AMERICAN METEOROLOGICAL SOCIETY

The Maury Project

SHALLOW-WATER OCEAN WAVES

TEACHER'S GUIDE

The Maury Project

This guide is one of a series produced by The Maury Project, an initiative of the American Meteorological Society and the United States Naval Academy. The Maury Project has created and trained a network of selected master teachers who provide peer training sessions in precollege physical oceanographic education. To support these teachers in their teacher training, The Maury Project develops and produces teacher's guides, slide sets, and other educational materials.

For further information, and the names of the trained master teachers in your state or region, please contact:

The Maury Project
American Meteorological Society
1200 New York Avenue, NW, Suite 500
Washington, DC 20005

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Forward

This guide has been prepared to introduce fundamental understandings about the guide topic. This guide is organized as follows:

Introduction

This is a narrative summary of background information to introduce the topic.

Basic Understandings

Basic understandings are statements of principles, concepts, and information. The basic understandings represent material to be mastered by the learner, and can be especially helpful in devising learning activities and in writing learning objectives and test items. They are numbered so they can be keyed with activities, objectives and test items.

Activities

These are related investigations. Each activity typically provides learning objectives, directions useful for presenting and completing the activity and questions designed to reinforce the learning objectives.

Information Sources

A brief list of references related to the guide topic is given for further reading.

If we except the tides, and ... those that may be created by the wind, we may lay it down as a rule that all the currents of the ocean owe their origin to difference of specific gravity between sea water at one place and sea water at another; for wherever there is such a difference, whether it be owing to difference of temperature or to difference of saltiness, etc., it is a difference that disturbs equilibrium, and currents are the consequence.

Matthew Fontaine Maury
from The Physical Geography of the Sea. 1855.

Introduction: Shallow-Water Ocean Waves

Shallow-water ocean waves are waves occurring at the sea surface which are affected by the ocean bottom. These waves are created when the water's surface is disturbed by wind, gravity, earthquakes, or seafloor landslides. As a wave passes, the water surface is restored toward its original condition by the gravitational force exerted by Earth or, for the smallest ripples, by surface tension.

The patterns of shallow-water waves observed on the near-shore ocean surface are complex and ever changing. However, these patterns can be investigated by considering the characteristics of ideal waves. The pattern exhibited by an ideal ocean wave can be described by a number of characteristics including length, height, period, and speed. These characteristics are determined by factors that generate the wave, and for shallow-water waves, the wave's interaction with the ocean bottom.

Once formed, waves may travel very long distances. As the waves travel, they transfer energy through ocean waters without a significant horizontal transport of the water itself. Because deep-water waves do not interact with the ocean bottom as they travel, their speed is independent of the water depth.

But as waves enter shallow water, interaction with the bottom alters the waves. Wave speed decreases, wavelength shortens and wave height increases. Eventually shallow-water waves become so high and unstable that they break and create surf. During this process, shallow-water waves erode and transport sediment, altering the bottom. The newly altered bottom, in turn, affects the next wave to come along.

Tides and tsunamis, are special examples of shallow-water waves. Tides are shallow-water waves with global dimensions, generated by the gravitational attraction of the Moon and Sun. Seismic sea waves, called tsunamis, are ocean waves generated by a submarine earthquake, landslide or underwater volcanic eruption. With wavelengths up to hundreds of kilometers, tsunamis may cross entire oceans as shallow-water waves before encountering a coastline, often with disastrous results.

Shallow-water waves are studied because of their impacts on coasts, the economy, recreation, and defense. Although there is still interest in shallow-water waves as a source of pollution-free renewable energy, present day research is more focused on their role in near-shore geological, chemical, and biological processes. Breaking waves are also being investigated for their impact on beach erosion and coastal habitats as well as an important mechanism contributing to the exchange of energy and material across the air-sea interface.

