Ocean Waves

I. Some General Considerations about Waves

Perhaps the easiest way to think about waves moving across the ocean is to imagine that we are at the edge of a pond. We throw a rock into the middle of the pond. What do we see happening to the water surface? We see many "ripples" on the water surface travelling away from the location where the rock landed. This is rather similar to what happens when the wind generates waves.

Suppose a storm is situated in the Pacific Ocean south of Alaska. In this storm, the wind initially blows on the water and creates a "confused sea". By this we mean that there is not any particular direction that the waves are coming from. However, as the wind continues to blow and the waves increase in energy and begin to move faster than the storm, the waves begin to move in one direction and leave the general area of the storm, pushed by the wind.

This is similar to the way in which the ripples caused by the rock landing in the pond travel away from the rock's impact location and move towards the shore. In the case of the storm, the waves that travel long distances away from the storm are called ***swell waves***. A group of these waves together is called a ***wave train***. These wave trains travel away from the storm's center. The distance of travel is influenced by the amount of energy they receive from the wind. It is common for waves generated by a storm near Alaska to travel to the Hawaiian Islands and beyond!

A. <u>How do Waves Really Move?</u>

- Waves move by the transmission of energy by cyclic movement through matter. The medium itself (i.e., water) does not travel. Wave motion is NOT water flow, but is a flow of <u>energy</u>.
- This is the same as sound waves…the energy travels, not sound “particles”

B. Types of waves

- **Progressive waves** are any waves that you can see moving through the water.
- They are divided into 3 broad classes:
    1) Longitudinal (push-pull) – a good example are sound waves
    2) Transverse (side to side) – energy moves at right angles to the wave. Think of a rope that you send waves down.
    3) **Orbital** (interface waves) These occur at the interface of two materials with different densities (e.g. air and water)

- Ocean waves are all orbital waves, and are characterized by a circular (orbital) motion. They combine the characteristics of longitudinal and transverse waves

II. Defining a Wave

- Any wave can be described mathematically. It doesn't matter whether it's a light wave, seismic wave, sound wave, or ocean wave…the same rules apply

A. Mathematical Description

a. The **Height (H)** of a wave is the distance between the top, or crest, of the wave, and the bottom, or trough, of the wave.
b. The **Wavelength (L)** is the distance between any two similar points…in other words, the distance between the crests is the same as the distance between the troughs
c. The **Steepness** is simply the ratio of height and length (H/L)
d. The **Period (T)** is the time it takes for one wavelength (L) to pass a point
e. **Speed (S)** equals L/T, or how much distance (L) a wave covers in time (T)
f. **Frequency (f)** is 1/T, so S = L x f

- Because waves move much more slowly than light or sound, we don't use frequency very often (it's not very convenient). We usually talk about the Period or Speed instead.
- For a "pure" wave, there is no flow of particles…only the energy is propagated! Particles in a wave travel in a circular motion, with the circle diameter equal to H.
- In water, the wave particles slow down with depth, so that at L/2, there is essentially no motion

- Because the trough moves a little bit slower than the crest, there's actually a small net transport of particles (water) along the energy path, though, so ocean waves are not "pure" waves
- The period of a wave is set when the wave is created…therefore, any change in the wave results in a change in wavelength, and so results in slowing it down, speeding it up, or changing the height.

B. <u>Classification</u>

- We divide waves up into groups, dependent on their mathematical properties and how they are formed

1) Deep-Water Waves: deeper than L/2, so they don't feel the bottom at all
    - Speed is determined by L/T, but it's hard to measure L
    - So, we measure T, the Period
    - Using the equation: $S = gT / 2\pi$, we can calculate S (g is the gravitational constant)
    - Simplifying this, $S = 1.56 \times T$ (m/s)
    - Therefore, speed is controlled by length and period
    - These form the "pure" circular orbits

2) Shallow-Water Waves: The depth (d) of these waves is less than 1/20 the wavelength (L). Also called long waves.
    - Wind waves that move inshore become shallow-water waves
    - Tsunamis are always shallow-water
    - Tide waves are another example
    - Tsunamis and Tides are examples of shallow-water waves because they have a very long wavelength (L)
    - Speed, S = square root of g x d, or $3.1 \times d^{1/2}$
    - Therefore, speed is controlled by depth (increases with depth)
    - Shallow-water wave motion is flattened out, so the particles move in a shallow, elliptical pattern…almost horizontal

3) Transitional Waves: Length is greater than 2x but less than 20x depth (d)
    - They have properties somewhere between deep and shallow waves

III. Generating Waves

A. <u>Wind-Generated</u>

a. The smallest waves formed at the lowest wind speeds are ***capillary waves***
   - the restoring force is surface tension. (the restoring force is the force that tends to destroy waves)

b. As the wind speed increases, the next stage of waves are ***gravity waves***, named for their restoring force, gravity
   - as the wave height increases, it overcomes surface tension, and is instead dragged back down by gravity

B. White Caps

a. If the wind continues to blow, energy is continually transferred from the wind to the waves. Energy increases as:

1) Wind Speed (remember, 2-3% energy transfer!)
2) Duration (how long the wind blows)
3) Fetch (the distance over which the wind blows continuously)

- With increasing energy, the waves increase in H, L, S
- When wave speed equals wind speed, then no more energy can be transferred
- At that point, the wave has reached its maximum size (energy) without interacting with something other than winds

b. The entire area where winds create waves is called "***sea***", and is usually made up of many different sized waves moving in all directions

- When a storm moves through, lots of random waves are formed as the wind changes intensity and direction…this forms a "***confused sea***"
- When speed, duration, and fetch are maximal, you get ***"fully developed seas"***
- This means you can't get any bigger, even with more energy input
- This is because as energy increases, steepness increases…when H = 1/7 L, the wave forms ***white caps*** or ocean breakers
- Once white caps form, the wave loses as much energy from breaking as it picks up from increased energy

C. Swell

- When waves move beyond the area (sea) where winds are generating waves, you end up with waves moving faster than the local winds
- Steepness decreases, but there is essentially no loss of energy

- ***Swell*** refers to waves that move toward the ocean margin away from the wind source, become long-crested waves and may travel great distances with little loss of energy.
- Waves from Antarctic storms have broken on the coast of Alaska, 8,000 miles away!
- Eventually much of this energy is released along the ocean margins when swells hit the shore, causing erosion.

