miles, and the average depth of the upper end of the gulf may be taken as 55 fathoms. These values give a period of 3 hours.

133. *Examples of cul-de-sac seiches.*

The seiches at Malta are described by Airy in the Philosophical Transactions.* He finds the average observed period to be 21 minutes; the range to vary from nothing to a little more than 1 foot. The body of water responsible for this seiche he considers to be the deep arm of the sea lying between Sicily and Tunis, the shoals playing only a subordinate part.

From Figure 37, Part IV A, it is evident that the period of the transverse oscillation might vary from 1 to 2 or even more hours according to the amount of shoal water included in the estimate. Hence it is difficult to say how many nodal lines are present when the period of the oscillation is 21 minutes. Their number may be anywhere from 3 to 7.†

As Valetta, the place of observation, is situated upon the northeastern coast of the island, while the area in which the seiche arises in accordance with this hypothesis lies mainly to the west of the island, Airy says, "Such waves, once created, would be propagated to regions of the sea somewhat beyond those in which they are formed."

It seems probable that these oscillations are caused by the configuration of the harbor. For, the length of the harbor is 1.6 miles, and, if we call the average depth $6\frac{1}{2}$ fathoms, the period of the dependent oscillation would be $4\times\frac{1.6}{20.96}=0.31$ hour $=18$ minutes.

Tidal observations made at St. Thomas Island, West Indies, show that oscillation is going on in the harbor most of the time. The most regular ones have a period of 0.45 hour and a range varying from 0.5 foot to nothing—it generally being 0.1 or 0.2 foot. At times there is an oscillation whose period is about 0.7 hour.

The harbor is about 1.3 miles long, measuring from the head to the capes at the mouth. The average depth is $3\frac{1}{2}$ fathoms. This gives $4\times\frac{1.3}{15.35}=0.34$ hour for the period of the oscillation. The broadening of the harbor near the head, and the contraction near the mouth due to Rupert Rock, must cause the period to be somewhat greater than the one just calculated. It is probable that the arm of water taken as $\frac{1}{4}\lambda$ does really extend outside of the mouth of the harbor proper.

The less perfect oscillation having a period of 0.7 hour may be caused by the strip of shallow water lying between St. Thomas Island, West Indies, and deep water to the south. The width of this strip is 8 miles and the average depth 20 fathoms. This gives $4\times\frac{8}{38.8}=0.9$ hour.

The seiches in St. John Harbor, an arm of the Bay of Fundy, has been briefly described by W. Bell Dawson ‡ and more fully by A. W. Duff, the point of observation of the latter being a short distance above the narrows.§

