UNUSUAL TIDAL MOVEMENTS IN THE SULU SEA.

by

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Seven hundred miles north of the Equator, and 800 miles east of Saigon, Indo-China, the Island of Palawan stretches its gaunt length over nearly half the distance that lies between Manila and Borneo, and separates, in places by only a few miles, the waters of the Sulu and China Seas.

One of the products of Palawan is the ipil, or Philippine mahogany. This wood, being heavier than water, will not float and, since long stretches of the coast are without docks, it is the custom of the natives to drag the logs to the water's edge at low tide, attach to them logs of lighter wood or bamboo, and wait for a high tide to float them out to the vessels that are to receive them. On the eastern coast this work is sometimes rudely interrupted by a series of rapid risings and fallings of the water, many times more rapid than the rise and fall of the normal tide.

At Puerto Princesa, the principal city of the island, situated on the bay of the same name, there is a wharf built on bamboo poles. The frailty of this structure prevents the docking of vessels in the usual way. Instead, the vessel is brought up parallel to the wharf, an anchor cast from the bow, a line from the bow carried to the wharf in a small boat, a second anchor cast from the stern. and a second line carried by boat from the stern to the wharf. This procedure brings the vessel alongside the wharf without danger of injury to the bamboo piling, but it requires considerable time, and due allowance must be made for the current. The current at this point, however, is frequently an uncertain quantity. Its direction will sometimes reverse when the process of docking is half completed; the vessel will swing around, upsetting the whole scheme of operation and, by the time lines and anchors are straightened out, the vessel brought up to position again, and the docking process started anew, the current reverses again, and so it goes.

A field party of the United States Coast and Geodetic Survey, engaged in making a survey of Puerto Princesa, found it necessary to construct a signal tower, on a shoal near the head of the bay. This shoal was known to be bare at low tide, so the officer in charge, referring to his tide tables, selected for the work a time when the tide would be low. Arriving on the scene and starting the work of building a form for the concrete base of the tower, the members of the party noticed the water rising rapidly about them. Gathering up their tools amid floating chips and bits of lumber they scrambled aboard their boat. Starting away from the scene they noticed the water receding, the bits of wood which had drifted to the northward came floating back, and the men were soon able to resume their work.

WHAT IS A SEICHE ?

What is the explanation of the strange behavior of the waters of this region ? The native will tell you in two words — *mare loco*, "*crazy tides*", and the "crazy tides" of Palawan are *seiches.*

The term "seiche" is derived from the French word *sec*, meaning dry. It was used generations ago to designate the rapid fluctuations of the water level common in certain Swiss lakes, especially Lake Geneva. In more recent times, the scope of the term has been broadenea to include similar fluctuations in bays and harbors connecting with the sea, and even on the open sea-coast. Such fluctuations are oscillatory in nature, the period of time required for the rise and fall of the water surface at a given place being in general definitely fixed by the length, width, and depth of the oscillating body of water. The amplitude of the oscillation, that is, the amount of rise and fall of the water surface, is not regular but is continually varying while the seiche movement is going on.

The periods of different seiches vary from a few minutes to an hour or two, and the amount of the rise and fall may be anything from the smallest quantity that can be measured, to a number of feet. It is to be noted, however, that, whether the amount of the rise and fall is small or large, the period for a given seiche remains approximately constant.