- Waves with a longer wavelength move faster and therefore leave the area where they are produced sooner. This forms ***wave trains***
- The faster waves are followed by slower waves. This sorting by wavelength is called ***wave dispersion***.

D. Interference patterns (not a type of wave, but necessary to discuss this out of order to understand the other wave types)
- These form when two waves collide. They produce the algebraic sum of their individual disturbances.
- Interference can be:
    1) constructive (in phase, add crest to crest or trough to trough)
    2) destructive (add crest to trough),
    3) or most commonly mixed (constructive and destructive)

E. Rogue waves
- These are very rare large waves, probably due to unusual constructive wave interference.
- They are most frequent downwind from islands or shoals or where storm waves move against strong ocean currents, such as the Agulhas current off the southeastern coast of Africa.
- Rogue waves may sink or damage ships and often wash fishermen off rocks. Storm waves can often combine to produce waves as large as a 7-8 story building or 20-30 meters!

F. Storm surge
- A low pressure system such as a hurricane produces a hill of water which moves with the storm. As the storm approaches shallow water, the part of the hill blowing ashore produces a storm surge which raises the sea level.
- Storm surges can be very destructive in low-lying areas and may be the major cause of damage in some storms.

- These can become much larger than wind waves because they are the result of low pressure systems, and are not regulated by our wave math

G. <u>Tsunamis</u> (means “Harbor Wave” in Japanese)
- These are often incorrectly referred to as tidal waves

- Tsunamis are shallow water waves caused by seismic activity (sudden movement of earth's crust).
- This can be generated by an earthquake, volcano, explosion, a disturbance of sea floor, etc.
- The wavelengths of tsunamis can be >200 km (125 miles). The speed is determined by water depth, and the speed can exceed 700 km/h (435 miles/hour).
- These are very small waves at sea, but very large when they reach land and can cause great damage
- The leading edge of a tsunami can be a trough or a crest (so you may see a retreating 'tide' before the flood); or a wall of water may come straight in (some surfers actually seek out tsunamis - this is very dangerous!). Typically there is a withdrawal of water before one or more very large waves rushes into the shore.
- There are warning systems for tsunamis, which are particularly prevalent in the Pacific (Why?)

<u>H. Internal Waves</u>
- These are waves that travel along a density interface within the ocean
- Their heights may exceed 100 m (330 ft). The greater the density difference, the faster the waves will move.
- They often move along the pycnocline.
- They are poorly understood but well-documented. They may be caused by tidal forces or other underwater energy inputs such as turbidity currents or storms.
- They require little energy input because of small density differences.
- They are thought to move as shallow-water waves at speeds slower than surface waves.

IV. Wave Interactions with the Shore

<u>A. Surf</u>
- The energy of swells is released in the surf zone, where breakers form.

- This is because deep-water waves eventually reach water depths that are less than one-half of their wavelength.
- Friction removes energy from the waves and the wavelength decreases in the surf zone
- The wave height increases and when the steepness (H/L) reaches 1/7 (at a water depth of 1.3 times the wave height), the wave breaks as ***surf***.
- When the water depth becomes less than 1/20 of the wavelength, waves behave as shallow water waves and are greatly hampered by the bottom.
- There is a significant transport of water towards the shore under these condition (it goes from circular to horizontal movement)

<u>Plunging breakers</u> have a curling crest that moves over an air pocket. The curling particles outrun the wave. This usually occurs on moderately steep beach slopes, and surfers love these waves!

<u>Spilling breakers</u> are a more common type of breaker found on more gentle beach slopes. They last longer than plunging breakers because their energy is removed more slowly.

B. <u>Wave refraction</u>

- Waves seldom approach the shore at exactly a 90 degree angle, so the part that contacts the bottom first is bent or ***refracted***.
- The orthogonal lines of equal energy are always bent toward shallow water.
- This explains why wave energy is often bent toward headlands (which are therefore subject to erosion) with an increased wave height.
- Bays on the other hand receive more dispersed energy which may deposit sediment.

C. <u>Wave diffraction</u>

- This is the bending of waves around objects, such as wave energy that moves past barriers into harbors.
- On a smaller scale and more difficult to explain than refraction, diffraction happens because any point on a wave front can be a source which can propagate in any direction.

<u>D. Wave reflection</u>

- Minimum energy loss occurs when a wave is reflected at a right angle.
- Less ideal reflections produced standing waves which have no net movement.
- ***Standing waves***, sometimes called stationary waves because they appear to stand still, have ***nodes*** where there is no vertical movement.

- ***Antinodes*** are the points of greatest vertical movement
- Reflection of a wave from a barrier occurs at an angle equal to the angle of approach to the barrier
- The Wedge in Southern California is an example of reflection and constructive interference that produces a famous body-surfing beach. Its waves may exceed 26 feet (8 m) in height.