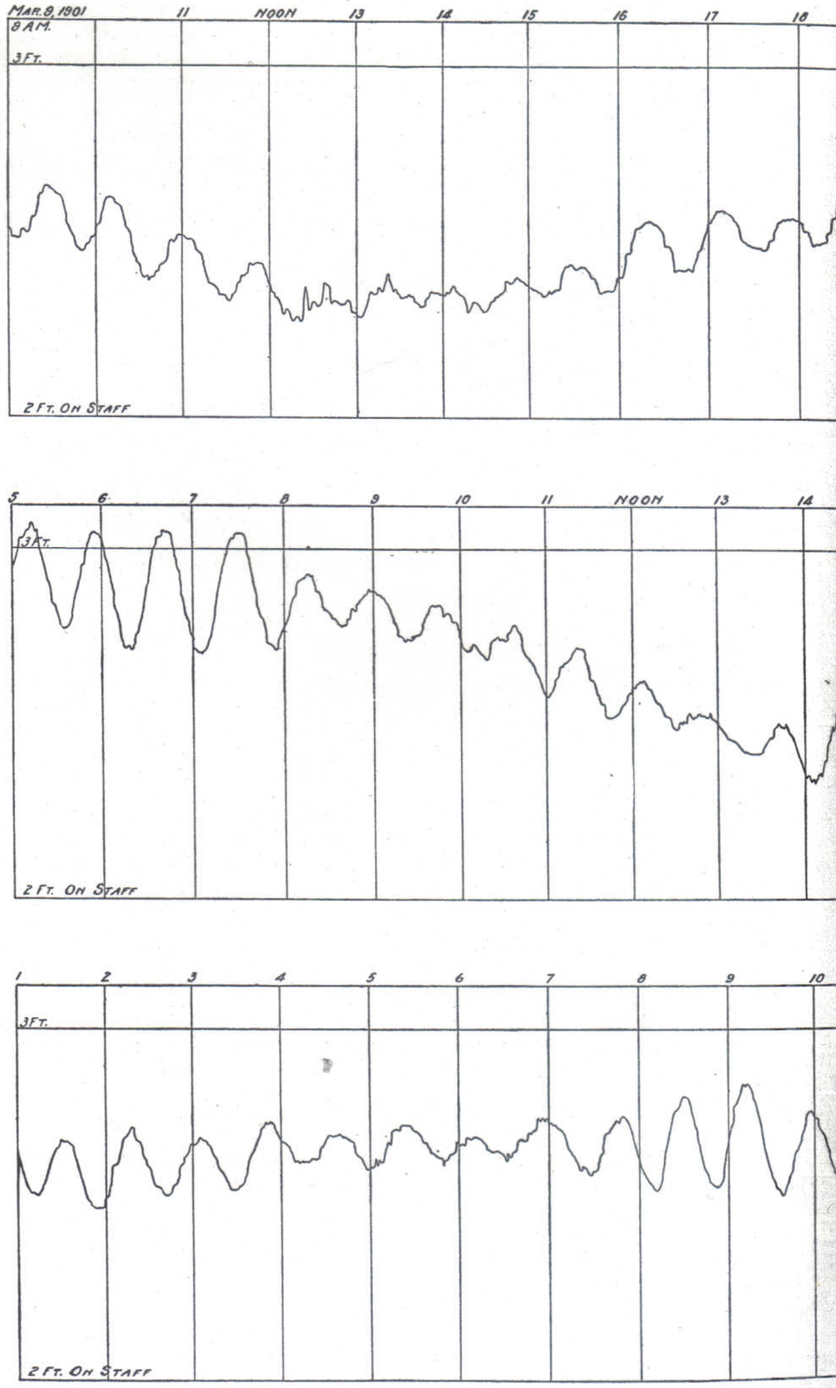
Duff gives 42.2 minutes as the length of the average period of the oscillations. Off St. John the bay is 32 miles wide. The average depth being 40 fathoms, it might be concluded from Table 50 that the period of the uninodal seiche is 1.23 hours

* Vol. 169 (1878), pp 136–138.

† Cf. Krümmel: Handbuch der Ozeanographie, Vol. II, p. 148.

‡ Transactions of the Royal Society of Canada, Meeting of May, 1895, Section III, pp. 25–27.

§ Amer. Jour. Sci., Vol. 153 (1897), pp. 406–412.


MAR. 9, 1901
8 A.M.
11
NOON
13
14
15
16
17
18
3 FT.
2 FT. ON STAFF
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6
7
8
9
10
11
NOON
13
14
3 FT.
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3
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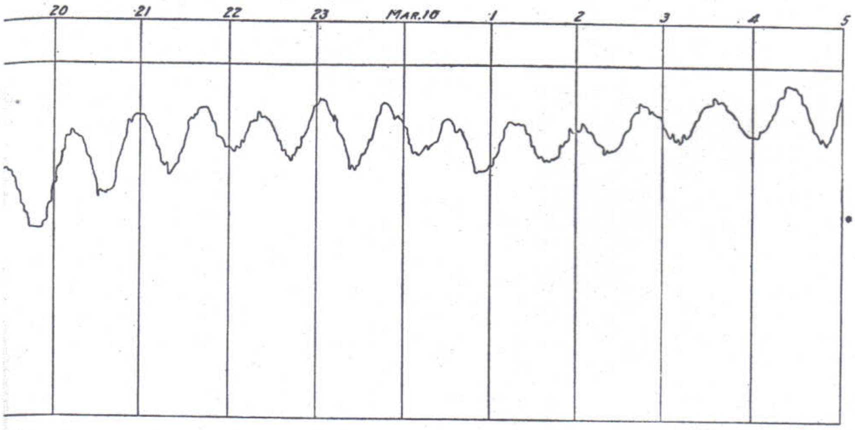
9
10
3 FT.
2 FT. ON STAFF

