Wave Energy and Wave Changes with Depth

Wave Energy

Many forms of energy are carried in heat, light, sound, and water waves. **Energy** is defined as the ability to do work; all forms of energy can be transformed into work. In science, **work** is defined as the movement of an object in the direction of the force applied to it. Waves do work when they move objects. We can see this work when heavy logs move across ocean basins or sand is transported. Work can also be converted into sound energy heard when waves crash on the shore. The powerful energy in waves can also be used to do work by moving generator parts to produce electricity.

Climate Connections: Wave Power

Ocean waves carry huge amounts of energy. The amount of energy can be measured in joules (J) of work, calories (c) of heat, or kilowatt-hours (kWh) of electricity (Table 4.8). The standard measurement of energy in science is the joule.

Table 4.8. Measurements of energy and conversions between measurements

	joule	**calorie**	**kilowatt-hour**
joule A joule (J) is the energy needed to lift 1 kilogram of matter 1 meter at sea level		1 calorie = 4.18 joules	1 kilowatt-hour = 3.6 x 10^6 joules
calorie A calorie (c) is the energy needed to raise the temperature of 1 gram of water 1 degree centigrade. 1 calorie = 1000 kilocalories (also recorded as Calorie with a capital C)	1 joule = 0.24 calories		1 kilowatt-hour = 8.6 x 10^5 calories
kilowatt-hour A kilowatt-hour (kWh) is the standard measurement of energy in the United States. It is equivalent to the work of a kilowatt for one hour (about the power used by a toaster for one hour	1 joule = 2.78 x 10^{-7} kilowatt-hours	1 calorie = 1.16 x 10^{-6} kilowatt-hours	

The amount of energy in a wave depends on its height and wavelength as well as the distance over which it breaks. Given equal wavelengths, a wave with greater amplitude will release more energy when it falls back to sea level than a wave of lesser amplitude. Energy (E) per square meter is proportional to the square of the height (H): $E \propto H^2$. In other words, if wave A is two times the height of wave B, then wave A has four times the energy per square meter of water surface as wave B.

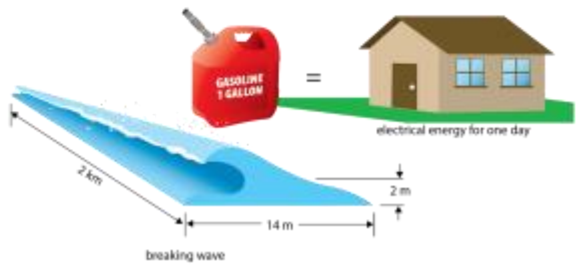

Fig. 4.17. Energy comparison between a wave with a height of 2 m and a wavelength of 14 m breaking over 2 km, a gallon of gasoline, and an average home's daily use shows that the three are relatively equivalent.

Image by Byron Inouye

A wave with a height of 2 m and a wavelength of 14 m breaking along 2 km of coastline (surface area = 32,000 m^2) has approximately 45 kWh of energy. This is roughly equivalent to one gallon of gasoline, which contains about 160 million (1.6×10^8) joules (J) of energy. According to the US Department of Agriculture, the World Bank, and the US Energy Information Administration, the average American eats 3.14 kWh per day in food, uses about 37 kWh in electricity, and uses a combined 250 kWh per day in electricity and petroleum. This means that the energy in one 2 m by 14 m by 2 km wave is equivalent to the amount of energy needed to feed a person for two weeks, power their home for one day, or power their electrical and transportation needs for 5 hours (Fig. 4.17). Ocean waves offer a very large source of renewable energy. Technologies that efficiently harvest this energy resource are actively being researched and developed by scientists.

Orbital Motion of Waves

By watching a buoy anchored in a wave zone one can see how water moves in a series of waves. The passing swells do not move the buoy toward shore; instead, the waves move the buoy in a circular fashion, first up and forward, then down, and finally back to a place near the original position. Neither the buoy nor the water advances toward shore.

As the energy of a wave passes through water, the energy sets water particles into orbital motion as shown in Fig. 4.18 A. Notice that water particles near the surface move in circular orbits with diameters approximately equal to the wave height. Notice also that the orbital diameter, and the wave energy, decreases deeper in the water. Below a depth of half the wavelength (D = 1/2 L), water is unaffected by the wave energy.

