1.8 SUMMARY OF CHAPTER 1

1 Idealized waves of sinusoidal form have wavelength (length between successive crests), height (vertical difference between trough and crest), steepness (ratio of height to length), amplitude (half the wave height), period (length of time between successive waves passing a fixed point) and frequency (reciprocal of period). Water waves show cyclical variations in water level (displacement), from $-a$ (amplitude) in the trough to $+a$ at the crest. Displacement varies not only in space (one wavelength between successive crests) but also in time (one period between crests at one location). Steeper waves depart from the simple sinusoidal model, and more closely resemble a trochoidal wave form.

2 Waves transfer energy across/through material without significant *overall* motion of the material itself, but individual particles are displaced from, and return to, equilibrium positions as each wave passes. Surface waves occur at interfaces between fluids, either because of relative movement between the fluids, or because the fluids are disturbed by an external force (e.g. wind). Waves occurring at interfaces between oceanic water layers are called internal waves. Wind-generated waves, once initiated, are maintained by surface tension and gravity, although only the latter is significant for water waves over 1.7 cm wavelength.

3 Most sea-surface waves are wind-generated. The stronger the wind, the larger the wave, so variable winds produce a range of wave sizes. A constant wind speed produces a fully developed sea, with waves of $H_{1/3}$ (average height of highest 33% of the waves) characteristic of that wind speed. The Beaufort Scale relates sea state and $H_{1/3}$ to the causative wind speed.

4 Water particles in waves in deep water follow almost circular paths, but with a small net forward drift. Path diameters at the surface correspond to wave heights, but decrease exponentially with depth. In shallow water, the orbits become flattened near the sea-bed. For waves in water deeper than 1/2 wavelength, wave speed equals wavelength/period ($c = L/T$) and is proportional to the square root of the wavelength ($c = \sqrt{gL/2\pi}$); it is unaffected by depth. For waves in water shallower than 1/20 wavelength, wave speed is proportional to the square root of the depth ($c = \sqrt{gd}$) and does not depend upon the wavelength. For idealized water waves, the three characteristics, c, L and T, are related by the equation $c = L/T$. In addition, each can be expressed in terms of each of the other two. For example, $c = 1.56T$ and $L = 1.56T^2$.

5 Waves of different wavelengths become dispersed, because those with greater wavelengths and longer periods travel faster than smaller waves. If two wave trains of similar wavelength and amplitude travel over the same sea area, they interact. Where they are in phase, displacement is doubled, whereas where they are out of phase, displacement is zero. A single wave train results, travelling as a series of wave groups, each separated from adjacent groups by an almost wave-free region. Wave group speed in deep water is half the wave (phase) speed. In shallowing water, wave speed approaches group speed, until the two coincide at depths less than 1/20 of the wavelength, where $c = \sqrt{gd}$.

6 Wave energy is proportional to the square of the wave height, and travels at the group speed. Wave power is rate of supply of wave energy, and so it is wave energy multiplied by wave (or group) speed, i.e. it is wave energy propagated per second per unit length of wave crest (or wave speed multiplied by wave energy per unit area). Total wave power is conserved, so waves entering shallowing water and/or funnelled into a bay or estuary (see also 7 below) increase in height as their group speed falls. Wave energy has been successfully harnessed on a small scale, but large-scale utilization involves environmental and navigational problems, and huge capital outlay.

7 Dissipation of wave energy (attenuation of waves) results from white-capping, friction between water molecules, air resistance, and non-linear wave–wave interaction (exchange of energy between waves of differing frequencies). Most attenuation takes place in and near the storm area. Swell waves are storm-generated waves that have travelled far from their place of origin, and are little affected by wind or by shorter, high-frequency waves. The wave energy associated with a given length of wave crest decreases with increasing distance from the storm, as the wave energy is spread over an ever-increasing length of wave front.

8 Waves in shallow water may be refracted. Variations in depth cause variations in speed of different parts of the wave crest; the resulting refraction causes wave crests to become increasingly parallel with bottom contours. The energy of refracted waves is conserved, so converging waves tend to increase, and diverging waves to diminish, in height. Waves in shallow water dissipate energy by frictional interaction with the sea-bed, and by breaking. In general, the steeper the wave and the shallower the beach, the further offshore dissipation begins. Breakers form a continuous series from steep spilling types to long-period surging breakers.

9 Waves propagating with a current have diminished heights, whereas a counter-current increases wave height, unless current speed exceeds half the wave group speed. If so, waves no longer propagate, but increase in height until they become unstable and break. Tsunamis are caused by earthquakes or by slumping of sediments, and their great wavelength means their speed is always governed by the ocean depth. Wave height is small in the open ocean, but can become destructively large near the shore. Seiches (standing waves) are oscillations of water bodies, such that at antinodes there are great variations of water level but little lateral water movement, whereas at nodes the converse is true. The period of oscillation is proportional to basin length and inversely proportional to the square root of the depth. A seiche is readily established when the wavelength of incoming waves is four times the length of the basin.

10 Waves are measured by a variety of methods, e.g. pressure gauges on the sea-floor, accelerometers in buoys on the sea-surface, and via remote-sensing from satellites.

