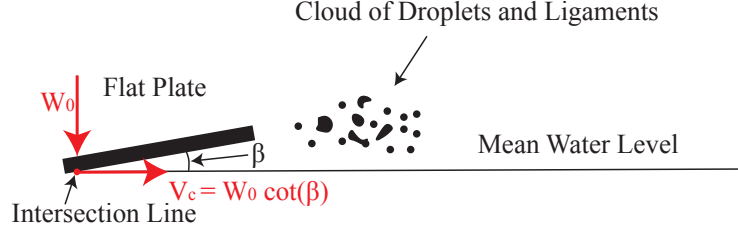


Figure 3.15: The definition sketch for the determination of V_c .

at each value of Fr . The dashed line in the plot is the velocity $V_c (= W_0 \cot \beta)$ of the geometric intersection point of the plane of the plate and a fixed horizontal line as the plate moves downward at constant speed W_0 , see Figure 3.16(b). As can be seen in Figure 3.16(a), the droplet velocity v_d increases as the Fr increases and v_d is more than twice the value of the horizontal velocity of the intersection line at the same Fr . The difference between v_d and the horizontal velocity of the geometrical intersection line also increases with Fr . A plot of droplet velocity versus y/B for $Fr = 0.63$ is given in Figure 3.16(c). The data shows quantitatively the slow down of v_d with increasing y , probably due to the effect of the drag of the air on the droplets.

3.3.1.4 Behavior of the Spray Root in Type II Spray

The spray root point is defined as the point where the spray sheet originates, as illustrated in Figure 3.19. In three dimensional space, the spray root is a straight line perpendicular to the plane of the light sheet. Because the cameras capture some features of the water surface shape between the light sheet plane and the camera sensor, the spray root appears as a straight line in the LIF images. For image points

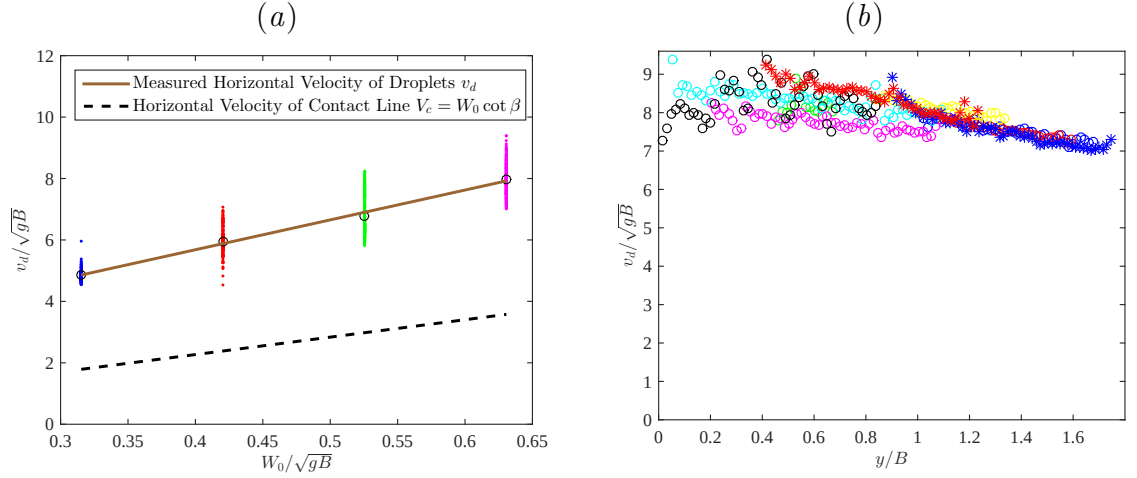


Figure 3.16: Velocity of the droplets in the Type I spray. (a) Velocity of the droplets vs Froude number ($Fr = W_0/\sqrt{gB}$). The dots with the same color represent the velocities of different individual droplets at different cross-stream positions at the same Froude number. The dashed line is the velocity $V_c(= W_0 \cot \beta)$ of the geometrical intersection point of the plate with the mean water level vs Froude number. The solid straight line is a least squares fit to the average velocity of the droplets at each Froude number. (b) The velocity of the droplets vs cross-stream position at $Fr = 0.63$.

below the spray root line, the camera sees through the air-water interface and into the wave below. For points above the spray root line, the camera sees through the spray sheet into the air underneath it. These effects result in a high image intensity gradient at the spray root line; therefore, allowing the spray root point to be detected in the plane of the light sheet. This detection process is shown in Figure 3.17(a) where the intersection of the surface profile and the extension of the detected spray root line gives the coordinate of the spray root point in the light sheet. The

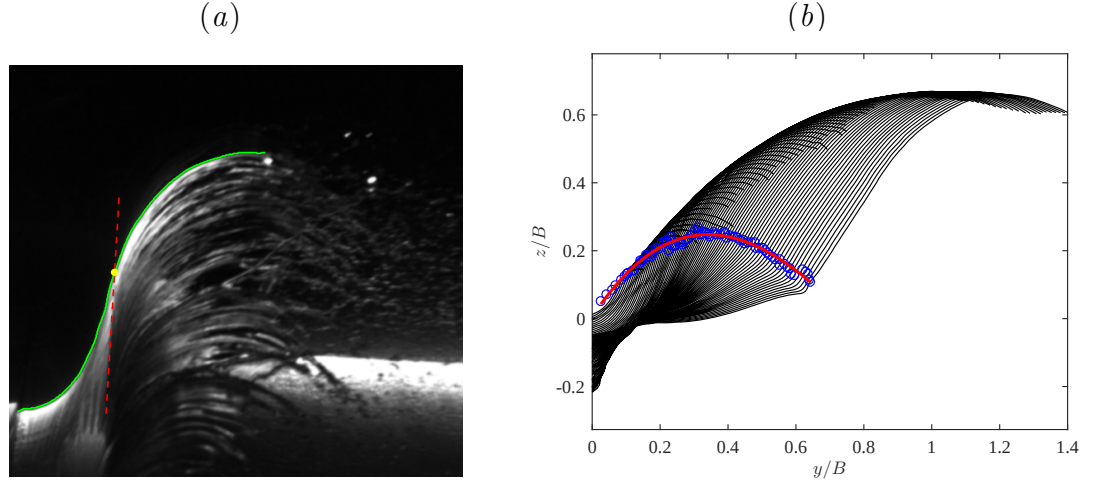


Figure 3.17: Definition of the spray root point. (a) Detection of the spray root point from the LIF image. The green solid line is the profile of the spray sheet. The red dashed line is the spray root line while the yellow dot is the spray root point in the plane of the light sheet. (b) Detected spray root points (blue dots) for each spray profile, $Fr = 0.42$. The red solid line is a 3^{rd} polynomial fit to the detected spray root points.

positions of the spray root point are plotted on top of the spray profiles for the $Fr = 0.32$ case in Figure 3.17(b), and the spray root trajectory, as determined by fitting a 3rd order polynomial to the position data, is given as well. The trajectories of the spray root point for the four values of Fr are shown in Figure 3.18. At early times, the trajectories are quite similar. At later times, roughly when $y/B > 0.2$, the trajectories of the spray root diverge from one another; the maximum height and the y/B position of this maximum increase with increasing Fr .

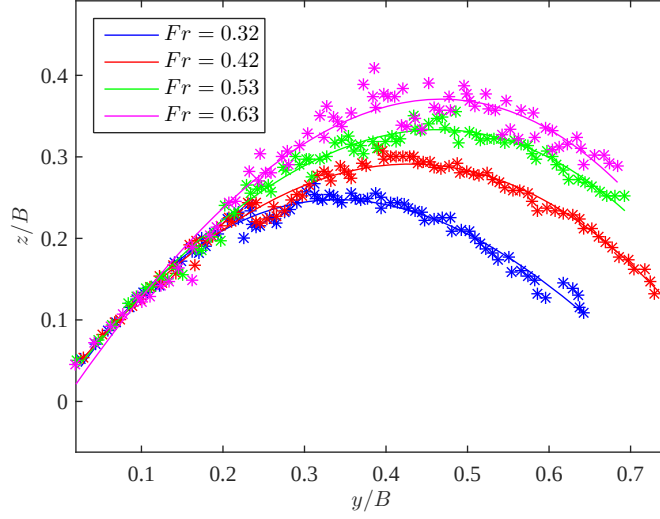


Figure 3.18: The trajectory of the spray root point for each Froude number. The asterisks are the spray root points detected from the LIF images and the solid lines are the 3rd polynomial fits to these points.

3.3.1.5 Behavior of the Crater in Type II Spray

As depicted in Figure 3.10, starting from the trailing edge of the plate, a crater is formed and grows as the plate keeps moving downward. One end of the crater is in contact with the trailing edge of the plate while the other end is connected to the spray root point. Below the spray root point, as the crater grows in size, the shape of the surface is analogous to a propagating wave crest. The intersection of the trailing edge of the plate and the local water surface when they first meet is defined as the initial impact point. If the horizontal distance from the initial impact point to the crater surface is taken as L_H and the vertical distance from the initial impact point to the crater surface is taken as L_V , the aspect ratio of the crater can be computed as L_H/L_V . Values of the crater aspect ratio vs time for the

four values of Fr are shown in Figure 3.19. For all four Fr cases, the aspect ratio decreases initially and reaches a nearly constant value after about $t = 0.04$ s. The initial aspect ratio decreases monotonically with increasing Fr , but, in all cases, the aspect ratio is always larger than one.

In order to explore the expanding rate of the crater in different directions, a length scale $L_c(t, \theta)$ can be defined as the distance from the initial impact point to the surface profile at t along the direction which is at angle θ from the negative z -axis. The definition of $L_c(t, \theta)$ is shown in Figure 3.20. This examination is performed for all four Froude number before the time when a breaker forms on the crater and starts to plunge backward.

The time history of the length scale $L_c(t, \theta)$ is explored at 10 different directions between the negative z -axis and the positive y -axis, as shown in Figure 3.21. It is found that the expansion of L_c over time can be well represented by power law. If the expansion rate is defined as the exponent of the power law, the expansion rate seems to be very similar for all values of θ and ranges from 0.85 to 0.95. The expansion rate is not found to be significantly different at different Froude numbers.