SEICHES


20
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MAR. 10
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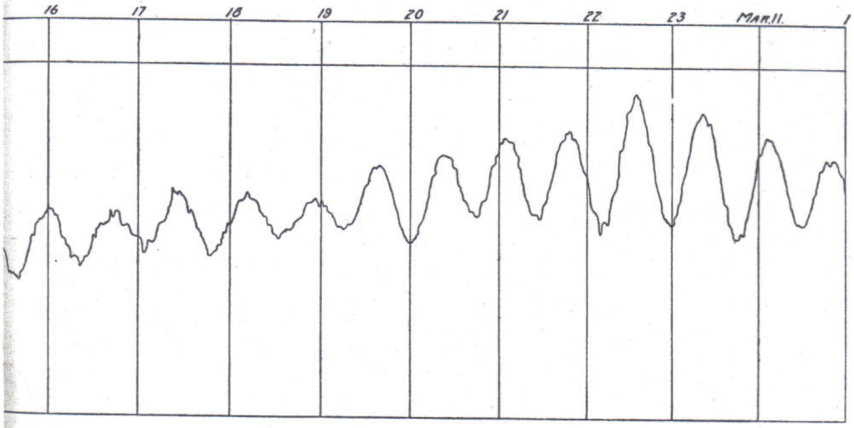
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17
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MAR. 11.
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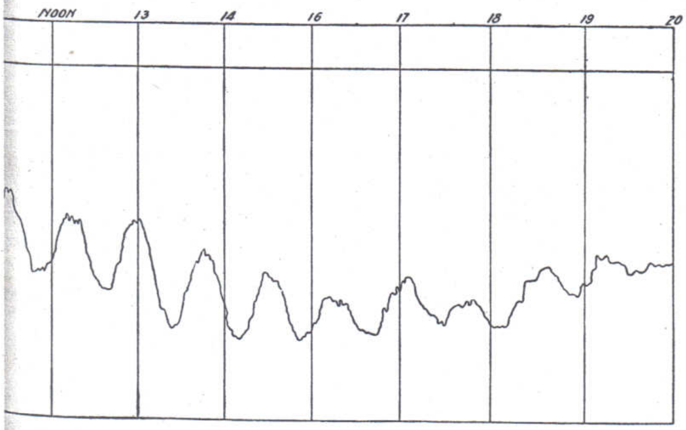
NOON
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PORTO RICO.

and the period of the binodal 0.62 hour. Now it seems in this case to be highly improbable that a binodal seiche should occur across the bay and not one of the uninodal type; for surely the winds sweeping over the surface of the bay would act most favorably across its axis and so incite uninodal motion. Again, Dawson says: "These minor undulations often continue for a week at a time; or even longer." This accords well with the facts witnessed at Guanica and described in the next paragraph. The harbor at St. John is 3.3 miles long from its head just south of the narrows to its mouth east of the northern part of Partridge Island. The average depth at half-tide level may be taken as 8 fathoms. These dimensions give as the period $4\times\frac{3.3}{23.27}=0.567$ hour, or 34 minutes. At the bend in this arm depths of more than 20 fathoms occur, while near Partridge Island the depth of the channel is only 5 fathoms at half-tide level. These circumstances must increase the length of the period.

Remarkably regular seiches occur in Guanica Harbor. The observed period is 45 minutes, and the range varies from 1 to 4 inches. So persistent is this phenomenon that as many as 60 consecutive oscillations have been noted. (See Figure 30.)

That the phenomenon at Guanica does not depend upon a trinodal seiche across the Caribbean Sea is proved by the fact that no indication of a seiche having a period of 45 minutes occurs at Ponce or at Guayanilla.

The length of this harbor is 2 miles and the average depth 3 fathoms. The period of a rectangular dependent arm of these dimensions is, by Table 50, $4\times\frac{2}{14.25}=0.55$ hour. This period must be increased by one-third part of itself in order to agree with the observed value. The average width of the harbor is at least one and one-half times its width at the narrowest part near the mouth. This fact increases the period somewhat, but it is partially offset by the increase in depth at the narrows. It seems probable that the oscillating arm of water extends some distance outside of the harbor proper, thus increasing the size and period of the body.

