A C T A   A D R I A T I C A
INSTITUT ZA OCEANOGRAFIJU I RIBARSTVO — SPLIT
FNR JUGOSLAVIJA

Vol. VII. No. 3.

ON THE SEICHES OCCURRING IN THE BAY OF KAŠTELA

by
M. Zorè

SPLIT 1955

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Mira Zorè

Institute of Oceanography and Fisheries, FNRJ, Split

I.

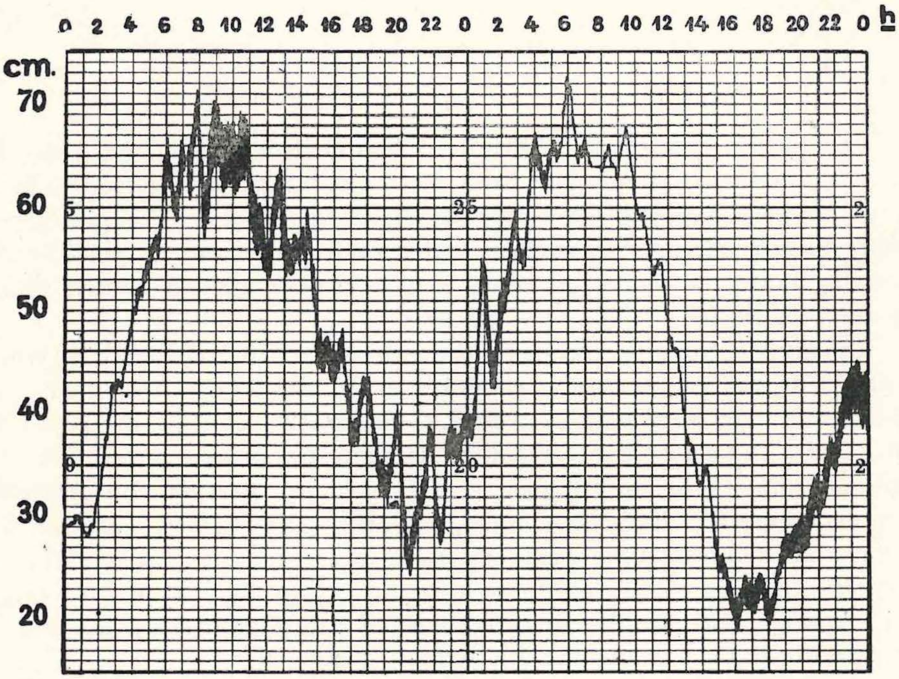
The eastern coast of the Adriatic is highly developed which accounts for its numerous channels and bays. If the water mass, enclosed in such limited basins get an impulse of motion, standing waves are then produced, manifesting themselves as surface water oscillations and as periodically occurring horizontal water currents, i. e. as a phenomenon known under the name of seiche.

Researches into the seiches in the Adriatic started about 1870, when shortperiod oscillations were established by E. Stahlberger (14) A more thorough work was done by E. Gratzl (9), while A. Defant (5) and D. v. Sterneck (4) tried to explain by means of seiches the relatively great tide amplitudes in the northern part of the Adriatic. A rather summary study in seiches, covering the eastern coast of the Adriatic as a whole, was made by R. v. Sterneck (15) in 1914. A complete analysis of the oscillations found in the Bay of Bakar, taken as a starting point for the investigations of the oscillations occurring in the Adriatic basins, is given in the works (7) and (8).

The seiches occurring in Kaštela Bay were earlier not investigated, so this bay was chosen to be dealt with in this paper since it is a basin situated in the central Dalmatian Littorall and, moreover, in the immediate vicinity of the Institute of Oceanography and Fisheries, which circumstance rendered the special measurements easier.

In the Bay of Kaštela, moreover, the Institute is planning and performing various physical and biological observations wich makes the knowledge of currents therein most important, and these currents are partly explained by means of seiches.

