Team Project 2:
Propagation of a Forced Wave

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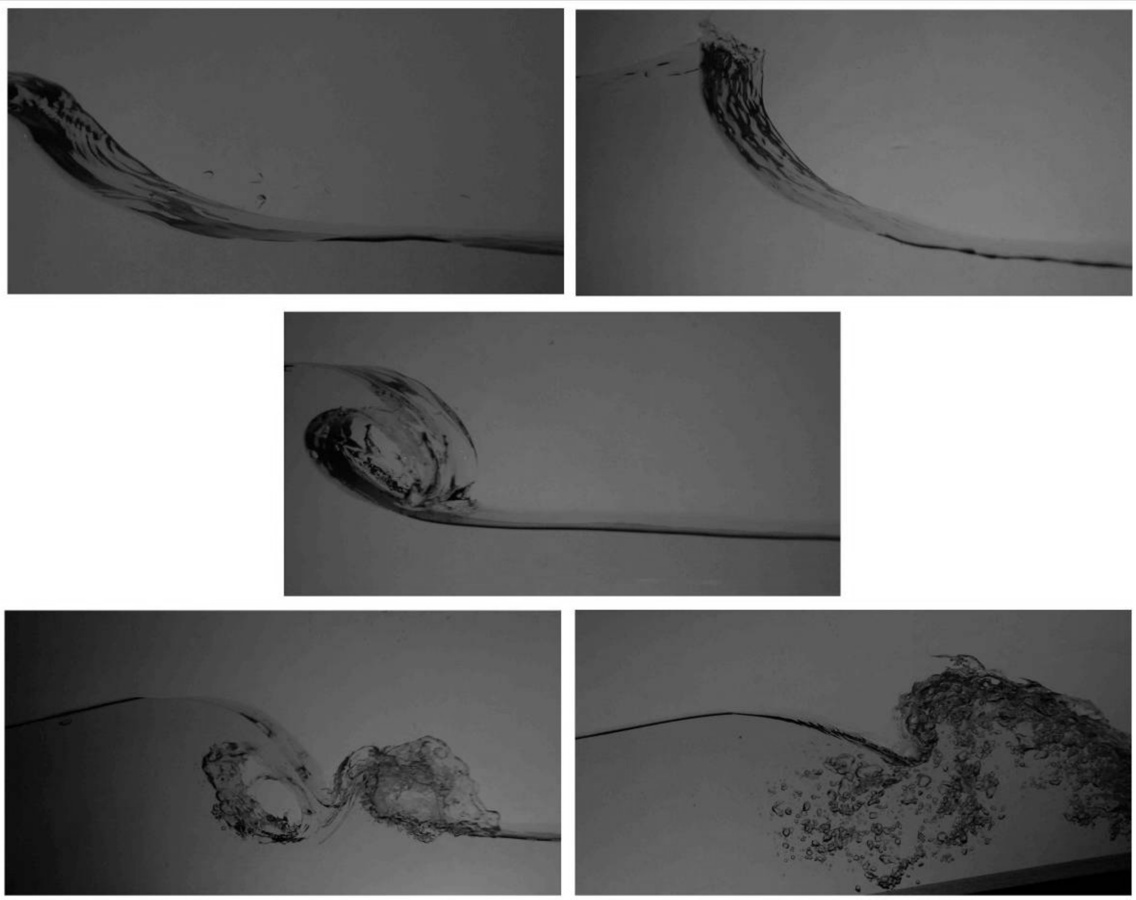

Abstract: Breaking waves form when a critical value in the velocity shear is reached. This can occur in either the vertical or horizontal direction for shallow water depths. This series of images aims to help gain a better understanding of this process by depicting different time steps of a plunging wave. Visually following this event from formation to destruction will help to develop a good understanding of the physical phenomena developed in this flow.

The photographic series produced for this second group project depicts a breaking wave from the point it crests to the point that it plunges back into a surrounding body of water. The idea behind this series is to recreate a wave similar to one that may be viewed breaking in a large body of water. To do this, a flume was used to contain the fluid and to provide an ideal set up for controlling water level as well as viewing the breaking wave edge on above and below the water surface. The scientific purpose of the series is to gain a better understanding of the physical phenomena related to the formation of a cresting wave.

The flow in this series was generated by filling the flume with between 4-5 inches of water (the width of the flume is approximately 3") and blocking the outflow. A wooden wedge was placed just after the field of view to simulate a change in the height of the ocean floor. A block was then used to force horizontal motion in the standing water from a distance roughly 3ft away from the point the image was taken. This scenario generated a flow from left to right creating a relatively large surface wave with similar characteristics to that scene in the ocean or in open channel flow.

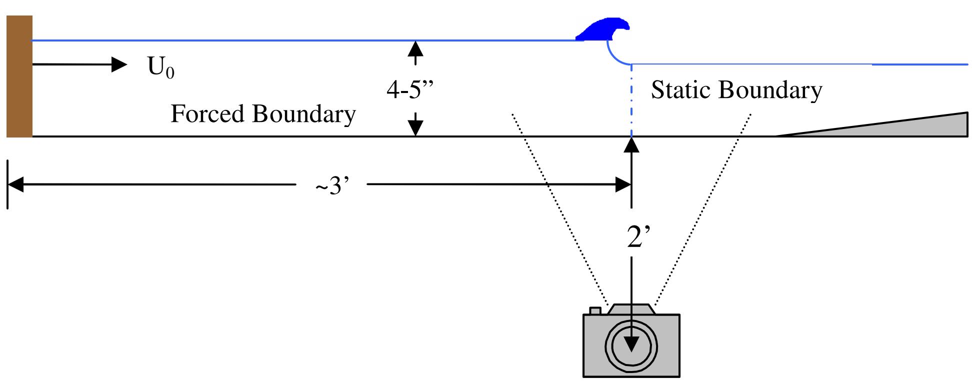

Figure 1: Schematic of the flow apparatus showing general dimensions. In this sketch, U_0 is the initial block velocity driving the forced flow, the "Forced Boundary" is the moving volume of fluid forced into motion by the block, and the "Static Boundary" is the volume of fluid that has no added velocity aside from minimal momentum transfer for small time steps.