2.5 SUMMARY OF CHAPTER 2

1 Tides are long-period waves, generated by gravitational forces exerted by the Moon and Sun upon the oceans. They behave as shallow-water waves because of their very long wavelengths. Tidal currents are the horizontal water movements corresponding to the rise and fall (flood and ebb) of the tide.

2 A centrifugal force, directed away from the Moon, results from the Earth's (eccentric) rotation (period 27.3 days) around the Earth–Moon centre of mass, which is within the Earth. This centrifugal force is exactly balanced *in total* by the gravitational force exerted on the Earth by the Moon. However, gravitational force exceeds centrifugal force on the 'Moon-side' of Earth, resulting in tide-producing forces directed towards the Moon, whereas on the other side of the Earth centrifugal force exceeds gravitational force, resulting in tide-producing forces directed away from the Moon.

3 Tractive forces (horizontal components of tide-producing forces) are maximal on two small circles either side of the Earth, and produce two (theoretical) equilibrium tidal bulges – one directed towards the Moon, and the other directed away from it. As the Earth rotates with respect to the Moon (with a period of 24 hours 50 minutes), the equilibrium tidal bulges would need to travel in the opposite direction (relative to the surface of the rotating Earth) in order to maintain their positions relative to the Moon. The elliptical orbit of the Moon about the Earth causes variation in the tide-producing forces of up to 20% from the mean value.

4 With the Moon overhead at the Equator, the equilibrium tidal bulges would be in the same plane as the Equator, and at all points the two bulges would theoretically cause two equal high tides daily (equatorial tides). The Moon has a declination of up to 28.5° either side of the Equator, and when the plane of the tidal bulges is offset with respect to the Equator, there are two unequal, or tropic, tides daily. The declination varies over a 27.2-day cycle.

5 The Sun also produces tides which show inequalities related to the Sun's declination (up to 23.4° either side of the Equator), and vary in magnitude due to the elliptical orbit of the Earth around the Sun. The Sun's tide-producing force has about 46% of the strength of the Moon's. Solar tides combine with and interact with lunar tides. When Sun and Moon are in syzygy, the effect is additive, giving large-ranging spring tides; but when Sun and Moon are in quadrature, tidal ranges are small (neap tides). The full cycle (a lunar month), includes two neaps and two springs, and takes 29.5 days.

6 Tidal speed is limited to about 230 m s^{-1} in the open oceans (less in shallower seas), and land masses constrain tidal flow. Water masses have inertia and experience friction with coasts and the sea-bed, so they do not respond instantaneously to tractive forces. The Coriolis force, and constraining effects of land masses, combine to impose amphidromic systems upon tides. High tidal crests circulate (as Kelvin waves) around amphidromic points which show no change in tidal level, i.e. tidal range increases with distance from an amphidromic point. Amphidromic systems tend to rotate in the opposite direction to the deflection caused by the Coriolis force.

7 The actual tide is made up of many constituents (partial tides), each corresponding to the period of a particular astronomical motion involving Earth, Sun or Moon. Partial tides can be determined from tidal measurements made over a long time at individual locations, and the results used to compute future tides. Actual tides are classified by the ratio (F) of the summed amplitudes of the two main diurnal constituents to the summed amplitudes of the two main semi-diurnal constituents.

8 Tidal rise and fall are produced by lateral water movements called tidal currents. Tidal current vectors typically display 'tidal ellipses' rather than simple to-and-fro motions.

9 Areas of low atmospheric pressure cause elevated sea-levels, whereas high pressure depresses sea-level. A strong wind can hold back a high tide or reinforce it. Storm surges are caused by large changes in atmospheric pressure and the associated strong winds. Positive storm surges may result in catastrophic flooding.

10 In estuaries, the tidal crest travels faster than the tidal trough because speed of propagation depends upon water depth; hence the low water to high water interval is shorter than that from high water to low water. Tidal bores develop where tides are constrained by narrowing estuaries and the wave-front is forced by the rising tide to travel faster than the depth-determined speed of a shallow-water wave. Where tidal ranges are large and the water can be trapped by dams, the resultant heads of water can be used for hydro-electric power generation.

Now try the following questions to consolidate your understanding of this Chapter.

QUESTION 2.11 Write an expression for the tide-producing force at point P on Figure 2.4(a), using the terms as defined for Equations 2.1, 2.2 and 2.3. It is not essential to try to simplify or approximate the expression.

QUESTION 2.12 Which of the following statements are true?

(a) 'In syzygy' has the same meaning as 'in opposition'.

(b) Neap tides would be experienced during an eclipse of the Sun.

(c) Spring tides do not occur in the autumn.

(d) The lowest sea-levels of the spring–neap cycle occur at low tide while the Moon is in quadrature.

QUESTION 2.13 Briefly summarize the factors accounting for differences between the equilibrium tides and the observed tides.

QUESTION 2.14 How will each of the following influence the tidal range at Immingham (Figure 2.18(a)):

(a) The Earth's progress from perihelion to aphelion?

(b) The occurrence of a tropic tide?

(c) A 30 millibar rise in atmospheric pressure?