The author has the pleasure to express his heartfelt thanks to Dr. Josip Goldberg, the academician, Head of the Institute of Geophysics of the Faculty of Natural Sciences and Mathematics at the University of Zagreb, upon whose suggestion this paper had been written, originally designed as a diploma work, and whose advice in the course of preparation was most helpful. The author is also grateful to Mr. A. Zupan, the professional collaborator at the Institute of Oceanography and Fisheries, Split, who took pains to make measurements in the field indispensable for this study. Thanks are also due to the Marine Department of the Hydrometeorologic Service, Split, for putting at the author's disposal as yet unpublished meteorologic data.



Marigram (produced weekly) taken at Cape Marjan on November 24th and 25th 1949. A series of oscillations of period 104 minutes with superposed oscillations of period 60 minutes; SE-wind (jugo) prevailing in the whole of the Adriatic.

II.

The Bay of Kaštela is situated in the central part of the Dalmatian Littoral, to the north-west of Split, and is encircled by the slopes of the Mount Kozjak, by Split Peninsula, and by Čiovo Island. The mouth of the bay is morphologically not clearly defined, wherefore two mouths are dealt with in the paper, i. e. one lying between Cape Marjan and Cape Čiovo, and the other lying between the latter and Cape Sustipan. Beside this mouth there is another in the proximity of Trogir, but this one is unlikely to contribute to the dynamic of seiches occurring in the bay since its opening is very narrow (measuring about 100 m), and very shallow owing to a conspicuous submarine sill in that place, lying at a depth less than 10 m. This mouth, then, cannot let a sufficient quantity of water into the bay in order to influence in a manifest way the motions occurring therein, so we shall neglect it in our further considerations, the more so as it is distant from the place where the horizontal displacements attain their greatest amplitudes.

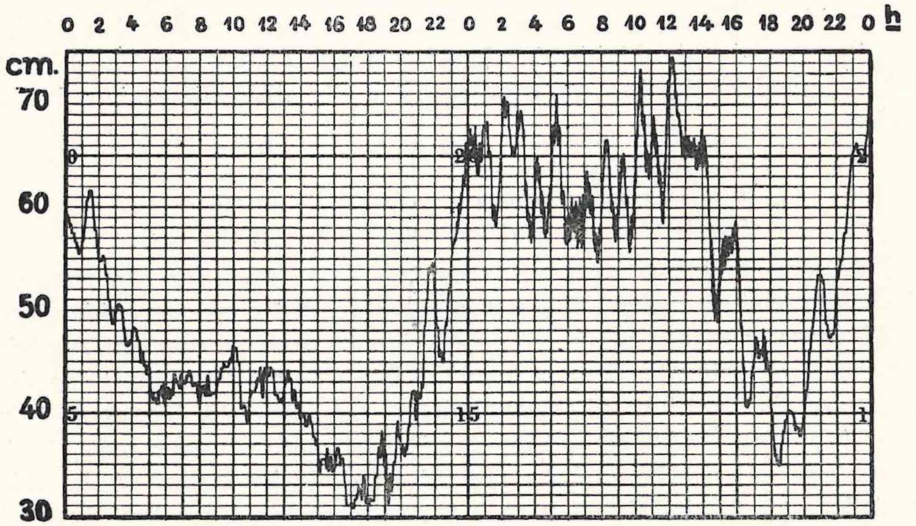
The course of the bay is not clearly defined, and, consequently, its axis either, but we can assume that the axis follows an uneven line going from the mouth of the bay to a place lying between Kaštel Stari and Kaštel Lukšić, where it meets the northern coast at right angles. By considering the coastline, we find that the bay has an inner basin whose axis goes along the line drawn from Trogir to Vranjic Peninsula.

