CHARACTERISTICS OF TIDAL ENERGY

L.B. Bernshtein (Deceased)
Share -holding Company, Institute Hydroproject, Moscow, Russia

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Summary

The term tide implies a complete cycle of tidal oscillations of sea level, including the flood- tide (rise of level) and the ebb- tide (drop of level).

The cause of tide is a tide generating force, originating from gravitational interaction of the Earth with the Moon and the Sun. The tide caused by the Sun, due to the large distance of the Sun from the Earth, is smaller by a factor of 2.17.

Tidal oscillation has a strictly definite periodicity, which can be determined for any required period of time.

Semi-diurnal (12 hours 24 minutes), diurnal (24 hours 48 minutes) and mixed tides can be observed on the shores of the World Ocean.

The tidal amplitude varies from minimum values during quadrature (the first and the third quarters of the Moon) to maximum in the syzygy (at new and full moon). The largest tide of 17.3 m was observed in the Bay of Fundy in Canada.

Tidal energy is generated as a result of the action of tide generating forces in natural conditions is dissipated due to friction in water and power interchange with land and atmosphere. The regions known for high local tidal energy content are located in the Bays of Fundy, Penzhin, Bristol Channel and St-Malo.

Tidal power potential at designing TPP with separation of large sea basins is assessed on the base of prediction calculations of tidal regime with consideration of its transformation.

Invariability of mean monthly tide value in any place is one of the main advantages for TPP operation, i.e. it guarantees firm energy supply in power systems as compared to HPP, power generation which depends on annual water availability.

1. Tide Characteristics

The tide is a complete cycle of tidal oscillations of sea level, including the flood-tide (rise of level) and the ebb-tide (drop of level).

The cause of such tidal reversals, even in sites where the tides are strictly regular, remained unknown for many years. The ancient Greeks, even in their time, suspected that the tides are associated with the lunar phases, but the complexity and variety of tidal oscillations led to the ancient proverb: "Tides are the grave of human curiosity", remaining plausible for many centuries. At present navigators have at their disposal tide tables where the height and the time of low and high tides for any day of any year are indicated for the main points of the coast. The tables are compiled with the help of harmonic analysis of data of observations.

The tidal wave floods vast areas. Depending upon the position of the site on the globe, the coastal configuration, and bathymetry, the tidal range varies from a few centimeters in the land-locked seas (Black Sea, Baltic Sea, Mediterranean Sea, and others) to many meters at the funnel-shaped bays open towards the ocean. So, at the head of such a bay named Fundy, Canada, the highest Earth's tide with a range equal to 17.3 m is observed. In most sea areas, two tidal rises and two falls occur during each lunar day, i.e. with the period of approximately 12 hours 24 minutes (semidiurnal tides) or only one high and one low tide occurring in each 24 hours 48 minutes (diurnal tides). In most cases, the actual tidal oscillations are a combination of both above-mentioned types and are named after that substantially prevailing over the other. If both types of tidal oscillations play an essential role, the resultant tide is called a mixed tide. The highest point reached by the sea in any one tidal period is called the high water, HW, and the lowest point reached by it is termed the low water, LW.

The difference in the height of the water at low and high tides is known as the tidal range, A; the intensity of tidal oscillations may be characterized by the height of the high or low water with respect to the mean sea level and is called tidal amplitude, $A/2$.

In the course of semidiurnal tides, the maximum amplitudes take place at new Moon or full Moon (spring tides) while the minimum amplitudes are observed about the time of the first and third quarters of the Moon (neap tides). In the course of diurnal tides, the maximum amplitudes are observed at the extreme declinations of the Moon (tropic tides), and the minimum at the zero declination (equatorial tides). When the tropic tides are in phase with the spring ones the amplitude of the resultant tide reaches its maximum magnitude. The chart (see Figure 1) shows the values of maximum range, mean spring (tropical) range, and mean range in the sites that permit utilization of tidal energy. Note that the atlases, textbooks and monographs on oceanography usually give data on maximum amplitudes of tide. The publications dedicated to the use of tidal power present the mean ranges of tides that are decisive in specifying the TPP parameters.