The similar expansion rates show that the temporal evolution of the crater might be self-similar. At $\theta = 0^\circ$, the surface of the crater is constrained by the prescribed motion of the trailing edge of the plate. In a reference frame moving with the impact plate, the surface of the crater at $\theta = 0^\circ$ is a fixed point, defined as the origin. The surface profiles of the crater in this moving reference frame are plotted in Figure 3.22(a). If both the vertical and cross-stream coordinates of the profiles in this moving reference frame are scaled by a power law of time, the surface

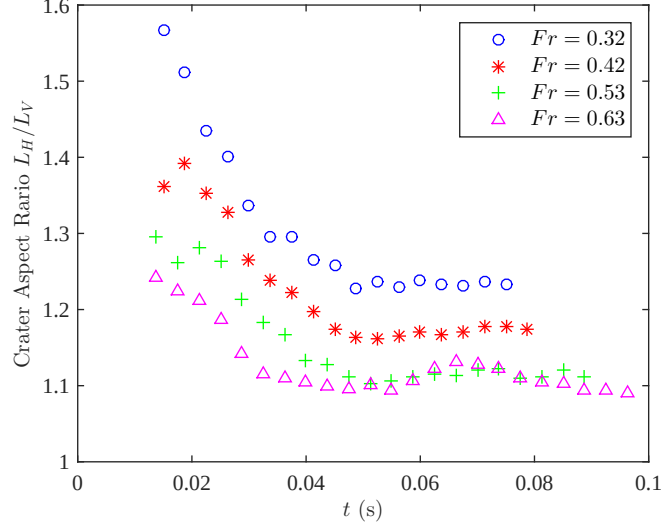


Figure 3.19: The aspect ratio of the crater (L_H/L_V) vs time for the four values of Fr . $t = 0$ is the time of the initial impact of the trailing edge.

profiles collapse favorably, as shown in Figure 3.22(b). The exponent to collapse these profiles is about $2/3$.

3.3.1.6 Behavior of the Spray Sheet in Type II Spray

The spray sheet above the spray root point is a thin layer of water. The pressure at the upper and lower surfaces of the spray sheet is constant atmospheric pressure if the motion of the air is ignored. The thickness of the spray sheet is very small and its curvature is small, so there should be little pressure gradient along the sheet. The motion of the fluid particles in the spray sheet is thus dominated by the gravitational force. Therefore, the motion of fluid particles in the spray sheet is analogous to the projectile motion of fluid particles ejected from the spray root with given velocity under the effect of gravity. The spray sheet at one instant consists of fluid particles ejected from the spray root from all previous times. With

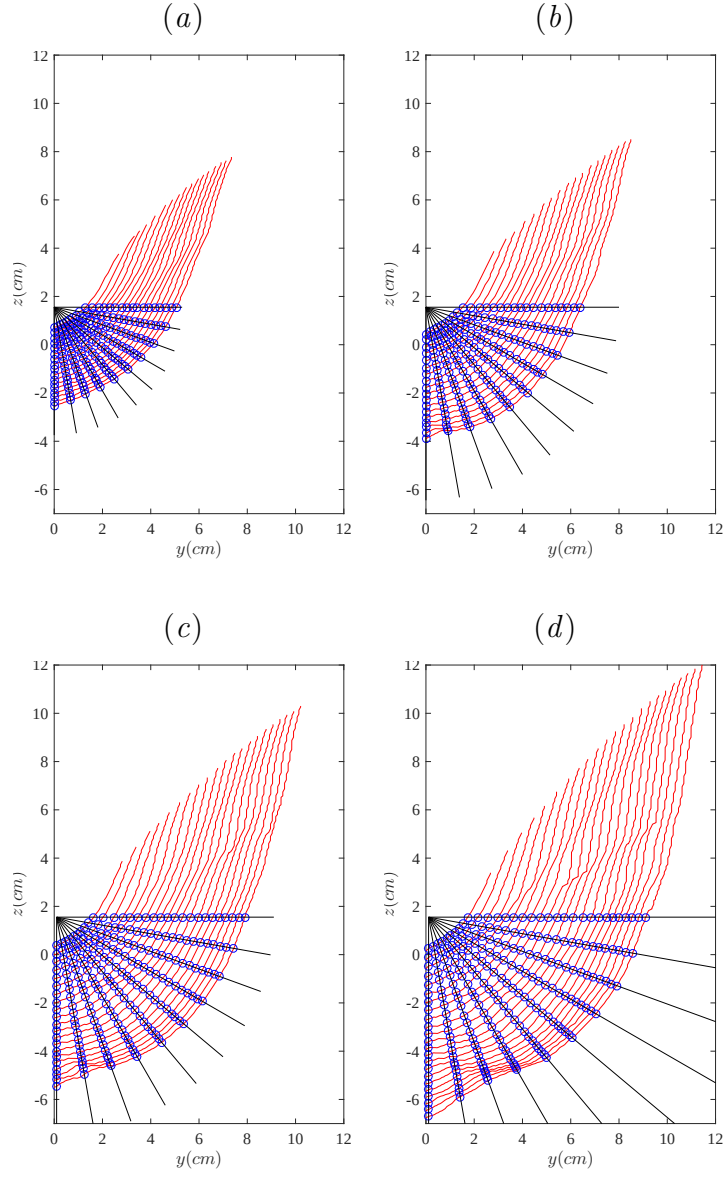


Figure 3.20: The definition of $L_c(t, \theta)$ at different Fr . (a)(b)(c)(d) represent $Fr = 0.32, 0.42, 0.53, 0.63$, respectively. Each circle is the intersection of the surface profile at one particular time and the ray originated from initial impact point at angle θ from the negative z -axis. The length scale $L_c(t, \theta)$ is defined as the distance from the initial impact point to these intersection points at different t and θ .

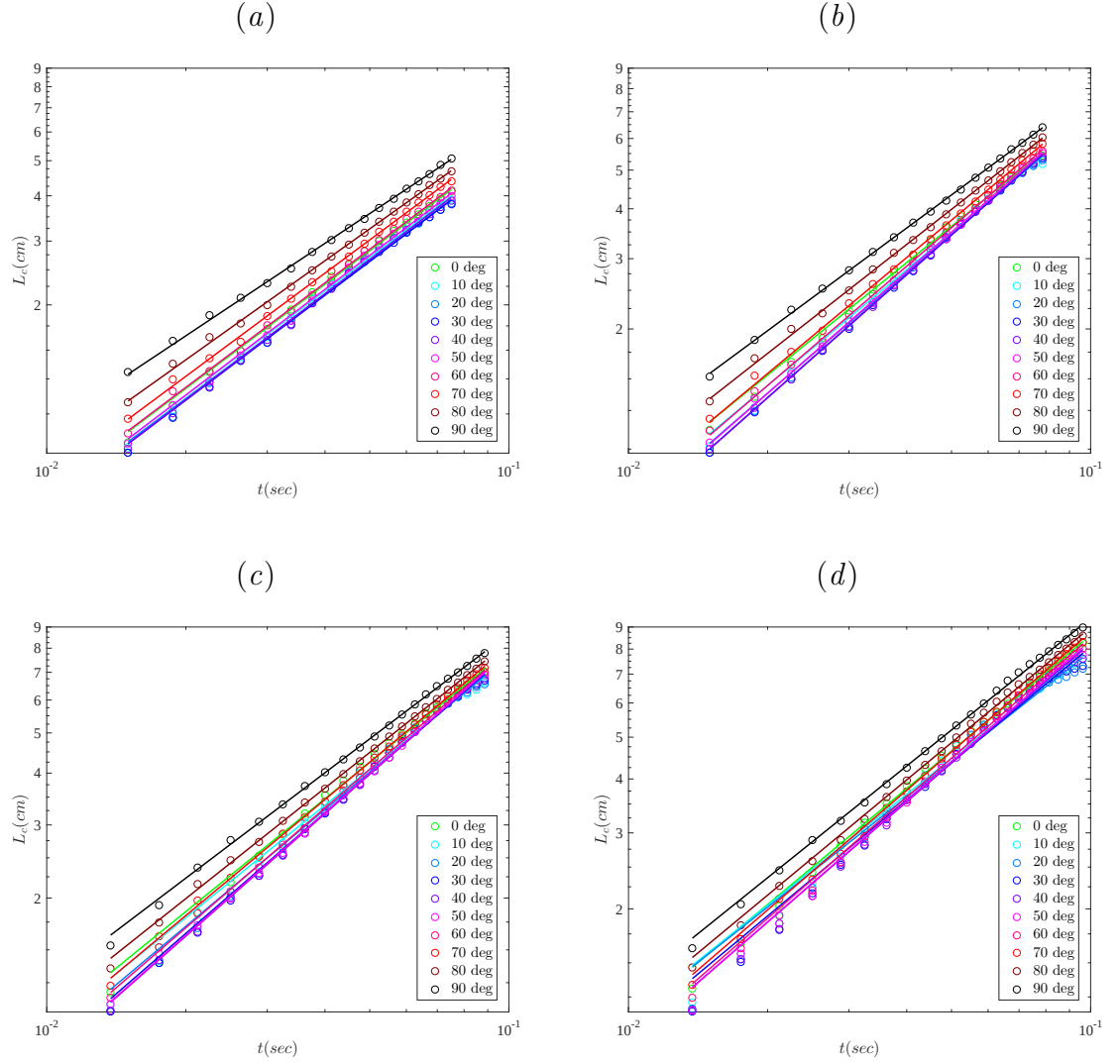


Figure 3.21: L_c vs t at different angle and Fr . (a)(b)(c)(d) represent $Fr = 0.32$, 0.42, 0.53, 0.63, respectively. The figure is plotted in logarithmic scale.

this concept, the streak lines of these fluid particles at one instant approximately represents the surface profile of the spray sheet at the same instant. The position of the spray root and the ejection velocity vector (including ejection speed and angle) of the fluid particles are both functions of time. The motion of equation for the

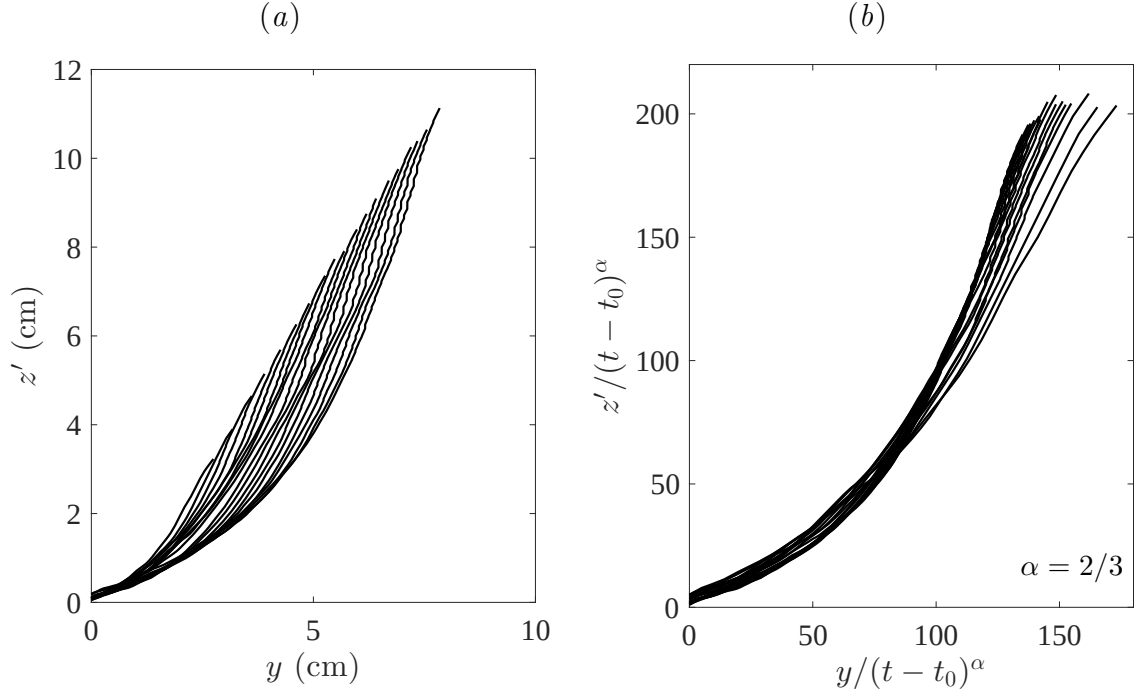


Figure 3.22: (a) Unscaled surface profiles of the crater in a reference frame moving with the trailing edge of the plate. (b) Surface profiles of the crater scaled by $(t-t_0)^{2/3}$ in a reference frame moving with the trailing edge of the plate. $Fr = 0.32$ for both (a) and (b).