The ideal course of the bay is affected by the configuration of the sea bottom and by the highly developed coastline of the bay. The largest depth recorded in the bay amounts to 56 m, its other dimensions being as follows:

area	61 km²
average depth	23 m
length of the bay's axis	9 km
length of the axis of the inner basin	18 km

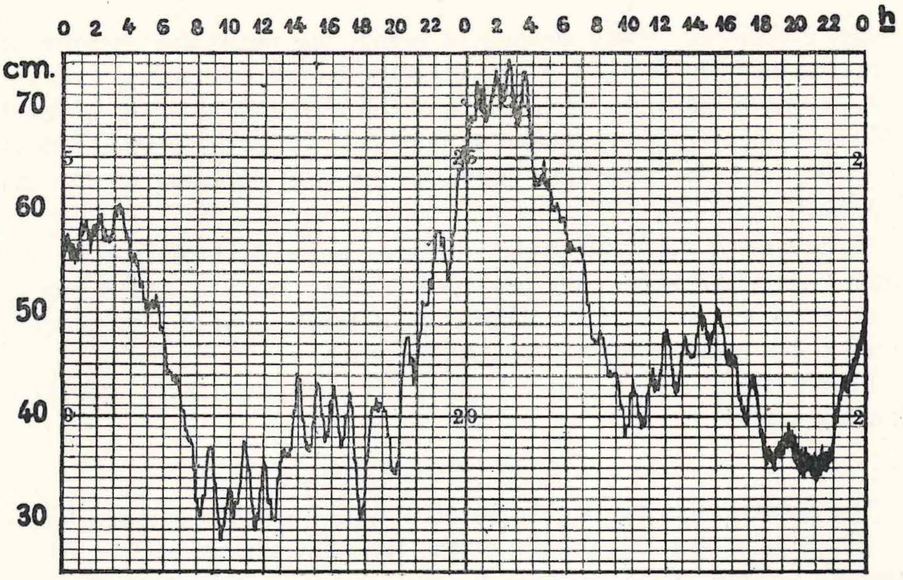
Tide gage and currentmeter recordings were used for the purpose of investigations of seiches. The marigrams were taken as our guide since the tide gage is placed at the Cape Marjan to provide constant records of changes occurring in the sea level of the little harbour built for the purposes of the Institute of Oceanography and Fisheries. The gage is a Ganser type one producing weekly marigrams with a gage-scale 1 : 5. We also availed ourselves of the recordings made by means of the tide gage belonging to the Hydrographic Institute of the Yugoslav Navy at Divulje. This one is of Russian make, GUGMS type, with a gage-scale 1 : 10, producing marigrams every five days. Beside these two, a tide gage of the latter type, but producing daily marigrams, was placed at St. Kajo. for a period of eight days. Finally, comparisons were made by means of recordings obtained by means of a tide gage, belonging to the Hydrographic Institute of the Yugoslav Navy, permanently placed at the Mole »26th of October«. The recordings made by a currentmeter of the Wollaston type, and placed at Cape Marjan, were usefull for the investigations of the horizontal displacements.

Marigrams were used to establish the period of the oscillations. In marigrams, namely, seiches appear like short period oscillations superposed on the tide curve. The marigrams deriving from Cape Marjan and covering the period of time from the beginning of 1949 to the end of 1950 were examined. A fleeting look at these marigrams reveals that the tide curve of the investigated bay is relatively quiet, i. e. that there are intervals of several days with no outstanding oscillations superposed on the tide curve. The amplitudes of these oscillations are usually not great ones and reach an average os a sew centimeters, owing to the fact that the tide gage is placed not far from the mouth of the bay, in the vicinity of the nodal line of the denivellation. But sometimes the values of amplitudes may be as high as 20 cm and more. The establishment of periods, however, was not sufficiently precise since 3,2 mm is the graphical length of an hour in marigrams and since each period covers a one hour span, so when short period seiches are superposed on seiches of longer periods, the latter