The resulting wave will break depending on the fluid velocity and the water height.

A breaking wave is formed when the velocity of the top of the wave exceeds the velocity of the main wave body [2]. A wave will break if there is either a very sharp vertical or horizontal velocity shear [1]. For the given series of images, the flow is driven by a large horizontal velocity shear produced by the velocity difference between the static and forced fluid boundaries. The velocity of the main wave body is roughly 40in/s corresponding to a Reynolds number on the order of 10,000 (turbulent regime). As this fast paced, pressure driven flow collides with the static fluid the resulting exchange of momentum generates pressure along the front of the moving boundary. The generated pressure forces an increase in the free surface height at the front of the flow due to the hydrostatic pressure distribution associated with incompressible fluids, such as water. As the height of the wave increases, the top portion carries forward with a greater velocity than the bottom portion [1]. This occurs because the velocityh of the fluid near the bottom of the wave is reduced by the static fluid boundary while the fluid near the top of the wave experiences resistance only from the diffusion of momentum from lower layers (by Navier-Stokes momentum equations, where effects from air is negligible on shear). Therefore, once the wave reaches a critical height, surface tension effects can no longer maintain the smooth shape of the wave and the top breaks free creating a crest. After breaking, gravity dominants the crest’s motion and it falls back into the surrounding body of water. Theoretically, the criterion for a wave to break is based on the non-dimensional Froude number, relating the wave speed to the water depth in shallow waves. The Froude number for this flow is approximately 3.2, which is larger than the critical wave breaking limit of $Fr_t \approx 1.6$, thus supporting this theory [2].

The wave images were created using light bending to mark the boundaries of the flow. Light bent by the difference in refractive index in the water helped to generate shadows in the surface, especially in areas where there were variations in the surface angle. By backlighting the flume with three 250W spotlights, a greater level of contrast could be achieved. Further lighting was provided by the ambient fluorescent lighting in the building. The blue tint in the fluid was caused by food coloring added to the flume; however, this was purely coincidental and was not the primary mode for boundary marking.

The photographs were created using a Nikon D80, digital SLR body with an image resolution of 3872x2592 pixels. The field of view of each image is approximately 1.5'x1' giving a spatial resolution of 1.9×10^{-4} in^2/pixel (length per pixel is 0.0046") and was taken approximately 2 ft from the lens. The lens focal lengths used were between 38 and 44mm on a Nikon DX AF-S Nikkor 18-135mm 1:3.5-5.6G lens with a polarizing filter. Each image was exposed at an f-stop of 5.0, an ISO speed rating of 800, and shutter speeds between 1/1250sec and 1/1600sec. The velocity of the flow was roughly 40 in/s, therefore the wave moved 0.032" during the exposure which is somewhat above the spatial resolution of the image; however, the small amount of motion blur is not apparent in much of the flow. For final processing, images were cropped from the top and bottom to about ¾ of their original height and layered onto a single image file.

This series of images depicts the short life of a breaking wave. Starting from the smooth surface of the wave before it reaches the critical state of crest formation to the point when the breaking wave crashes back into the surrounding body of water. One of my favorite aspects of this series is the ability to see five distinct periods of time in the development of this flow. The top right image is one of my favorites because it seems to freeze the instant in time that the wave reaches the critical breaking point. I feel my intent was realized in this series, however, I would have liked to have been able to take more pictures in order to of had a greater freedom with the series layout. If I were to further work on this idea, I would like explore waves below the surface as well as above. To do this I would use denser, colored fluids to view the momentum and pressure effects below the surface. Overall, the physics and purpose to this series met my expectations

References:

1. Dimas, Athanassios A. "Free-Surface Waves Generation by a Fully Submerged Wake." Science Direct: Wave Motion 27 (1998): 48-54. Inspec. Chinook, Boulder. 9 Oct. 2007.

2. Okamoto, Takashi, and David R. Basco. "The Relative Trough Froude Number for Initiation of Wave Breaking: Theory, Experiments and Numerical Model Confirmation." Science Direct: Coastal Engineering 53 (2006): 675-690. Inspec. Chinook, Boulder. 9 Oct. 2007.

3. Sawaragi, T. Coastal Engineering-Waves, Beaches, Wave-Structure Interactions. Vol. 78. New York: Elsevier, 1995. 42-45.

Appendix: Calculations

Using the following values the non-dimensional Reynolds and Froude numbers can be calculated.

U_0 = average wave velocity = 0.762m/0.7s =1.09 m/s
D = water depth at trough = 0.01 cm (assumed trough depth for flow)
ν = kinematic viscosity of water = 1.12E-6 m^2/s
g = acceleration of gravity

Reynolds number:

$$\mathrm{Re} = \frac{U_0 * D}{\nu} = \frac{\left(\frac{0.762m}{0.7\sec}\right)(0.01m)}{1.12\times10^{-6} m^2 / s} \cong 9{,}700$$

Critical Froude number:

$$RFTN = Fr_t = \frac{\left|u_{trough}\right| + C}{\sqrt{gD}}$$

where utrough + C is approximately the average velocity U_0.

$$\rightarrow RFTN = \frac{1.1m/s}{\sqrt{\left(9.8m/s^2\right)\left(0.012m\right)}} \cong 3.2$$