Basics of Ocean Waves and significance in Marine operations

Training Course on
'Remote Sensing of Potential Fishing Zones and Ocean State Forecast'

March 27, 2014

K G Sandhya

Scientist

INCOIS

Ocean surface waves

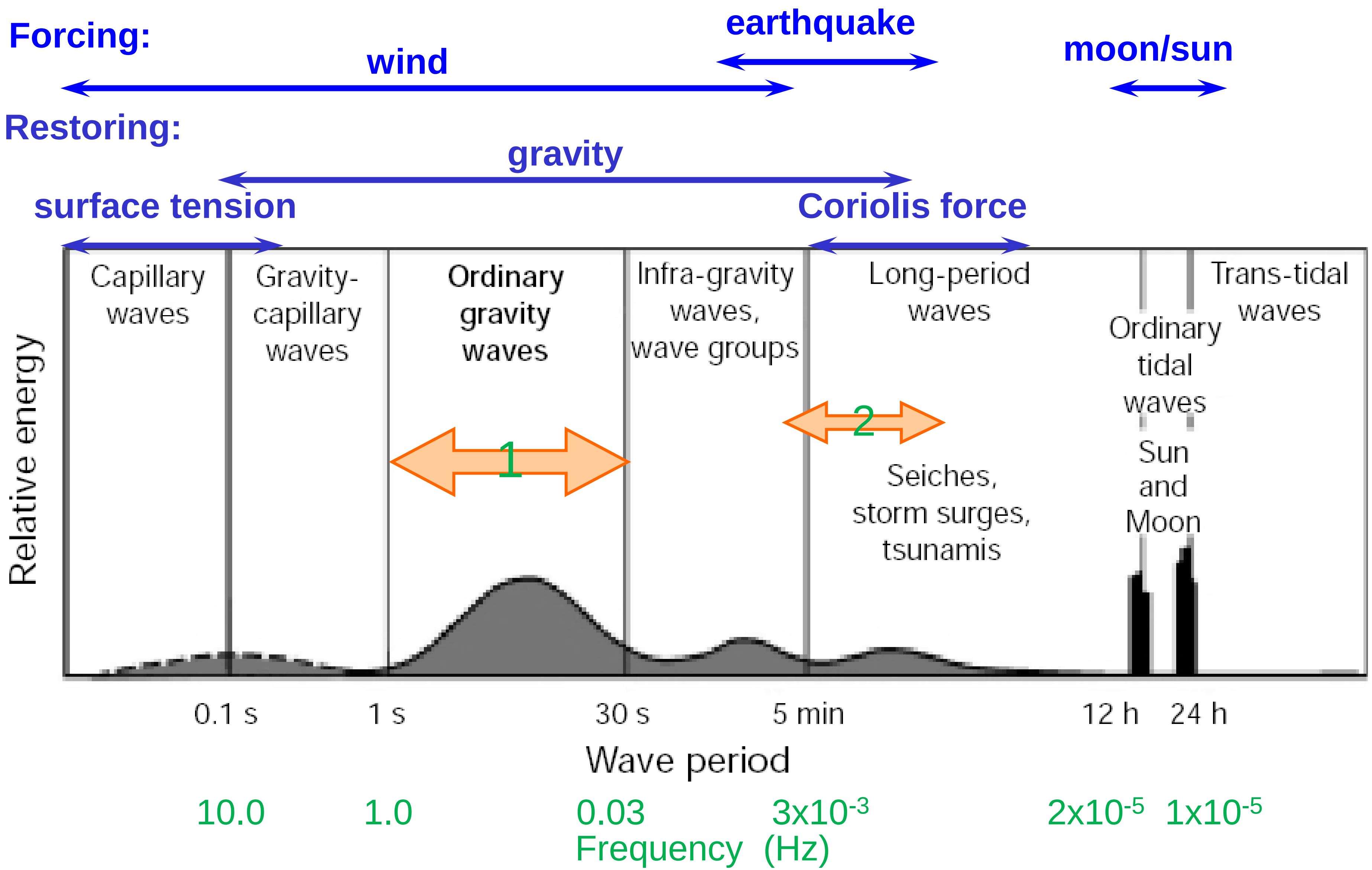
Ocean surface waves are the result of forces acting on the ocean surface.

Predominant natural forces are:

- Stress from atmosphere (through wind)
- Earthquakes
- Gravity of earth and celestial bodies (moon & sun)
- Coriolis force (due to earth’s rotation)
- Surface tension

Characteristics of the waves depend on the controlling Forces.

Classification of ocean waves by wave period (Munk, 1951)

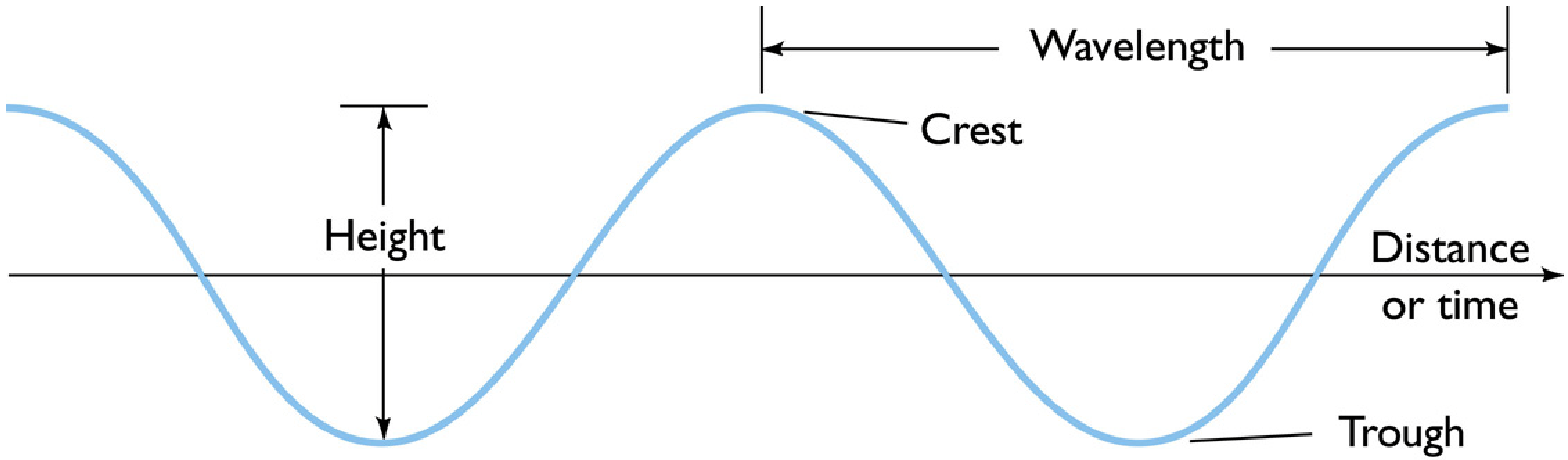


Properties of ocean waves

Waves are the undulatory motion of a water surface.

- Two general wave categories:
  - Progressive waves (waves that move forward across the ocean surface)
    - Surface waves
    - Internal waves
    - Tsunamis
  - Standing waves
    - Seiches (water surface “seesawing” back and forth)

A simple sinusoidal wave



The shape of a wave is defined by the vertical displacement of the water surface from the undisturbed sea level, as a function of both time and space.

OCEAN SURFACE WAVES

- **Wave profile (η)**
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- **Wave crest**
- **Wave trough**
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- **Wave amplitude (a)**
- Wave height (H)
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- **Wave height (H)**
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- **Wave length (L)**
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- **Wave period (T)**
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- Wave period (T)
- **Wave frequency (f)**
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- **Wave number (k)**
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- **Angular wave frequency (σ)**
- Wave celerity (C): (C=L/T).
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- **Wave celerity (C)**
- α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.

OCEAN SURFACE WAVES

- Wave profile (η)
- Wave crest
- Wave trough
- Wave amplitude (a)
- Wave height (H)
- Wave length (L)
- Wave period (T)
- Wave frequency (f)
- Wave number (k)
- Angular wave frequency (σ)
- Wave celerity (C): (C=L/T).
- **α and β: horizontal and vertical water particle displacements respectively, and functions of time and depth.**

Some Definitions

- Crest – highest point of a wave
- Trough – lowest point of a wave
- Wave Height (H) – vertical distance between the crest and the trough
- Amplitude (a) – half the wave height
- Wavelength (L) – horizontal distance between two crests or two troughs
- Wave period (T) – The time in seconds between successive wave crests as they pass a stationary point on the ocean surface
- Wave frequency – reciprocal of wave period (number of crests passing a fixed point in one second)

  F = 1/T

Some Definitions

- Wave number – number of waves per unit distance

$$k = 2\pi/L$$

- Angular frequency – number of radians per second.

$$\omega = 2\pi/T$$

- Wave celerity – is the speed of a wave and is given by the distance travelled by a crest or trough per unit time, commonly referred to as wave speed or phase speed

$$C = L/T$$

- Wave steepness – is the ratio of wave height to wave length

$$S = H/L$$

CLASSIFICATION OF WAVES ACCORDING TO PERIOD (SHORT, INTERMEDIATE AND LONG WAVES)

Wave Classification (Ippen 1966)		
Range of h/L (water depth /wave length)	**Range of kh= 2πh/L**	**Types of waves**
0 to 1/20	0 to π/10	Long waves (shallow-water wave)
1/20 to ½	π/10 to π	Intermediate waves
½ to ∞	π to ∞	Short waves (deepwater waves)

Dispersion relation

The variation of wave speed with wave length is called dispersion and the functional relation is called dispersion relation. It could be expressed as

$$\omega^2 = gk \tanh(kh),$$

where h is the water depth.

For deep water, h is large, hence $\tanh(kh) \approx 1$

$\Rightarrow \omega^2 = gk$

Substituting for ω and k, we have

$$L = \left(\frac{g}{2\pi}\right)T^2 = 1.56\,T^2$$

Further, the wave speed c = L/T = ω/k = $\sqrt{\frac{g}{k}}$

The wave speed in deep water is not a function of water depth, but a function of wave number. Thus deep water waves are dispersive.

Dispersion relation

For shallow water, h is small and hence $\tanh(kh) \approx kh$

=> $\omega^2 = gk^2h$

Further, the wave speed c = L/T = ω/k = $\sqrt{gh}$

The wave speed in shallow water is a function of water depth, but not a function of wave number. Thus shallow water waves are non dispersive.

Wave profile

Wave profile of a simple sinusoidal wave could be expressed as

$$\eta(x,t) = a \sin (kx - \omega t),$$

where a is the amplitude of the wave. The greater the wave's amplitude is, the more energy the wave carries.