fluid particles can be written in the following form.

$$y(t, 0 < t_0 < t) = y_0(t_0) + V_0(t_0) \cos [\theta_0(t_0)](t - t_0) \quad (3.1)$$

$$z(t, 0 < t_0 < t) = z_0(t_0) + V_0(t_0) \sin [\theta_0(t_0)](t - t_0) - \frac{1}{2}g(t - t_0)^2 \quad (3.2)$$

Where $y(t, 0 < t_0 < t)$ and $z(t, 0 < t_0 < t)$ are the current (at time t) cross-stream and vertical coordinates of the streak line consisting of the fluid particles which were ejected from the spray root at all previous times t_0 , $0 < t_0 < t$. $V_0(t_0)$ and $\theta_0(t_0)$ are the magnitude and angle (measured from the positive y -axis) of the ejection velocity at time t_0 , respectively, and $y_0(t_0)$ and $z_0(t_0)$ are the cross-stream

and vertical coordinates of the spray root point at time t_0 . In this set of equations, if the coordinates of the streak line $(y(t, 0 < t_0 < t), z(t, 0 < t_0 < t))$ at any instant t and the coordinates of the spray root $(y_0(t_0), z_0(t_0))$ at any previous time $t_0 < t$ are known values, the ejection speed $V_0(t_0)$ and angle $\theta(t_0)$ at all $t_0 < t$ can be solved. Since the coordinates of the streak line at any instant t can be represented by the coordinates of the measured surface profile of the spray sheet at this instant, and the coordinates of the spray root $y_0(t_0)$ and $z_0(t_0)$ can be obtained from experiments by the method introduced in §3.3.1.4, the ejection speed and angle at the spray root at any instant can be found using a minimization algorithm, based on the error between the predicted and measured spray sheet trajectory.

In order to reduce the number of parameters to be optimized, the ejection speed is assumed to be a 2^{rd} polynomial function of t_0 and ejection angle is assumed to be a linear function of t_0 , as shown below

$$V_0 = C_2 t_0^2 + C_1 t_0 + C_0 \quad (3.3)$$

$$\theta_0 = C_4 t_0 + C_3 \quad (3.4)$$

The optimum parameter set $C_i (i = 0, \dots, 4)$ are determined by minimizing the residual of Equation (3.1)(3.2). The simulated spray profiles for the four Fr are shown in Figure 3.23. The simulated spray sheet profiles agree with the experiments favorably. The simulation provides an estimation to the ejection speed and ejection angle, as shown in Figure 3.24. From the simulation, we found that higher Fr results in higher ejection speeds and larger ejection angles. Both the ejection speed and ejection angle decreases with time.

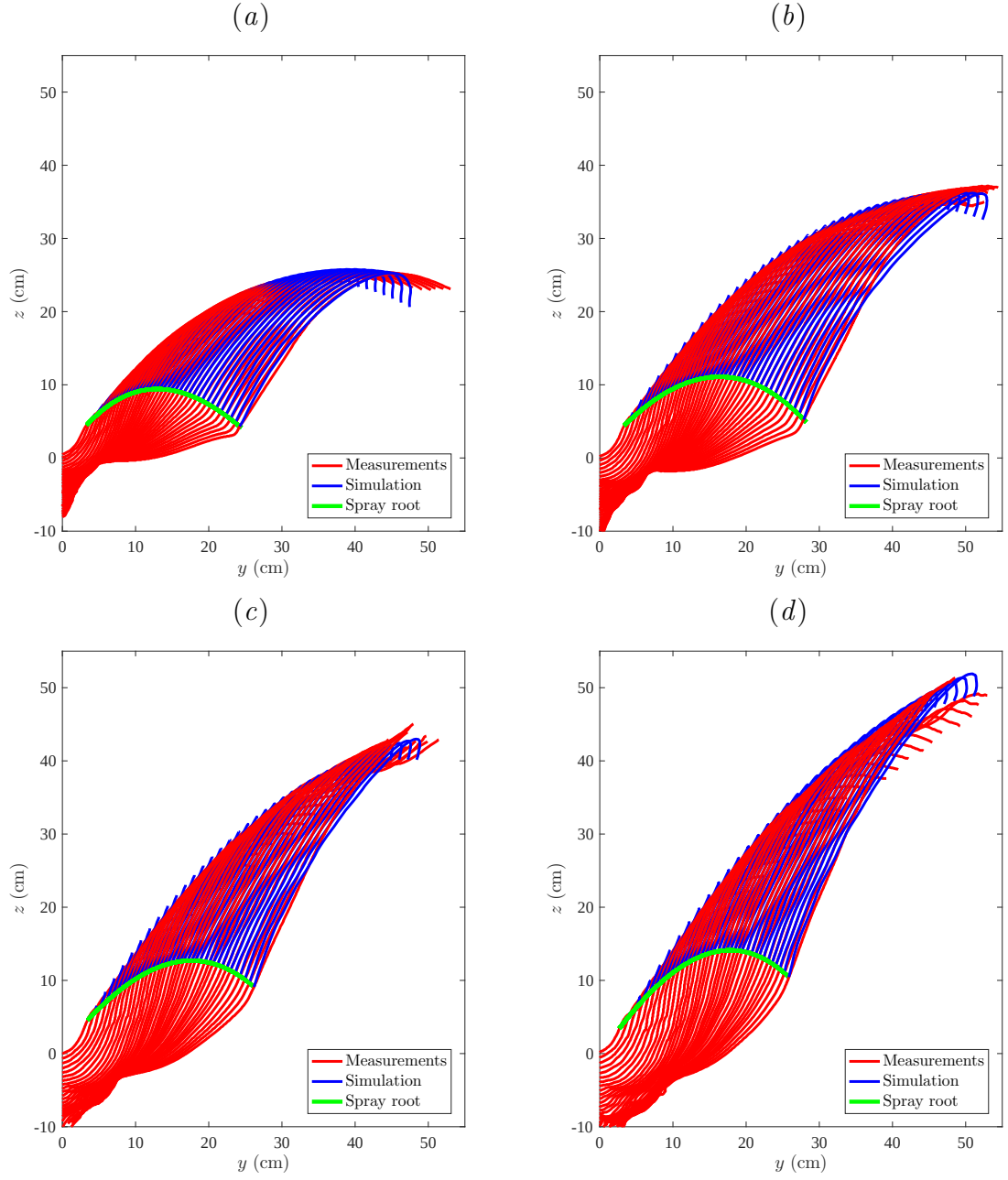


Figure 3.23: The comparison of the simulated spray sheet profiles with measurements. (a)(b)(c)(d) represent $Fr = 0.32, 0.42, 0.53, 0.63$, respectively. The values for the set of parameters $(C_0, C_1, C_2, C_3, C_4)$ in Equation (3.3) is $(250, 100, -946, 0.9, -1.2)$, $(290, 100, -1250, 0.99, -1.1)$, $(310, 140, -1673, 1.02, -0.8)$, $(350, 140, -2302, 1.03, -0.5)$ for (a)(b)(c)(d), respectively.

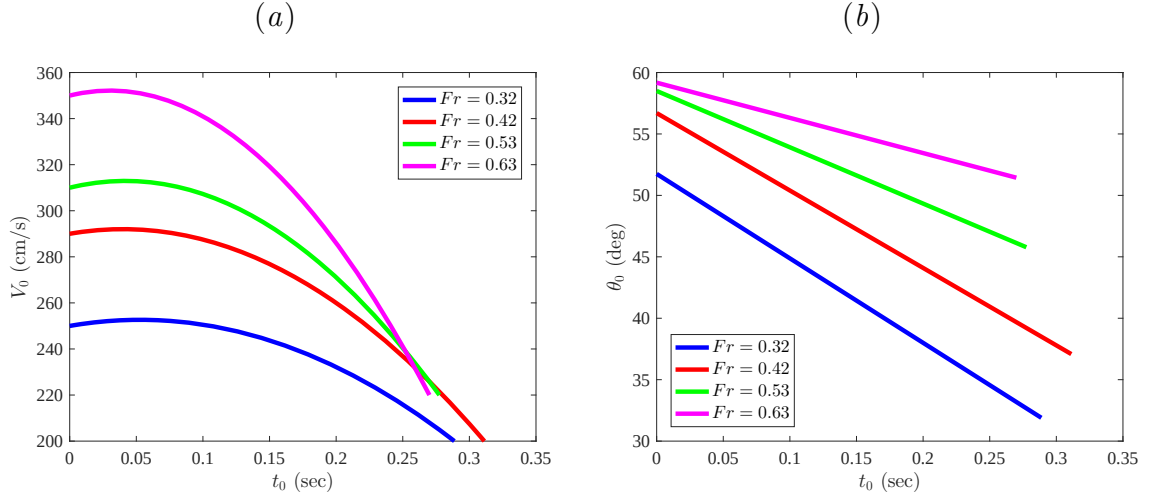


Figure 3.24: The ejection speed and ejection angle vs time at different Fr by simulation. (a)(b)(c)(d) represent $Fr = 0.32, 0.42, 0.53, 0.63$, respectively.

