Chapter 8

Tides

Introduction:- The word, ‘Tide’ derived from low-German ‘tiet’ = time is a planetary phenomenon creating rise and fall of sea levels which is due to the combined effects of the gravitational forces exerted by the Moon and the Sun in conjunction with the rotation of the Earth. The physical process of formation of tides takes place continuously day in and day out. But, the effect is seen only twice a day (High Tide and Low Tide). Nobody can stop the formation of tides. They are harmless. As the saying goes, “Time’ and ‘Tide’ wait for no man” and they go on. They are very much required for the life of aquatic animals and other organisms in the coastal areas so as to get periodically expose to the Sun and air during low tides and at times sink in water during high tides. It is the work of almighty to synchronize their lives with the motion of tides.

In this chapter we shall briefly deal with the history of tides, its cause and effects; and power generation from tides. We shall also go through few research papers titled, Tides and the Evolution of Planetary Habitability; The effects of tides on dense water formation in Arctic shelf seas; Ocean tides and the Earth’s rotation; Atmospheric tide disturbances as earthquake precursory phenomena.

REVIEW OF LITERATURE

History of Tides:- 8.1 Prof. M. Natarajan, et al have given a brief account of Waves and Tides in their article published from Centre of Advanced Study in Marine Biology, Annamalai University and the same almost coincides with what is given in the 8.2 Wikipedia, the free encyclopedia on Tides. The study of tides started as early as 2300 BC in the ruins of coastal cities along the Gulf of Cambay in India. The coastal tribes, in order to keep their boats floating, they used to trap the tidal water in an enclosure fitted with gates during high tides and close the gate before the tides recede. Ancients in India during the 4th and 3rd century BC believed of a link between tides and the phases of the Moon. Tides play a very important role in the culture and commerce of the coastal areas of any region. Ancients were not very much interested in the ‘cause and effect’ formalism regarding tides except taking that it is the work of almighty and something
A detailed study from the point of view of ‘Physics of Tides’ started in the year 1632 with Galileo (1564-1642).

**Physics of Tides:** In the year 1632, Galileo published an article ‘Dialogue on the Tides’ in his “Dialogue concerning the two Chief World Systems”. In that article, he attributed the cause of tides to the motion of Earth around the Sun and the theory was disputed and finally discarded. Later, Johannes Kepler (1571-1630) a German mathematician and founder of Celestial Mechanics, based upon ancient observations and correlations, correctly suggested that Moon caused the tides. Isaac Newton (1642-1727) in the year 1687 published his *Principia* in which he mentioned that the tide generating forces are due to the lunar and solar attractions.

**Tidal Force:** The tidal force produced by a massive object such as the Moon (we call it massive because of its nearness to the Earth) on an extensive body such as the Earth is the vector difference between the gravitational force exerted by the Moon on the Earth if it were located at the Earth’s centre of mass. Thus the tidal force essentially depends not on the strength of the lunar gravitational field but on the gradient which falls off approximately as the inverse cube of the distance to the originating gravitational body. Even though the solar gravitational force on the Earth is some 179 times stronger than the lunar one, its field gradient is weaker as the Sun is about 389 times farther from the Earth. The lunar tidal acceleration on Earth’s surface along the Earth-Moon axis is calculated and found to be about \(1.1 \times 10^{-7}\) g where g is the acceleration due to gravity, whereas the solar tidal acceleration on Earth’s surface along the Earth-Sun axis is \(0.52 \times 10^{-7}\) g which is just half of the former. It should be noted that gravitational force varies inversely as the square of the distance whereas tidal forces vary inversely as the cube of the distance.

The theory of tides were given a firm mathematical basis in 1776 by Pierre Simon Marquis de Laplace (1749-1827). David A. Randall has extensively dealt with the mathematics of Laplace Tidal Equations and Atmospheric Tides. Laplace considered the tide-generating force and the Earth’s dynamic response to that force, a response influenced by bathymetry, rotation of Earth and other related factors and finally arrived at differential equations that are complicated and trivial known as Laplace Tidal Equations (LTE). He represented the tidal force, F by
\[ F \left( \Theta_n^{\alpha,s} \right) = -\varepsilon_n \Theta_n^{\alpha,s} \quad \ldots (1) \]