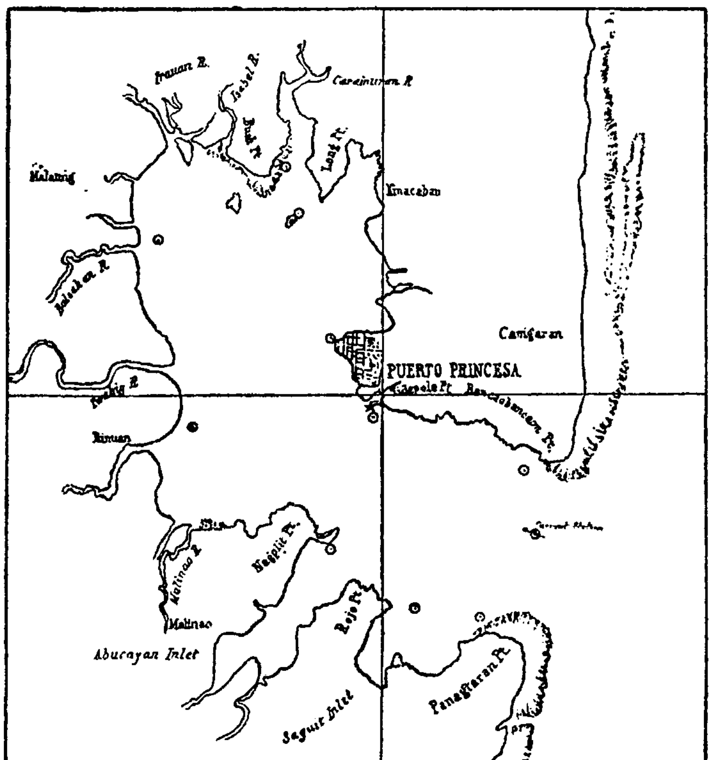

FIG. 1.

Chart of Puerto Princesa, Palawan Island, P. I.

The position at which simultaneous heights of the water surface were observed are shown.

If we wish to produce a miniature seiche in its simplest form, it is only necessary to fill partly a small rectangular tank with water, and then quickly raise and lower one end of the tank. A wave motion will be set up in the tank and it will be noted that a seesaw movement of the water surface takes place. When the water is high at one end of the tank it will be low at the other; near the center, there will be very little, if any, up-and-down motion. This type of wave is called a stationary wave, in contradistinction to a progressive wave such as is formed by dropping a pebble into a still pond. The portion of the wave where the vertical motion is at a maximum, as at one end of the tank, is called a loop, and the part where no up-and-down motion occurs, as at the center of the tank, is a noae. The time required for the water to rise from its lowest level to its highest and fall again to its lowest is the period of the wave, and the distance between loops, that is, the length of the tank, is the wave length. If the length of the tank or the depth of the water in it is changed, the period of the wave will be changed.

In the same way, each large body of water, such as a lake or bay, has its own natural period of oscillation and, for this reason, the seiche waves at many places follow each other in uniform succession. This i p rticularly true of landlocked waters having definite boundaries. The seiches occurring in suc bodies are usually very regular, whereas those observed on the open sea coast are nearly always broken and irregular, probably because the oscillating areas are variable and without fixed boundaries.

The example of the tank is, of course, the simplest form of seiche movement. In some cases, two or more such movements are combined, and the same seiche movement may have two, three, or more nodes and loops. On the other hand, the oscillation in a landlocked bay communicating with the sea by a single entrance, usually corresponds to that in one half of the tank, the node being at the entrance and the loop at the head of the bay.

Various investigators have shown that, in a bay of this sort, the approximate period of the seiche may be determined mathematically, when the dimensions of the body of water in the bay are known, by use of the following formula :

$$\text{Period} = \frac{4\,L}{\sqrt{gh}}$$

where L is the length of the bay, g the acceleration of gravity, and h the average depth of the water in the bay. In the case of the tank with the nodal line at the center, the relation becomes :

$$\text{Period} = \frac{2\,L}{\sqrt{gh}}$$

The periods determined by the above formulæ, in general, approximate the observed periods, although experiments have shown that irregularities of various sorts in the shapes of liquid bodies considerably modify this relation.

Early investigators, in attempting to determine the cause of the seiche in Lake Geneva, found that it usually was accompanied by storms or changes in atmospheric pressure, and they therefore concluded that the seiche was caused by these variations.

About the year 1875, F. A. Forel, after investigating for several years the seiches of Lake Geneva and finding similar phenomena on other Swiss lakes, agreed with earlier observers that the phenomenon was caused by atmospheric disturbances. He found that the period of "duration" of a seiche varies directly with the length and inversely with the depth of the section in which it oscillates. He also ventured the opinion that seiches occur in all large bodies of water, (1) an opinion subsequent investigators have shown to be in accord with fact.

Since the time of Forel, a number of scientists have made important contributions to our knowledge of the subject of seiches. Dr R. A. Harris, a well-known authority on tides, discussed seiche movements in considerable detail and classified them according to the forms of the bodies of water in which they occur, giving characteristic features and examples of each class. (2).

About the year 1905, a group of Japanese scientists, (3) endeavoring to determine the nature of the destructive sea waves that sometimes visit the coast of Japan, made a systematic investigation of seiches, using models of bays and harbors to study the different modes of oscillation.