Basic Understandings

Ocean Waves

1. An ocean wave is a pattern of rising and falling water level that is transmitted along the sea surface.

2. Ocean waves transmit energy away from an initial disturbance without the physical transport of water.

3. The patterns of rising and falling water observed on the ocean surface are complex and ever changing. However, these patterns can be investigated by studying ideal waves.

Ocean Wave Characteristics

1. The pattern exhibited by an ideal ocean wave can be described by a number of characteristics, including wave height, wavelength, period, and speed.

2. The highest point of each wave is the **wave crest**, and the lowest point is the **wave trough**.

3. The vertical distance between the wave crest and trough is the **wave height**. The greater the wave height, the more energy associated with the wave.

4. The horizontal distance between the crests or any other two corresponding points of consecutive waves, is the **wavelength**.

5. The time it takes for two successive wave crests (one wavelength) to pass a fixed point is the **wave period**. Once a wave forms, its period remains constant.

6. How fast a wave is moving, the **wave speed**, can be determined by dividing the wavelength by the period.

7. The factors that generate a wave help determine its height, wavelength, period, and speed.

Waves in Motion

1. Wind, gravity, and earthquakes disturb the water surface and generate ocean waves. After a wave passes, the water surface is restored by gravity or, for the smallest ripples, by surface tension.

2. Ideal waves transfer energy through ocean waters without significant horizontal transport of the water itself.

3. A side view of the ocean surface with a wave moving from left to right would show water particles near the surface moving in clockwise circles called **orbits**. If the wave moves from right to left, then the orbits are counterclockwise.

4. The diameter of the orbits of water particles at the surface is equal to the wave height.

5. The diameter of the orbits of the water particles decreases with increasing depth below the surface. Orbital motion is negligible below a depth of about one-half the wavelength.

6. **Deep-water waves** are those occurring in water with a depth greater than one-half the wavelength. There is no significant interaction between the orbital motion associated with deep-water waves and the sea bottom.

Wave Characteristics in Shallow Water

1. Waves that occur in water with depths less than one-half their wavelengths interact with the bottom and some of their characteristics are altered. As they advance through water whose depth is decreasing, some of their characteristics are increasingly altered.

2. Waves existing where the water depth is between one-half and one-twentieth the wavelength are called **transitional waves**. These waves exhibit the increasing effects of the ocean bottom as water depth decreases.

3. A **shallow-water wave** exists in water shallower than one-twentieth the wavelength. These waves are strongly affected by the ocean bottom because of the relatively small water depth.

4. Although the wave period remains constant, waves interacting with the ocean bottom slow down, their wavelengths shorten, and wave heights increase.

5. The wave speed in shallow-water waves is related to water depth, rather than wave period as it is for deep water waves. The shallower the water, the slower is the wave speed.

6. In shallow water, the orbits of the water particles gradually flatten from circular to elliptical and ultimately to back-and-forth motion as the bottom is approached.

Waves Approaching Shore

1. With a gently sloping sea bottom, waves approaching a shoreline at other than a right angle are bent, or **refracted**, so their crests turn to a more parallel alignment with the shore. This refraction focuses wave energy on a headland and disperses wave energy along a bay coastline.

2. As a wave enters shallow water, wave height increases and wavelength decreases. As the ratio of wave height to wavelength, called **wave steepness**, increases, the wave becomes less stable.

3. The breaking of shallow-water waves is dependent on a number of factors such as the slope of the ocean bottom, with the relationship between wave height and mean water depth being of major importance. Generally, the greater the ratio between wave height and water depth, the more likely the wave will break.

4. The band of nearly continuous breaking waves, or **breakers**, along the shore is called **surf**.

Tides and Other Shallow-Water Ocean Waves

1. **Tides** are shallow-water ocean waves of global dimensions, generated by the gravitational attraction of the Moon and the Sun. High tide is the crest of the wave and low tide the trough.

2. Seismic sea waves, called **tsunamis**, are ocean waves, generated by submarine earthquakes, volcanic eruptions, or landslides. Tsunamis have such a long wavelength that they travel as shallow-water waves across an ocean basin.