where \( \varepsilon_n \) is a dimensionless quantity given by \( \varepsilon_n = \frac{4\Omega^2 a^2}{gh_n} \). Using the definition of \( F \), Laplace expanded the equation (1) to get

\[
\frac{d}{d\mu} \left[ \frac{1 - \mu^2}{v^2 - \mu^2} \frac{d\Theta_n^{\alpha,s}}{d\mu} \right] - \frac{1}{(v^2 - \mu^2)} \left[ \frac{s}{v} \left( \frac{v^2 + \mu^2}{v^2 - \mu^2} \right) + \frac{s^2}{1 - \mu^2} \right] \Theta_n^{\alpha,s} + \varepsilon_n \Theta_n^{\alpha,s} = 0 \quad \ldots (2)
\]

is the Laplace Tidal Equation (LTE) in the final form.

In the above, \( \sigma \) is the frequency which is \(< 0\) for eastward motion, \( > 0\) for westward motion,

\[ s \text{ zonal wave number} = 0, 1, 2, 3 \ldots \]

\[ v \text{ normalized frequency}, \]

\[ \mu \text{ latitude variable} = \sin \varphi \]

\( \varepsilon_n \) is a dimensionless quantity given by \( \frac{4\Omega^2 a^2}{gh_n} \),

\( a \) planetary radius,

\( h_n \) is the separation constant and is called the “equivalent depth”,

\( \Theta_n^{\alpha,s}(\varphi) \) is the meridional structure and bounded at the poles \( \mu = +1 \) and \(-1\).

The Laplace Tidal Equation given by (2) is a second order ordinary differential equation and requires two boundary conditions. It is sufficient to assume that the \( \Theta_n^{\alpha,s} \) must be bounded at the poles, i.e. at \( \mu = -1 \) and \(+1\).

Academie Royale des Sciences in Paris in the year 1740 declared a prize for the best theoretical essay on tides. Eminent scientists of the time, Daniel Bernoulli, Leonhard Euler, Colin Maclaurin and Antoine Cavalleri shared the prize. Maclaurin was the first to include the rotational effect of the Earth in the mathematical treatment on tides. Sir William Thomson (later named Lord Kelvin) (1824-1907) rewrote Laplace’s equations in terms of vorticity which allowed for solutions describing tidally driven coastally trapped waves called Kelvin waves. Later, Henri Poincare joined Lord Kelvin in modifying Laplace’s theory, which was used by Arthur Thomas in 1921 following E. W. Brown’s lunar theory. Doodson has distinguished nearly 388 tidal frequencies some of which are still in use today.
It is the solution of the LTE equation that is trivial. A detailed solution of the equation is given by Myrl Hendershott. He has first obtained the Laplace Tidal Equations for a stratified ocean and considered various solutions such as Barotropic solution, Baroclinic solution and finally Numerical solution to LTE. He has also dealt with the mathematics of solid Earth tides and their energetics.

Yair De-Leon and Nathan Paldor in their research paper have dealt with Zonally propagating wave solutions of Laplace Tidal Equations in a baroclinic ocean of an aqua-planet. According to them, the
solutions so far obtained by earlier researchers are applicable only to slow rotating planets and hence cannot be applied to Earth. The authors have applied the time-independent Schrodinger equation in one dimension whose energy levels yield the dispersion relations of zonally propagating waves. The meridional structure of the amplitude of these waves can be determined by the respective eigenfunctions. When
the LTE is formulated as a Schrodinger equation, analytical solutions can be obtained in which the latitudinal variation of the variables is given by Hermite functions and explicit expressions of the dispersion relations of the various waves are given by the roots of a cubic relationship between phase velocity and energy levels of the Schrodinger equation. Such a method can be applied to bounded domains (channels) also.

An undated and rare illustration of formation of tides, probably of those times of Lord Kelvin, is shown in Fig. 8.1.

The mechanism of formation of tides is schematically shown Fig. 8.2. The gravitational force exerted by the Moon pulls the water of the oceans on Earth and there is a bulge of water as shown in Fig. (a). Now, the rotation of the Earth comes into picture and it is considerable. The rotational velocity of the Earth at equator is 465 m/s and hence there is a centrifugal force at the centre of mass of the Earth-Moon system creating a bulge of water on the opposite side as shown in Fig. (b). This is but natural and shows that even nature loves symmetry. The bulging on one side of the globe creates a similar bulge on the opposite side. As physicists, we believe in mathematics which is the language of Physics and hence the centrifugal force is brought in.

