Lecture 21: Potpourri

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1 Introduction

In this last lecture of the 2009 GFD series, a collection of topics is presented including:
A. Near-Shore processes such as "Wave Shoaling" and"Rip Currents".
B. Rogue waves.
C. Wave breaking in shallow water.

2 Wave shoaling

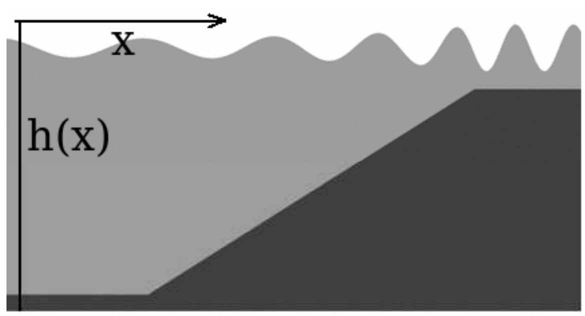

Figure 1: Wave shoaling

Wave shoaling refers to the change in the amplitude of surface waves as they travel in a water layer of decreasing depth (e.g. as they approach the coast). According to the 2-D shallow-water wave equation with x-dependent depth, we have (see Lecture 8)

$$\partial_t^2 \eta = \nabla \cdot \{g\, h(x) \nabla \eta\}, \tag{1}$$
$$c(x) = \sqrt{g\, h(x)}, \tag{2}$$

where η is the displacement of the free surface, $c(x)$ is the local phase speed and $h(x)$ is the local depth of the water layer. As a long wave in shallow water travels into even shallower water (as shown in Figure 1), the front of the wave feels the decrease in the depth sooner than the back of the wave. Correspondingly, the phase speed of the wave front decreases while the back is still traveling at a faster speed. This phenomenon compresses the wave as it moves to the shallower region, as shown in the Figure. This compression also naturally

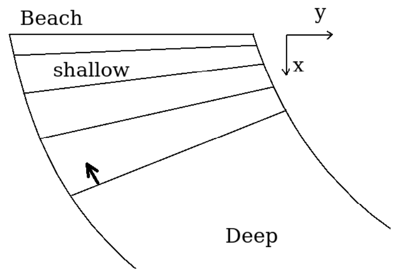

Figure 2: Wave crests turning towards the beach as they approach it.

leads to an increase in the wave amplitude, the combination of these two effects being referred to as wave shoaling.

The dependence of phase speed on the water depth also explains why wave crests line up parallel to the coast as they approach a beach. Consider a sloping beach, such as the one shown in Figure 2, and incoming waves with crests making an arbitrary angle with the coast. As they move into the shallow water region, waves begin to feel the effect of the bottom boundary and react by adjusting their phase speed: the part of the wave which is closer to the coast (the right sides of the waves shown in the Figure) slows down sooner than the other end of the wave crest (left side). Consequently, the left side of the wave catches up with the right side and the wave crest progressively turns towards the coast. This phenomenon owes its existence to the inhomogeneity of the medium (due to change in depth) and is similar to wave refraction in optics (i.e. the bending of light due to density change along a ray-path). Figure 3 illustrates this process near the coast of Duck, NC.

Figure 3: Waves near the coast at Duck, NC (1991). Photo by C. Miller. The photo was taken at a time when Hurricane Grace was passing 100 miles off-shore.

3 Rip currents

A rip current is a narrow jet which carries water away from shore. They typically form in the region of breaking waves, and extend somewhat beyond the breaking region. They are observed on ocean and sea beaches, and even on beaches of large lakes. Figure 4 shows rip currents formed in Rosarita beach, Baja California. These currents can be very dangerous, dragging swimmers (and non-swimmers who are standing in water) away from the beach and drowning them as they attempt to fight the current. In this scenario, the best action is to try getting out of the current by swimming in the cross-current direction.

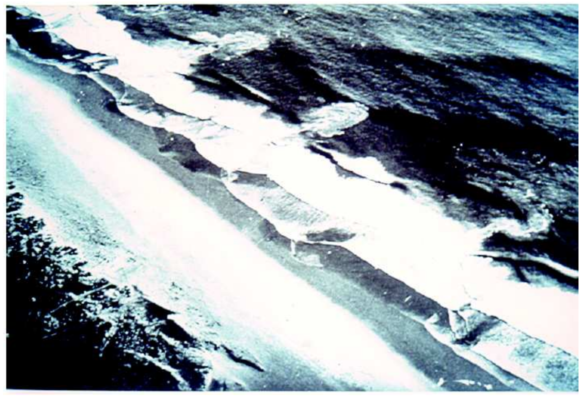

Figure 4: Rip currents along the coast of Rosarita beach, Baja California.