If we consider a snapshot at time t=0 then the wave profile is frozen as

$$\eta(x) = a \sin (kx).$$

If a waverider buoy is recording the waves at x=0, then the wave profile will be varying in time as

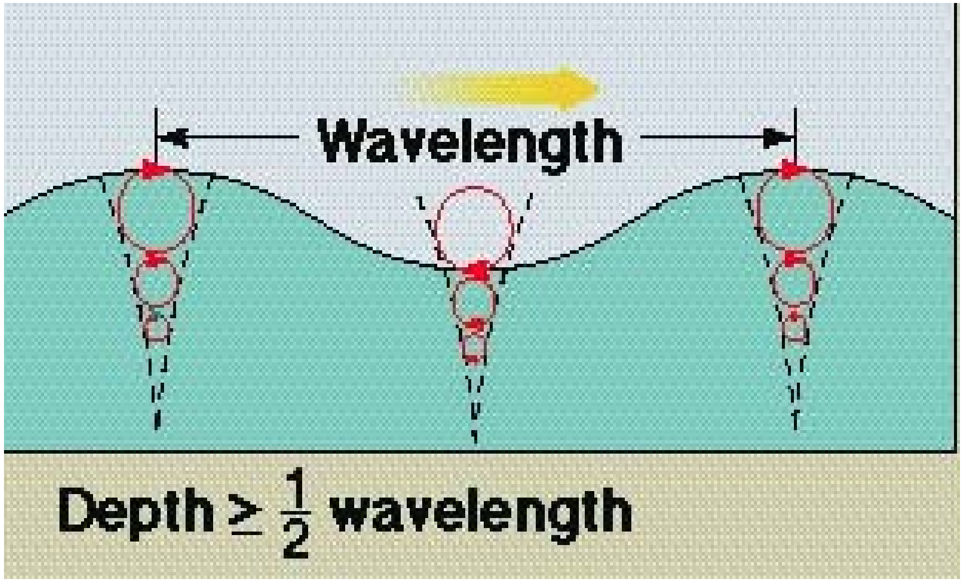
$$\eta(t) = a \sin (- \omega t).$$

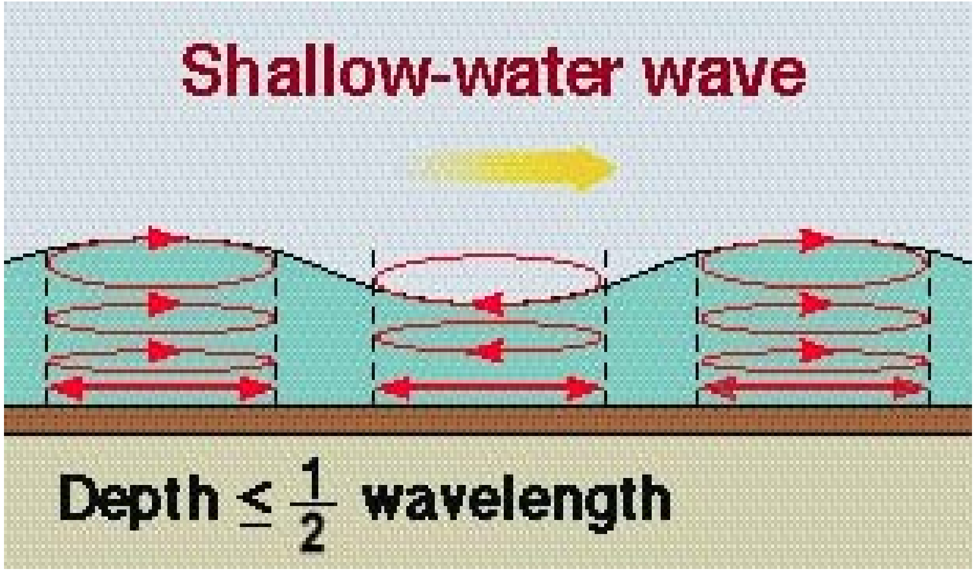
In reality, simple sinusoidal waves are never observed in ocean, only swells passing through an area with no wind will come close.

Orbital motion of water particles

- As waves pass, wave form and wave energy move rapidly forward, not the water.
- Water molecules move in an orbital motion as the wave passes
- In deep water, the horizontal and vertical displacements of water particles are approximately the same (It is a circular orbit)
- In shallow water, the motion of water particles follows an elliptical path
- The wave speed (speed of the wave profile or phase speed, L/T) is much higher than the speed of individual water particles (equal to $\pi H/T$)