3.3.2 Oblique Impact

This subsection presents a typical experimental measurement of the spray formation during the oblique impact. The primary goal of this subsection is to show the successful outcome of the reconstruction of the three dimensional geometry of the spray surface. In the current oblique impact experiments, the vertical carriage follows the same motion as shown in Figure 3.8. Before the vertical carriage starts its motion, the horizontal carriage already reaches a constant velocity. This constant velocity is maintained until after the measurement is over. Both the horizontal and vertical motion are under control by the position-feedback system, as described in sec 3.2.1. The laser light sheet is oriented vertically in a cross-stream plane, perpendicular to the horizontal rails. The laser light sheet is at a fixed position for all experimental runs herein. The motion control system and cameras are synchronized

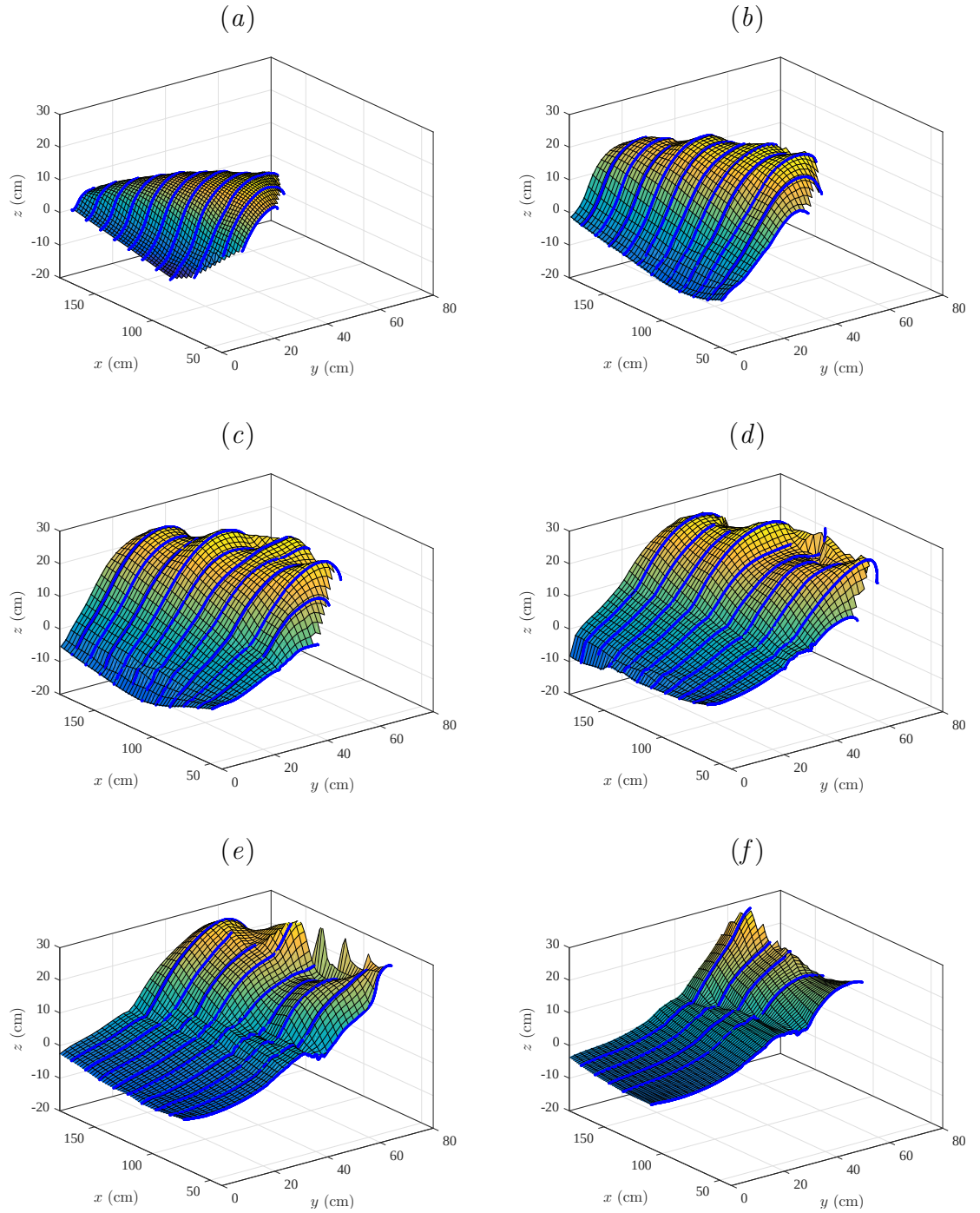


Figure 3.25: The 3D spray geometry reconstructed from surface profiles at 11 cross-stream planes for $Fr = 0.32$ (horizontal carriage speed: $U = 3$ m/s and vertical carriage impact speed: $W_0 = 0.6$ m/s). The stream-wise spacing between two neighboring measurement planes is 12.2 cm. The time interval between successive subplots is 75 ms.

following the scheme shown in Figure 3.6. The temporal evolution of the surface profiles are measured at 12 different cross sections relative to the stream-wise position of the lowest point of the impact plate at the moment when this point is at the mean water level. This process was done by varying the delay time between the trigger event and the time when the vertical motion starts. At the same vertical carriage height, the run-to-run variation of the horizontal position of any point on the plate is on the order of 1 mm. Figure 3.25 shows the reconstructed geometry of the spray surface profile at 6 different times for $Fr = 0.32$. When the lowest point on the impact plate is at the mean water level, the stream-wise position of this point is defined as X_0 . The stream-wise location of the i^{th} measurement plane is at $X_0 + 0.4L_d + (i - 1)0.1L_d$, where $L_d = 121$ cm is the streamwise distance between downstream and upstream edges of the impact plate. It is found that the evolution of the spray profile at each cross section is similar to that in the vertical impact. However, the maximum heights of the spray at the planes $X_0 + 0.4L_d$ and $X_0 + 0.5L_d$ are smaller than other 10 planes. This is because the impact plate does not penetrate the water surface for a large depth before the plate passes these two planes. The sprays in the two planes also last for shorter time before they collapse on the water surface.

3.4 Summary

A novel system consisting of a towing tank, hydraulic system and a two-axis high-speed carriage is constructed. This unique device provides precise high-speed

motion under position-feedback control in both horizontal and vertical directions. With this device, the spray generated during the impact of a flat plate with prescribed motion on a quiescent water surface is explored. A laser induced fluorescence technique is used for the measurements of the water surface profiles resulting from the plate impact.

The spray generated by the vertical impact of a flat plate with roll angle $\beta = 10^\circ$ on a quiescent water surface is studied at different impact Froude numbers. The formation of two types of sprays, called Type I and Type II, is found. The Type I spray is a cloud of high-speed droplets and ligaments generated when the leading (lower) edge of the plate impacts the water surface. The Type II spray is formed after the trailing (upper) edge of the plate starts to impact on the local water surface. Type II spray consists of a growing crater, a thin spray sheet and droplets that break up from the sheet.

The velocities (v_d) of the droplets in the Type I spray are measured in the experiments. It is found that, at the same Fr , v_d is about 3 times larger than the initial horizontal velocity of the geometrical intersection point of the plate of the plate and the plane of the mean water level. As the droplets move farther from the edge of the plate, v_d decreases, probably due to the effect of the drag of the air.

The surface profiles of the Type II spray are measured and several geometrical parameters are studied. The behaviors of the spray envelope and the spray root point trajectory are found to be independent of Froude number close to the trailing edge of the plate, while further away from the trailing edge, the envelopes and root point trajectories reach higher vertical positions for larger Froude numbers. The motion

of the spray root point is also explored. The spray root reaches higher position with larger Froude numbers. The cross-stream position of the spray root when it reaches maximum height is closer to the plate for smaller Froude numbers. The length scale of the crater expands over time following a power law at all direction. The temporal evolution of crater is found to be self-similar in a reference frame with its origin fixed at the trailing edge of the impact plate. The profiles in this reference frame collapse when scaled by $t^{2/3}$. The spray sheet at any time can be simulated by the streak lines of fluid particles which were ejected from the spray root point from all previous times and move under the effect of gravity. The ejection speed and angle is time dependent. By using experimental results, the ejection speed and angle can be approximated by this model.

The spray generated by the oblique impact of the flat plate (roll angle $\beta = 10^\circ$ and pitch angle $\gamma = 5^\circ$) on quiescent water surface is also measured. By using a laser-triggering scheme, the impact location can be accurately repeated from run to run. The highly repeatable motion allows the measurement of surface profiles at different cross sections of the impact plate from multiple runs. The three dimensional geometry of the spray surface can be reconstructed.

Chapter 4: Conclusions

In this dissertation, two types of water impact problems are investigated experimentally: 1) wave impact on a structure with finite vertical extent and 2) the slamming of a flat plate on quiescent water surface.

The first part of the dissertation explores the deep-water wave impact on a structure when the distance from the bottom of the structure to the mean water level is small compared with the wave length and water depth. A structure with vertical front and back surfaces is installed in a wave tank at a fixed stream-wise location of 6.415 m from the back of the wave maker. The height of the structure's bottom surface is varied. A dispersive focusing technique is used to create the wave maker motion, which generates a plunging breaker in open water. The water surface evolution is measured by a laser induced fluorescence technique and the impact pressure along the vertical center line of the structure's front surface is measured by piezoelectric pressure sensors. The surface profile measurements and pressure measurements are synchronized with the wave maker motion. Three classes of impact are categorized based on whether the bottom of the structure exits or enters the water phase before the main crest arrives at the structure. In Class I, the bottom of the structure remains submerged for the entire time. Flip-through

phenomenon is found under this category. In the flip-through impact, the water surface between the contact point and the crest forms a circular arc with decaying radius as the surface focuses toward a point. A double pressure peak is found for the flip-through impact. A critical Froude number based on the velocity of the contact point and the vertical distance between the contact point and the wave crest is found to determine the existence of pressure maximum on the wall. In Class I impact, small waves are generated and propagating upstream, which modifies the behavior of the breaker significantly. The effect of these upstream propagating waves is more significant with less submergence of the structure. In Class II, the bottom of the structure exits and reenters the water phase at least one time during the wave impact process. Stronger ripples are generated during the exit and reenter process than in Class I. When the bottom of the structure is at the height of the mean water level, pressure oscillation is found after the impact and gives support to the idea that air is entrained into the water. In Class III, the bottom of the structure remains above the local water level before the main crest arrives. Under this category, depending on the velocity of the water surface at the moment it touches the bottom of the structure, either a ripple or a micro-jet is formed. Pressure oscillation is found in the case with the formation of a micro-jet. The collision of the micro-jet with the plunging jet is likely to cause air entrainment.

The second part of the dissertation explores the spray formation during the slamming of a flat plate on a quiescent water surface under prescribed motion. A novel system with a towing tank and a two-axis high-speed carriage is constructed, allowing the controllable slamming motion during the nonlinear process. A laser

induced fluorescence technique is used for measuring the water surface evolution and the motion of the droplets generated during impact. Two sets of impact experiments are performed. The first set of experiments studies vertical impact. The impact plate has 10° roll angle and 0° pitch angle. Two types of sprays are discovered. The Type I spray consists of a cloud of high-speed droplets and ligaments generated when the leading edge of the plate impacts the water. The horizontal velocities of these droplets are found to be about 3 times of the initial horizontal velocities of the geometrical intersection line between the plate and the mean water level. The Type II spray is generated when the trailing edge of the plate pushes on the local water surface and consists of three components: the crater between the edge of the plate and the spray root, the spray sheet above the spray root and the droplets that break up from the spray sheet when the sheet becomes unstable. It is found the profiles of the crater collapse when scaled by $t^{2/3}$ in a reference frame fixed at the trailing edge of the impact plate. The profile of the spray sheet at any instant can be well simulated by the streak line of fluid particles which were ejected from the spray root point from all previous times and move under effect of gravity. This concept can give a reasonable approximation to the water ejection velocity at the spray root. It is also found that the behaviors of the Type II spray's envelop lines and the spray roots' trajectories are strongly affected by the impact Froude number. The second set of experiments studies oblique impact. The impact plate has 10° roll angle and 5° pitch angle. With the help of highly repeatable plate motion, the temporal evolution of the 3D geometry of the spray is reconstructed faithfully.