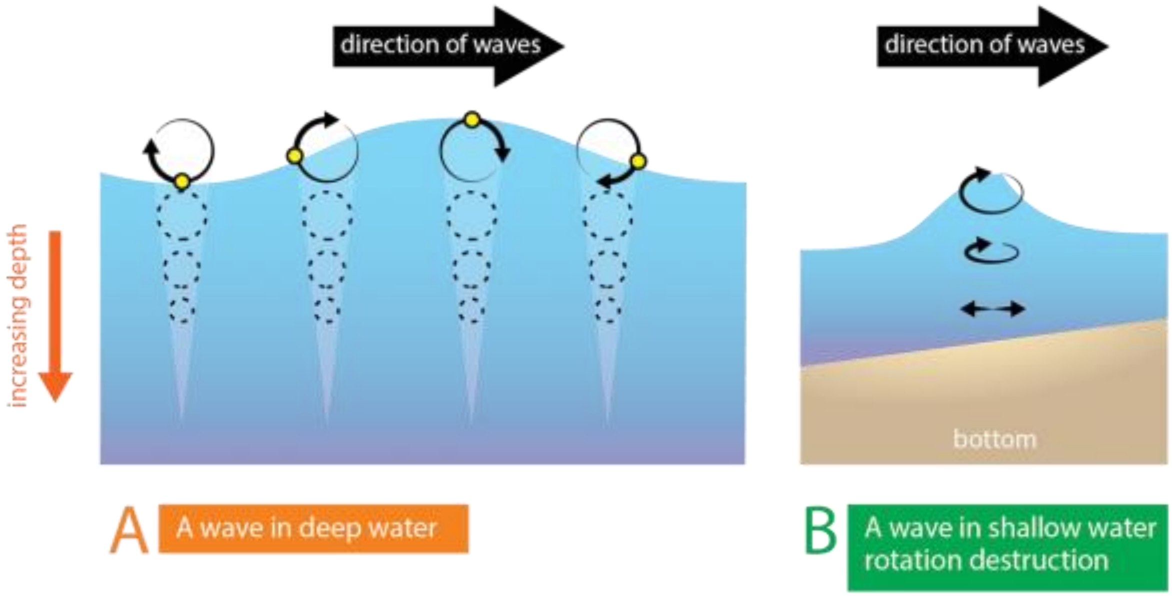

Fig. 4.18. (**A**) If a small buoy (black circle) was on the surface of the water, it would move in a circular motion, returning to its original location due to the orbital motion of waves in deep water. (**B**) As deep-water waves approach shore and become shallow-water waves, circular motion is distorted as interaction with the bottom occurs.

Image by Byron Inouye

Deep-Water, Transitional, and Shallow-Water Waves

Swells are **deep-water waves**, meaning that the depth (D) of the water is greater than half the wave's wavelength (D > 1/2 L). The energy of a deep-water wave does not touch the bottom in the open water (Fig. 4.18 A).

When deep-water waves move into shallow water, they change into breaking waves. When the energy of the waves touches the ocean floor, the water particles drag along the bottom and flatten their orbit (Fig. 4.18 B).

Fig. 4.19. The action of someone tripping is similar to the interaction between a shallow-water wave and the bottom of the ocean

Image by Alyssa Gundersen

Transitional waves occur when the water depth is less than one-half the wavelength (D < 1/2 L). At this point the water movement of particles on the surface transitions from swells to steeper waves called **peaking waves** (Fig. 4.19). Because of the friction of the deeper part of the wave with particles on the bottom, the top of the wave begins to move faster than the deeper parts of the wave. When this happens, the front surface of the wave gradually becomes steeper than the back surface.

When the water depth is less than one-twentieth the wavelength, the wave becomes a **shallow-water wave** (D < 1/20 L). At this point, the top of the wave travels so much faster than the bottom of the wave that top of the wave begins to spill over and fall down the front surface. This is called a **breaking wave**. A breaking wave occurs when one of three things happen:

1. The crest of the wave forms an angle less than 120˚,
2. The wave height is greater than one-seventh of the wavelength (H > 1/7 L), or
3. The wave height is greater than three-fourths of the water depth (H > 3/4 D).

In some ways a breaking wave is similar to what happens when a person trips and falls. As a person walks normally, their feet and head are traveling forward at the same rate. If their foot catches on the ground, then the bottom part of their body is slowed by friction, while the top part continues at a faster speed (see Fig. 4.19). If the person's foot continues to lag far behind their upper body, the angle of their body will change and they will topple over.