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(1) *See* "Nature", *Volume* 12, *June* 1875.

(2) *See* "Manual of Tides", *Part V*, 1907.

(3) *See* "Secondary Undulations of Oceanic Tides", K. Konda ; T. Terada ; Y. Yoshida ; D. Isitani, Journal College of Science, Imperial University of Tokio, Volume 24 (1907).

All careful investigators agree that seiche oscillations are generally due to meteorological conditions, such as winds and changes in atmospheric pressure, and that they are sometimes caused by earthquakes or other disturbances that upset the equilibrium of the water. Since the causes of seiches are nonperiodic in character, the times when they are likely to occur cannot be foreseen, and consequently they cannot be predicted as is the tide.

THE SEICHE ON THE PALAWAN COAST.

Records of tide observations for that part of the east coast of Palawan lying between the ninth and tenth parallels of north latitude show that the waters washing this coast are peculiarly subject to seiche oscillations. While in most bodies of water seiches occur only occasionally, it appears that here they hold sway for a considerable portion of the time. Slight traces of seiche movement have been noted on tide curves for stations both north and south of the limits mentioned above, but the main strongholds of the seiche seem to be Island Bay, Honda Bay, and the area that lies between them. Here the "crazy tides" frequently disport themselves without waiting for storm or earthquake to excite them to action.

Charts of this region show that the depth of the Sulu Sea is 1.000 fathoms or more over the larger part of its area. Extending out for some miles from the coast under discussion toward this deep water is a relatively shoal area with depths averaging around 20 fathoms. A break in this shelf-like bank occurs off the entrance to Puerto Princesa, where a depth of 200 fathoms approaches close to the shore line. It appears that the seiche oscillation is confined mainly to the relatively shoal water near the coast. That it does not cross the deep waters of the Sulu Sea is shown by the fact that tide records, obtained at a number of places on the east and south shores of this body of water, show no trace of the seiche.

The theory has been advanced that the oscillations are set up by the strong currents in the Sulu Sea, striking the edges of the banks and forcing the water surface to rise, thus disturbing its equilibrium. It is the opinion of the writer, however, that, in common with similar phenomena at other places, the cause could, if sufficient meteorological data for the entire region were available, be traced to atmospheric variations. The problem is, however, a complex one and attempts to coordinate the seiche movements with the meager weather records at hand for this vicinity have proved futile.

Short series of tide observations are available for Island Bay, Panacan, and Aborlan, south of Puerto Princesa. These observations show that seiches occur frequently at all these places.

A SEICHE THAT NEVER CEASES.

In Puerto Princesa itself, however, the seiche reaches its acme of perfection. This body of water is continuously in a state of rhythmic vibratory motion. Day after day, month after month, its surface rises and falls with a persistent regularity that is surpassed only by the

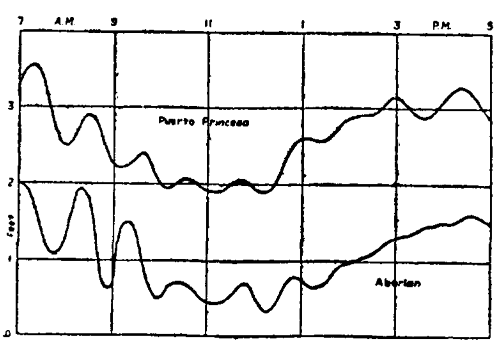

FIG. 2.

Tide Curves Showing Simultaneous Seiche Oscillations. Observed at Puerto Princesa and Aborlan July 2, 1918.

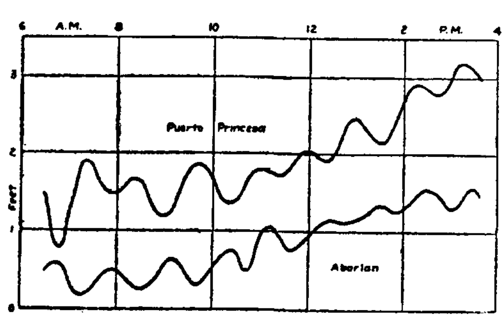

FIG. 3.