Chapter A: Additional water surface evolution during wave impact
in Class I, II

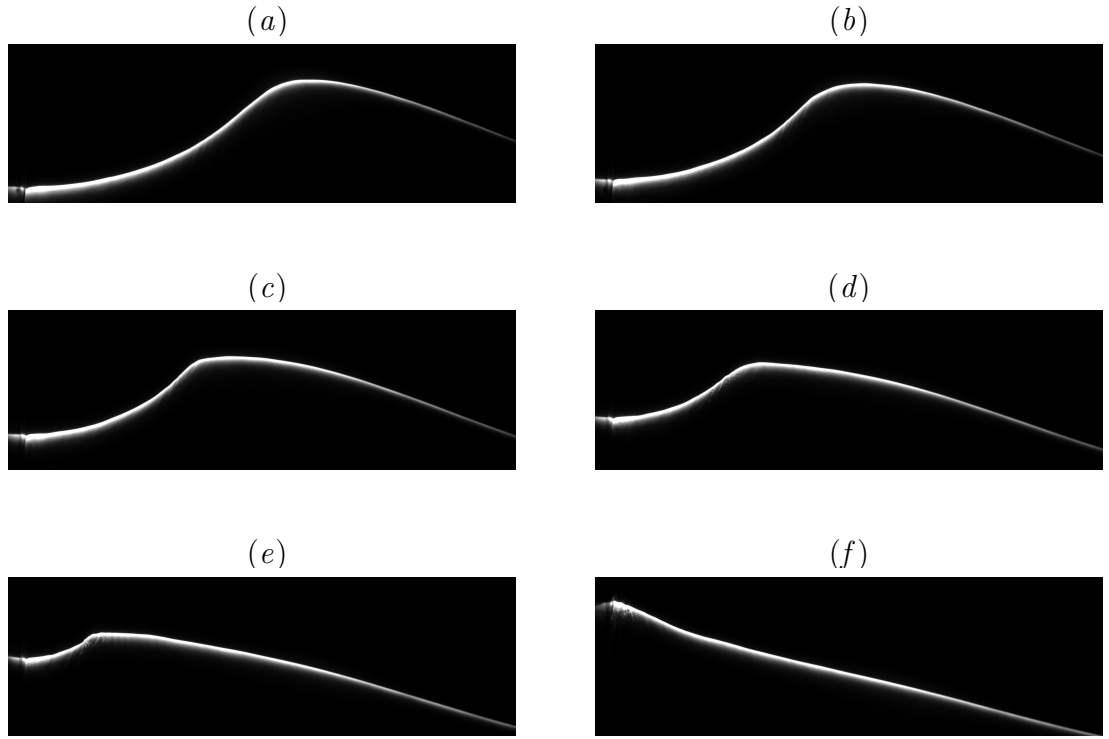


Figure A.1: A sequence of images from the high-speed LIF movies showing the evolution of the water surface at $z_b = -0.0914\lambda_0$. The field of view is $52 \text{ cm} \times 16 \text{ cm}$. The time interval between successive images are 33 ms.

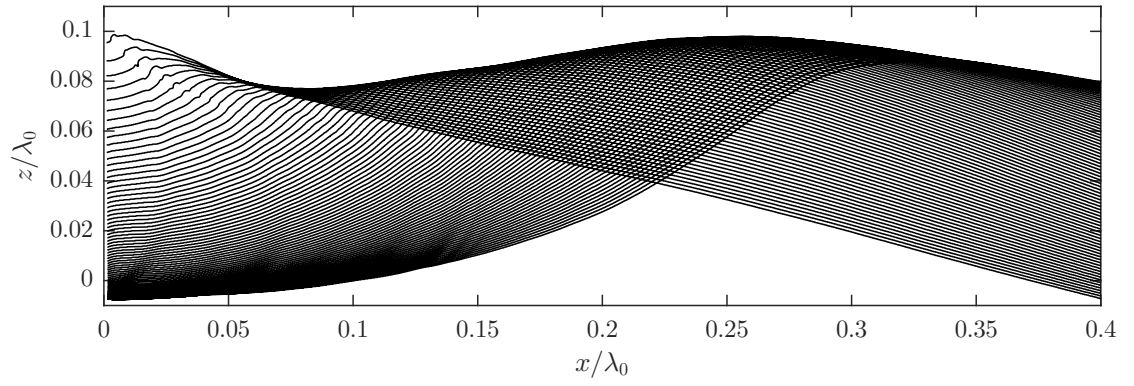


Figure A.2: Surface profile history plotted in a reference frame fixed in laboratory for condition $z_b = -0.0914\lambda_0$. The time between profiles is 3.3 ms. A total time of 264 ms before this time is covered. The front surface of the wall is located at $x/\lambda_0 = 0$. The mean water level is at $z/\lambda_0 = 0$.

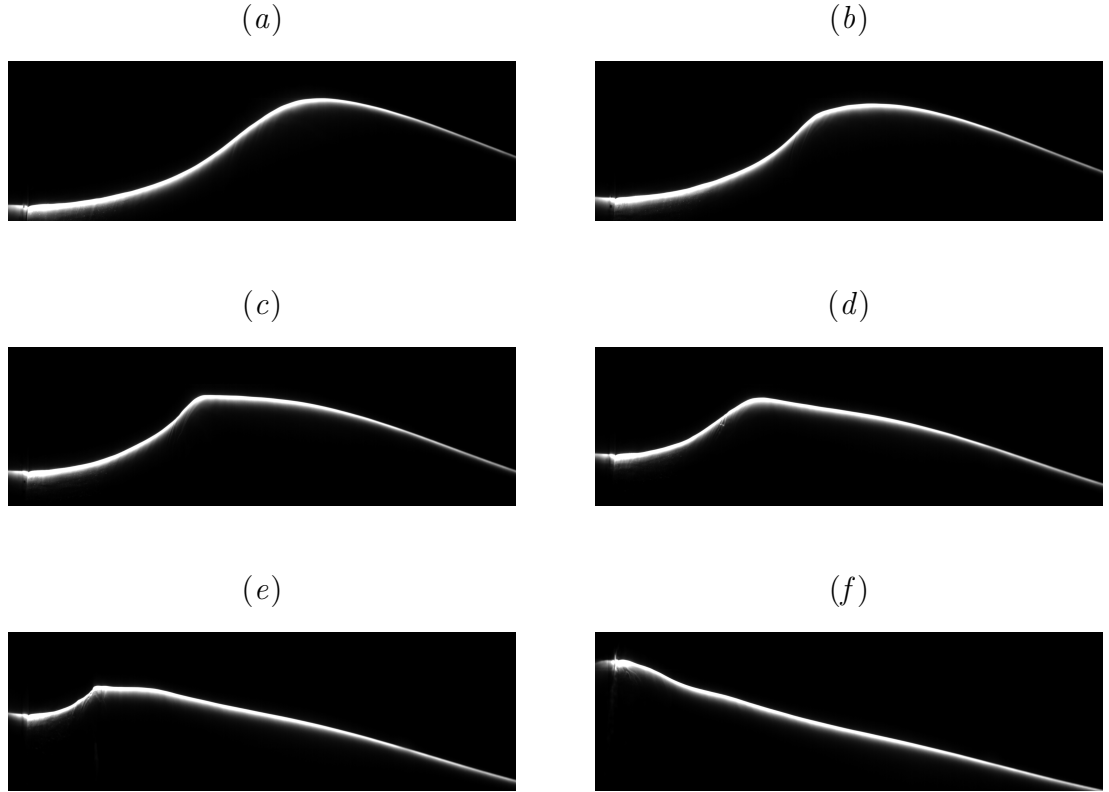


Figure A.3: A sequence of images from the high-speed LIF movies showing the evolution of the water surface at $z_b = -0.065\lambda_0$. The field of view is $52 \text{ cm} \times 16 \text{ cm}$. The time interval between successive images are 33 ms.

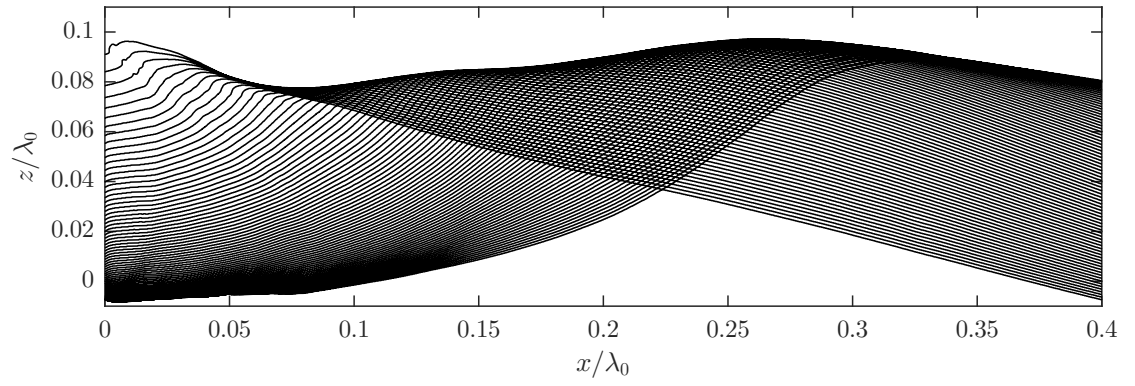


Figure A.4: Surface profile history plotted in a reference frame fixed in laboratory for condition $z_b = -0.0645\lambda_0$. The time between profiles is 3.3 ms. A total time of 264 ms before this time is covered. The front surface of the wall is located at $x/\lambda_0 = 0$. The mean water level is at $z/\lambda_0 = 0$.