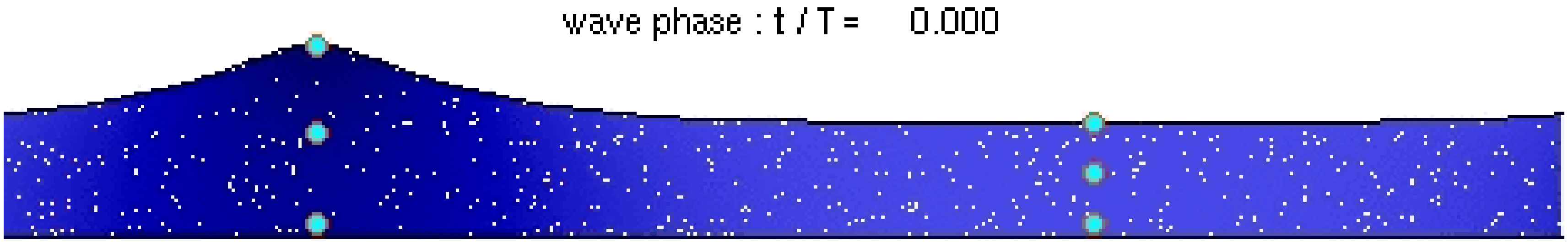
Water Particle Trajectories

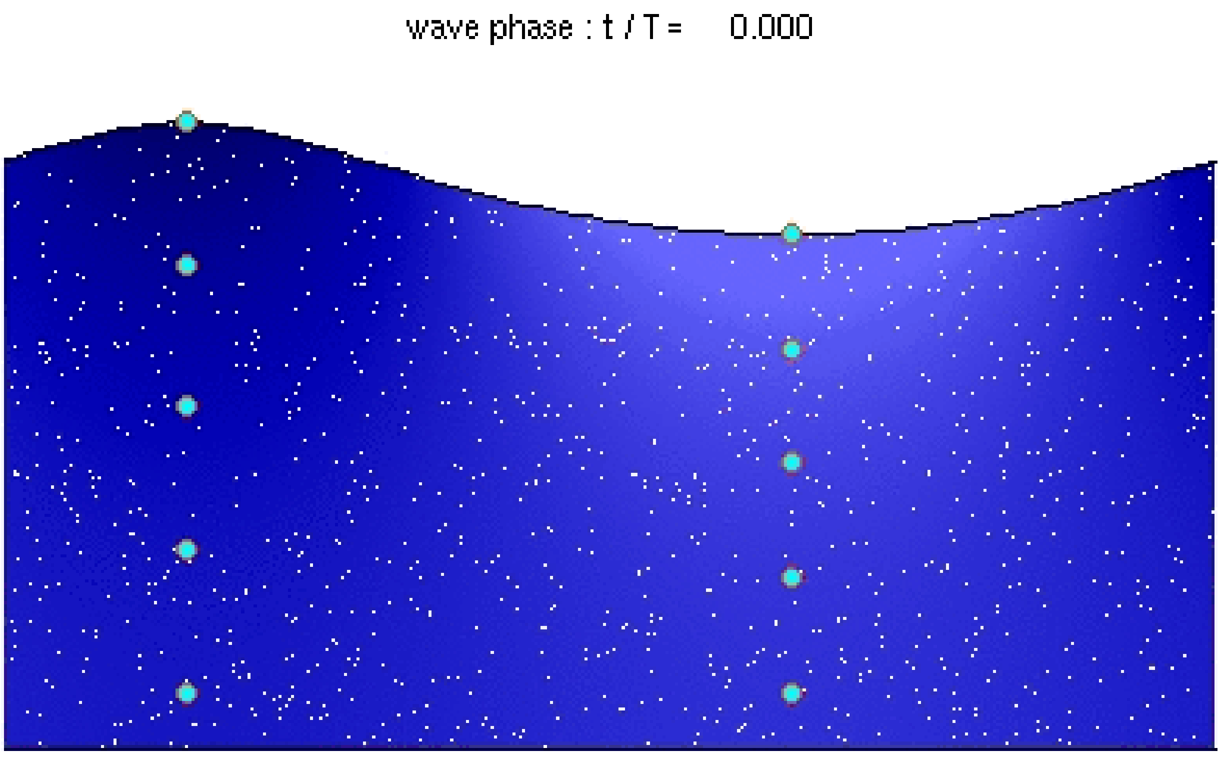




Water Particle Trajectories for Long and Short Waves as A Function Depth

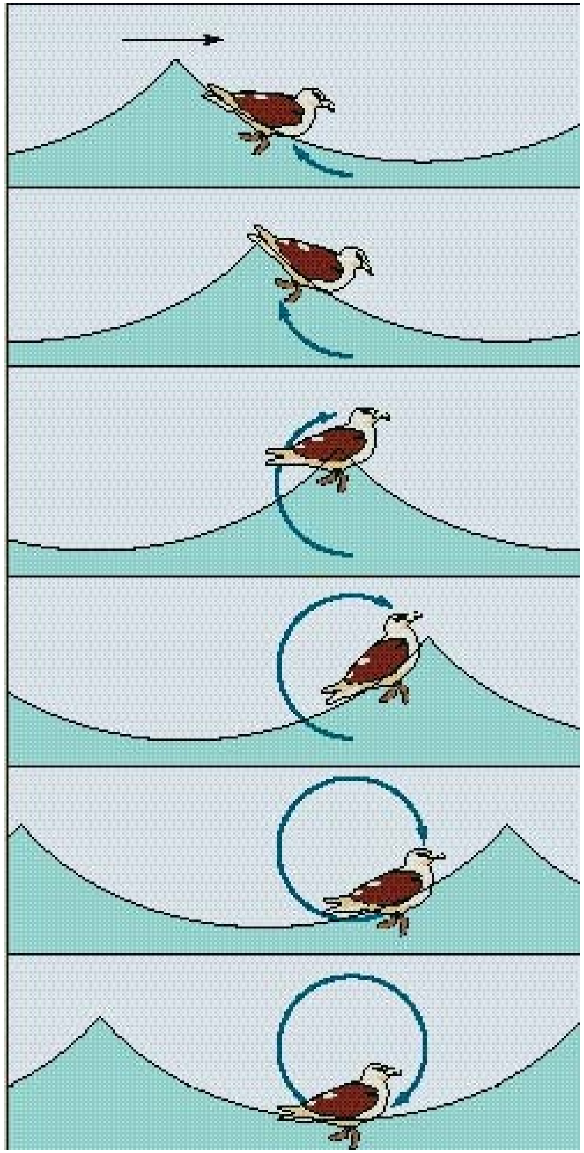
Water Particle Trajectories





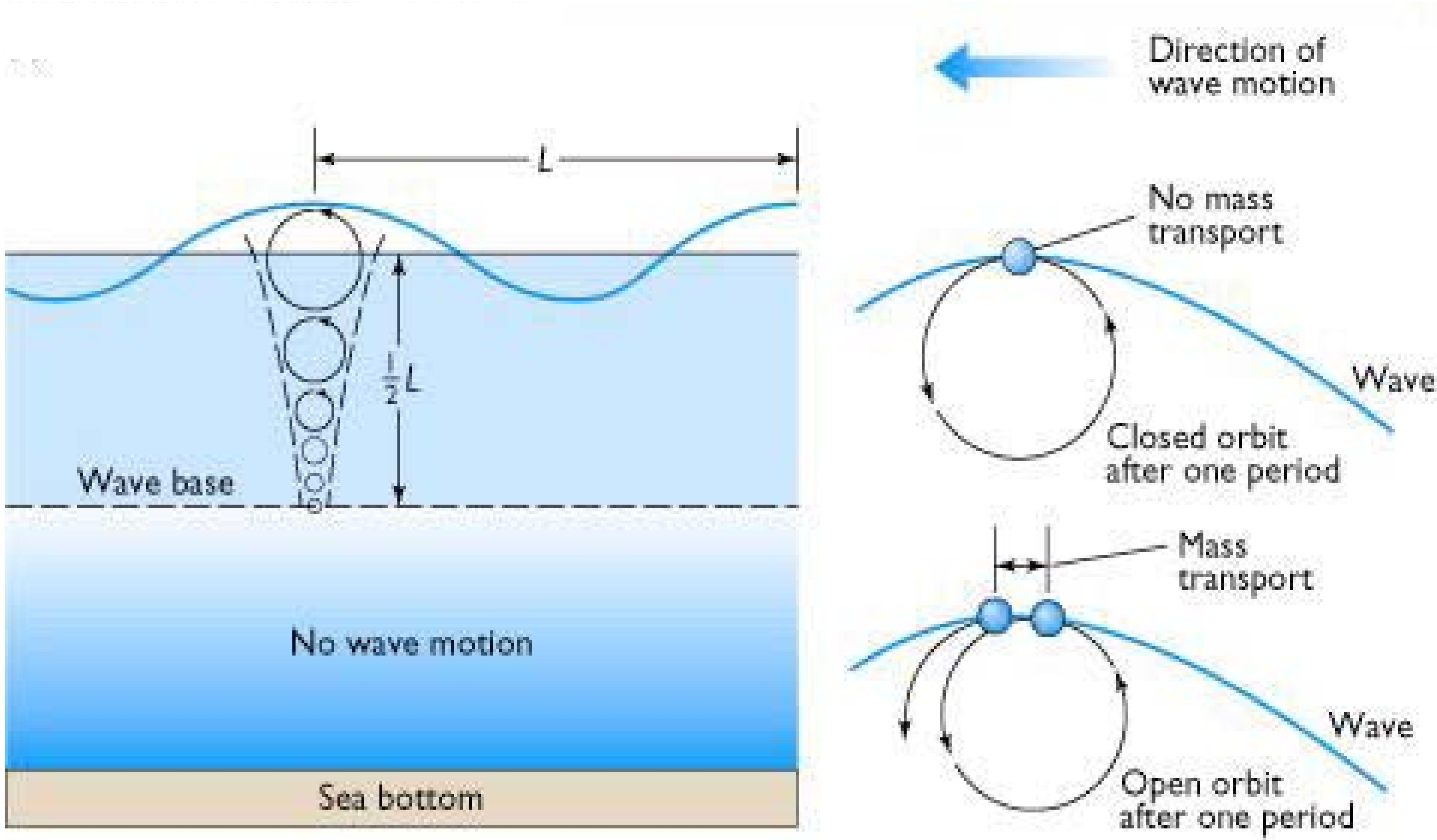
How Water Moves in a Wave

Water particle motion in a progressing wave



Actual orbit of a water particle and the Stoke's drift

In reality water particles do not return exactly to the starting point of its path. It ends up in a slightly advanced position in the direction in which the waves are travelling, and thus a small net forward shift remains. This shift is more for steeper waves.



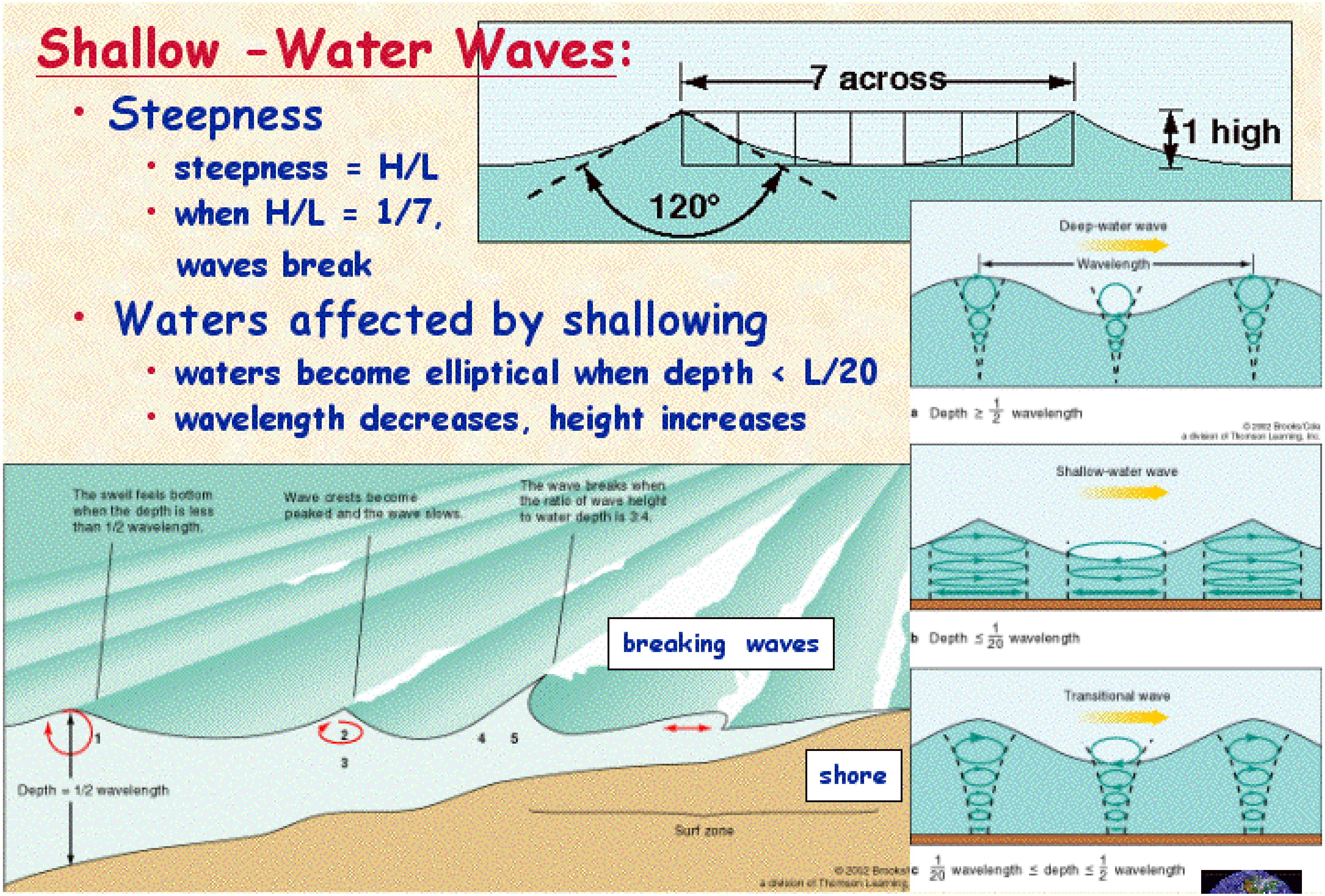
Energy in waves

- ✓ Waves disturb the water and hence there is kinetic energy associated with the waves, which moves along with the wave.
- ✓ Waves also displace water particles in the vertical and hence affect the potential energy of the water column, which also moves along with the wave.
- ✓ Wave energy moves at the group velocity, which is the speed of the group of waves.
- ✓ The total energy of a simple linear wave is

$$E = \frac{1}{2}\rho g a^2 = \frac{1}{8}\rho g H^2$$

where ρ is the density of water.

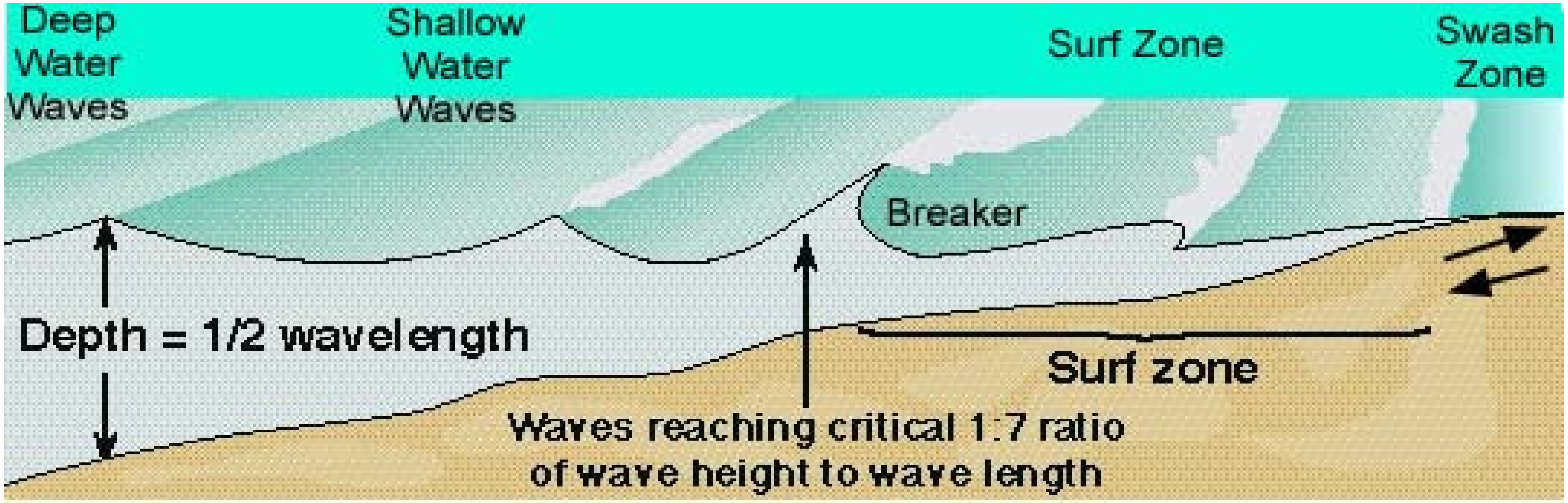
WAVE BEHAVIOR IN SHALLOW WATER

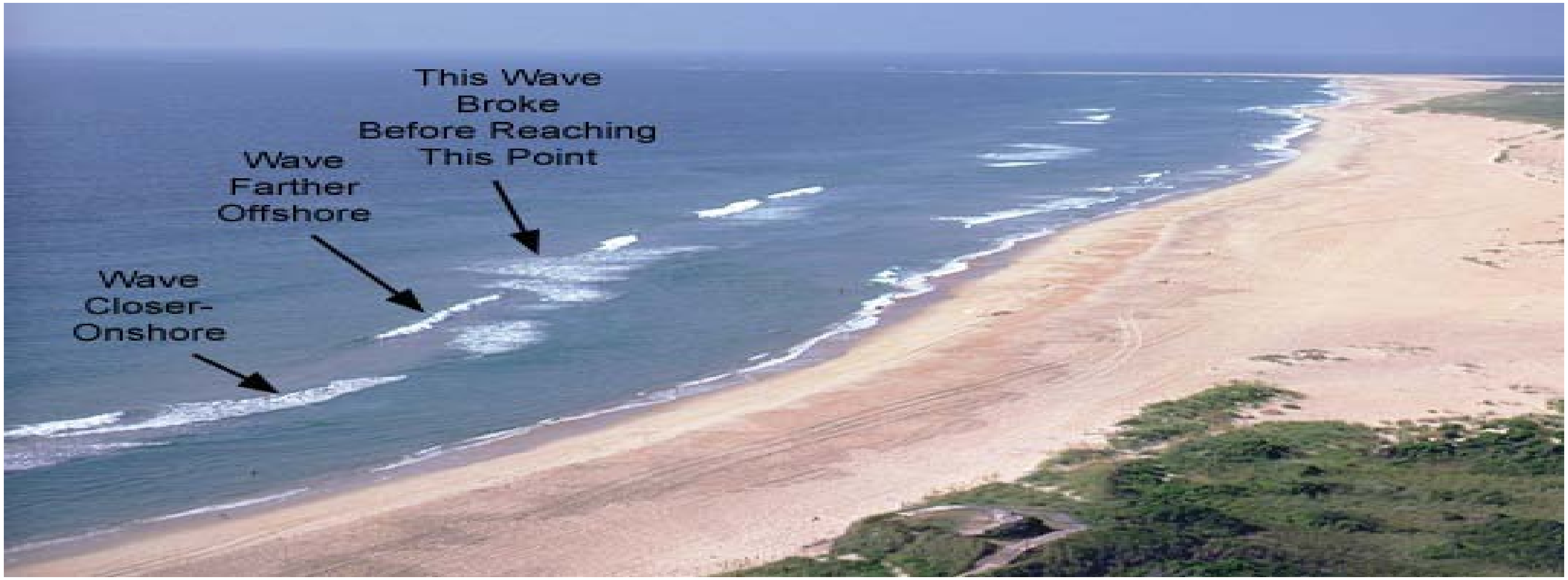


WAVE BEHAVIOR IN SHALLOW WATER

- When the water depth h > L/2, water particle motion is negligible.
- When waves propagate into shallow water, they begin to “feel” the bottom.
- Wave period remains constant.
- Wave speed decreases and hence wave length decreases (since L=cT).
- Wave height increases. (By law of conservation of energy - when group velocity and wave length decrease, energy in each wave length must increase => H increases, as $E \propto H^2$)