Tide Curves as in Fig. 2, *May* 18, 1918.

periodic response of the great oceans to the mighty tidal forces of moon and sun. The period of this vibration is almost exactly one hour and a quarter — one-tenth the average period of a demi-daily lunar tide — and its amplitude varies from a few hundredths of a foot to 3 or 4 feet. Three years of automatic tide-gauge records have been obtained at Puerto Princesa wharf for use in connection with hydrographic work in this vicinity. From these gauge records, a few portions were selected that were simultaneous with observations showing pronounced seiche oscillations at places along the coast to the north and south of Puerto Princesa.

These records show that, at the time when the seiche is noticeable at other places along the coast, it has considerable amplitude in Puerto Princesa, and this fact seems to indicate that there is a close relationship between the seiches at the various places. It will be noted also that the periods of oscillation, while differing somewhat at the different points of observation, are roughly the same for the entire area. In fact, there seems to be a progressive increase in the period from the vicinity of Island Bay northward. This is indicated in the following table in which the stations are arranged in order from south to north :

TABLE I. — Observed Periods and Ranges of Seiche, East Coast of Palawan Island, Philippine Islands.

Location	*Date of Observations*	*Number of Seiche Waves*	*Average Period Hours*	*Maximum Observed Range Feet*
Island Bay	September, 1918	140	1.051	1.2
Panacan	September, 1918	51	1.045	1.8
Aborlan	May-July, 1918	16	1.144	1.1
Puerto Princesa Wharf	October, 1917	600	1.245	2.6
Makesi Island	November, 1917	82	1.494	1.3
Babuyan	March, 1917	26	1.592	0.8

Since the period in Puerto Princesa differs somewhat from that at Aborlan, for example, there can be no fixed phase relation between the two oscillations. Nevertheless, an examination of simultaneous seiche curves for the two places indicates that a relationship exists between the individual waves. (*See* Figures 2 and 3). The first five or six waves shown on the simultaneous curves for July 2, 1918, show a remarkable similarity at the two places. At this time the two movements were approximately in phase.

The curves for May 18, 1918, also show a similarity, but here the phase relation has been reversed, the water being for the most part high at one place when it is low at the other. Likenesses may also be traced between the Puerto Princesa curves and those for the other points of observation, and this condition leads to the belief that a connected and complex oscillatory system covers all the water area between, and adjacent to, these places.

TEN STATIONS OBSERVED SIMULTANEOUSLY.

In October 1918, a field party of the United States Coast and Geodetic Survey, under the command of A. M. Sobieralski, secured about three and one-half days of simultaneous tide observations at ten stations in Puerto Princesa. These observations were taken by reading the heights of the water surface on tide staffs which were graduated in feet and tenths, and readings were taken at ten-minute intervals at each of the stations during the entire period of observation. Some of the data derived from the observations are given in the following table ;

TABLE II. — VARIATION IN RANGE OF SEICHE, PUERTO PRINCESA, EAST COAST OF PALAWAN ISLAND, PHILIPPINE ISLAND
(from thirty-three observed seiche waves, October 21 to 24, 1918)

NORTHEAST SHORE *Location*	*Average Range Feet*	*Ratio to Range at Puerto Princesa Wharf*
Bancaobancaon Point	0.253	0.49
Tidepole Point	0.388	0.74
Puerto Princesa Wharf	0.521	1.00
Cana Island	0.647	1.24
Bush Point	0.745	1.43

SOUTHWEST SHORE *Location*	*Average Range Feet*	*Ratio to Range Puerto Princesa Wharf*
Tabuntabun Point	0.282	0.54
Village Rocks	0.292	0.56
Heron Point	0.380	0.73
Binuan	0.467	0.90
Balsahan	0.763	1.46

A portion of the record in the form of curves, plotted from observations at the ten stations, appears in Fig. 4. The results of the observations show that the rise and fall of the water is simultaneous in all parts of the bay, and that the amplitude of the oscillation increases from the entrance to the head. The curves show that a somewhat irregular movement of relatively small amplitude near the entrance, is gradually transformed, as it approaches the head of the bay, into a regular undulation of considerable amplitude. The rate of increase in amplitude becomes greater as the head of the bay is approached, the increase per unit distance for

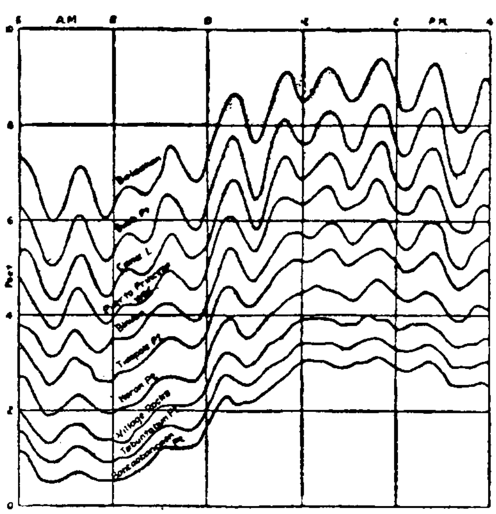

FIG. 4.