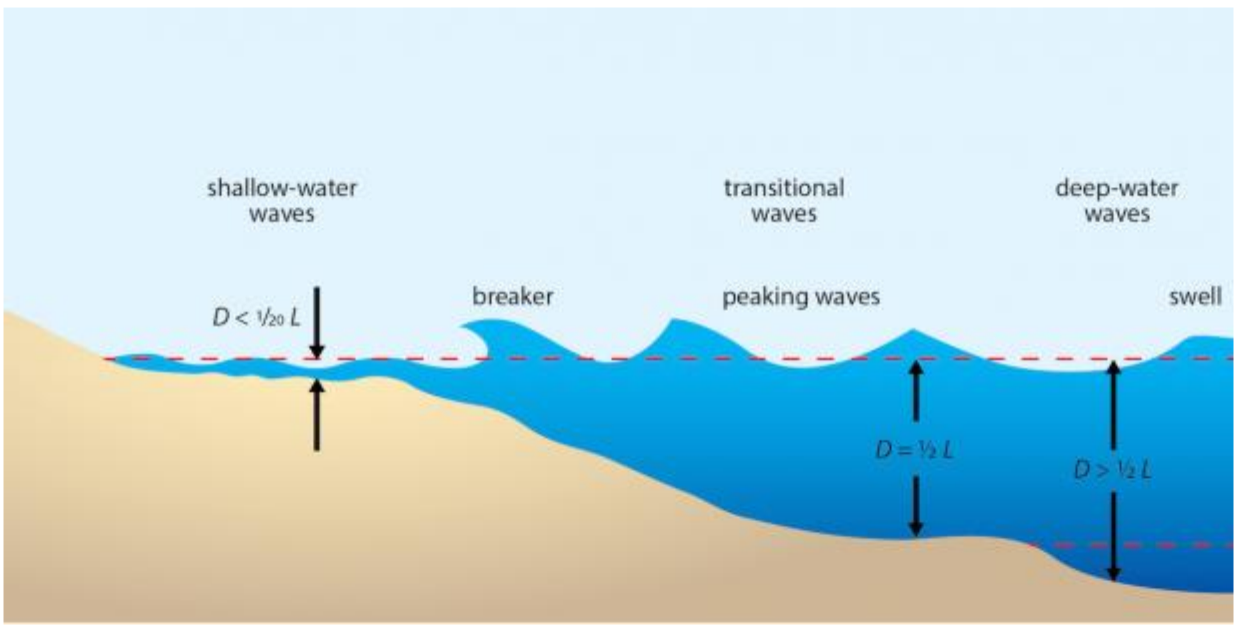

Fig. 4.20. Waves change as they approach the shore.

Image by Byron Inouye

The transition of a wave from a deep-water wave to a shallow-water breaking wave is shown in Fig. 4.20. Terms relating to wave depth a described in detail in Table 4.9.

Table 4.9. Terms relating waves to water depth

Symbols

D = Depth of water
L = Length of wave
H = Height of wave

Deep-water waves

Deep-water waves are waves traveling across a body of water where depth is greater than half the wavelength (D > 1/2 L). Deep-water waves include all wind-generated waves moving across the open ocean.

Transitional waves

Transitional waves are waves traveling in water where depth is less than half the wavelength but greater than one-twentieth the wavelength (1/20 L < D < 1/2 L). Transitional waves are often wind-generated waves that have moved into shallower water.

Shallow-water waves

Shallow-water waves are waves traveling in water where depth is less than one-twentieth the wavelength (D < 1/20 L). Shallow-water waves include wind-generated waves that have moved into shallow, nearshore areas, tsunamis (seismic waves) generated by disturbances in the ocean floor, and tide waves generated by the gravitational attraction of the sun and moon.

Breaking shallow-water waves

Breaking shallow-water waves are unstable shallow-water waves. Usually shallow-water waves begin to break when the ratio of wave height to wavelength is 1 to 7 (H/L = 1/7), when the wave's crest peak is steep (less than 120˚), or when the wave height is three-fourths of the water depth (H = > 3/4 D).

Breaking deep-water waves

Breaking unstable deep-water waves are waves that begin to break when the seas are confused (waves from mixed directions) or when the wind blows the crests off waves, forming whitecaps.