The periodic rise and fall in the level of the water in the world's oceans and tidal currents are caused by the tide generating force resulting from the gravitational interaction between the Earth and the Moon and Sun. The tide generating force of the Moon at a given point of the Earth's surface is determined as the difference between the local gravitational attraction of the Moon and the centrifugal force due to the rotation of the Earth-Moon system about their common center of gravity. The distribution of tide generating force over the Earth's surface is illustrated in Figure 1. In the course of its rotation, the Earth turns within the force field that rather slowly changes its orientation (following the position of the Moon in the sky) and intensity (increasing when the Moon approaches the Earth and decreasing when it retreats).

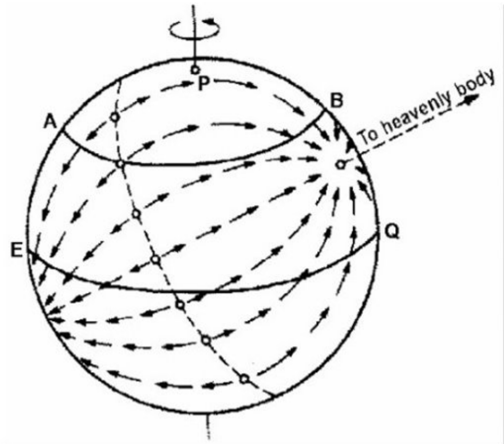

Figure 1. Distribution of horizontal components of tide-generating force upon Earth's surface
P - North Pole; EQ - equator; AB - fixed parallel

The simplest reaction of the Earth's hydrosphere envelope to the action of the tide generating force is determined by Newton's equilibrium theory. According to this theory, the envelope of the hydrosphere assumes the shape where the water surface slope at any moment of time is balanced by the tide generating force. If a continuous water layer covered the Earth, the surface of this body of water would acquire the shape of an ellipsoid of revolution, its larger axis always pointing toward the Moon. While the ellipsoid following the Moon makes a revolution about the Earth, the earth itself revolves 29.53 times around its own axis. Obviously, in the course of this rotation, each point of the Earth's surface passes at different distances from the surface of the tidal force ellipsoid. It is readily seen that the distances between the relevant points of the ellipsoid surface and the sphere revolving inside it continuously and regularly vary from a minimum to a maximum and again to the minimum. It is this that accounts for the tidal oscillation having a strictly definite periodicity. Once the Moon is in the equator plane, the periodicity is truly semidiurnal. The tide caused by the Sun follows from the same principles as the lunar tide but is smaller by a factor of 2.17, due to the greater distance of the Sun from the Earth.

However, three basic factors affect the simple semidiurnal periodicity of tidal oscillations. There is a variable declination of the tide-generating celestial bodies (the Moon and the Sun) with respect to the Earth's equator plane, changes in their relative positions with reference to the Earth, and finally, changes in their respective distances from the Earth. As a result, differences occur in the heights and times at which the high and low waters take place: inequalities of tide. By their periodicity, the inequalities can be categorized as diurnal, fortnightly, monthly and of long periods. The causes of these inequalities can be explained on the basis of the equilibrium theory.

The diurnal inequality of height shows itself as a difference in two adjacent high and low waters during 24 hours and as their differing times of fall and rise. This inequality is associated with the declination of the tide generating heavenly body relative to the equator plane of the Earth (see Figure 2). With the ellipsoid in the position shown in the Figure, the regular semidiurnal tide remains unchanged only at the equator (PP’ = QQ’), while inequalities occur to the north and to the south of it. For example, the high water having a maximum height determined by BB’ is observed at point B. The next high water determined by AA’ will be far less. Nor are the sea level fall time and the time of the subsequent rise equal. At the poles and in high latitudes (points E and F), the second high water will be absent and the tide will be diurnal. Therefore, it may be stated that the diurnal inequality results from the occurrence of a diurnal component increasing with the distance from the equator.

The fortnightly inequalities include phase and tropic inequalities.