Tide Curves Showing Simultaneous Seiche Movement Observed at ten stations in Puerto Princesa, Palawan Island, on October 23, 1918.

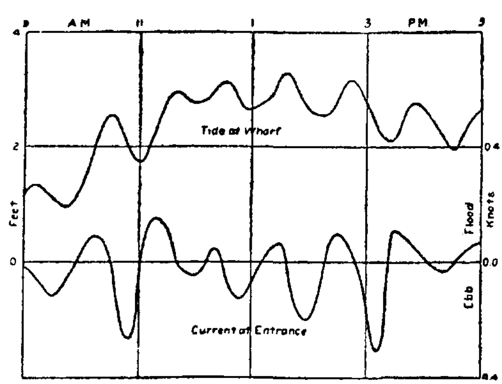

FIG. 5.

Simultaneous Tide and Current Curves, Puerto Princesa. These are of the same date as the seiche movement curves in the preceding figure.

the upper part being about twice that near the mouth. The tide records for Puerto Princesa wharf show that seiches of 2 feet or more are not uncommon at this point, and, since the simultaneous observations show that the amplitude at Puerto Princesa is about two-thirds that off Balsahan, it appears that seiches of 3 or 4 foot range occur at the latter place.

The existence of the remarkable seiches in Puerto Princesa seems to be due to the impression of the relatively weak, and for the most part unnoticed oscillations outside upon the body of water in Puerto Princesa, with a frequency corresponding approximately to its own natural period of oscillation. Under such conditions, in accordance with the well-known principle of resonance, such impulses are built up or amplified to many times their original amplitude.

In order to determine the period of oscillation of Puerto Princesa, by means of the previously mentioned formula, $4L$ divided by $\sqrt{gh}$, the approximate average depth was obtained by first drawing contour lines on a hydrographic chart of the bay, measuring with a planimeter the areas between these lines, multiplying each area by its estimated average depth, adding the products thus obtained; and dividing the sum by the total area of the bay. By this methoa, an approximate average depth of 55 feet was obtained. Measuring along the axis of the bay, from a line connecting the low-water marks at the entrance to the heaa, gave a length of very nearly 40.000 feet. Taking the acceleration of gravity as 3.22 feet per second, and substituting in he above formula, we have :

$$\text{Period} = \frac{4 \times 40{,}000}{\sqrt{32.2 \times 55}} = 3800 \text{ secs.} = 1.055 \text{ hours.}$$

This value falls considerably short of the observed value of 1.245 hours. However, the above formula applies to a rectangular area of constant depth, and the previously-mentioned Japanese investigators found that, for bays of this sort, a mouth correction depending upon the ratio of the breadth to the length of the bay should be applieo. The factor given by them for a bay whose breadth is one-fourth its length, approximately the ratio for Puerto Princesa, is 1.187 (1). Applying this factor to the value 1.055, obtained above, gives a corrected period of 1.252 hours. This determination is, of course, a rough one, and the fact that the computed value agrees very closely with the observed value should be attributed, in part, to accident.

All vertical movements of the surface of natural bodies of water are accompanied by corresponding horizontal movements. These horizontal movements are called currents It is obvious that, if the whole surface of a body of water such as Puerto Princesa is rising, water must be coming into it from somewhere and, if it is falling, water must be going out to some place.