WAVE BEHAVIOR IN SHALLOW WATER





Near shore Wave Processes

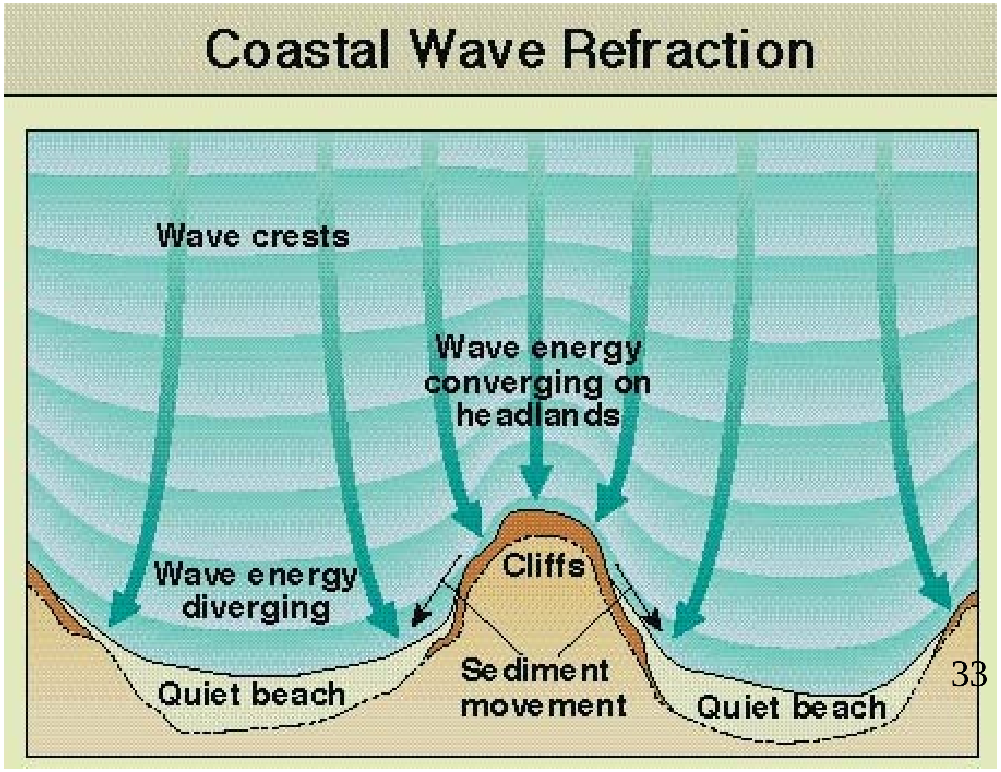
WAVE REFRACTION

Wave Refraction in a bay

WAVE REFRACTION

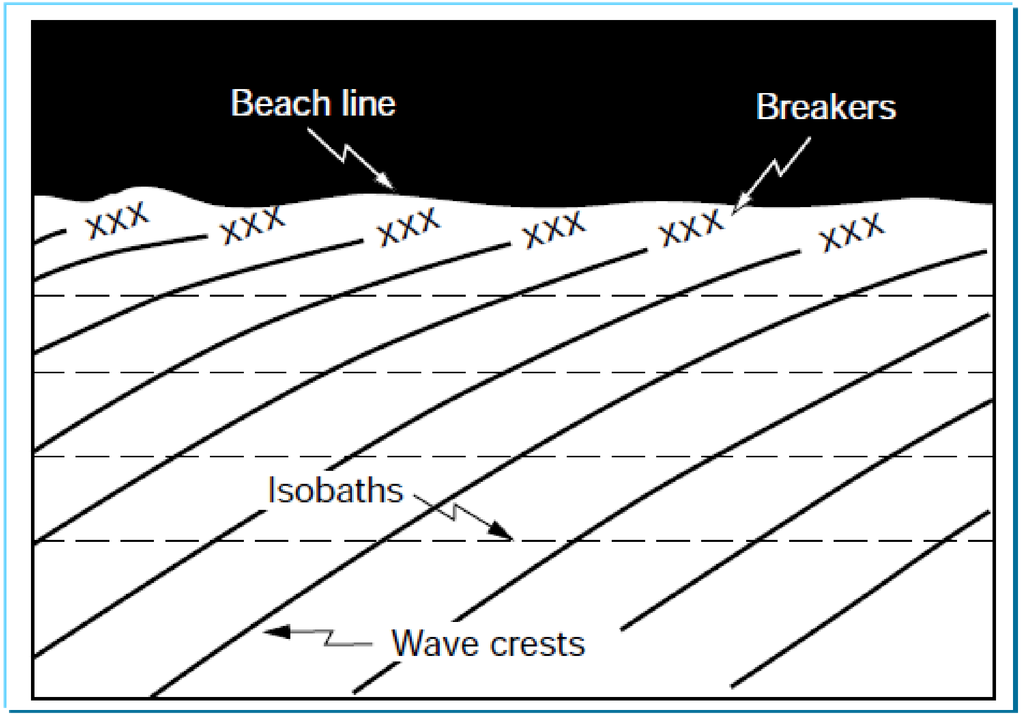
- Refraction may occur when the waves begin to “feel” the bottom. When waves enter water of transitional depth, if they are not travelling perpendicular to the depth contours, the part of the wave in deep water travel faster than the part in shallower water. This causes the crest to turn parallel to the bottom contours.
- Generally any change in wave speed (eg. due to gradients of surface currents) may lead to refraction, irrespective of the water depth.

Refraction along an irregular shoreline

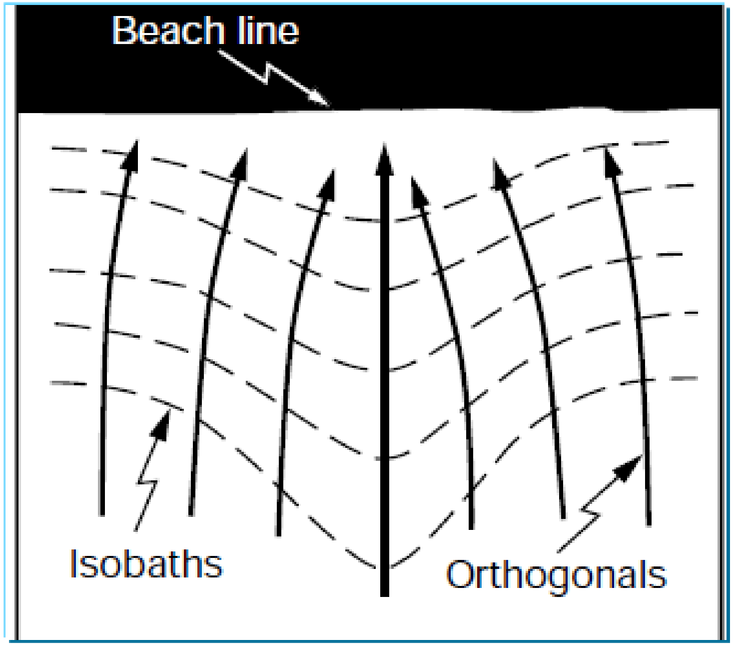


WAVE REFRACTION

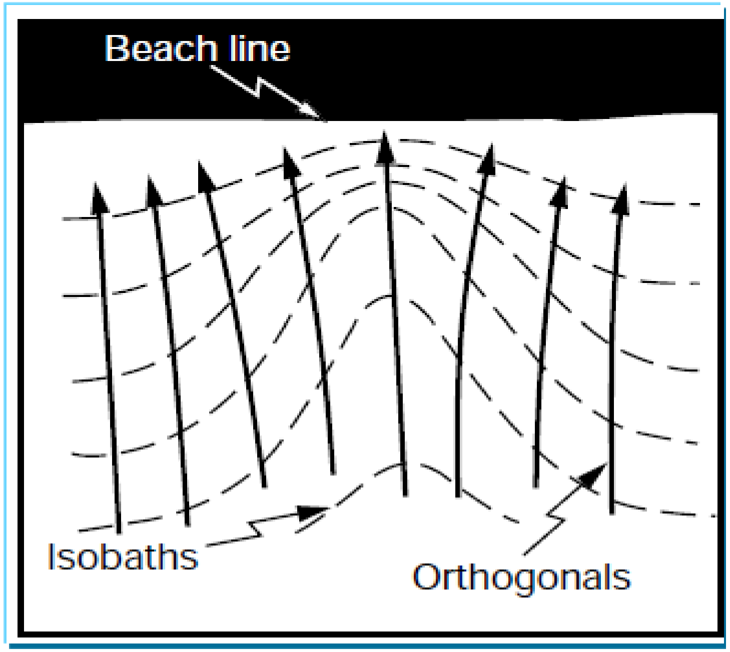
Refraction along a straight beach with parallel bottom contours