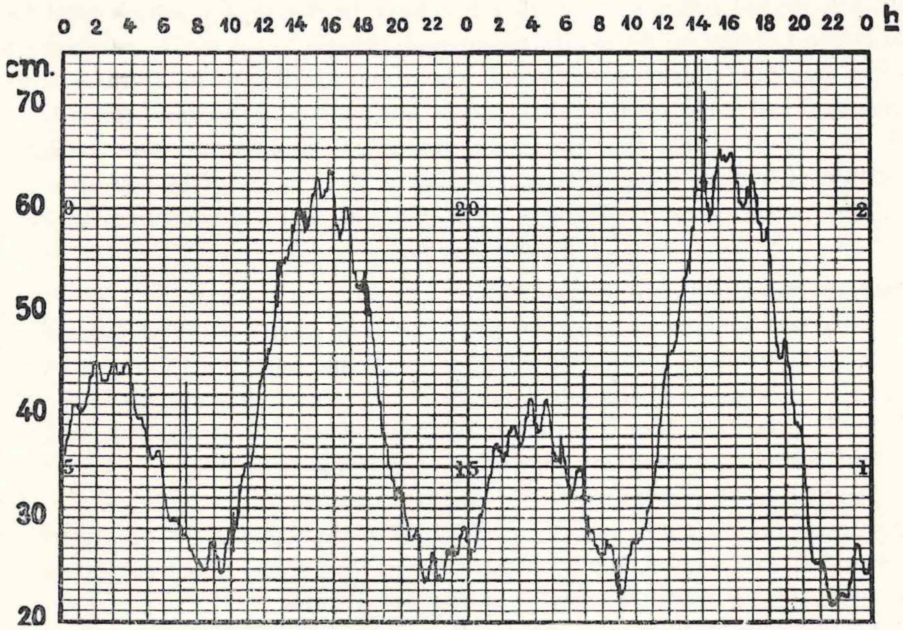


Marigram (produced weekly) taken at Cape Marjan on December 14th and 15th 1949. A series of oscillations of period 60 minutes with superposed oscillations of a shorter period. This series is followed by oscillations of period 104 minutes; NE-wind (bura), blowing on December 14th, and turning to SE-wind at about 19.00 hours, prevails in the whole of the Adriatic during all December 15th.

sometimes appear apparently lengthened or shortened. The span between two neighbouring maxima or minima corresponds to the graphical length of a period. In order to avoid the possible occurrence of the mentioned errors, series of oscillations of the same period were sought and average periods were found out for each series. The average periods were then assembled in groups of the same order of magnitude and the means of these groups were then calculated. It should be pointed out, however, that two physically different periods, if lying near each other by their sizes, may become confluent.



Marigram (produced weekly) taken at Cape Marjan on January 18th and 19th 1951. A series of oscillations of period 60 minutes with superposed oscillations of period 104 minutes; light NE-wind in the whole of the Adriatic.



Marigram (produced weekly) taken at Cape Marjan on May 8th and 9th 1952. Distinct oscillations of period 60 minutes are visible on May 9th from 0.00 to 6.00 hours, which are also evident from the currentmeter recording; light NE-wind blowing in the north Adriatic, and a light wind, alternating its direction, prevails in other parts of thea sea; light SE-wind starts blowing on May 9th

But beside the above sources of errors we must also mention the errors due to imperfections in the construction of tide gages, i. e. such errors as caused by irregular rotations of the record cylinder by which the periods are apparently lengthened or shortened, or by the friction between the spring and the recording paper, or by the slackness of the gage mechanism, etc.

By means of the method shown above generally three periods were obtained from the marigrams produced at Cape Marjan. A 150 minutes' period could not be precisely defined as it rarely appears, but a seiche-period of that order of magnitude surely occurs.

Fourteen series including a total of 86 oscillations have yielded the following period:

$$T = 104 \text{ min.} \pm 4 \text{ min.}$$

The large dissipation of this period is not of a physical character, but it is likely to be the conse.uence of the fact that the seiche T = 60 min. is usually superposed on the former, rendering the establishment of exact maxima and minima for each of the series impossible, the more so as the series of that period are generally nonpersistent. Since usually a 60 minutes' period follows them, it is not easy to determine which additional oscillation belongs to the series concerned. Owing to all these, a 90 minutes' period was determined during the first examination of marigrams; but it was found out later on that this period had arisen as a combination of the 104 and 60 minutes' periods; once, however, this period was positively determined from a series of 4 oscillations with a value of 91 minutes.

The period most frequently appearing in these marigrams, in which

$$T = 62 \text{ min.}$$

was determined with more certainty.