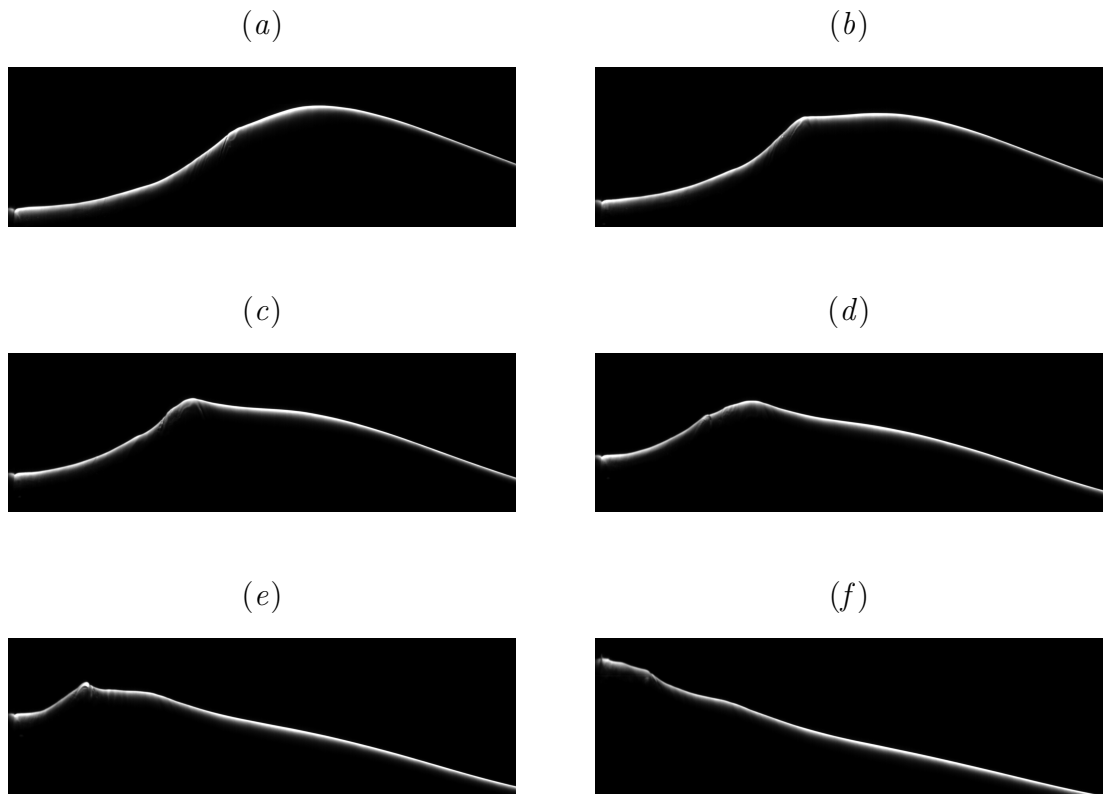


Figure A.5: A sequence of images from the high-speed LIF movies showing the evolution of the water surface at $z_b = -0.0376\lambda_0$. The field of view is $52 \text{ cm} \times 16 \text{ cm}$. The time interval between successive images are 33 ms.

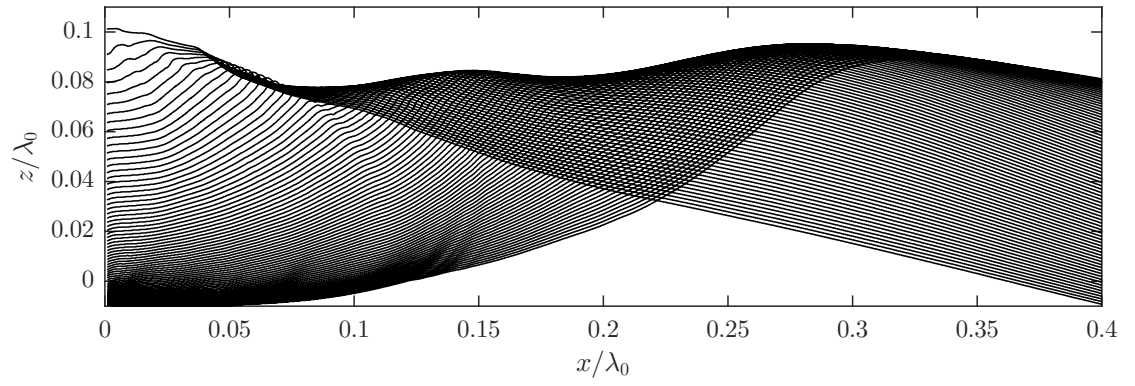


Figure A.6: Surface profile history plotted in a reference frame fixed in laboratory for condition $z_b = -0.0376\lambda_0$. The time between profiles is 3.3 ms. A total time of 264 ms before this time is covered. The front surface of the wall is located at $x/\lambda_0 = 0$. The mean water level is at $z/\lambda_0 = 0$.

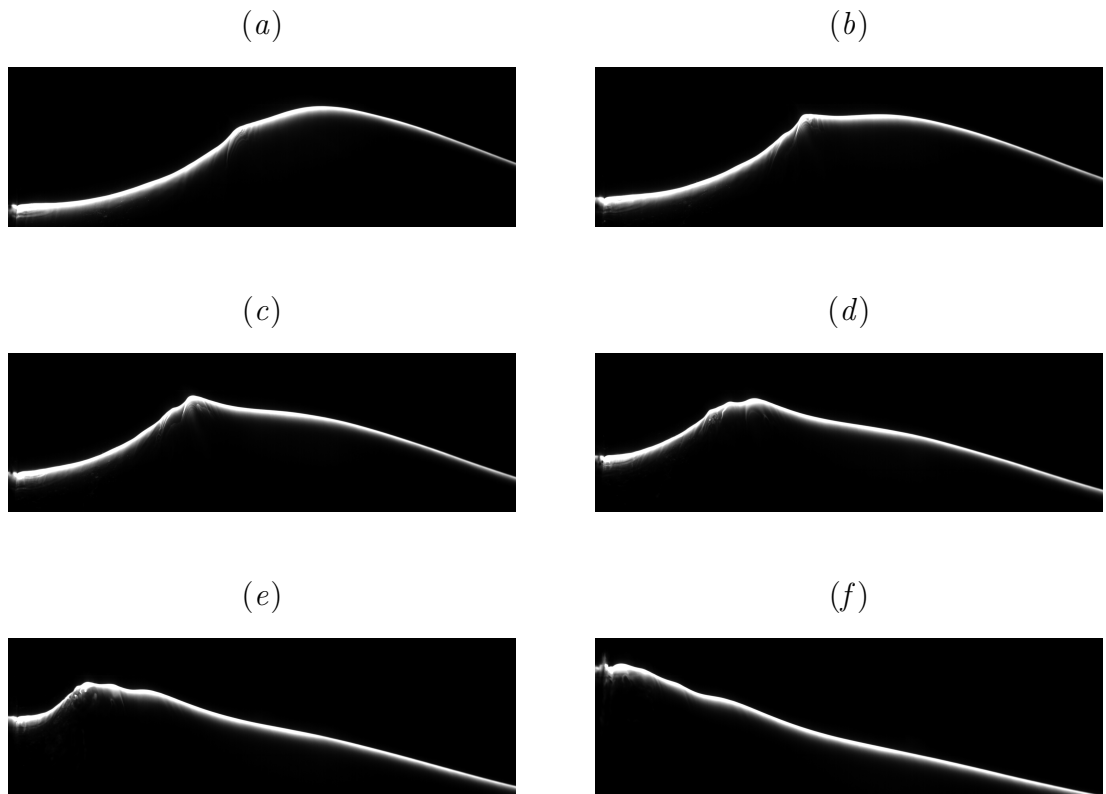


Figure A.7: A sequence of images from the high-speed LIF movies showing the evolution of the water surface at $z_b = -0.0215\lambda_0$. The field of view is $52 \text{ cm} \times 16 \text{ cm}$. The time interval between successive images are 33 ms.

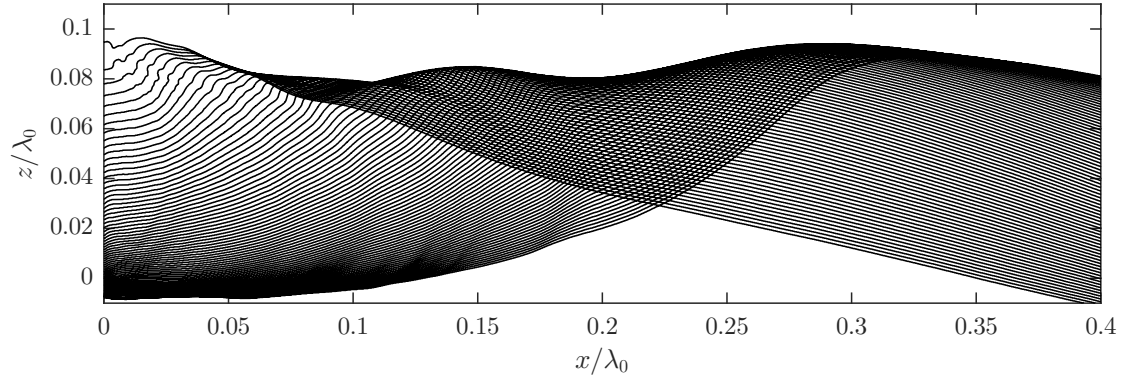


Figure A.8: Surface profile history plotted in a reference frame fixed in laboratory for condition $z_b = -0.0215\lambda_0$. The time between profiles is 3.3 ms. A total time of 264 ms before this time is covered. The front surface of the wall is located at $x/\lambda_0 = 0$. The mean water level is at $z/\lambda_0 = 0$.

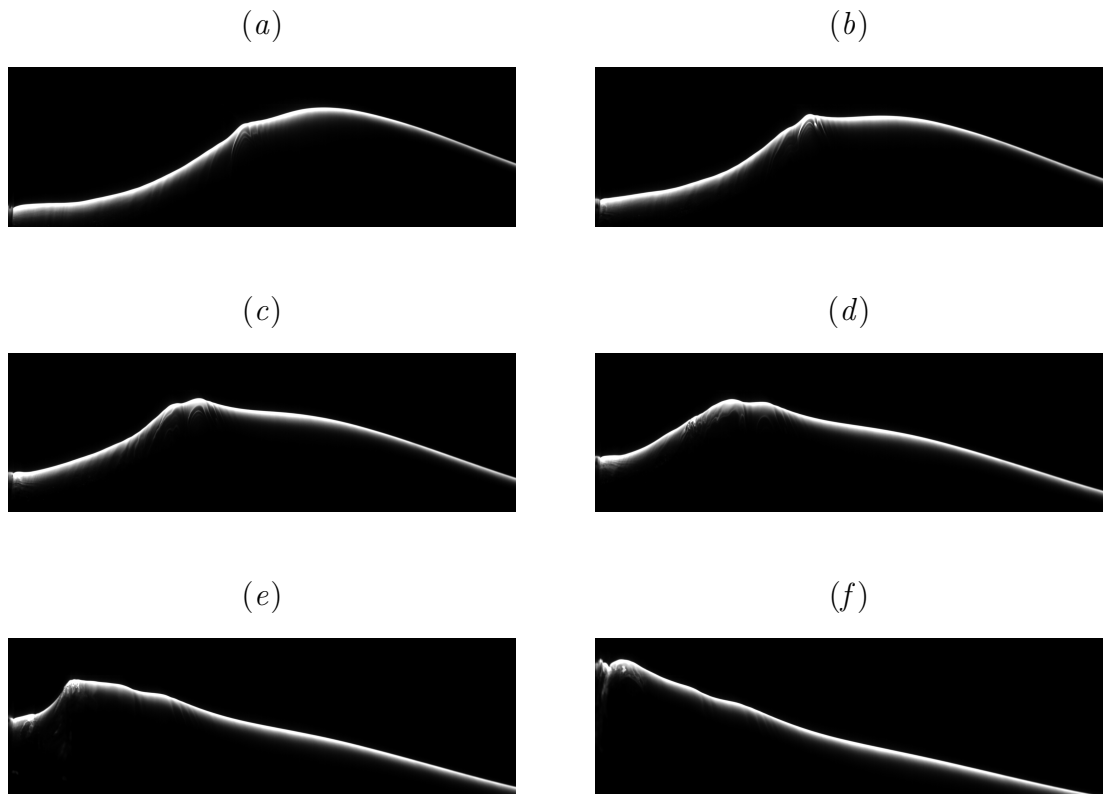


Figure A.9: A sequence of images from the high-speed LIF movies showing the evolution of the water surface at $z_b = -0.0135\lambda_0$. The field of view is $52\text{ cm} \times 16\text{ cm}$. The time interval between successive images are 33 ms.