Various theories have been proposed to explain the mechanisms responsible for the formation and evolution of rip currents. The standard explanation is that the backwash water associated with wave breaking needs to find its way back into the sea. Although a part of it returns through undercurrents, water is also pushed sideways along the shoreline looking for an exit into the sea. Thus, a rip current can form in a trench between sandbars as shown schematically in Figure 5. Several issues have been raised regarding this sandbar

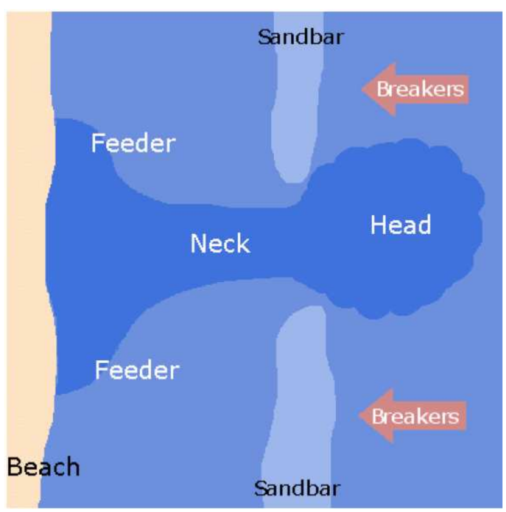

Figure 5: A rip current formed between two sandbars. Figure from http://www.ripcurrents.noaa.gov/science.html

theory. Observations have shown that these currents can appear in a spatially periodic fashion along a coastline. Figure 6 shows one such example in Sand City, California. As there is no a priori reason for the existence of a periodic array of sandbars in the shallow depth along the shoreline, the sandbar theory alone cannot explain the pattern seen in the Figure. Another problem with the sandbar theory is the temporal evolution of the rip currents. Some shorelines are characterized by permanent rip currents which form at a fixed location such as a break in a reef or other hard structures. Meanwhile, some currents are also observed to migrate along a stretch of coastline. Some rip currents are persistent, lasting for many days or months in one location and some are ephemeral, forming quickly and lingering for a few hours or days before dissipating. All these facts are somehow in contradiction with the sandbar theory.

Figure 6: Rip currents along the coast of Sand City, California.

An alternative explanation for the rip currents might be the following. Recall our description of KP solutions of genus 2 in water of uniform depth (see Lecture 7) and the associated experimental results of Hammack *et al.*(1995) [4] (shown in Figure 7). In these solutions (and experimental results) some areas have smaller velocities (see for example the regions marked by arrows in Figure 7). If such a pattern reaches the shore and breaks, the circled regions would be good candidates for the backwash water to return to the ocean and form rip currents. Some experiments by Hammack, Scheffner & Segur (1991) [5] have shown the formation of rip currents in these regions, visualising them using dye injection.

The KP solutions (of genus 2) used in the rip current experiment of Hammack *et al.*(1995) [4] were symmetric, and propagated normal to the sloping beach. More general KP solutions (of genus 2) are not symmetric and would therefore not propagate normal to the beach (as shown in lower panel of Figure 7). This raises the interesting question of whether such waves could generate slowly migrating rip currents. One can also ask the question of "How far can the incoming waves deviate from symmetry before the rip currents disappear?"

To answer these questions and explain rip currents in a more systematic manner one has to create a suitable mathematical model to describe them. Such model should allow for variable depth (uniform slope will do), wave breaking and return flows, and finally 3-D motion in order to describe the currents properly. Once a good mathematical model exists,