This period was determined from 30 long series with at least 6, but also with 20 or more oscillations. These series are persistent, but sometimes, however, a phase disturbance is noticed. A more accurate determination of the 60 minutes' period was not difficult since the graphical length of the sections in the record paper represented 60 minutes.

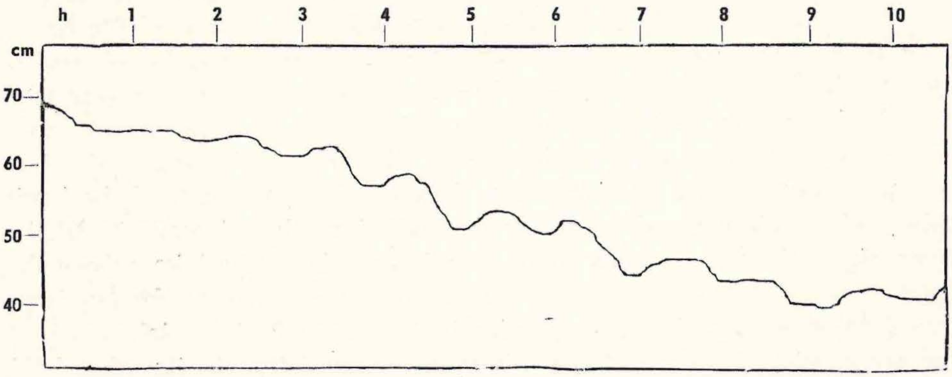
Short period oscillations — of about a quarter of an hour — are often superposed on all these oscillations. Weekly marigrams no not permit us to establish this period, but it is interesting that these short period seiches not infrequently exibit relatively great amplitudes.

In order to obtain a look into the system of oscillations occurring in the interior of the bay, marigrams recorded at Divulje were worked out, but these were not found to be the most convenient ones. Owing to their seale of gage being 1 : 10, the sharpness of the maximum or minimum denivellation disappears.

These marigrams yielded more or less the same periods as those recorded at Cape Marjan. The 150 and 104 minutes' periods were but approximately determined. The period

$$T = 60\ min.,$$

was more accurately determined, as a mean value obtained from 17 series of oscillations, with a total of 119 oscillations. The departure from the



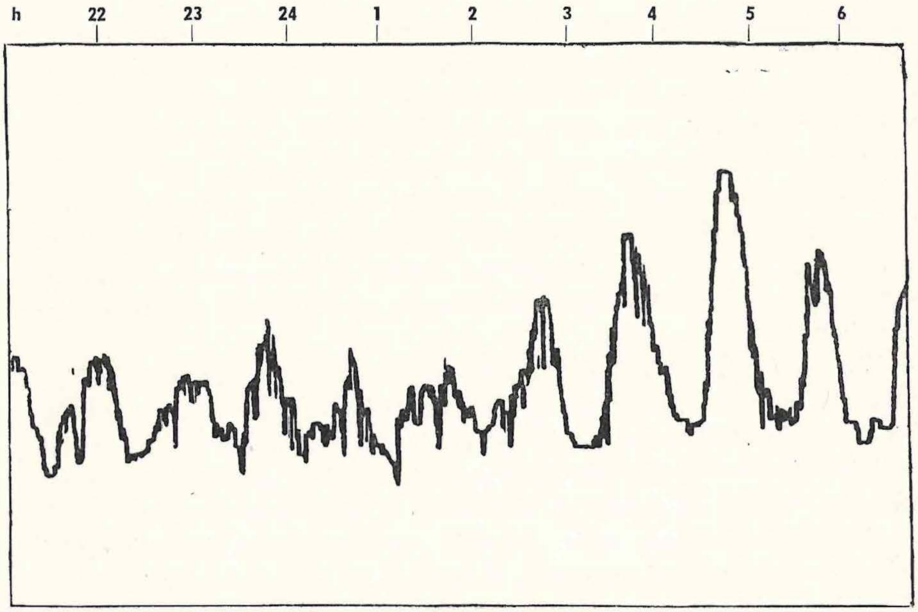
Marigram (produced daily) taken at St. Kajo, on April 17th 1952. Oscillations of period 60 minutes with superposed oscillations of short period; light NW-breeze.

value T = 60 min. is likely due to the fact that the marigrams made at Divulje are less suitable for the investigation of seiches than those made at Cape Marjan.