![Fig. 8.2 (a) Effect of Gravitational Force](image)

![Fig. 8.2 (b) Effect of Centrifugal Force](image)

The resultant of the gravitational and the centrifugal force is as shown in Fig. (c). The bulging of water is symmetrical with a high tide at A and B and low tide at C and D.
Paul W. Zitzewitz in his book which is almost an encyclopedia for fundamentals in physics, says that tides greatly vary with location. The largest tidal variations occur in the Bay of Fundy between the Canadian provinces of Nova Scotia and New Brunswick where the largest recorded range was 17 metres. (Fig. 8.3). There have been many proposals to build a dam across the bay to generate electricity from the tides, but environmentalists objected to such a proposal.

**Types of tides:-** The tidal forces affect the entire Earth. In the case of ocean waters, the tide is the ocean tide where the surface moves in metres. It affects the solid Earth too, i.e. the Earth tide which is in few centimetres. The atmosphere is much more fluid and compressible and the tide in that case is the atmospheric tide, where the surface moves in kilometres. The timing of

![Fig. 8.3 High tide, Alma, New Brunswick In the Bay of Fundy](image1)

![Low tide at the same fishing port in the Bay of Fundy](image2)

the tidal events is related to the Earth’s rotation and the revolution of the Moon around the Earth. Assuming the Moon to be stationary, the cycle of tides will be 24 hours long i.e. for the entire day, but that is not the case. The Moon revolves round the Earth and one revolution takes 27 days and adds about 50 minutes to the tidal cycle and hence the tidal period is 24 hours and 50 minutes in length.

Now, let us take into consideration the effect of solar gravity. The height of the average solar tide is about half the average lunar tide. When the Sun and Moon are aligned with the Earth as shown in Fig. 8.4, the two tide producing bodies (Sun and Moon) act together to create
The highest and lowest tides of the year. These are Spring Tides that occur every fortnight during full Moon and New Moon. Pytheas travelled the British Isles about 325 BC and seems to be the first to have related spring tides to the phase of the Moon. The name Spring Tide has no connection with the Spring Season. It is like a mechanical spring which jumps and bumps and rises.

Now, when the gravitational pull of the Sun and Moon are at right angles to each other as shown in Fig. 8.5, the resultant variation on the Earth is the least. The tides in this situation are called Neap Tides. Neap tides occur during the first and last quarter of the Moon, i.e. there is about a seven-day interval between Spring tides and Neap tides.

The formation of tides is highly rhythmic and strictly follows the position of the Moon in conjunction with the Sun. In South-East Asia and parts of northern Gulf of Mexico, a high tide is followed by a low tide every day. These are called Diurnal Tides and their tidal cycle is illustrated in Fig. 8.6.

There are some Semi-diurnal Tides having two high and two low waters per tidal day. Their tidal cycles are shown in Fig. 8.7. These tides are common on the Atlantic coasts of the United States and Europe.
Fig. 8.6 Tide cycles of Diurnal Tides
The tides in the western coastal regions of Canada and United States are of a different type. The high and low tides in these regions differ considerably. In these regions, there is higher high water and lower high water as well as higher low water and lower low water. Such tides are called Mixed Tides. Fig. 8.8 illustrated the tide cycles of the mixed type.

Other Tides:- In addition to the ocean tides, are Lake Tides, Atmospheric Tides and Earth Tides. Some of the lakes like Lake Superior, Lake Michigan also experience tides, but hardly few cm. Lake Superior experiences a tide of maximum 4 cm. Atmospheric tides are both gravitational and thermal origin. The atmosphere being a mixture of gases is pulled to a height ranging from 80 to 120 km. Earth tides cause the crust being pulled due to gravity of the Sun and Moon to a height of 55 cm at the equator. We standing on the Earth, cannot notice this.

In addition, the bottom topography of the ocean is uneven and the oscillating tidal currents in the stratified ocean flow over this uneven stretch thereby generating internal waves with frequencies matching with the tides. These tides are called internal tides.