3. As tsunamis approach the coast, interaction with the bottom results in a rapid decrease in wave speed and wavelength and a rapid, potentially dangerous, increase in wave height.

Activity: Breaking Waves

Introduction

As ocean surface waves approach shore, they build, become too high for their supporting base, and eventually break to produce surf. This happens as the orbital motions of water that move the waves forward are affected by the change in water depth. Waves in water deep enough so that the bottom has no effect on them are termed deep-water waves, whereas waves most affected by the bottom are called shallow-water waves. Those in between are called transitional waves. The physical characteristics of both transitional and shallow-water waves are altered by interaction with the bottom.

This activity uses the simulated advance of surface waves toward shore to investigate changes in wave characteristics that eventually lead to breakers and surf. The simulation assumes an ocean bottom that slopes gradually upwards toward shore.

Materials

Paper-towel tube, photocopies of diagram pages, scissors, 3/4" clear tape, pencil.

Objectives

After completing this activity, you should be able to:

- Describe the major characteristics of shallow-water waves.
- Describe how these characteristics change as the water becomes shallower.
- Describe the water motions associated with shallow-water ocean waves.

Investigations

1. Build the ***Wave Tube*** by first following the directions on the ***Wave Page*** to construct the cylindrical insert part of the device. Then follow the directions on the ***Shore Page*** to build the outer sleeve.

2. Hold the completed Wave Tube horizontally by its outer sleeve with its window on top and the beach end away from you. Rotate the cardboard cylinder clockwise a few times until it turns smoothly. Look through the viewing window while turning the cylinder. In the window is a view of a strip of coastal ocean surface, perpendicular to the shore, with labels marking deep-water, transitional, and shallow-water zones. The moving dark lines represent wave crests, the highest parts of each wave. As the tube is rotated clockwise, a succession of wave

crests can be seen crossing the ocean surface and moving into (***shallower***) (***deeper***) water. (Note: For the purposes of this activity, imagine that the wave crests are all parallel to the shoreline.)

3. Ocean waves can be described by several characteristics. One is wavelength, the horizontal distance between any two successive wave crests (or other corresponding points on the wave). You can approximate wavelengths on the Wave Tube by using the scale marked in increments of 10 meters along the viewing window. Imagine yourself on the "boat" anchored in the deep-water wave part of the tube. Turn the cylinder until a wave crest is lined up with the boat's bow. Using the scale, measure the distance to the next wave crest in the direction towards shore. Record this wavelength value on the ***Wave Characteristics*** page in the deep-water wave part of the table. Repeat the procedure at the locations of the boats in the transitional and shallow-water zones and record your measurements. Your observations show that as the wave travels from deep into shallow water, the wavelength (***increases***) (***remains the same***) (***decreases***).

4. An ocean wave is also described by its wave period, the time it takes one wavelength to pass a fixed point. To determine the wave period of waves passing by the boat anchored in deep water, turn the cylinder until a wave crest is lined up with the boat's bow. Then count the number of waves which pass by the boat in one complete rotation of the tube, which represents 16 seconds of elapsed time. (Note: You can determine one rotation by making a mark on the cylinder part of the Wave Tube. Then, turn the cylinder until the mark returns to its original position.) Calculate the wave period by dividing the time, 16 seconds, by the number of waves which passed the boat. Record in the ***Wave Characteristics*** table. Repeat the procedure to determine wave periods in the transitional and shallow-water zones. Your observations indicate that as the waves travel from deep to shallow water, the wave period (***increases***) (***remains the same***) (***decreases***).

5. Ocean waves are also described by their wave speeds. Wave speed is determined by dividing the distance traveled by the travel time. Because you have already determined the time it took waves of different wavelengths to travel one wavelength, you can calculate their wave speeds. Divide each wavelength by its wave period, and place the resulting wave speed in the ***Wave Characteristics*** table. Your results show that as a wave travels from deep to shallow water, the wave speed (***increases***) (***remains the same***) (***decreases***).