Port Real is a body of water 0.8 mile long and $1\frac{1}{2}$ fathoms deep. Here a fairly regular seiche occurs, having a period of 0.62 hour and a maximum range of generally 0.2 feet. A rectangular tongue of water would have for its critical period $4\times\frac{0.8}{10.08}=0.32$ hour.

Near the entrance to this harbor the distance across the channel, counting from the 1-fathom line, is only one-twelfth of a mile, while the breadth within the capes, counting from this same contour, is two-thirds of a mile. It seems probable that the period for the actual body should be perhaps double that of the rectangular body just alluded to.

The oscillation does not persist as long as the one at Guanica; still as many as sixteen consecutive periods may at times be observed.

Edgartown Light-House, Massachusetts, is situated near the head of a bay bounded by land on one side and land and shoals on the other. This arm of water is 3 miles long and 4 fathoms deep on the average. These dimensions give for the critical period $4\times\frac{3}{16.45}=0.73$ hour. Observation shows that when a strong northwest wind is blowing, a seiche may arise having a period of three-fourths of an hour and continuing for several hours.

The undulations in the tide curve at Colon on August 27–28, 1883, do not seem to have been connected with the Krakatoa eruption; for, they are remarkably regular and occur too early for allowing a reasonable time for the disturbance to be propagated around South Africa. The observed period of this oscillation is 1.17 hours.

On September 6–7, 1882, the tide curve showed an earthquake disturbance. There were apparently two oscillations thus set up, the period of the first being 1.17 hours and of the second 0.40 hour; the maximum ranges being 1.3 feet and 0.5 foot, respectively.

On June 15 and again on June 17, 1883, a good oscillation, having a period of 1.17 hours and a range of 0.2 or 0.3 foot, is recorded on the tide curve.

The form of the western portion of Carribean Sea is not favorable to seiche oscillations, even if such were possible in a sea of such great depth. Turning to the harbor of Colon, we find its length to be 4 miles and its average depth $2\frac{3}{4}$ fathoms. The resulting period is therefore $4\times\frac{4}{13.64}=1.17$ hours.

At Dutch Harbor, Alaska, observations show a seiche having a period of about one-half hour. The extreme length of Iliuliuk Bay, of which Dutch Harbor is a branch, is $4\frac{1}{2}$ miles. The average depth is about 15 fathoms. These dimensions give, by Table 50, a period of $4\times\frac{4\frac{1}{2}}{31.86}=0.565$ hour $=34$ minutes.

At Honolulu, Hawaiian Islands, the period of a regular sine-like fluctuation, groups of which appear from time to time, is $0.43\frac{1}{2}$ hour or 26 minutes. The larger ones are caused by earthquake sea waves, but the smaller ones may be due to meteorological disturbances. The following are some of the earthquakes whose observed effects had very nearly the above period: Krakatoa, August 27, 1883; Northern Japan, June 15, 1896; Ecuador, January 31, 1906; and Valparaiso, Chile, August 16, 1906.

The maximum range, depending upon the intensity of the disturbance at Honolulu, varies from 0.1 foot to 0.4 foot.

Assuming that the dependent body at Honolulu Harbor is $1\frac{3}{8}$ miles long and $2\frac{1}{2}$ fathoms deep on an average, the computed period is $4\times\frac{1\frac{3}{8}}{13.01}=0.42$ hour.

Following the Krakatoa eruption, irregular oscillations, having a period of 2.6 hours and a maximum range of $2\frac{1}{2}$ feet, were observed at Lyttleton, New Zealand. The length of Port Cooper is $8\frac{1}{4}$ miles, and average depth $2\frac{1}{2}$ fathoms. The resulting period is therefore $4\times\frac{8\frac{1}{4}}{13.01}=2.54$ hours.

At Olongapo, Subic Bay, Philippine Islands, a seiche, having a period of 1.3 hours and range of about 9 inches, has been observed; also smaller undulations having a period of from one-third to one-half an hour. The former can hardly be due to an oscillation of the greater part of China Sea lying between Luzon and Siam and Hainan Island; for, although a trinodal east-and-west seiche has a computed period of about $1\frac{1}{3}$ hours, no oscillation of such period is to be found at Manila.