Chris Garrett, Eric Kunze is of the view that the internal tides are internal gravity waves generated in stratified waters by the interaction of tidal currents with variable bottom topography. The tidal energy gets dissipated and leads to mixing in the deep ocean. The tidal excursion and the bottom slope are some of the key parameters in the propagation of these internal tides. The height of the topography is more important as compared to the depth of the ocean. The author has shown in his paper that the energy flux is associated with low modes and the energy flux is strongly dependent on the bottom slope.
8.9 Rory Barnes, et al in their research paper on “Tides and the Evolution of Planetary Habitability” have extensively discussed with mathematics and calculated the tidal evolution of hypothetical terrestrial planets around low-mass stars and showed that tides can evolve planets past the inner edge of the habitable zone within a period of one billion years. According to them, for planets orbiting very close to their host stars, the tides raised by the gravity of its host star, such as our Earth and the Moon, can reduce the planet’s orbital semi-major axis and eccentricity. The habitable zones of low-mass stars are also close in and the tides can alter even the axis of these planets. Such a change requires large eccentricities (> 0.5) and low-mass stars (≤ 0.35 M\(_\odot\)). But, this will create lot of implications for the evolution of the atmosphere, internal heating and gaia hypothesis. The authors have considered the past habitability of the recently discovered ~5M\(_\oplus\) planet, Gliese 581 c. It was found to be habitable some 2 Gyr ago. In their mathematical treatment, as per assumption, some resonance capture should have been observed, but it did not take place and hence they concluded that the planet Gliese 581 c can never be habitable. The authors have concluded that the detection of a terrestrial planet around a low-mass star is insufficient to determine the planet’s past and future habitability. The tidal forces between planet and star can significantly change the orbits and hence limit the habitable lifetime. The tides can move habitable planets into non-habitable orbits.

8.10 D.N. Arabelos, et al have considered the Atmospheric tide disturbances as Earthquake precursory phenomena. Their research is of a long-term type means they took hourly measurements for atmospheric changes such as pressure and temperature for 21 long years starting from 1981 to 2001 during tides in the city of Thessaloniki, Greece. The basic parameters amplitude and phase difference were considered as the mean values for the long time period. Making a set of observations for each year, 21 such sets were prepared by them. An observable correlation in amplitude, they found corresponding to an earthquake (M > 4) in the neighborhood of Thessaloniki during years of their experimentation.

Even though the atmospheric tides are comparatively weaker, the authors have found that the tides at the site are responsible for the noise to the determination of the local potential. An attempt is made to reveal exalting in atmospheric tides by measuring
barometric pressure measurements. A correlation between atmospheric tides and atmospheric temperature was estimated. The 21 amplitude values computed for each tidal wave were considered as the amplitude variation with respect to a corresponding mean value. The authors have systematically considered the following:

- Model of tidal potential
- Barometric pressure data
- Atmospheric temperature data and
- Earthquake catalogue.

It is concluded in their experiments that the estimated amplitude and phase difference parameters of the atmospheric tides are characteristics for the area of Thessaloniki. An amplitude exalting of some waves may precede an earthquake near the area of the test. The exalting of tidal waves by taking a shorter time interval will prove a better precursor for earthquakes.

C.F. Postlethwaite, et al in their research paper titled, “The effect of tides on dense water formation in Arctic shelf areas”, have used a 25 km × 25 km 3-D ocean circulation model coupled to a dynamic and thermodynamic sea ice model. The tidal amplitudes from the model are compared with the tide gauge data. The sea ice extent is compared with the tide gauge data and the sea ice extent is compared with the satellite data. In tidally active coastal regions, it is observed that there is a delay in the freezing. The impact of tides on the salt-content is, however, found to vary from region to region. In the Pechora Sea and around Svalbard, where the tides are strong, the vertically integrated salt budget is dominated by lateral advection. It is found that tides increase the salt flux by 50% in the Pechora and White Seas. The authors have stressed in their paper that ocean tides and sea ice should be considered while modeling the Arctic.

Tidal mixing within a water column and at the base of the sea ice cover can increase the flow of heat from the deep interior to the surface thereby decreasing the ice formation and ice melting. The tidal currents cause a sort of stress and strain on the ice bed. There is a loss of heat in winter and creating an additional fall in temperature with the ice floating on top and the high density salt water (brine) remaining at the bottom.
The interaction between tides and the sea ice bed is schematically illustrated in Fig. 8.9. Process-1 is the tides bringing more heat from the bottom to the surface creating melting of ice. Process-2 represents the heat loss and increased brine rejection. The alternation of convergence and divergence periods during the tidal cycle creates a mechanical redistribution of ice itself and this is shown in Process-3.