6. The *Wave Tube* shows the movement of wave crests across the ocean surface as seen from above. On the ***Wave Characteristics*** page, the *Water Motion* figures show the idealized internal motions of water particles in vertical cross-sections as the surface waves progress shoreward. The side views show the changing positions of surface water particles as crests and *troughs*, the lowest

parts of waves, pass by. In the deep-water zone, particles of water are sent in near circular motion, called orbits, by the energy of the passing wave. These circular motions decrease downward, until at a depth one-half the wave's wavelength, they are negligible. At lower depths, there is no significant water motion associated with the passing wave. Consequently, a wave is classified as a *deep-water wave* if it is in water that is deeper than one-half its wavelength.

You recorded in the table a wavelength of _______ meters for a wave in the deep-water zone of the *Wave Tube*. That wave must have been in water with a depth of at least _________ meters to be classified as a deep-water wave. Record this value in the table.

7. Beginning in the transitional-wave zone and throughout the shallow-water zone, interactions with the bottom cause the shape of the orbits of water particles near the surface to become more (***circular***) (***elliptical***) and for water particles near the bottom to become (***circular***) (***elliptical***) (***back and forth***) in their motions.

8. A wave is classified a *shallow-water wave* when it is in water having a depth less than one-twentieth its wavelength. Shallow-water waves strongly move water back and forth just above the bottom. You recorded in the table a wavelength of _______ meters for a wave in the shallow-water zone of the *Wave Tube*. That wave must have been in water with a depth of no more than _________ meters to be classified as a shallow-water wave. Record this value in the table.

9. Transitional waves occur between deep- and shallow-water waves. As their name implies, they exhibit a transition ranging from being almost deep-water to shallow-water in their characteristics as the water depth decreases relative to wavelength. They occur when water depth ranges from ____________ to ____________ the wavelength.

   You recorded in the table a wavelength of _______ meters for a wave in the transitional zone of the *Wave Tube*. That wave must have been in water with a depth between ______ and ______ meters to be classified as a transitional wave. Record these values in the table.

10. Examine the Shore Profile on the ***Wave Characteristics*** page. It summarizes, although not to scale, relationships among deep-water, transitional, and shallow-water waves. It shows that as a wave approaches shore, its wavelength (***increases***) (***decreases***). The wave profile also shows that the *wave height*, the vertical distance between the crest and succeeding trough, (***increases***) (***decreases***) as the water depth decreases. Eventually, the building wave collapses into breakers. The zone of breakers near shore forms *surf*.

Questions

1. One wavelength is the distance between two successive wave crests. Wave period is the time required for (***1/20***) (***1/2***) (***1***) wavelength to pass by a fixed point.

2. Speed is equal to the distance traveled divided by the travel time. For ocean waves, wave speed is equal to (***wave length***) (***wave period***) divided by (***wave length***) (***wave period***).

3. As a wave moves from deep water towards shallow water, it will begin to interact with the ocean bottom as it passes across water having a depth less than (***1/4***) (***1/2***) (***3/4***) the wavelength.

4. The shallower the water, the (***lesser***) (***greater***) the interaction between a shallow-water wave and the bottom and the (faster) (***slower***) the wave moves.