Now the length of Subic Bay is 10 miles and its average depth 18 fathoms. Regarding this bay as a dependent arm, the period computed by Table 50 is $4\times\frac{10}{36.8}=1.09$ hours. By supposing the line marking the mouth of the bay to be convex, the length of the bay may be increased to 11 or 12 miles. The computed period of the east-and-west oscillation of Subic Bay at Olongapo is 0.3 hour and in a southeast-and-northwest direction 0.4 hour.

A seiche was observed at Aden, Arabia, as a result of the Krakatoa eruption, the period being 1.02 hours and the maximum range of about 0.8 foot. Small undulations of this period may sometimes be seen on the tide curve for this station.*

Aden Harbor is about 1.8 miles long, measuring from the mouth to the low-water line at the head. It is 0.4 mile broad at the mouth and $2\frac{1}{2}$ miles at its broadest part. The average depth is $1\frac{1}{2}$ fathoms. A rectangular arm 1.8 miles long and $1\frac{1}{2}$ fathoms deep has as its period $4\times\frac{1.8}{10.08}=0.71$ hour. For the actual harbor the period must be considerably greater than 0.71 hour and may approach the observed value.†

134. *Examples of shelving seiches.*

The larger earthquake oscillations at San Francisco must be due to the shelving shore outside and not to any oscillation of the bay, for, the disturbance resulting from the earthquake at Arica, Chile (May 9, 1877), and which reached California early on the following day, arrived at Fort Point about 7 minutes earlier than at Sausalito. This is about the difference which the depths between these two stations might imply. There is a tolerably close resemblance between the records upon the tide gauges at the two places. The maximum range of this disturbance is about 1 foot, and the irregular periods vary from 0.3 hour to an hour or more.

The saw-teeth-like disturbance having an average period of three or four minutes and which frequently occur during and after heavy westerly winds are, as already stated, due to irregular reflections across the Golden Gate and so belong to another class of seiches.

The disturbance caused by the Krakatoa eruption was well marked at Negapatam, Madras, False Point, Beypore, Port Elizabeth, and Table Bay. The resulting oscillations, although very irregular, may be said to have the following respective periods and maximum ranges:

1.5, 1.4, 2.8, 1.1, 1.1, 1.0 hours, and
1.5, 0.5, 1.6, 1.2, 4.5, 1.5 feet.

These periods are too short for permitting the assumption that all of the shallow water along the continental shelf forms a stationary wave $\frac{1}{4}\lambda$ in length. It seems probable that more or less of the water will partake of such motion at a given station according as the intensity of the disturbing force varies. The very uniformity of the slope of the bottom in these regions of shallow water must militate against the existence of definite oscillating arms of water; hence, the great variety of periods and amplitudes at a given place of observation.

Shelving seiches are by far the most common of all. Every considerable earthquake disturbance of the water of the ocean produces them in nearly all parts of a shelving coast. When caused by winds, their appearance is less striking, in that their

* Great Trigonometrical Survey of India, Vol. XVI, Details of the Tidal Observations, Part II, opposite p. 4.

[† After the MS. of Part V had gone to the printer, I learned that Messrs. K. Honda, T. Terada, and D. Isitana, had anticipated me in applying $\tau = 4\,L/\sqrt{g\,h}$ to such seiches as are described in sections 133 and 134. This oversight was due to the fact that while the MS. was being prepared, only three numbers of the Proceedings of the Tôkyô Mathematico-Physical Society were accessible to me.—R. A. H., Dec. 24, 1907.]

amplitude is generally less and the tendency to periodicity less evident. The record of these may then be likened to irregular saw-teeth.

In regular broad and open bays their size and regularity are increased, e. g., the Krakatoa disturbance is much greater and more seiche-like at Port Elizabeth than at Table Bay. At Galle, Ceylon, the tide curves contain at times minute oscillations less regular than a cul-de-sac seiche, but more regular than a shelving seiche.* The period is about 0.4 hour and the range about 0.1 foot. The bay or harbor is broad and open, but does not extend far inland. Hence, it is natural to expect a case lying between the two kinds just mentioned. The harbor helps in making the seiche definite, but because of its openness the outside water forms a large part of the fractional oscillating area.

135. *References to papers relating to the Causes of Seiches.*

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References to descriptions of Limnimeters or Limnographs.

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* Details of Tidal Observations, *l. c.*, II, opp. p. 64.