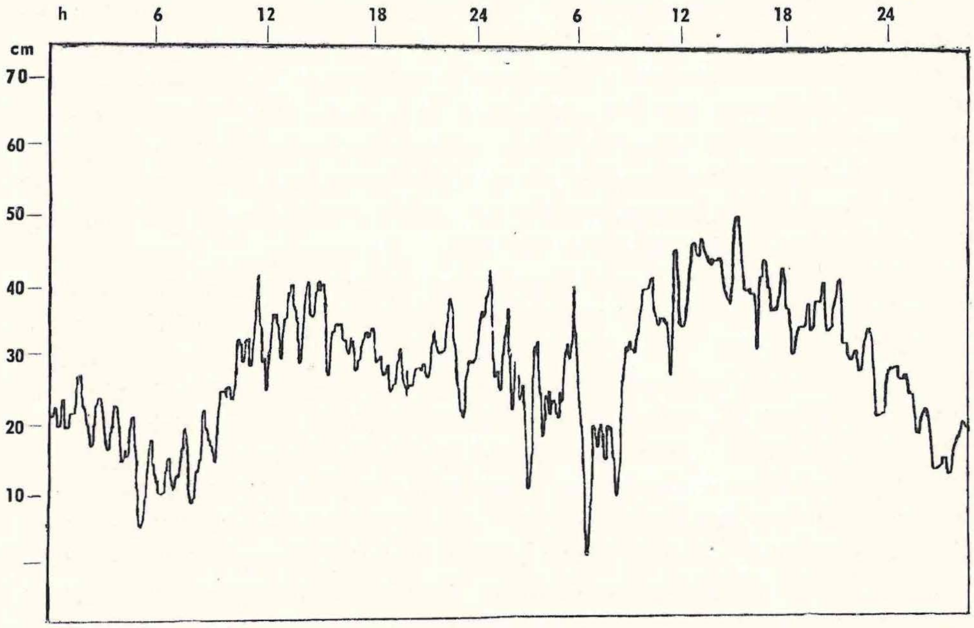
Since the coast surrounding the investigated area is a higly developed one, forced oscillations, in addition to the bay's own ones may also occur in the bay. In order to find out which of the occuring seiches belonged to the bay's own ones and which to the forced ones, we resorted to the examination of the marigrams obtained by means of the tide gage placed in the Split port. The investigated bay is in direct connection with the Brač—Split channel, so if equal periods of oscillations are found for both basins, this may likely confirm that here we are confronted with the seiches occurring in the said channel, the more so if these seiches happen to be long period ones, since the channel is a larger basin. So the 1950 and 1951 marigrams, referring to the Split port, which is a component of the channel, were examined and it was found that the 15 minutes' periods were most frequently occurring in them. According to its size, this period obviously corresponds to the Split port's own period and it logically does not appear in the marigrams referring to the Bay of Kaštela. The seiche of period 104 min., according to its frequency in these marigrams, comes next. It appeared, besides, at the same time in both the Kaštela Bay and Split port marigrams and we can infer that it was not the bay's own seiche. On the contrary, a 60 minutes' period could not be found in the Split port marigrams although our best attention was given to them, which circumstance allows the conclusion that here we are faced with a period of the free oscillation of the investigated bay.

It had been empirically established that longitudinal seiches occur in bays, with their horizontal component in the direction of the main, i. e. the longest axis of that bay which is marked by the course of the basin. Lateral motions, according to theory, may be disregarded in elongated basins. Since the basin of Kaštela Bay is not of that kind, we supposed that the bay's own oscillations might develop in its so called inner basin, which would be analogous to those of a lake. The basic seiche of a bay having a wave length $\lambda = 4\ l$, where l stands for the length of the bay's axis, both maximum and minimum denivellations should occur in all the parts of that bay at the same time. In a basic seiche of a lake, where the node of the vertical displacement lies in the middle of the lake, we have the state of the maximum denivellation in one half of the lake, and, at the same time, the state of the minimum denivellation in its other half, i. e. the oscillations at one end of the lake have a phase difference of T/2 in comparison with the other end.