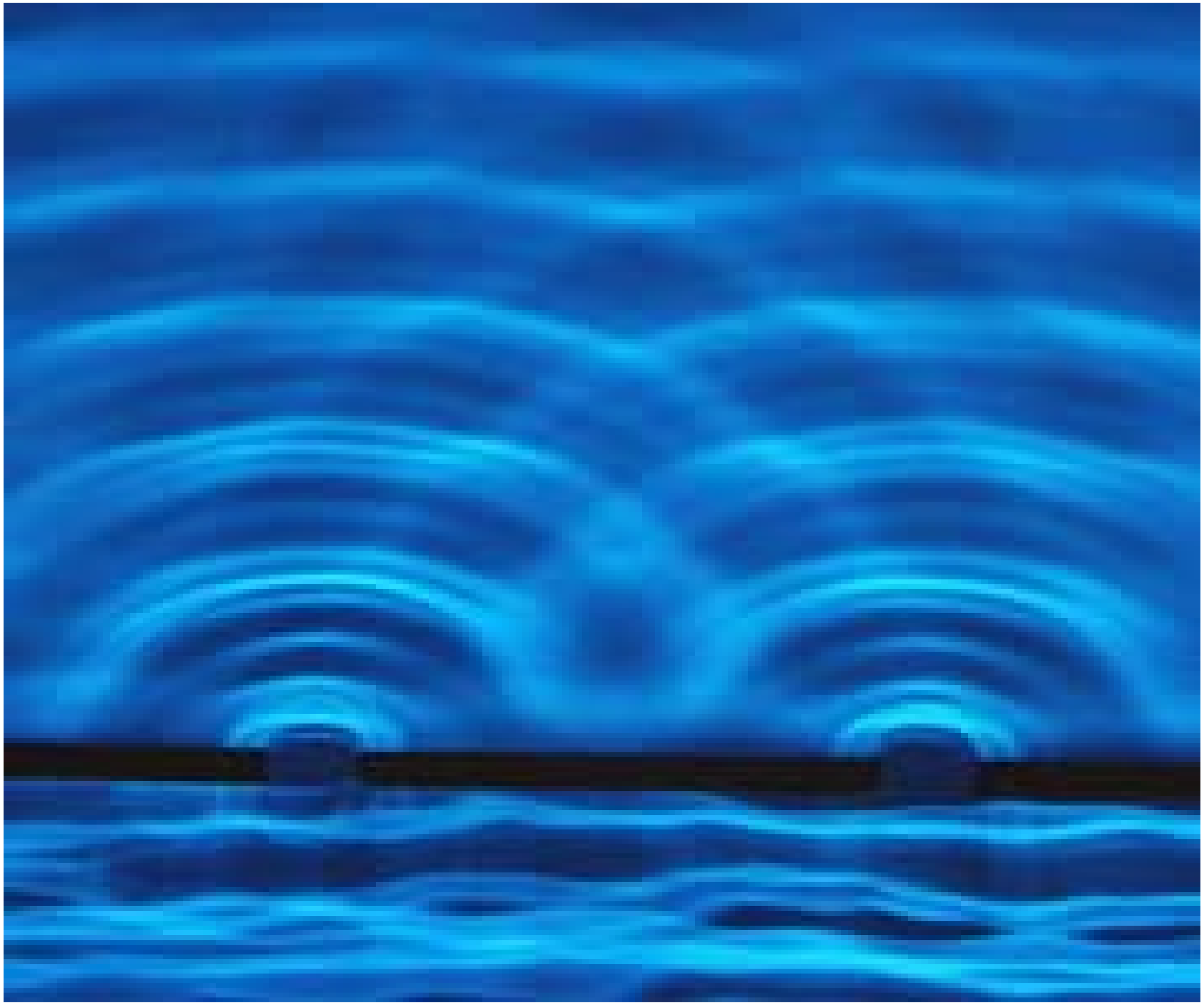
Refraction by a submarine ridge



Refraction by a submarine canyon

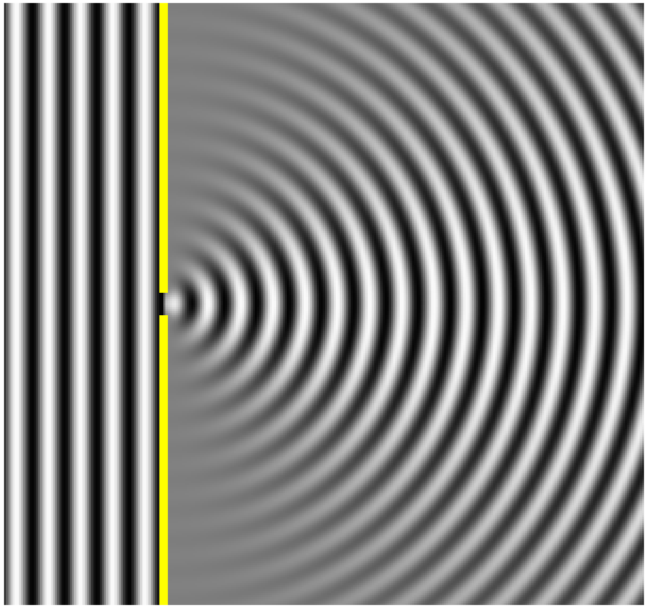


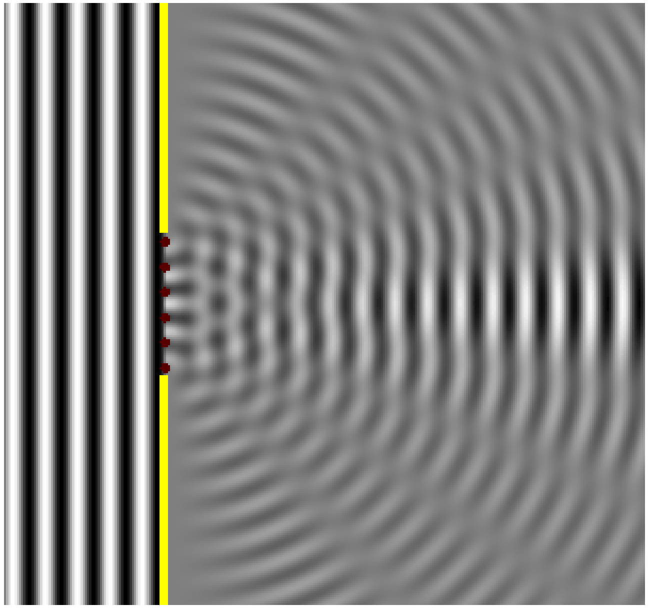
WAVE DIFFRACTION



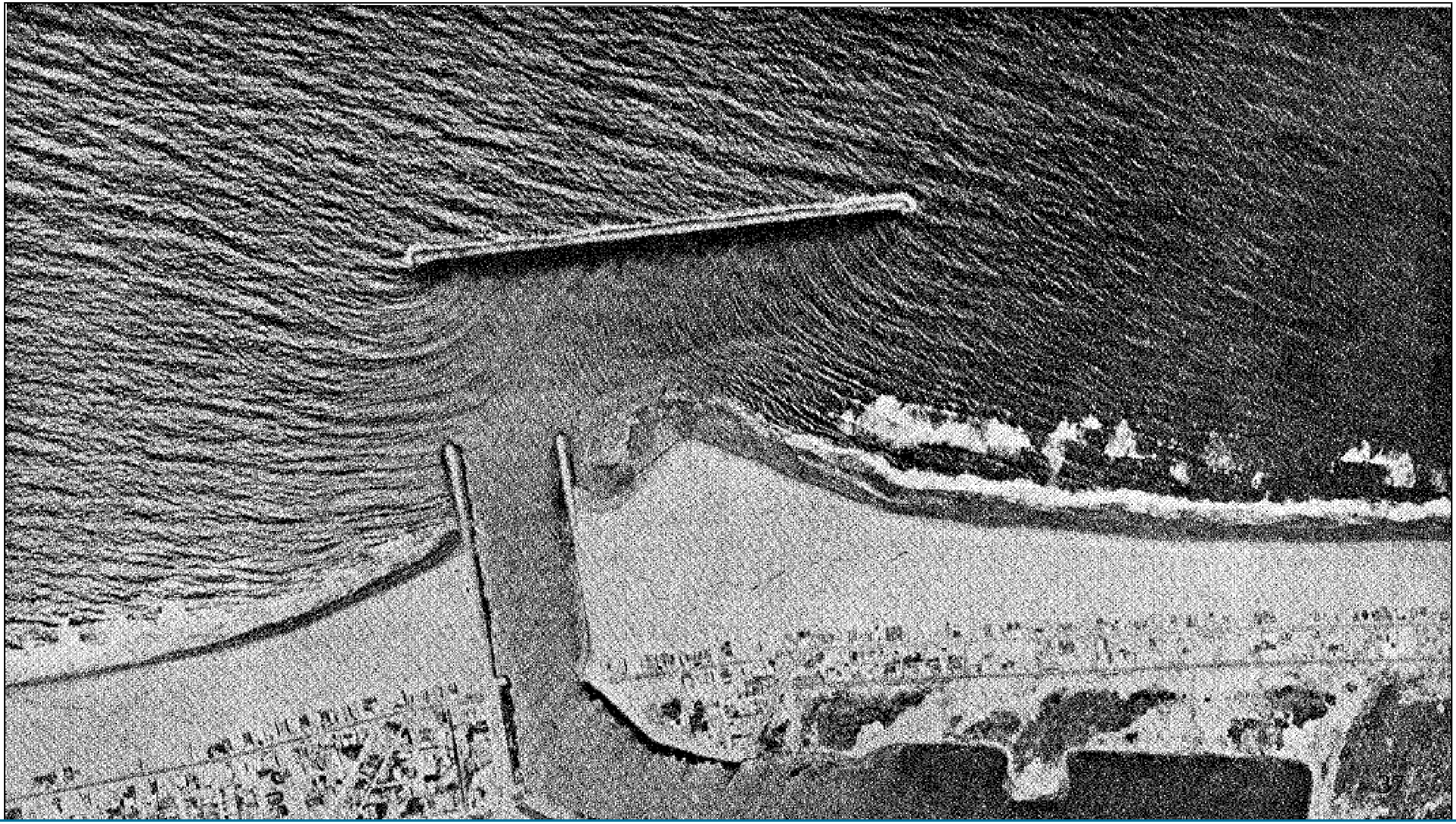
WAVE DIFFRACTION

- Diffraction usually happens when waves encounter an obstacle, such as a breakwater or an island.
- The waves bend around an obstacle to reach the lee side of the obstacle. The waves can affect the lee side of a structure, although their heights are much reduced.
- Diffraction of water waves is the simplest kind as it happens in two dimensions. Diffraction along with interference can create patterns like that shown below.





Wave diffraction at Channel Islands breakwater (California) (from CERC, 1977)



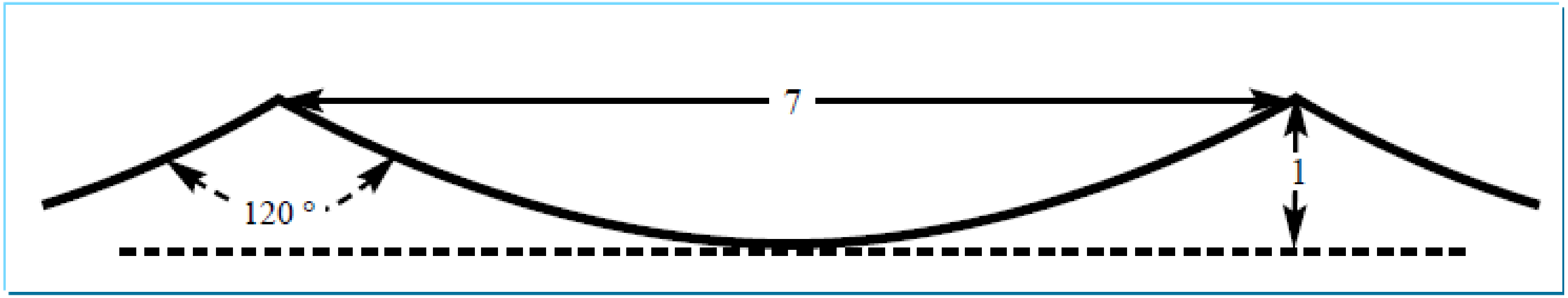
WAVE BREAKING

WAVE BREAKING

- Speed of water particles at the crest is slightly greater than that at the trough. The steeper the waves this effect is more.
- Once (wave height/wave length) becomes equal to 1/7, the forward speed of the water particles at the crest becomes equal to the wave propagation speed.
- Once this happens, the water particles plunge forward out of the wave or the waves break.

Wave Steepness and breaking

- **The limiting angle at the crest of a deep-water wave is 120 degrees.**



- **At this point the steepness (S) of the wave is 1:7.**
- **According to Stoke's theory waves can not attain a height more than L/7 without breaking. At this point, the forward and backward slopes of the wave meet in the crest at an angle of 120°. To break in deep water, steepness must exceed 0.142 which is a ratio of 1:7.**

WAVE BREAKING

Types of Wave Breaking

Spilling Breaker

Plunging and Collapsing Breaker

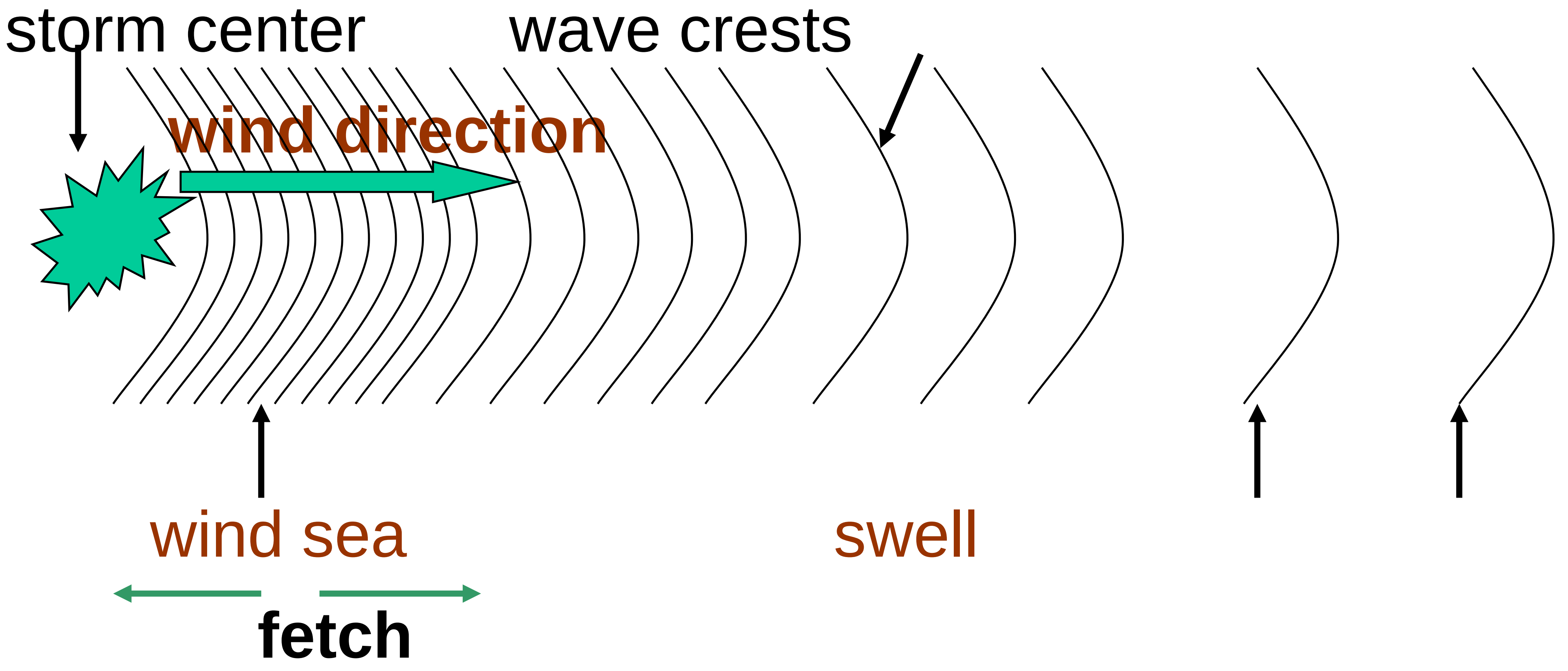
Surging Breaker

LONG WAVES and EXTREME WAVES IN NATURE

- **TIDAL WAVES**
- **SWELL WAVES**
- **SEICHES (RESONANCE OF BASINS)**
- **FREAK WAVES**

Wind seas and Swells

Sea state is a combination of wind seas and swells.