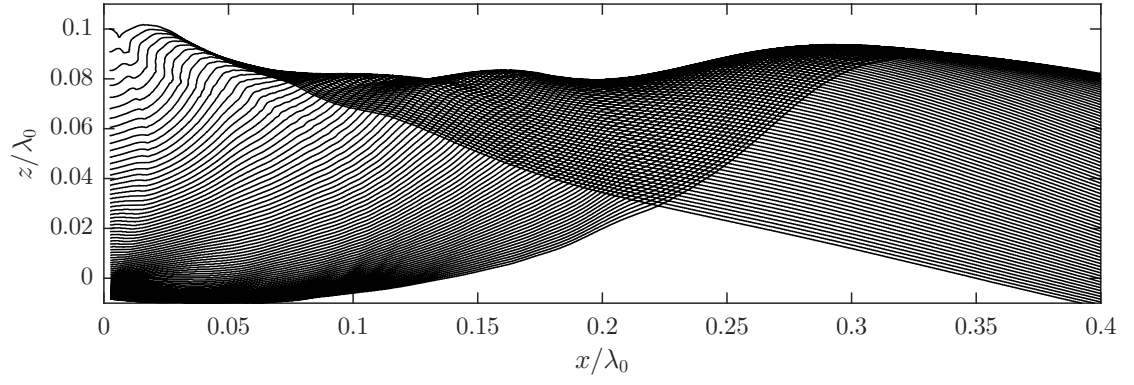


Figure A.10: Surface profile history plotted in a reference frame fixed in laboratory for condition $z_b = -0.0135\lambda_0$. The time between profiles is 3.3 ms. A total time of 264 ms before this time is covered. The front surface of the wall is located at $x/\lambda_0 = 0$. The mean water level is at $z/\lambda_0 = 0$.

Chapter B: Time histories of pressure on the wall during wave impact

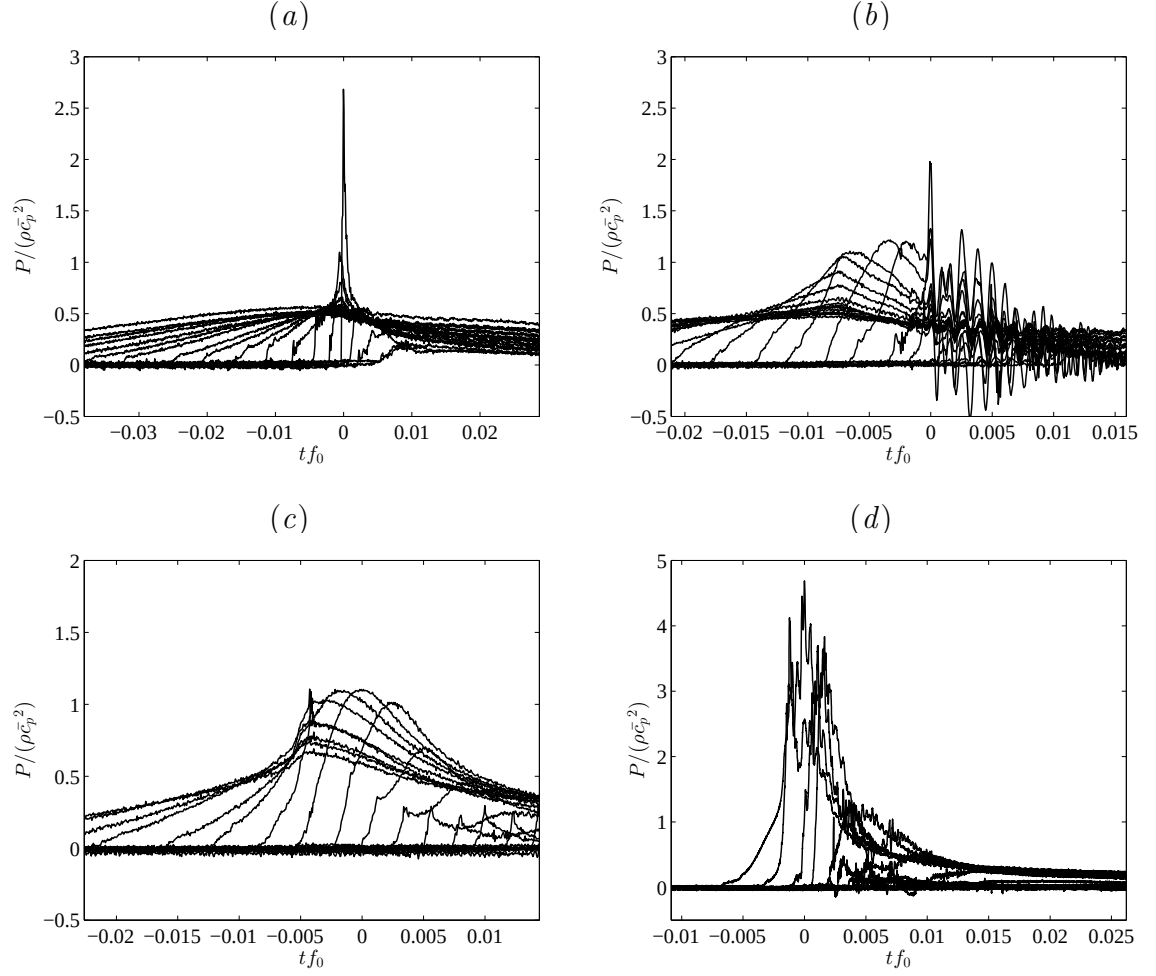


Figure B.1: (a)(b)(c)(d) represent the pressure time histories of all pressure sensors during wave impact in condition $z_b = -0.1129\lambda_0$, $z_b = 0$, $z_b = 0.0215\lambda_0$, $z_b = 0.043\lambda_0$, respectively. These time histories of wall pressure correspond to the contour plots in Figure 2.23 shown in §2.3.3. $tf_0 = 0$ at each plot represents the time when the maximum pressure is reached.

Bibliography

- [1] R.A. Bagnold. Interim report on wave-pressure research. *Proc. Inst. Civil Eng.*, 12:202–226, 1939.
- [2] J A Battjes. Surf-zone dynamics. *Annual Review of Fluid Mechanics*, 20(1):257–291, 1988.
- [3] PA Blackmore and PJ Hewson. Experiments on full-scale wave impact pressures. *Coastal Engineering*, 8(4):331–346, 1984.
- [4] Henrik Bredmose, GN Bullock, and AJ Hogg. Violent breaking wave impacts. part 3. effects of scale and aeration. *Journal of Fluid Mechanics*, 765:82–113, 2015.
- [5] Henrik Bredmose, DH Peregrine, and GN Bullock. Violent breaking wave impacts. part 2: modelling the effect of air. *Journal of Fluid Mechanics*, 641:389–430, 2009.
- [6] G.N Bullock, A.R Crawford, P.J Hewson, M.J.A Walkden, and P.A.D Bird. The influence of air and scale on wave impact pressures. *Coastal Engineering*, 42(4):291 – 312, 2001.
- [7] GN Bullock, C Obhrai, DH Peregrine, and Henrik Bredmose. Violent breaking wave impacts. part 1: Results from large-scale regular wave tests on vertical and sloping walls. *Coastal Engineering*, 54(8):602–617, 2007.
- [8] E Chan and W Melville. Deepwater breaking wave force on surface piercing structures. In *OCEANS 1984*, pages 565–570. IEEE, 1984.
- [9] E. S. Chan and W. K. Melville. Deep-water plunging wave pressures on a vertical plane wall. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 417(1852):95–131, 1988.
- [10] Hubert Chanson, Shin ichi Aoki, and Mamoru Maruyama. Unsteady air bubble entrainment and detrainment at a plunging breaker: dominant time scales and similarity of water level variations. *Coastal Engineering*, 46(2):139 – 157, 2002.
- [11] Sheng-Lun Chuang and David T Milne. Drop tests of cones to investigate the three-dimensional effects of slamming. Technical report, DTIC Document, 1971.

- [12] Sheng-Lung Chuang. Slamming tests of three-dimensional models in calm water and waves. Technical report, DTIC Document, 1973.
- [13] Raymond Cointe. Free-surface flows close to a surface-piercing body. *Mathematical Approaches in Hydrodynamics*, pages 319–334, 1991.
- [14] M. J. Cooker and D. H. Peregrine. *Violent Motion as Near Breaking Waves Meet a Vertical Wall*, pages 291–297. Springer, Berlin, Heidelberg, 1992.
- [15] Mark J Cooker. Unsteady pressure fields which precede the launch of free-surface liquid jets. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 458(2018):473–488, 2002.
- [16] Mark J. Cooker and D.H. Peregrine. Wave impact pressure and its effect upon bodies lying on the sea bed. *Coastal Engineering*, 18(34):205 – 229, 1992.
- [17] Mark J Cooker and DH Peregrine. Pressure-impulse theory for liquid impact problems. *Journal of Fluid Mechanics*, 297:193–214, 1995.
- [18] MJ Cooker and DH Peregrine. A model for breaking wave impact pressures. *Coastal Engineering Proceedings*, 1(22), 1990.
- [19] MJ Cooker and DH Peregrine. Violent water motion at breaking-wave impact. *Coastal Engineering Proceedings*, 1(22), 1990.
- [20] Richard F Day, E John Hinch, and John R Lister. Self-similar capillary pinchoff of an inviscid fluid. *Physical review letters*, 80(4):704, 1998.
- [21] Grant B. Deane. Sound generation and air entrainment by breaking waves in the surf zone. *The Journal of the Acoustical Society of America*, 102(5), 1997.
- [22] JD Diorio, X Liu, and JH Duncan. An experimental investigation of incipient spilling breakers. *Journal of Fluid Mechanics*, 633(1):271–283, 2009.
- [23] ZN Dobrovol’skaya. On some problems of similarity flow of fluid with a free surface. *Journal of Fluid Mechanics*, 36(04):805–829, 1969.
- [24] JW Dold and DH Peregrine. Steep unsteady water waves: an efficient computational scheme. *Coastal Engineering Proceedings*, 1(19), 1984.
- [25] Douglas G Dommermuth, Dick KP Yue, WM Lin, RJ Rapp, ES Chan, and WK Melville. Deep-water plunging breakers: a comparison between potential theory and experiments. *Journal of Fluid Mechanics*, 189:423–442, 1988.
- [26] James H Duncan, Haibing Qiao, Vasanth Philomin, and Alexandra Wenz. Gentle spilling breakers: crest profile evolution. *Journal of Fluid Mechanics*, 379:191–222, 1999.
- [27] JH Duncan, V Philomin, M Behres, and J Kimmel. The formation of spilling breaking water waves. *Physics of Fluids*, 6:2558, 1994.