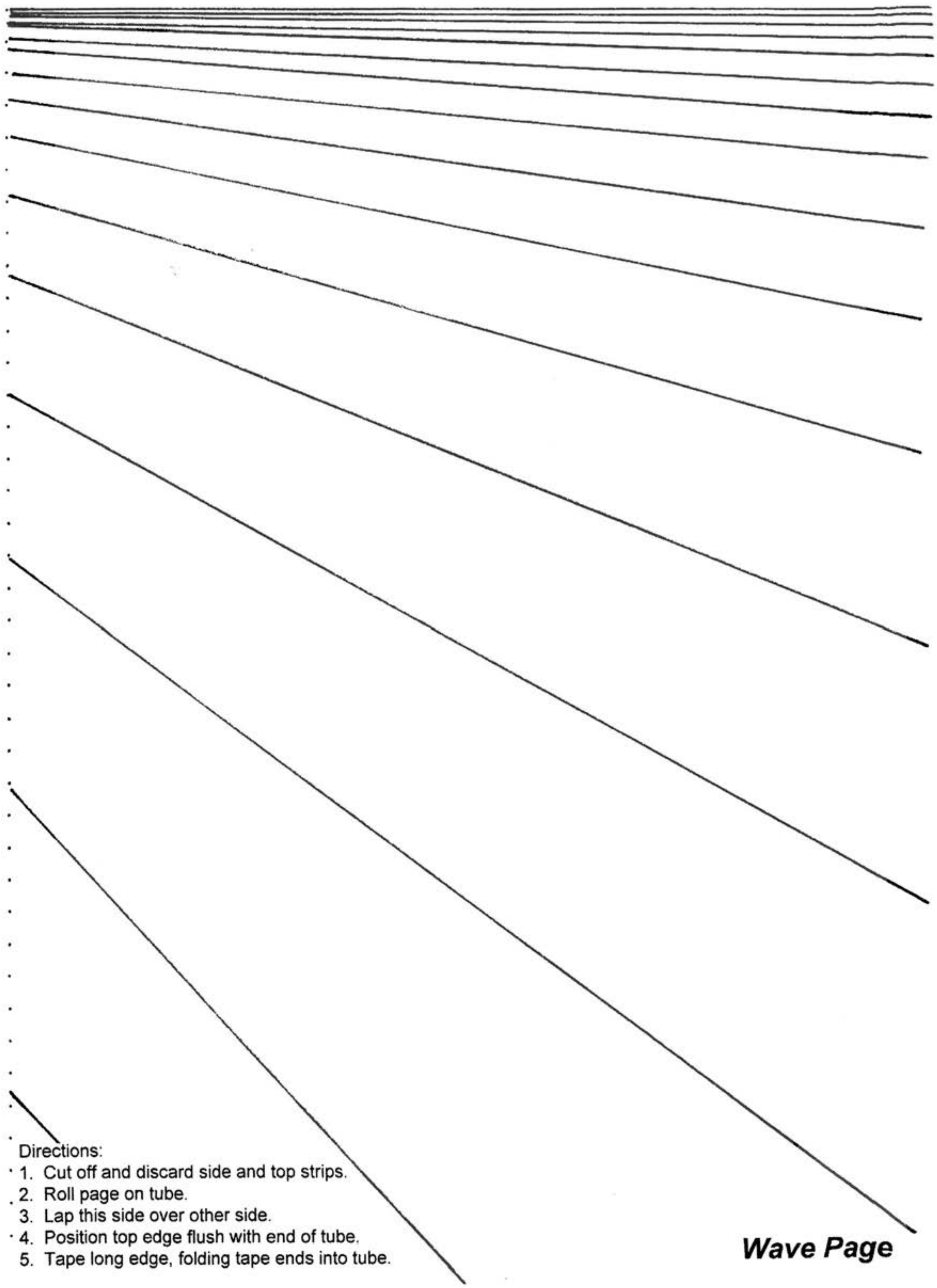
5. You learned from your *Wave Tube* observations that as a shallow-water wave approaches shore, its wave period remains the same and its speed changes. Knowing this and the relationship among wavelength, speed, and period, from question 2 above, it follows that as the wave speed decreases due to interaction with the bottom, wavelength must (***increase***) (***decrease***) (***remain the same***).

6. As a wave enters shallow water, increased wave height results as the wave's energy is packed into less surface area with the accompanying (***increase***) (***decrease***) in wavelength and wave speed.