Observations taken at the entrance to Puerto Princesa, in connection with the simultaneous tide observations discussed above, show periodic fluctuations in the current corresponding to those noted on the tide staffs. The observations were taken from a vessel anchored between the points at the entrance, in the position indicated in Figure 1. The velocity and direction were recorded at ten-minute intervals, simultaneously with the reading of the tide staffs. A pole, weighted at one end, so as to float vertically in the water, and attached to a graduated line, was used. In taking the observations, the pole was allowed to drift for a given length of time, and, from the distance covered by the pole in that time as measured on the graduated line, the velocity was obtained. The directions were obtained by sextant angles between the pole and fixed objects on shore, checked by compass. A portion of the record obtained is shown in the form of a curve, Figure 5, plotted below the corresponding tide curve for Puerto Princesa wharf. These curves show that the variations in the velocity of the current increase and decrease with the range of the seiche. These variations apparently amount to three or four-tenths of a knot, nautical mile, per hour, when the range of the seiche at Puerto Princesa wharf is about 1 foot. Stronger currents of this sort have been reported at Puerto Princesa wharf, where they interfere at times with the handling of vessels.

It will be noted that the maximum current-producing effect of the seiche comes approximately midway between the high and low points of the water surface and, when the water

(1) See *Secondary Undulations of Oceanic Tides*, p. 60.

surface is stationary, that is, at its maximum or minimum height, the current effect is near zero. This condition is characteristic of all stationary wave movements, the horizontal motion being a maximum when the vertical motion is a maximum and zero when the vertical motion is zero.

OTHER SEICHES.

A few curves copied from automatic tide-gauge records showing interesting forms of seiche movements are pictured in Figure 6. An irregular seiche of considerable amplitude occurs occasionally in Cape Lookout Bight, North Carolina. This bight is open on one side to a considerable area of water which is from 40 to 60 feet in depth, and this area, when its equilibrium is disturbed by a storm or high wind, is apparently set into a complex oscillation which sometimes persists for several days. The tide curve for this station for February 19, 1927, shows that, just before 9 : 00 p.m., the water surface dropped about 2 3/4 feet in ten or twelve minutes.

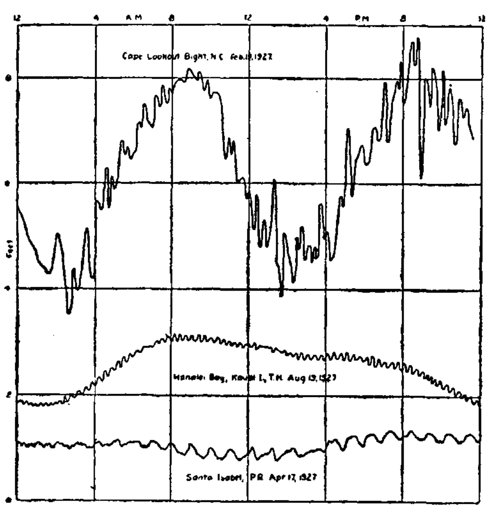

FIG. 6.

Automatic Tide-gauge Records Showing Seiche Movements.

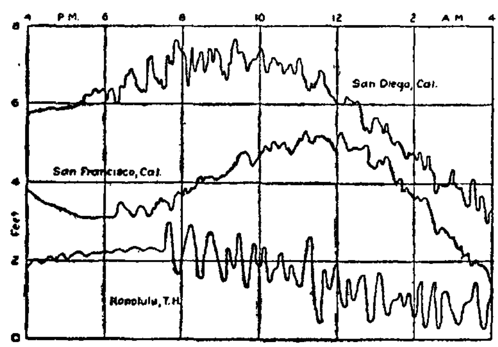

FIG. 7.

Seiches Set Up by Sea Waves from Earthquake. This occurred off the coast of Chile. November 11, 1922, *and was recorded by automatic tide gauges at San Diego, San Francisco, and Honolulu.*

Fairly regular seiches of small amplitude have been noted at a number of stations on the south coast of Porto Rico. The tide curve for Santa Isabel for April 17, 1927, shows a range of seiche of about 0.2 foot, the period being almost exactly one hour. At Gaunica on this same coast, Dr. HARRIS found a period of forty-five minutes and a range of from 1 to 4 inches.

A recent tide record for Hanalei Bay on the north side of Kauai Island, Hawaiian Islands, shows that a practically continuous osclation exists in this bay. The amplitude of this oscillation is from one to two-tenths of a foot and the period about twenty minutes.

Examples of seiche oscillations set up by earthquake waves are shown in Figure 7. Such waves travel for great distances and, entering bays and harbors, set up oscillations which may sometimes be traced on the tide curves for days after the exciting wave has disappeared. The character of the movements thus set up in the various bays differs as much as the bays themselves, depending upon the peculiarities of the individual oscillating bodies of water rather than upon any properties of the exciting wave.