Fetch is the distance over which wind blows over the water surface

Chaotic Sea exhibiting complex surface wave forms

SWELL WAVES

wind sea

- Waves growing under the influence of wind
- Poorly organized, short-crested waves of irregular size and spacing

swell

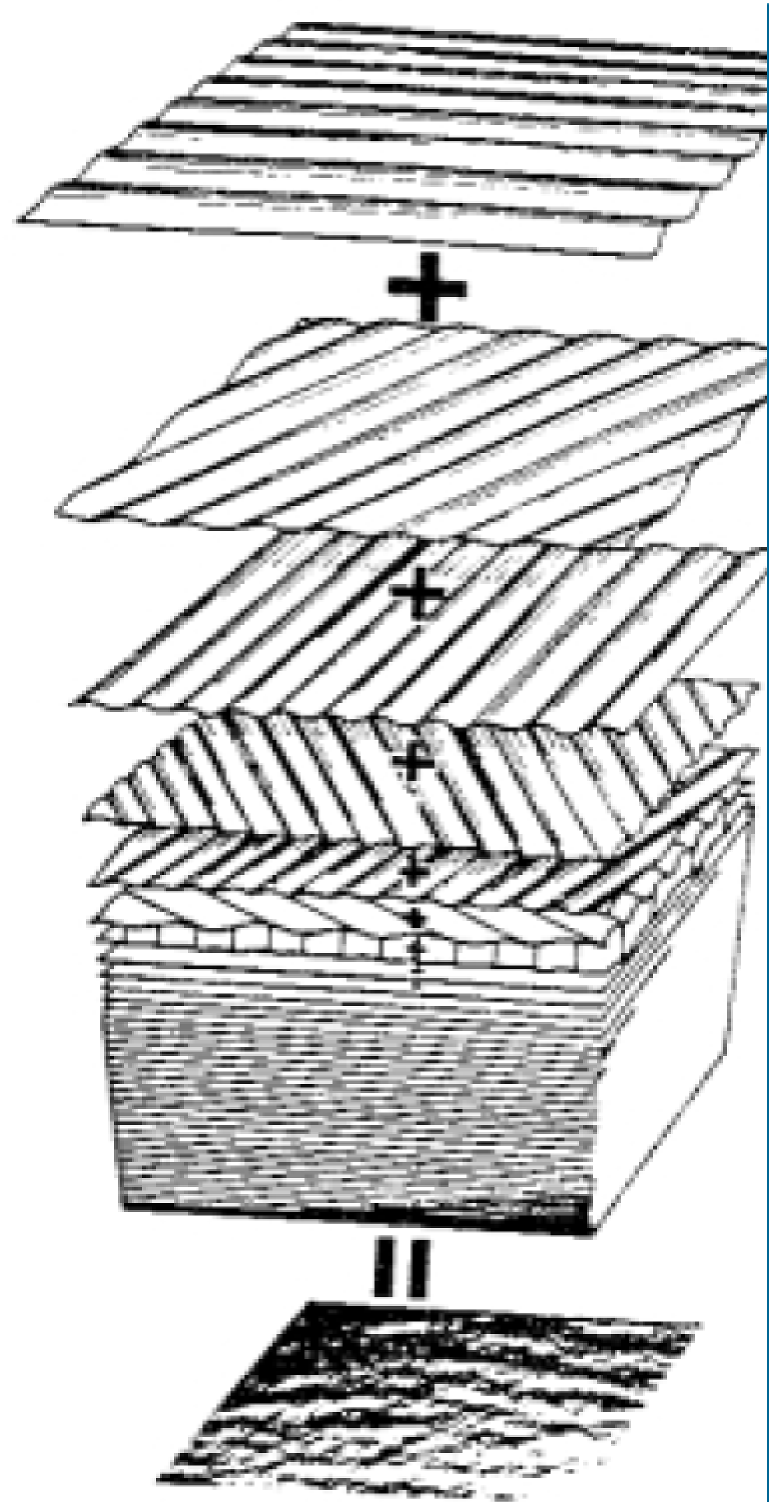
- Waves outside the generating area
- Well organized, regularly-spaced wave train
- If height of the wind waves is H_{sw} and height of swell waves is H_{ss} then total wave height = $(H_{sw}^2 + H_{ss}^2)^{1/2}$

Difference Between Sea (Wind) and Swell Waves

- **"Sea (Wind) Waves"** are produced by local winds and measurements show they are composed of a chaotic mix of height and period. In general, the stronger the wind the greater the amount of energy transfer and thus larger the waves are produced.
- As sea waves move away from where they are generated they change in character and become swell waves.
- **"Swell Waves"** are generated by winds and storms in another area. As the waves travel from their point of origin they organize themselves into groups (Wave trains) of similar heights and periods. These groups of waves are able to travel thousands of miles unchanged in height and period.
- Swell waves are uniform in appearance, have been sorted by period, and have a longer wave length and longer period than sea waves. Because these waves are generated by winds in a different location, it is possible to experience high swell waves even when the local winds are calm.

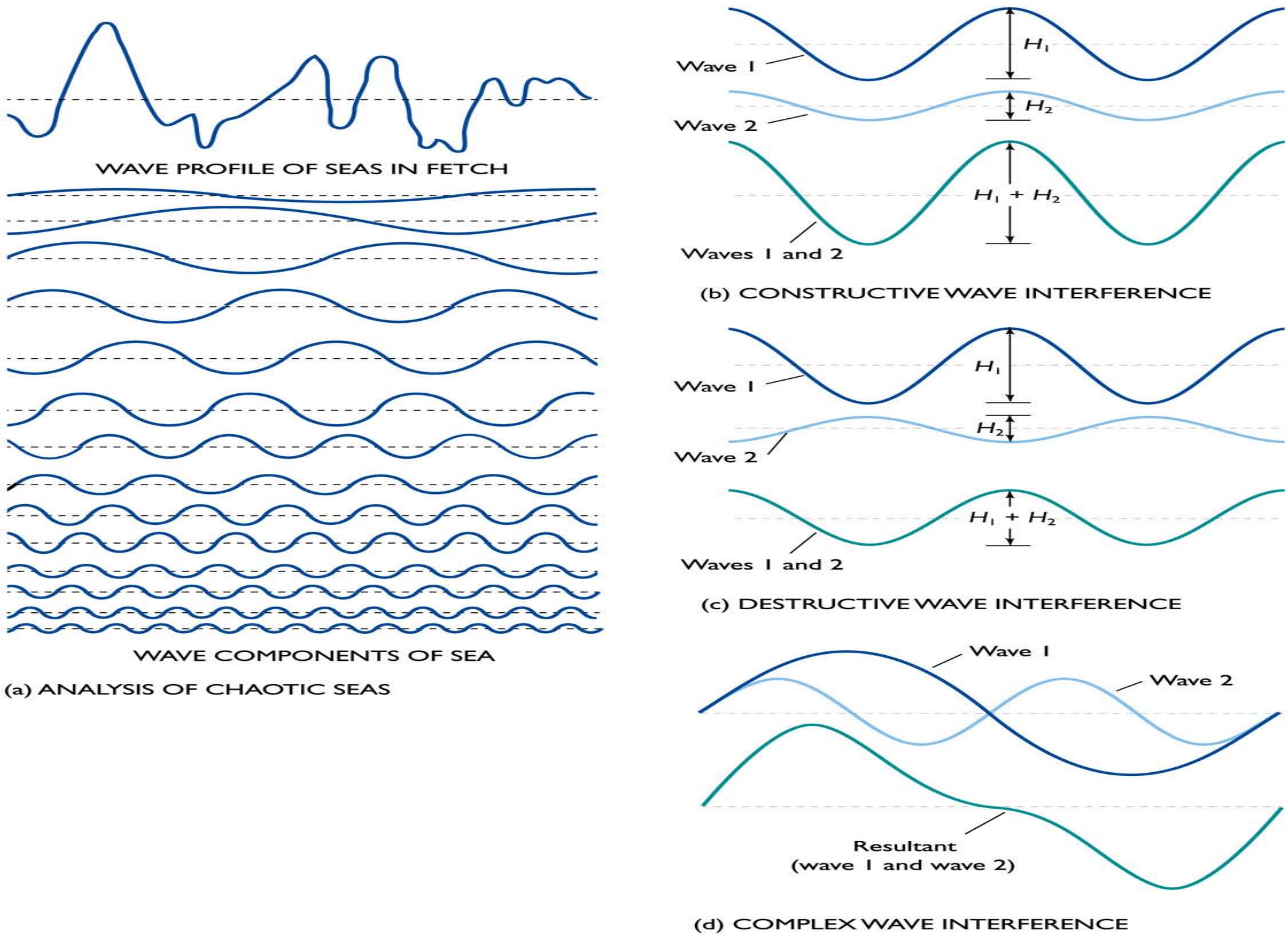
Wave fields on the ocean – a composition of simple waves

The sea surface obtained from the sum of many sinusoidal waves



Any observed wave pattern in the ocean could be shown to comprise a number of simple waves, which differ from each other in height, wavelength and direction.

How a complex wave pattern could be analyzed???