The authors have dealt in details the following:

- Model description
- Surface and boundary forcing
- Description of the modeled tides
- Impact of tides on sea ice distribution
- Impact of tides on salinity distribution
- Salt Budget
- Lateral advection of salt
- Surface salt fluxes from ice free areas
- Surface salt fluxes from ice covered areas.

It is concluded that tides can create strong vertical current shear that increases vertical mixing thereby facilitating to homogenize the water column in order to bring warm water to the surface. It is of great interest to study increased brine rejection due to tide ice interaction.

**Effects of Tides:** The following are the effects of tides:

(i) Affecting the salinity and freezing of sea water as discussed in the paper of 8.11.

(ii) Affects navigation. Sailors should have up to date information regarding high and low tides at various places in the sea on the globe. Many rivers and harbors have a shallow bar at the entrance which prevents boats with significant draft from entering at
low tide. They carry charts having this information. Tidal flow timings and velocities appear in tidal charts also called tidal atlas. The procedure adopted is as follows:

- Calculate a “dead reckoning” position (DR) from travel distance and direction.
- Mark the chart with a vertical cross like a plus sign and
- Draw a line from the DR in the direction of the tide.

The distance the tide moves the boat along this line is computed by the tidal speed and this gives an “estimated position” (EP) traditionally marked with a dot in a triangle.

(iii) Useful for fishing. Some of the deep sea fish appear on the surface during high tides and hence beneficial to fishermen.

(iv) Some aquatic animals and other insects are more aware regarding tides than humans. They follow the tide cycle for gestation and egg laying and hatching. Some of them lay eggs having a hatching time of a fortnight or so immediately after end of a high tide. The eggs get hatched before the arrival of the next high tide in that region. Some aquatic animals and some of the vertebrates requiring sunlight and atmospheric air automatically get them during low tides. The menstrual cycle in women almost follow a lunar month which is an even multiple of the tidal period indicating a common descent of man from a marine ancestor. This is known as intertidal ecology.

Other than the above four effects, the fifth one which is very important from the point of view of geology and astronomy is the slowing down of Earth’s rotation due to tidal friction which we shall now deal with.

(v) Ocean Tides and the Earth’s Rotation.-- Wikipedia, the Encyclopedia has given a brief account of this topic. Due to the continuous formation of tides throughout the globe at all times, the tidal oscillations introduce dissipation of energy at the rate of 3.75 tera Watt (10^{-12}). A majority of this rate of dissipation is due to marine tidal movement, which in turn causes friction known as tidal friction on the surface of the Earth. The word, ‘friction’ is general and may refer to many physical mechanisms. It can be bottom friction induced by tidal currents flowing across the ocean floor, various kinds of wave breaking, and scattering of tidal waves into oceanic internal waves are all thought to play a role. This tidal drag creates a torque on the Moon which in turn transfers angular momentum to its orbit and a gradual increase in Earth-Moon separation. An equal and opposite torque on the Earth creates a decrease in its rotational velocity which otherwise means that the Earth is slowing down in its rotation.
It has been worked out and found that the Moon recedes from the Earth by about 3.8 cm per year. This recession of Moon creates an increase in the terrestrial day by about 2 hours in the last 500 million years. As a point of interest, it can be said that if the recession rate to be constant, 70 million years ago, the length of the day was shorter adding to 4 more days per year!


In the Fig. 8.10 is shown rapid variations in the rotation rate in terms of Universal Time (UT) as observed by hourly measurements and as predicted by a numerical model of ocean tides. The measurements are carried out in January 1994 with Very Long Baseline Interferometry (VLBI) and provided by IERS Special Bureau for Tides.

**Fig. 8.10 Rapid variations in Universal Time as measured by VLBI and predicted by ocean Model**

**Observation and Prediction of Tides:** Tides were observed and studied by the ancients centuries even before Christ. As already mentioned somewhere, Pytheas travelled to the British Isles sometime about 325 BC and it is believed that he was the first to have related Spring tides to the phase of the Moon.