7. The ratio of wave height to wavelength is a measure of the steepness of a wave. Generally, the steeper the wave, the more likely it will break. A deep-water wave will break when it reaches a steepness value near 1/7. A deep-water wave with a wavelength of 70 meters is likely to break if its wave height reaches ________ meters.

8. The breaking of shallow-water waves is dependent on a number of factors such as the slope of the ocean bottom, with the relationship between wave height and mean water depth being of major importance. Generally, the greater the ratio between wave height and water depth, the more likely the wave will break. A shallow-water wave is (***more***) (***less***) likely to break if its wave height increases while the water depth decreases.

Wave Page

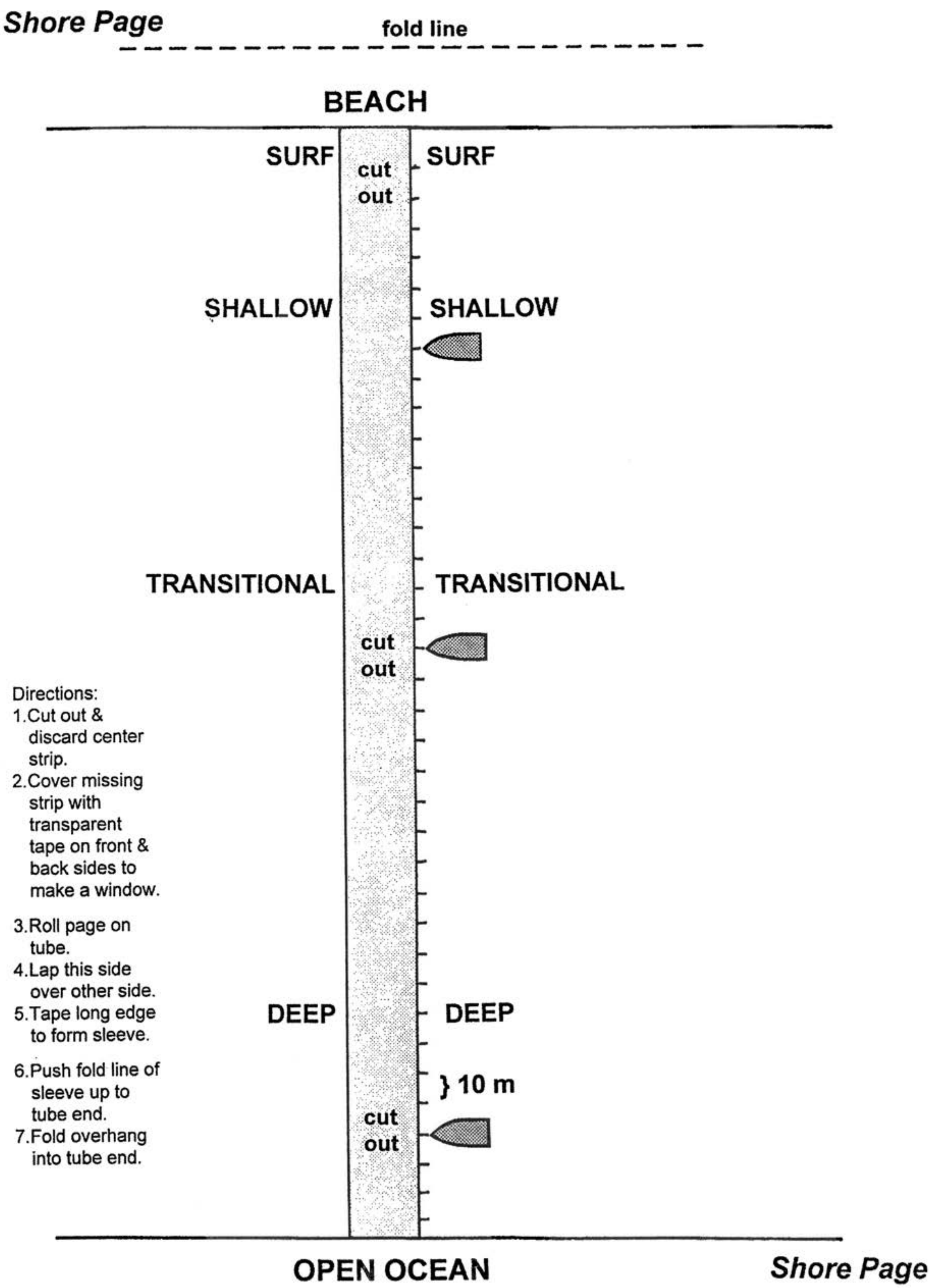


Cut off this strip and strip across top - including dotted lines - and discard.

Directions:

1. Cut off and discard side and top strips.
2. Roll page on tube.
3. Lap this side over other side.
4. Position top edge flush with end of tube.
5. Tape long edge, folding tape ends into tube.

Wave Page

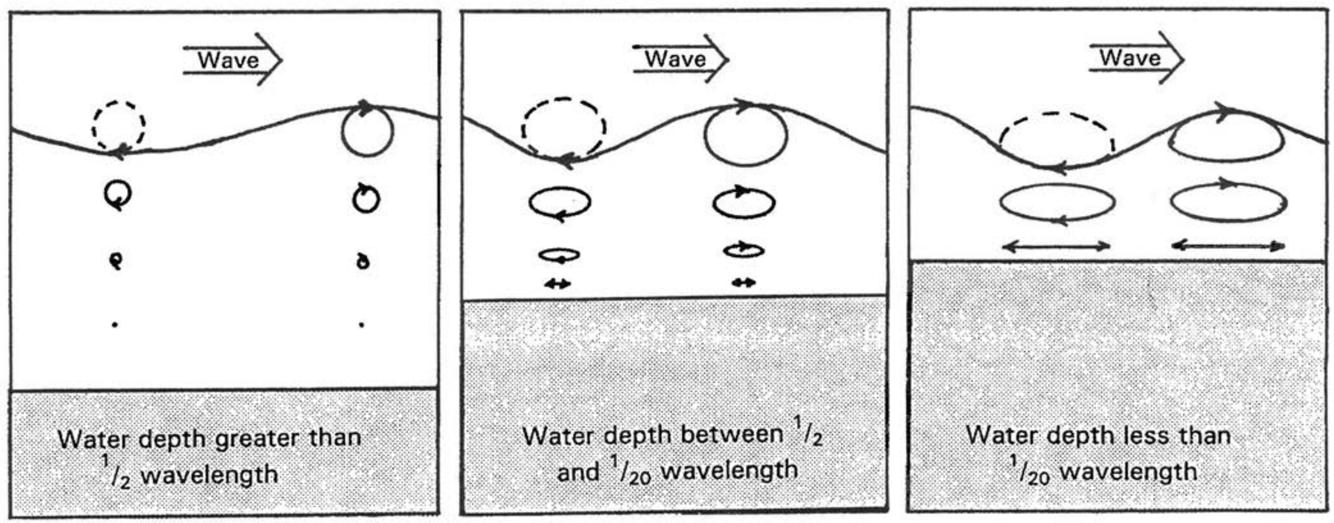

Shore Page
fold line
BEACH
SURF
cut out
SURF
SHALLOW
SHALLOW
TRANSITIONAL
TRANSITIONAL
cut out
Directions:
1.Cut out & discard center strip.
2.Cover missing strip with transparent tape on front & back sides to make a window.
3.Roll page on tube.
4.Lap this side over other side.
5.Tape long edge to form sleeve.
6.Push fold line of sleeve up to tube end.
7.Fold overhang into tube end.
DEEP
DEEP
} 10 m
cut out
OPEN OCEAN
Shore Page