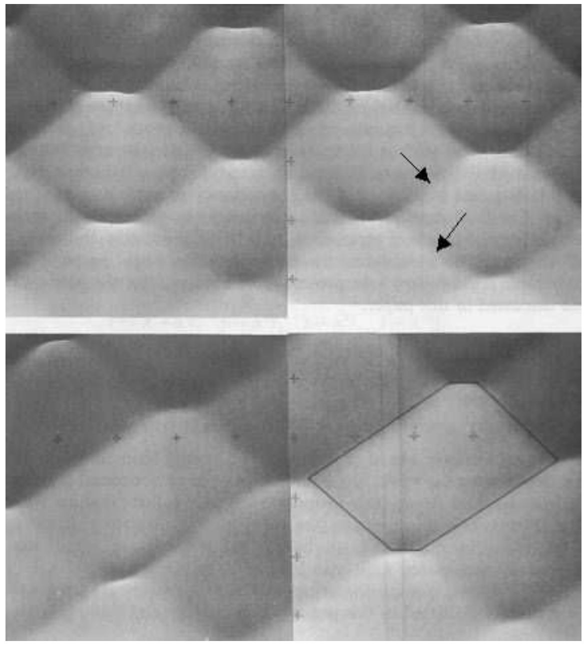

Figure 7: Two 2-dimensional surface patterns of nearly permanent form, propagating in shallow water.(Hammack *et al.*, 1995), [4]

Harry Yeh's tank (at Oregon State University) would be a suitable place to test the theory.

4 Rogue waves

Rogue waves are large ocean surface waves which appear spontaneously and are usually unexpectedly large compared with the typical wave amplitude in their environment. Figure 8 shows an example of a rogue wave breaking over a supertanker in a storm off Durban, S.A. in 1980. These waves are also referred to as freak waves, monster waves, killer waves, or extreme waves. They are extremely dangerous due to their size, and are thought to be responsible for many ship accidents and disappearances in the oceans. Figure 9 shows a map of ship accidents for the period between 1995 and 1999; from Lloyd's Marine Information Service (LMIS) database, two ships per week are lost at sea due to heavy weather. This highlights the importance of understanding the physics behind the formation of rogue waves, with the hope of predicting their occurrence (e.g. location and time).

Because of their rarity, rogue waves are almost impossible to measure in a systematic manner. Their existence was originally inferred from the damages inflicted to ships. Today, one of the only solid scientific measurement of a rogue wave is the sea-surface height data from the Draupner oil platform, in the North Sea on January 1, 1995, showing the passage of an 18.5m wave (see Figure 10). The damages inflicted on the platform during this event confirmed the validity of the measurement.

There seems to be no obvious reason behind the much larger amplitude of the rogue wave compared with the nearby waves, thus raising the conceptual question " Is a rogue wave a rare event from a known population or is it an element of an entirely different population?"

Figure 8: Rogue wave breaking over a supertanker in a storm off Durban, S.A. in 1980. The mast seen starboard stands 25 m above the mean sea level. The mean wave height at the time was 5-10 m. Photo: Phillipe Lijour, first mate.

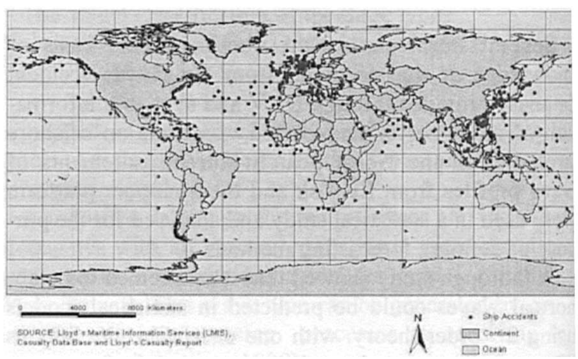

Figure 9: World-wide ship accidents.

Several possible mechanisms have been proposed to explain the occurrence of these waves. One possibility, brought up by Smith (1976) [7] and supported by White & Fornberg (1998) [8] and Baschek (2005) [2], is that rogue waves occur as a result of the interaction between internal or surface waves and underlying currents. A second possibility could be wave breaking: satellite radar measurements have shown that extreme waves events can result from wave breaking. Two other candidates are the geometric focusing and frequency focusing of wave energies at a single point, leading to enhanced wave amplitudes and the formation of a rogue wave. A more general candidate is that the rogue waves are formed due to strongly nonlinear wave dynamics. Studies such as Bateman, Swan & Taylor (2003) [3] try to show that rare extreme events such as rogue waves can occur, and may in fact not be that rare.