The Babylonian astronomer, Seleucus of Seleucia in the 2nd century BC correctly theorized that the tides were caused by the Moon and they varied in time and strength in different parts of the world. Strabo another thinker supported the ideals of Seleucus.
specially regarding the heights of tides depending on the position of Moon relative to the Sun.

In China, Wang Chong (27-100) published a book entitled: Lunheng in which he has mentioned that the tides rise and fall follow the Moon and vary in magnitude. In 1730, another thinker from Europe explained the rise of tide water on one coast of British Isles and the fall on the other coast. In the 9th century, Al-Kindi, an Arabian earth scientist wrote a treatise entitled: “The Efficient Cause of the Flow and Ebb” in which he described a laboratory experiment to prove that tides are temperature dependent.

China was the first to prepare a tide table in 1056 for visitors to see the tidal bore in the Qiantang River.

In the following Fig. 8.11 is shown Brouscon’s Almanach of 1546: Compass bearings of high waters in the Bay of Biscay (Fig. (a)) and the coast from Brittany to Dover (Fig. (b)).

Lord Kelvin in 1867 built a tide predicting machine using a system of pulleys with which he could add together six harmonic time functions. It was the first systematic harmonic analysis of tidal records. The machine can be programmed by resetting gears and chains to adjust phasing and amplitudes. Such machines were in use till 1960.
In the Fig. 8.12 is shown a Tidal Indicator in the Delaware River, Delaware, US fitted sometime in 1897. It marked in feet. The height of tide is about 1-feet above mean sea level and is still falling as shown by the arrow. The indicator is powered by a system of pulleys, cables and float.

On the Navy Dock in the Thames Estuary an entire spring-neap cycle was made in 1831. By 1850, many large ports had automatic tide gauge stations. William Whewell prepared a global chart by mapping co-tidal lines and hypothesized the existence of no-tide zones which were confirmed in 1840 by Captain Hewett, RN from the soundings in the North Sea.

**Tidal Power**: The Handy Science Answer Book has given a brief account of tapping energy from tides and waves. Tides and waves contain enormous amount of energy to be harnessed. The first tidal powered mill was built in England in the year 1100; another in Woodbridge, England in 1170, has functioned over 800 years. The Ranee River Power station in France, in operation since 1966 was the first large tidal electric generator plant, producing 160 megawatts. A tidal station works like a hydropower dam, with its turbines spinning as the tide flows through them. Unfortunately, the tidal period of 13.5 hours causes problems in integrating the peak use with the peak generation ability. Ocean wave energy can also be made to drive electrical generators.

Inserting water turbine into a tidal current is the method adopted, but high energy tidal currents are always not available. Hence, what is done is building ponds that release/admit water through a turbine. Unlike wind power, generation levels can be reliably predicted. The efficiency gets decreased at low operating rates. Since the power available from a flow is proportional to the cube of the flow speed, the times during which high power generation is possible are less.
**Conclusion:** Tides! What a rhythmic physical process in the Earth formed as per time table in a geological scale related with the Sun and Moon and can be seen by the humans. Studying tides is a good lesson for the scientist with the Earth never getting tired of the process. But, however, the tiresome nature is revealed in the tidal friction creating a loss of power and slowing down its rotation. Is not that due to the Earth getting tired?

In the conclusion, I would like to add one interesting observation regarding tides. It is safer to swim in the sea during a high tide as the tidal waves of high amplitude and short wavelength have a tendency of approaching the shore and rarely the swimmer is dragged into the sea as shown in Fig. 8.13 (a) The situation, however, is different and dangerous during a low tide when the waves of low amplitude and large wavelength are pulled towards the sea with such gravitational pull that sometimes the swimmer loses control and might get drowned. This situation is shown if Fig. 8.13 (b). The curvature of the ocean bed acts like an inclined plane with the fast moving shallow water of the low tide virtually pulls the swimmer right inside the sea.

![Fig. 8.13 (a) Swimmer during high tide](Picture illustration exclusively by author of thesis)

![Fig. 8.13 (b) Swimmer during low tide](Picture illustration exclusively by author of thesis)

Tides, in general, with its continuous activity of high and low tides following a perfect time table, help to maintain life on Earth.

**REFERENCES :**


[7] 8.4 Hendershott Myrl, “Solutions to Laplace’s Tidal Equations, 2000 (yr. obtained from ref.), p.34-44.