Wave groups and group velocity

- Individual waves in a group travel at the velocities corresponding to their wave lengths, but the wave group as a coherent unit travels at its own velocity - the group velocity

- Group velocity is the velocity with which the wave energy is propagated

- Group velocity can be written as

$$C_g = d\omega/dk$$

- Deep water group velocity is

$$C_g = C/2$$

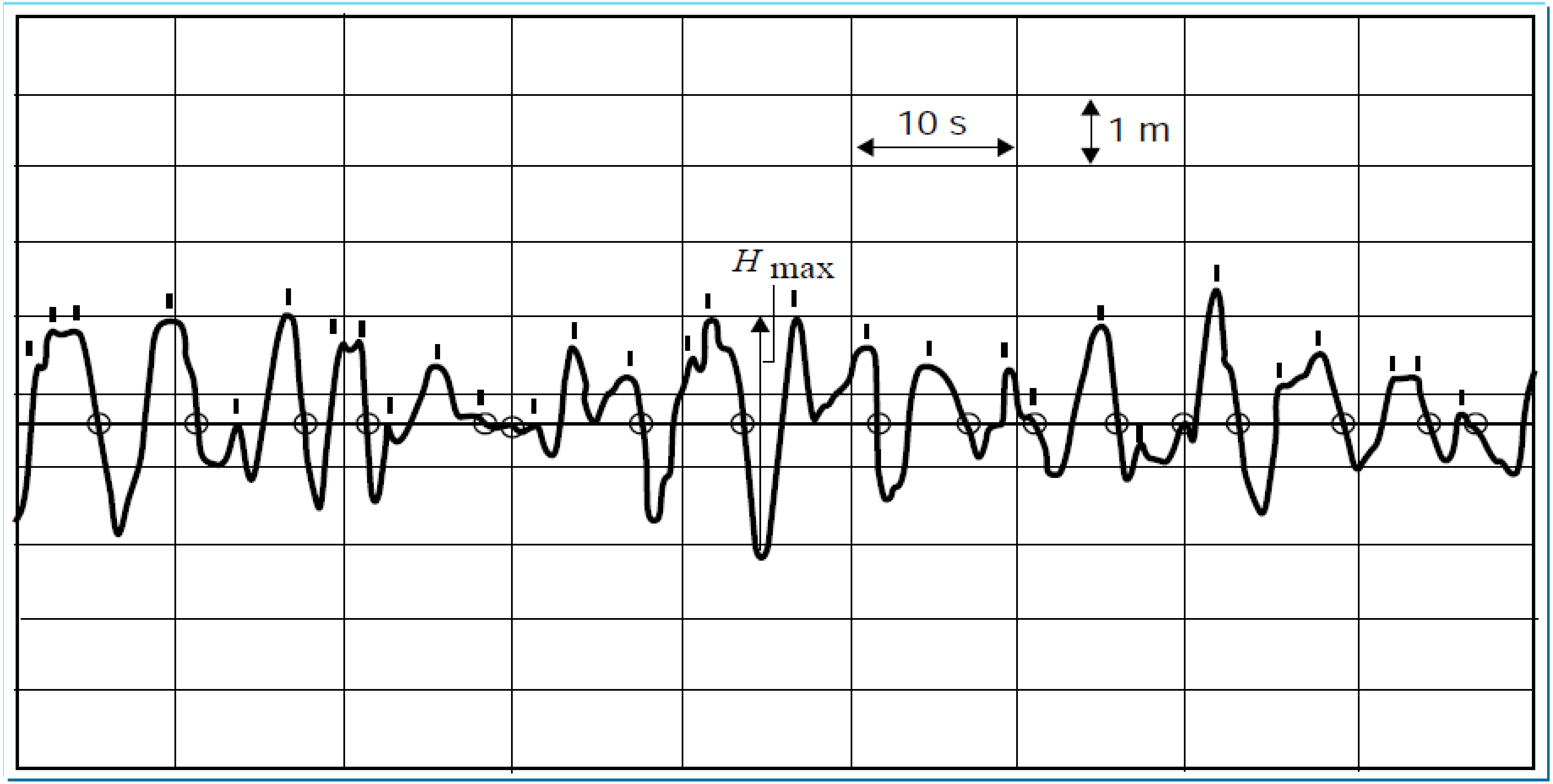
=> The wave group travels slower than the fastest wave in the group.

- Shallow water group velocity is

$$C_g = C$$

This is since the shallow water waves are non dispersive.

Wave record - the motion of water surface at a fixed point

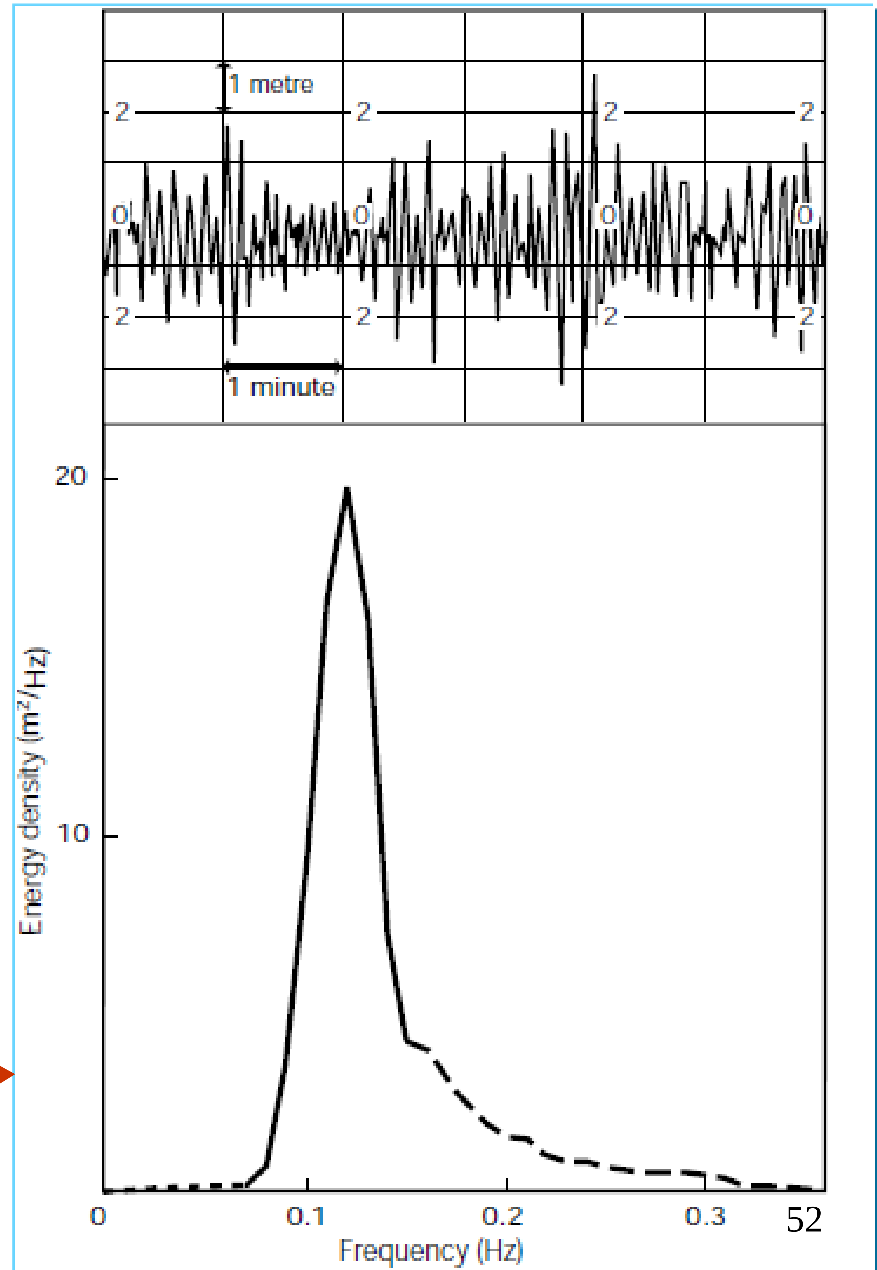


Wave spectrum - Concept

Wave spectrum is the distribution of wave energy over various frequencies (or directions or frequencies and directions). It is obtained by the FFT of the wave record.

The concept of wave spectrum is used in modelling the sea state.

Example of a wave spectrum with corresponding wave record.



Wave parameters derived from the spectrum

- The form of a wave spectrum is usually expressed in terms of the moments of the spectrum. The n^{th} order moment of the spectrum is given by

$$m_n = \int_0^\infty f^n E(f) df$$

where $E(f)df$ represents the variance $a_i^2/2$ contained in the i^{th} interval between f and $f+df$ and a_i is the amplitude of the i^{th} component in a wave record.

- Zeroth moment m_0 is the area under the spectral curve. It could be derived that the significant wave height H_{m0} (average (1/3)rd of the highest waves) is

$$H_{m0} = 4\sqrt{m_0}$$

Wave parameters derived from the spectrum

- Peak wave frequency f_p is the wave frequency

corresponding to the peak of the spectrum.

- Peak wave period T_p is the period corresponding to f_p ,

$$T_p = 1/f_p$$

- Mean wave period $T_{m02} = \sqrt{\frac{m_0}{m_2}}$

Wave spectrum

Model forms for wave spectra:

Usually expressed as: E(f); E(f,θ) (or) E(k)

As wave number and frequency are connected by the dispersion relation.

(i) Philips spectrum:

Usually used to represent the high frequency part of the spectrum, above the spectral peak. In general form:

$$\left. \begin{aligned} E(f) &= 0.005\frac{g^2}{f^5} \\ &= 0 \text{ (else)} \end{aligned} \right\} \text{ if } \; f \geq \left(\frac{g}{u}\right)$$

Earlier used for representing the tail

Wave spectrum

(ii) Pierson-Moskowitz spectrum (1964):

Used for a fully developed sea (equilibrium state when fetch and duration are unlimited):

Originally developed based on sub-set of 420 (1955 – 1960) wave measurements with ship-borne wave recorder (Tucker, 1956).

$$E(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{-0.74\left(\frac{g}{2\pi f U}\right)^4}$$

where, α = non-dimensional quantity = 0.0081

U = wind speed at 19.5 m above seasurface

Peak frequency of P-M spectrum:

$$f_p = 0.877 \frac{g}{2\pi U}; \quad H_{1/3} = 0.0246\, U^2 \text{(for fuly developed seas)}$$

Hence, $H_{1/3} = 0.04\, f_p^{-2}$

Wave spectrum

(ii) JONSWAP spectrum (1973):

JONSWAP (1973) gave a description of wave spectra growing in fetch limited condition. Basic formulation of the spectrum is expressed in terms of peak frequency rather than wind speed.

$$E(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{-1.25\left(\frac{f}{f_p}\right)^4} . \gamma(f)$$

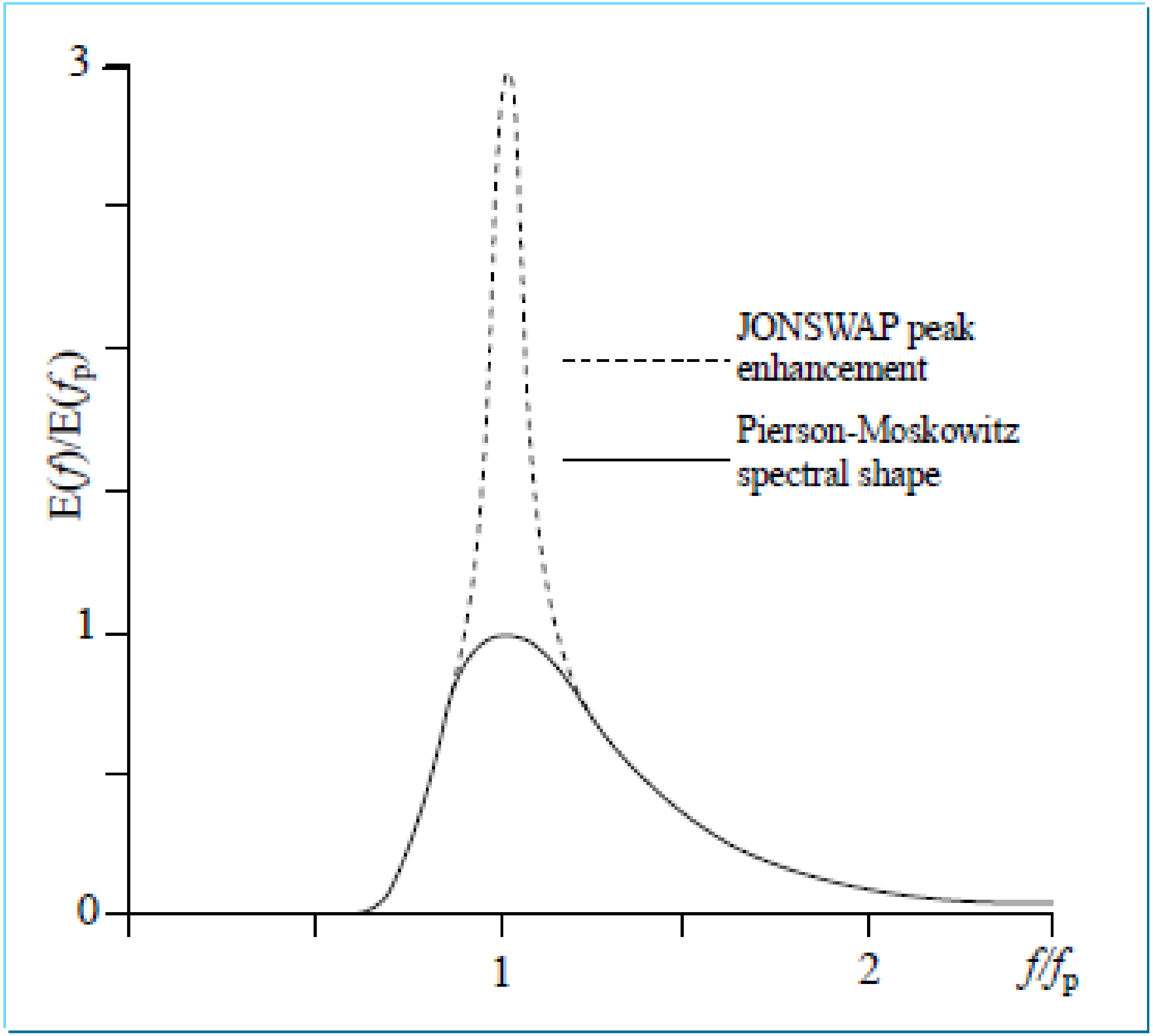
where, γ is peak enhancement factor which modifies the interval around spectral peak making it more sharper than PM spectrum (otherwise shape is similar). Using JONSWAP results, Hasselmann (1976) proposed a relation between variance and peak frequency for wide range of growth stages.