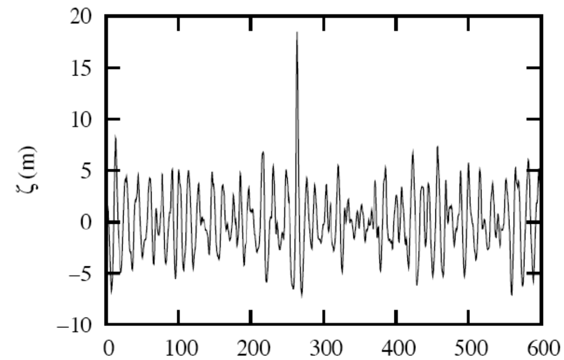

Figure 10: Waves measured at the Draupner oil platform in the North Sea, Jan. 1, 1995. Peak wave height: 18.5 m. Standard deviation of wave record: about 3 m.

In short, very little is known about the rogue waves. From an observational point of view, what information needs to be gathered to learn more about these waves and how that information can be sought, both remain to be determined. From a theoretical point of view, the general and fundamental question is whether one should try to learn more about the tail of our known distribution of ocean waves or whether one should instead look for a new kind of mechanism.

5 Waves breaking in shallow water

In general, a wave usually breaks once its amplitude grows to a critical level beyond which some process causes a large fraction of the wave energy to be dissipated. The physical models discussed thus far generally become invalid (the underlying assumptions break down) in this limit, particularly those which assume linear or weakly nonlinear behavior.

The shallow-water equations, for example, are hyperbolic, implying that waves may break in shallow water, and they do. In this case, the question is how should these equations be modified to describe more realistically wave breaking in shallow waters. Perhaps a dissipative term might help modeling "shock waves" or a dispersive term might help modeling "collisionless shocks" etc,. Both internal and surface waves can break, close or far from the coastlines. The water surface waves breaking at the coastline is perhaps the most familiar scenario. As the waves approach the shore, they refract and adjust themselves parallel to the shoreline, and their amplitude grows due to the shoaling effect explained earlier. Once their amplitude is sufficiently large, the waves overturn and break. However, note that waves can also break in the mid-ocean where refraction and shoaling effects are not present.

There are some basic types of breaking water waves like spilling, collapsing, surging and plunging [1]. As an example, Figure 11 shows a "plunging breaking" which occurs as the crest of the wave curls over and crashes down into the base of the wave. Plunging breaking is a dramatic form of break, usually associated with a sudden depth change (in the mid- or coastal ocean) or a steep sea floor near the shore.

Dramatic wave breaking events can have catastrophic consequences in the coastal areas.

Figure 11: A “plunging breaker”. Photo from Clark Little/SWNS.

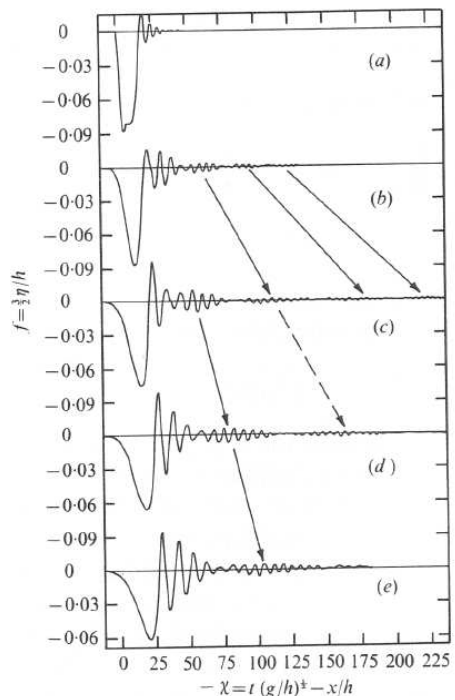

Figure 12: Hammacks experiments in shallow water, from Hammack *et al.*(1978) [6]

Recall Hammack’s experiments in shallow water which led to formation of an “Undular bore” (shown in Figure 12, see also Lecture 5). As the bore travels from right to left (in the Figure), the coast would experience a huge suction of the water into the ocean (which can attract curious people into the ocean following the lost water) followed by a train of large waves which break down at the shore and lead to tragedies such as the 2004 tsunami in Thailand, as discussed in Lecture 7. In summary, although the shallow-water equations are similar to the equations of gas dynamics in 2-D, breaking water waves seem to be more complicated than ordinary shock waves in gas dynamics and how to model wave breaking properly remains an open question.

References

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