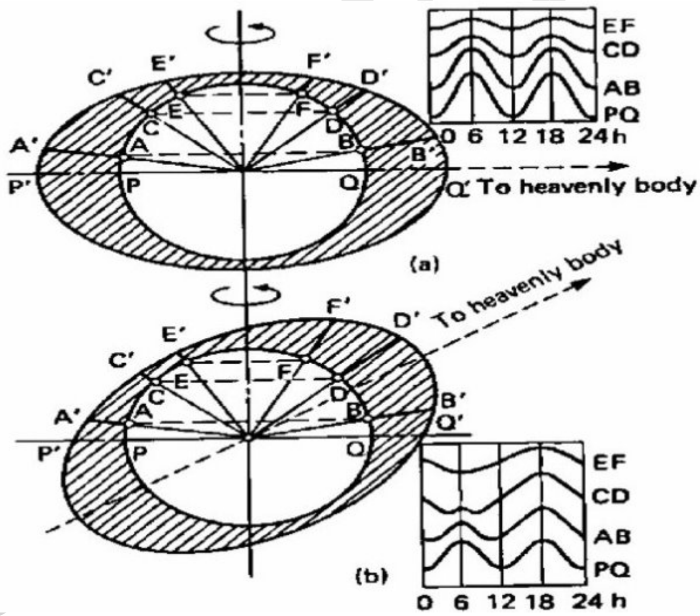

Figure 2. Tidal ellipsoid and diagram of diurnal inequality formation in equilibrium tide at declination of tide-generating heavenly body
(a) zero declination regular semi-diurnal tide in all latitudes; (b) declination does not equal zero growth of diurnal share with increase in latitude; (a) zero declination regular semi-diurnal tide in all latitudes; (b) declination does not equal zero growth of diurnal share with increase in latitude

The phase inequality that is characteristic for semidiurnal tides stems from the regular changes in the relative positions of the Earth, the Moon, and the Sun, i.e. in the Moon’s phases. In the course of new Moon and full Moon when the Moon, Sun and Earth are in the same straight line (syzygy), the ellipsoids of solar and lunar tides reinforce each other with the resultant increased spring tide. Once, the Earth, Sun and Moon are in quadrature, i.e. the Moon and the Sun are at right angles with the Earth at the apex (the first and third quarters of the Moon), the ellipsoids of lunar and solar tides attenuate each other, which leads to relatively high low water and relatively low high waters, resulting in neap tides. The mean period of phase inequality is equal to 14.7 days.

The tropic inequality manifests itself in the variation of the intensity featured by the above-considered diurnal inequality. This intensity, which is proportional to the fraction of the diurnal component in the tidal oscillation, grows with increase of the moon declination and reaches its maximum (tropic tides) with a concurrent decrease of the semidiurnal component every 13.7 days. At zero declination, the intensity of the diurnal inequality is minimal and the tides are equatorial.

The monthly inequality also known as parallax inequality is due to the variation of the Earth's distance from the Moon because the Moon orbits around the Earth in an elliptical path. When the Moon is at its perigee (at the distance of 57 earth radii) its tide-generating force, and hence the resultant tide, increases; with the Moon at its apogee (at the distance of 63.7 earth radii) the tide decreases. This variation of the tide range occurs every 27.55 days.

The variation of the Sun's declination and its distance from the Earth brings about tropic and parallax inequalities in the solar tide that have monthly and yearly (annual) periodicity; these inequalities are of the long-period type. There are inequalities with still larger intervals. The most perceptible of these is an inequality occurring every 18.6 years, which is associated with the variation of the maximum possible declination of the Moon. The influence of this inequality on the regular semidiurnal tides is relatively small.

The assumption of the static theory under which the hydrosphere envelope of the Earth is at all times in the equilibrium state is not satisfied in reality. Because of the inertial forces of ocean water, its reaction to the tide generating forces is dynamic rather than static and thus dependent upon the parameters of natural oscillations of the world ocean. The deep separation of the ocean in different parts and the variable configuration of the ocean bottom account for the very intricate nature of the above-mentioned parameters. The result is that the actual tidal motions have a very complicated spatial pattern. For actual tides, resonance properties of the ocean basin in which they occur are of high importance. If the periods of natural oscillations of the basin coincide with or are close to the tidal period, they contribute to an increase in the local amplitude of the tide, i.e. the resonance leads to the concentration of tidal energy.