Wave Characteristics Table

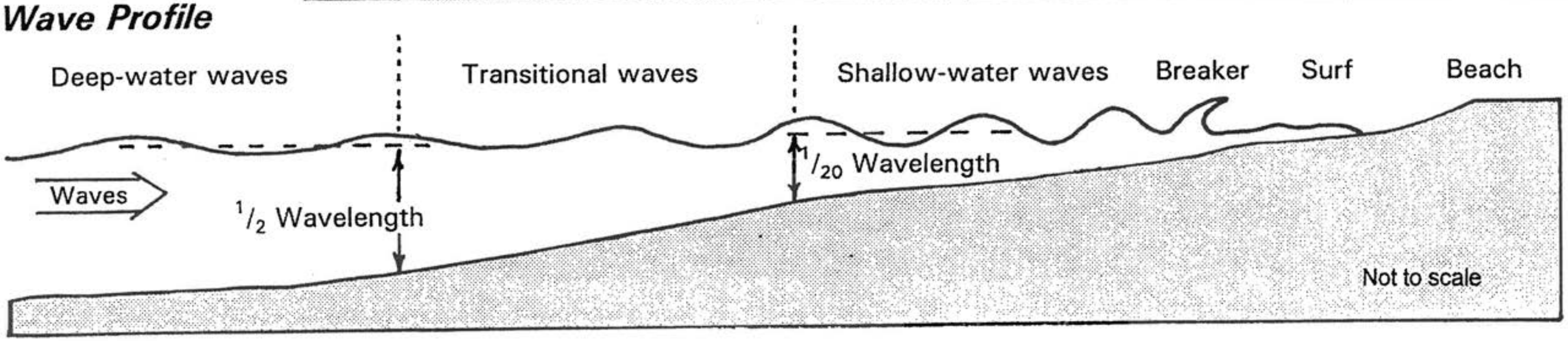
Wave Type	Deep-Water	Transitional	Shallow-Water
Wavelength (m)			
Wave Period (sec)			
Wave Speed (m/sec) = wavelength/period			
Water Depth (m)	More than ______ m	Between ___ and ___ m	Less than ______ m

Water Motion

(not to scale)



Wave Profile



Extensions

A. Tide Extension:

1. Tides are global-scale ocean waves generated by the gravitational attraction of the Moon and Sun acting on the ocean's waters. Moving along the ocean surface, high tide is the crest of the wave and low tide is the trough. Where one or two high tides occur each day, the wave period approaches 12 or 24 hours and the wavelength thousands of kilometers. If the average ocean depth is about 4 kilometers, would the tides be deep, transitional, or shallow-water waves and how would they be influenced by the bottom?

2. The Bay of Fundy is located along the North Atlantic coast near the border of the United States and Canada. The difference between high and low tide can range up to 15 meters at the end of this funnel-shaped bay. Use what you have learned about shallow-water waves to help explain this extreme tidal range.

3. In some coastal rivers, where the channel narrows and the river bed steepens, a high, often breaking wave generated by a tide crest advances rapidly up the river. Since these shallow-water waves, called tidal bores, may range in height up to 5 meters, what would be their effect on navigation?

B. Tsunami Extension:

1. Tsunami, sometimes erroneously called tidal waves, are ocean waves generated by submarine earthquakes, volcanic eruptions, and landslides. They have periods of about a half hour and wavelengths of about 200 kilometers. Considering average ocean depth is about 4 kilometers, would tsunami behave as deep, transitional, or shallow water waves?

2. As a tsunami approaches the shore, a potentially dangerous increase in wave height occurs. Use what you have learned about shallow-water waves to help explain the threat to coastal regions.

3. To alert coastal residents of potential danger, an international tsunami warning network is now in operation around the seismically active Pacific Ocean basin. If an earthquake at midnight in the Alaskan Aleutian Islands produced a tsunami with a quarter-hour period and 180 kilometer wavelength, at what time would the wave be expected to arrive at Hawaii, about 4,000 kilometers away?

4. From what you have learned about other shallow-water waves, why is the term tidal wave not accurate when referring to tsunami?

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