- [28] W.J. Easson and C.A. Greated. Breaking wave forces and velocity fields. *Coastal Engineering*, 8(3):233 – 241, 1984.
- [29] Odd M Faltinsen. The effect of hydroelasticity on ship slamming. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 355(1724):575–591, 1997.
- [30] Odd M Faltinsen. *Hydrodynamics of high-speed marine vehicles*. Cambridge University Press, 2005.
- [31] Odd M Faltinsen, Jan Kvålsvold, and Jan V Aarsnes. Wave impact on a horizontal elastic plate. *Journal of Marine Science and Technology*, 2(2):87–100, 1997.
- [32] Odd M Faltinsen and Yuriy A Semenov. Nonlinear problem of flat-plate entry into an incompressible liquid. *Journal of Fluid Mechanics*, 611:151–173, 2008.
- [33] PR Garabedian. Oblique water entry of a wedge. *Communications on Pure and Applied Mathematics*, 6(2):157–165, 1953.
- [34] Frederick W. Gibson. Measurement of the effect of air bubbles on the speed of sound in water. *The Journal of the Acoustical Society of America*, 48(5B), 1970.
- [35] Martin Greenhow and Woei-Min Lin. Nonlinear-free surface effects: Experiments and theory. Technical report, DTIC Document, 1983.
- [36] SD Howison, JR Ockendon, and SK Wilson. Incompressible water-entry problems at small deadrise angles. *Journal of Fluid Mechanics*, 222:215–230, 1991.
- [37] Alessandro Iafrati and Alexander A Korobkin. Initial stage of flat plate impact onto liquid free surface. *Physics of Fluids (1994-present)*, 16(7):2214–2227, 2004.
- [38] Alessandro Iafrati and Alexander A Korobkin. Hydrodynamic loads during early stage of flat plate impact onto water surface. *Physics of Fluids (1994-present)*, 20(8):082104, 2008.
- [39] M Salih Kirkgöz. Impact pressure of breaking waves on vertical and sloping walls. *Ocean Engineering*, 18(1-2):45–59, 1991.
- [40] MS Kirkgöz. Breaking wave impact on vertical and sloping coastal structures. *Ocean Engineering*, 22(1):35–48, 1995.
- [41] AA Korobkin. Wave impact on the center of an euler beam. *Journal of applied mechanics and technical physics*, 39(5):770–781, 1998.
- [42] AA Korobkin and TI Khabakhpasheva. Regular wave impact onto an elastic plate. *Journal of engineering mathematics*, 55(1-4):127–150, 2006.

- [43] AA Korobkin and VV Pukhnachov. Initial stage of water impact. *Annual Review of Fluid Mechanics*, 20(1):159–185, 1988.
- [44] Rouslan Krechetnikov. Stability of liquid sheet edges. *Physics of Fluids*, 22(9):092101, 2010.
- [45] David Leppinen and John R Lister. Capillary pinch-off in inviscid fluids. *Physics of Fluids*, 15(2):568–578, 2003.
- [46] Xinan Liu and James H Duncan. An experimental study of surfactant effects on spilling breakers. *Journal of Fluid Mechanics*, 567:433, 2006.
- [47] Michael S Longuet-Higgins. Vertical jets from standing waves. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 457(2006):495–510, 2001.
- [48] Michael S Longuet-Higgins and ED Cokelet. The deformation of steep surface waves on water. i. a numerical method of computation. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 350(1660):1–26, 1976.
- [49] Michael S Longuet-Higgins and Hasan Oğuz. Critical microjets in collapsing cavities. *Journal of Fluid Mechanics*, 290:183–201, 1995.
- [50] Michael S Longuet-Higgins and Hasan N Oğuz. Critical jets in surface waves and collapsing cavities. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 355(1724):625–639, 1997.
- [51] Pierre Lubin, Stphane Vincent, Stphane Abadie, and Jean-Paul Caltagirone. Three-dimensional large eddy simulation of air entrainment under plunging breaking waves. *Coastal Engineering*, 53(8):631 – 655, 2006.
- [52] C Lugni, M Brocchini, and OM Faltinsen. Wave impact loads: The role of the flip-through. *Physics of Fluids*, 18(12):122101, 2006.
- [53] AG Mackie. The water entry problem. *The Quarterly Journal of Mechanics and Applied Mathematics*, 22(1):1–17, 1969.
- [54] JO Marston and Sigurdur T Thoroddsen. Ejecta evolution during cone impact. *Journal of Fluid Mechanics*, 752:410–438, 2014.
- [55] WK Melville. The role of surface-wave breaking in air-sea interaction. *Annual review of fluid mechanics*, 28(1):279–321, 1996.
- [56] MR Moore, SD Howison, JR Ockendon, and JM Oliver. Three-dimensional oblique water-entry problems at small deadrise angles. *Journal of Fluid Mechanics*, 711:259–280, 2012.

- [57] Michel K. Ochi and Chen-Han Tsai. Prediction of impact pressure induced by breaking waves on vertical cylinders in random seas. *Applied Ocean Research*, 6(3):157 – 165, 1984.
- [58] Akio Okayasu, Tomoya Shibayama, and Nobuo Mimura. Velocity field under plunging waves. *Coastal Engineering Proceedings*, 1(20), 1986.
- [59] JM Oliver. Second-order wagner theory for two-dimensional water-entry problems at small deadrise angles. *Journal of fluid mechanics*, 572:59–85, 2007.
- [60] Adrián Pedrozo-Acuña, David J Simmonds, and Dominic E Reeve. Wave-impact characteristics of plunging breakers acting on gravel beaches. *Marine Geology*, 253(1):26–35, 2008.
- [61] D. H. Peregrine. Water-wave impact on walls. *Annual Review of Fluid Mechanics*, 35(1):23–43, 2003.
- [62] DH Peregrine and L Thais. The effect of entrained air in violent water wave impacts. *Journal of Fluid Mechanics*, 325:377–398, 1996.
- [63] Marc Perlin, Jianhui He, and Luis P Bernal. An experimental study of deep water plunging breakers. *Physics of Fluids*, 8(9):2365–2374, 1996.
- [64] Ivo R Peters, Devaraj van der Meer, and JM Gordillo. Splash wave and crown breakup after disc impact on a liquid surface. *Journal of Fluid Mechanics*, 724:553–580, 2013.
- [65] John D Pierson. The penetration of a fluid surface by a wedge. Technical Report 381, Stevens Institute of Technology, 1950.
- [66] Ronald James Rapp and WK Melville. Laboratory measurements of deep-water breaking waves. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 331(1622):735–800, 1990.
- [67] M Reinhard, A Korobkin, and MJ Cooker. The bounce of a blunt body from a water surface at high horizontal speed. In *Proc. 27th Int. Workshop Water Waves and Floating Bodies, Copenhagen, Denmark, 22–25 Apr*, 2012.
- [68] M Reinhard, AA Korobkin, and MJ Cooker. Water entry of a flat elastic plate at high horizontal speed. *Journal of Fluid Mechanics*, 724:123–153, 2013.
- [69] Nitin Repalle, Krish Thiagarajan, and Fiona Paterson. Wave run-up investigation on a square cylinder. In *17th Australasian Fluid Mechanics Conference*, 2010.
- [70] Guillaume Riboux and José Manuel Gordillo. The diameters and velocities of the droplets ejected after splashing. *Journal of Fluid Mechanics*, 772:630–648, 2015.

- [71] D Savitsky and JP Breslin. On the main spray generated by planing surfaces. Technical report, Davidson Laboratory, Stevens Institute of Technology, Hoboken, NJ, 1958.
- [72] Yuriy A Semenov and Bum-Sang Yoon. Onset of flow separation for the oblique water impact of a wedge. *Physics of Fluids (1994-present)*, 21(11):112103, 2009.
- [73] Francis C.K. Ting and James T. Kirby. Dynamics of surf-zone turbulence in a strong plunging breaker. *Coastal Engineering*, 24(34):177 – 204, 1995.
- [74] ME Topliss, MJ Cooker, and DH Peregrine. Pressure oscillations during wave impact on vertical walls. *Coastal Engineering Proceedings*, 1(23), 1992.
- [75] Th Von Karman. The impact on seaplane floats during landing. *Nat. Adv. Com. for Aeronautics. Tech. Note*, (321):309–313, 1929.
- [76] Arjan Voogt, Bas Buchner, et al. Prediction of wave impact loads on ship-type offshore structures in steep fronted waves. In *The Fourteenth International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers, 2004.
- [77] Herbrt Wagner. Über stoß-und gleitvorgänge an der oberfläche von flüssigkeiten. *ZAMM-Journal of Applied Mathematics and Mechanics/Zeitschrift für Angewandte Mathematik und Mechanik*, 12(4):193–215, 1932.
- [78] M.J Walkden, D.J Wood, T Bruce, and D.H Peregrine. Impulsive seaward loads induced by wave overtopping on caisson breakwaters. *Coastal Engineering*, 42(3):257 – 276, 2001.
- [79] J. Wienke and H. Oumeraci. Breaking wave impact force on a vertical and inclined slender pile: theoretical and large-scale model investigations. *Coastal Engineering*, 52(5):435 – 462, 2005.
- [80] Deborah J Wood and D Howell Peregrine. Two and three-dimensional pressure-impulse models of wave impact on structures. *Coastal Engineering Proceedings*, 1(26), 1998.
- [81] Benjamin W Zeff, Benjamin Kleber, Jay Fineberg, and Daniel P Lathrop. Singularity dynamics in curvature collapse and jet eruption on a fluid surface. *Nature*, 403(6768):401–404, 2000.
- [82] Sheguang Zhang, James H Duncan, and Georges L Chahine. The final stage of the collapse of a cavitation bubble near a rigid wall. *Journal of Fluid Mechanics*, 257:147–181, 1993.
- [83] Sheguang Zhang, Dick K. P. Yue, and Katsuji Tanizawa. Simulation of plunging wave impact on a vertical wall. *Journal of Fluid Mechanics*, 327:221–254, 11 1996.

- [84] Rong Zhao and Odd Faltinsen. Water entry of two-dimensional bodies. *Journal of Fluid Mechanics*, 246:593–612, 1993.