$$\mathrm{H}_{\mathrm{m0}} \approx \mathrm{H}_{1/3} = 0.0414 f_p^{-2} (f_p U)^{1/3}$$

(or) $\mathrm{f}_{\mathrm{p}} = 0.148 H_{m0}^{-0.6} U^{0.2}$

where, $\mathrm{U} = \mathrm{U}_{10}$ (wind speed at 10 m height)

General form of a JONSWAP spectrum as a function of f/f_p



A Rogue wave occurs when there is a momentary appearance of an unusually large wave formed by constructive interference of many smaller waves.

Rogue (freak) waves

Standing Waves

- Standing waves or seiches consist of a water surface "seesawing" back and forth.
- Node : No vertical movement
  - Located in centers of enclosed basins and toward the seaward side of open basins.
- Antinodes: Points where there are the maximum vertical displacement of the surface as it oscillates.
  - Antinodes usually located at the edge of the basin.

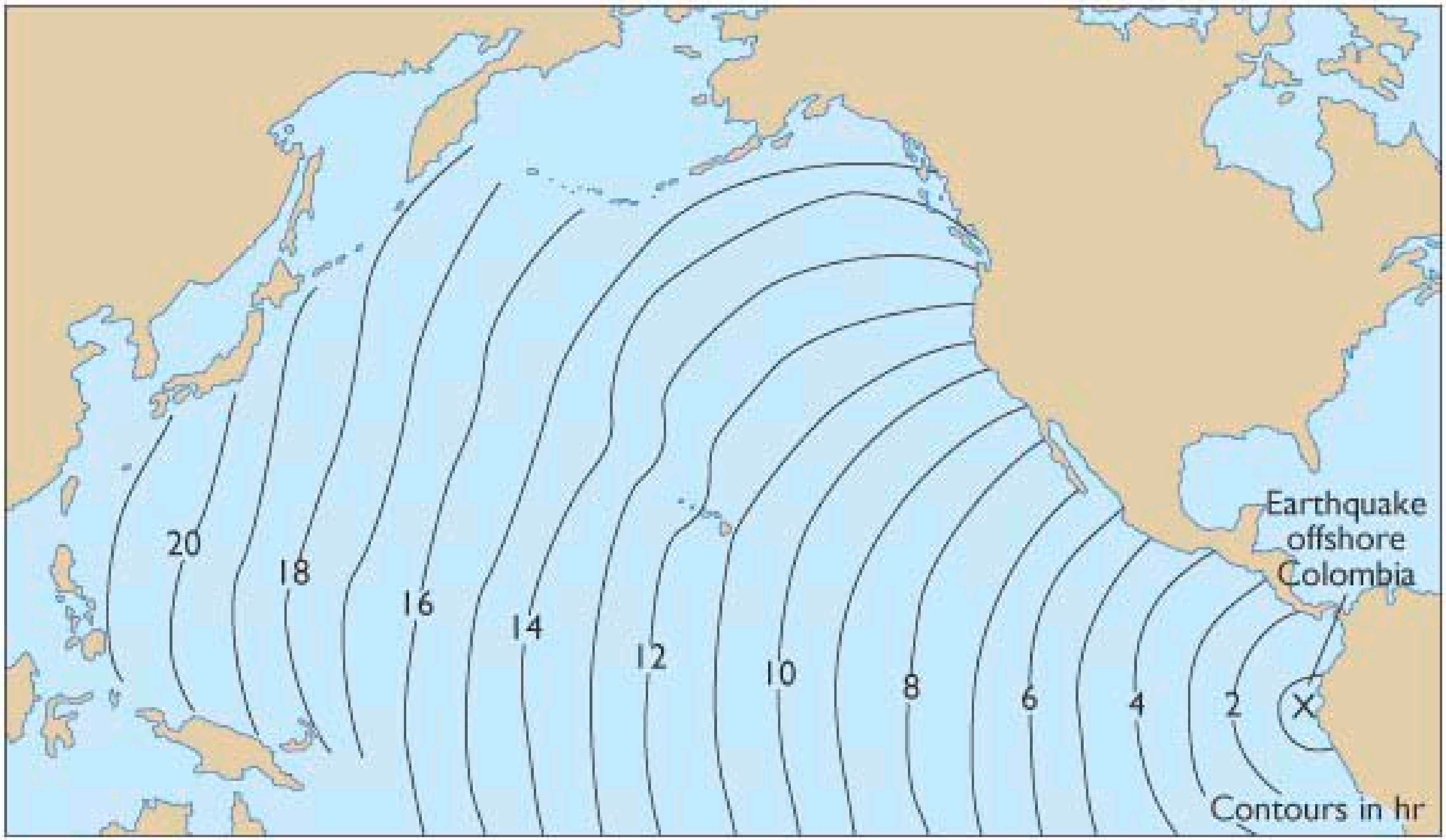
Tsunamis were previously called tidal waves, but are unrelated to tides.

- Tsunamis consist of a series of long-period waves characterized by very long wavelength (up to 100 km) and high speed (up to 760 km/hr) in the deep ocean.
- Because of their large wavelength, tsunamis are shallow-water to intermediate-water waves as they travel across the ocean basin.
- They only become a danger when reaching coastal areas where wave height can reach 10 m.
- Tsunamis originate from earthquakes, volcanic explosions, or submarine landslides.

Generation of a Tsunami

This diagram shows the position of the leading wave of a tsunami generated by a 1979 earthquake off-shore Colombia, South America.

Figure 7.13b



(b) REFRACTION PATTERN OF 1979 TSUNAMI

Tsunami damage

Tsunami damage in Riangkroko, Indonesia.

Figure 7.14

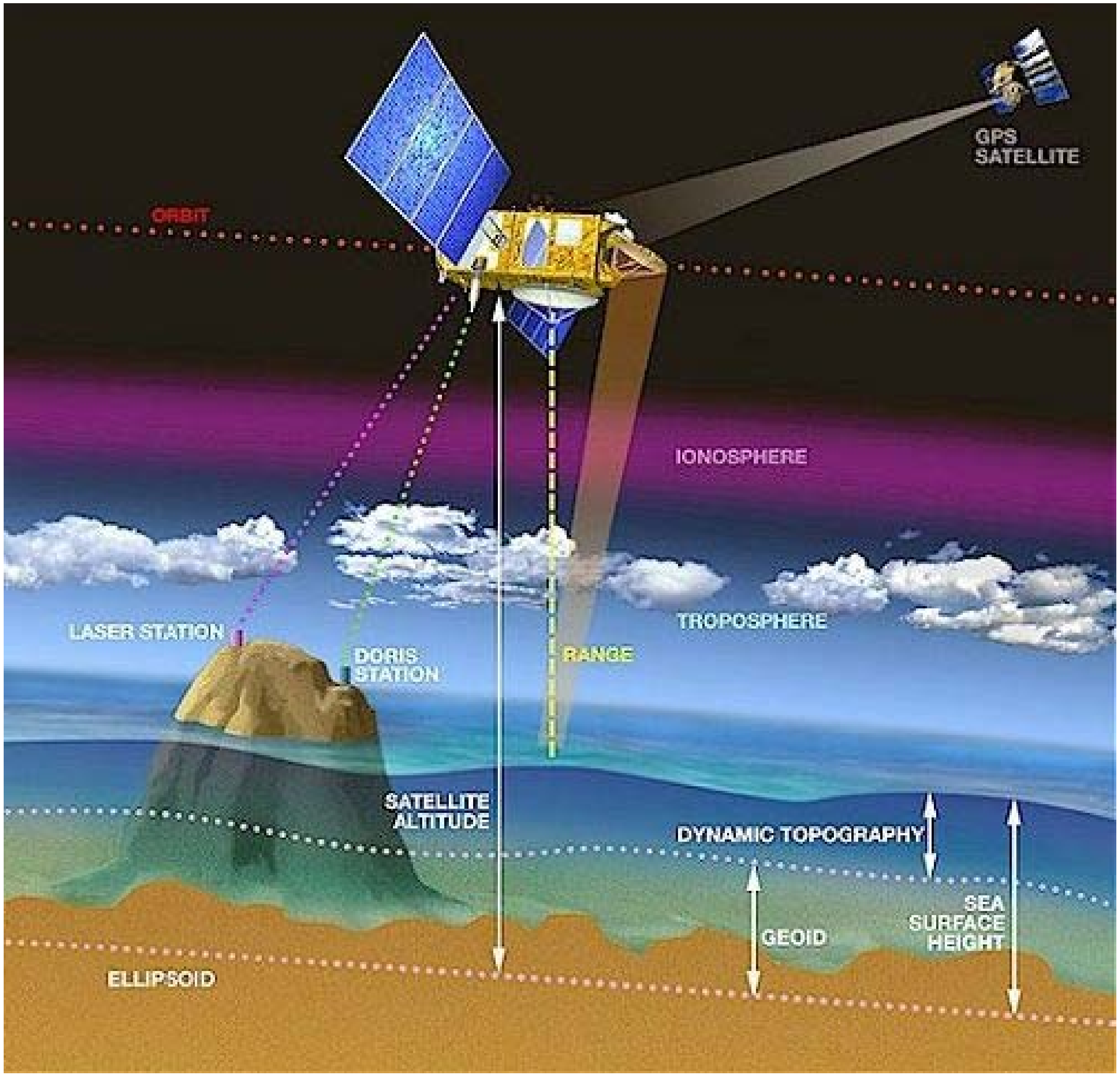
Wave measurement - Waverider buoys

- Small & light, deployable from small vessels

- The non-directional wave buoy measures its own vertical acceleration on a gravity stabilised platform.

- The directional wave rider buoys measures tilt (pitch and roll) in addition to vertical acceleration.

Wave height measurements using satellites



Altimetry is meant to retrieve "**Sea Surface Height**"

This is the difference between the **satellite-to-ocean range** *(calculated by measuring the signal's round-trip time)* and the **satellite's position on orbit** with respect to an arbitrary reference surface *(a raw approximation of the Earth's surface, called the* ***reference ellipsoid****)*

SIGNIFICANCE OF THE STUDY OF WAVES

•Waves are one of the most important parameter in coastal oceanography, ocean engineering and coastal management.

•Accurate measurement and long term observations of waves are required to understand the wave climate of a region.

•The waves in harbours and near shore regions affect the marine operations as well as the fishing activities.

•Coastal engineers require the wave climate to design harbours, jetties, ports, oil rigs and other coastal protection structures.

•Studies of sediment transport and coastal erosion require accurate knowledge of the wave climate of location.

•Waves also play a significant role in flux exchange and air sea interaction.

Thank You