In order to establish whether the 60 minutes' seiche belongs to a bay or lake type one, we have only to examine whether the oscillations occurring at both ends of the inner basin have a coincidence of phase or have a phase difference of T/2. For this purpose a transportable tide gage was temporarily placed at St. Kajo and a comparison was made between its records and those obtained at Divulje. It was found that the records of both tide gages, during the space of time between the 14th and 19th of April 1952, were produced by the revolving of the recording drum during 24 hours, while the gage-scale remained 1 : 10, this rendering the denivellation maxima and minima even more rounded. The hours, which were indicated on marigrams by means of time-marks, were also mutually compared. A careful examination of these marigrams disclosed that simultaneous maxima and minima of denivellations occurred with a greatest departure of 5 minutes, wich may be considered very accurate. This shows that the 60 minutes' seiche is really the basic seiche of the bay as a whole, and not a lake seiche of the bay's inner basin, since in the latter case, the occurrence of the maximum and minimum of the denivellation would involve a 30 minutes' phase difference (T/2).



Currentmeter recordings obtained at Cape Marjan from May 8th 1952 (22.00 hours) to May 9th 1952 (7.00 hours). Distinct oscillations of period 60 minutes, — visible in the marigram too.



Marigram (produced every five days) taken at Divulje on September 14th and 15th 1949. Oscillations of period 104 minutes with superposed oscillations of period 60 minutes; SE-wind prevailing in the whole of the Adriatic.

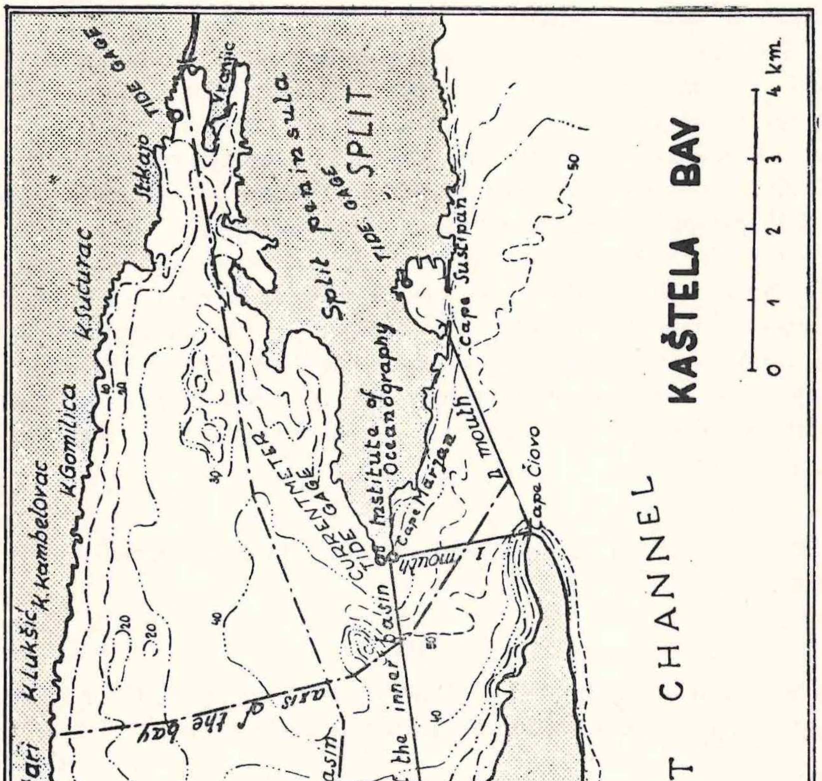
The 104 minutes' period was examined in a similar way and it was established that the seiche corresponding to this period had likewise a coincidence of phase in the whole of the bay, as it was supposed with regard to what was said before, since this is not a bay's own seiche. No 150 minutes' period seiche was found in these marigrams.