Although, the real dynamic tide differs much from the equilibrium tide by the spatial distribution of amplitudes and phases, the former tide, being a forced oscillation, preserves an important characteristic of the equilibrium tide. i.e. the frequency structure of the tide generating force. This means that all those inequalities that were characteristic of the equilibrium tide show up in the dynamic tide, i.e. the variability of the real tide in time is determined by the complex variability of the tide-generating force.

To analyze this complex variability, use is made of the expansion of the function describing the tide generating force in time harmonic constituents which, depending on the period, may be grouped into three major types of harmonics: (1) semidiurnal; (2) diurnal, and (3) long periods (from fortnightly to annual and more). The most significant of the harmonic constituents mentioned are tabulated in Table 1.

Type of constituent	Constituent	Period, hour
	Principal lunar	12.42
Semidiurnal	Principal solar	12.00
	Larger lunar elliptic	12.66
	Luni-solar declinational	11.97
	Luni-solar declinational	23.93
Diurnal	Larger lunar	25.82
	Larger solar	24.07
	Larger lunar elliptic	26.87
	Lunar fortnightly	327.86
Long-period	Lunar monthly	661.30
	Solar semi-annual	2191.43

Table 1. Basic harmonic constituents of tide-generating force

The world ocean as a whole, except for small shallow water areas along the coasts, responds to the action of tide generating forces as a linear oscillatory system consisting of interconnected basins. The linear nature of this reaction allows to represent the tidal motions in the form of the sum of time harmonic terms having the same periods as the harmonics of the tide generating force, i.e. it is assumed that each harmonic of this force generates its own tide with its own period. These individual tides are designated by the same symbols as the force harmonics, and frequently called waves (wave M_2, wave K_1, etc.). To avoid misunderstanding, the term (tidal) harmonic will be used to designate an individual tide (harmonic M_2, for example), and the term tidal wave will be used only in a hydrodynamic sense.

At each point of the world ocean, the harmonic tidal oscillation has, by definition, a stable value of amplitude H (here H is the standard designation of the amplitude of an individual harmonic constituent in contrast to $A/2$ which is the amplitude of a summary tide) and phase $g°$ expressed in its own time system (if use is made of the conventional solar time, the phase of all harmonics, except harmonic S_2, will slowly creep from day to day). For this reason the quantities H and $g°$ are called the harmonic constants. The space distribution of harmonic constants thus forms a stationary field. A chart of such field for an actual basin with the aid of isolines (lines of equal values) H (co-amplitudes) and $g°$ (co-tidal lines) is known as a tidal chart. The tidal constituents obtained in the course of the harmonic analysis in the form of harmonics (K_1, O_1 and M_2) determine not only the tidal range A but also the type of tide by the correlation of the amplitudes H of these constituents

$$D = \frac{H_{K_1} + H_{O_1}}{H_{M2}} \tag{1}$$

If the semidiurnal constituent is predominant in the tides, so that *D* varies within 0 to 0.5, then the tides involved are called regular semidiurnal ones. When diurnal constituents are predominant, so that the *D* is equal to 4 or has a greater value, the tides become regular diurnal. In case when *D* varies from 0.5 to 4, the tides are known as mixed, when during a month, the tidal character varies from semidiurnal to diurnal and vice versa. If semidiurnal constituents somewhat prevail the mixed tides are called irregular semidiurnal ones (*D* is within the limits 0.5 to 2). These are observed in the Indian and Pacific Oceans. When *D* increases from 2 to 4 (the predominance of diurnal tides having a noticeable diurnal inequality with an increase in the declination of the Moon) the tides are termed irregular diurnal tides.

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Biographical Sketch

Lev B. Bernshtein,
Born Dezember 21, 1911, Nizhni Novgorod, Russia/

1939 – graduated from Moscow Engineering Construction Institute.

1973 – Doctor of Technical Science (Thesis: On utilization of tidal power and construction of the pilot Kislaya Guba tidal plant).

1939-1999 – Chief Engineer of tidal power plant projects, Design, Survey and Scientific Research Institute «Hydroproject».

Author of more than 100 scientific papers and 8 monographs.

Main activities: Creator of a Russian school of tidal energy usage; author of the first Kislaya Guba tidal power plant; developer of lightened structure for low-head hydropower plants; leader in using of bulb units at hydropower projects.

Honorary member of the Academy of Water Economical Sciences, member of International Power Academy

He died (1999).