Periods measuring approximately 20 minutes were found in these diurnal marigrams, the only available of this kind. These, in all probability, were the periods of the first partial seiche of the bay which, according to weekly marigrams, was evaluated to be of period about a quarter of an hour.

The establishment of the horizontal displacements were based on the currentmeter recording obtained in the interval from 18th to 10th of May 1952. As this currentmeter was not gauged, its recordings rendered the determination of the absolute velocity of the current rather difficult, and only relative increases or decreases of that velocity could be found out. Analyses of currentmeter records are not practiced in the study of seiches, but we availed ourselves of this means also in order to determine the seiches with more certainty, bearing in mind that one of the direct advantages of the study in seiches consists in the acquaintance with the system of currents in the investigated area.

It is distinctly evident from the currentmeter recordings that the variations of the strength of the current occurred with the 60 minutes' periods. This was, naturally, brought into connection with the basic seiche of the bay. But since also tide gage recordings were obtained at that place at the same time, comparisons were possible between the horizontal and vertical diplacements. The place where the recordings were made was most suitable since the horizontal displacements, i. e. the seiche currents, are the fastest just at the mouth of the bay.

The seiche current, according to theory, attains its maximum when there is no denivellation of the surface, and the direction of the current is dependent on the acceleration of the rate of vertical motion, so that the current has an outward flow when the acceleration of that rate is in the direction of the negative denivellation. There is no seiche current when the surface attains the state of the maximum or minimum denivellation, as we have then a phase difference of T/4 of the horizontal displacement in comparison with the vertical displacement of the surface. The currentmeter records have shown that the current had a constant S (south) direction during the recording. A velocity reduction of the current may imply that the superposed current has an opposite direction, i. e. N-direction in our case, or in association with a component in that


KAŠTELA BAY
BRAČ - SPLIT CHANNEL
ČIOVO
TROGIR
SPLIT
Split peninsula
Institute of Oceanography
CURRENTMETER
TIDE GAGE
axis of the inner basin
axis of the bay
limit of the inner basin
mouth I
mouth II
Cape Marjan
Cape Čiovo
Cape Sustipan
Divulje
Slatina
Stobrec
Vranjic
K. Novi
K. Štafilić
K. Stari
K. Lukšić
K. Kambelovac
K. Gomilica
K. Sućurac
0 1 2 3 4 km.

direction. A velocity increase in the constant S-direction would signify, then, that the superposed current has the same direction, or that it coincides, at least, with one component in that direction. If this is supposed, a reduction of velocity in our case would mean that the superposed current is directed toward the bay, and an increased current velocity would imply that the superposed current follows the course toward the open sea.

If we can establish that the maximum velocity has a phase disturbance of T/4 with the minimum denivellation, the superposed current, then would really agree with the theoretical assumption on the horizontal motion of the water mass in seiches. By comparing the marigrams and the currentmeter recordings this has indeed been established with the possible accuracy, i. e. the phase difference was found between the maximum current velocity and the minimum denivellation, whose mean value is approximately

$$t = 15\ min.$$

This is exactly T/4, since we have here the basic period whose value is 60 minutes.

III.

The following approximate formula, according to J. Goldberg (6), was applied to the calculation of the bay's basic seiche:

$$T - 2\pi \sqrt{\frac{l\,F}{2g\,S_0}} \qquad \qquad (1)$$

where l is the lenght of the bay's axis, F the total free area of the bay, and S_0 the area of the cross-section of the mouth of the bay. This formula was obtained by applying the Method of Residuation (i. e. a method of numerical integration of the equation of seiche motion) to the bay as a whole. By means of the Method of Residuation we are able to calculate also the period of the partial multinodal seiches. It was not applied to Kaštela Bay, as its application would require a higher accuracy of recordings involving direct observations in the bay itself, while indistinct periods, which are not easy to establish, are found in marigrams covering the multinodal seiches.

The values marked with the index I resulted when the line connecting Cape Čiovo with Cape Marjan was taken as the mouth of the bay, and the values marked with the index II were obtaind when the line connecting Cape Čiovo and Cape Sustipan represented the mouth.

The area of the bay was obtained by means of planimetric mensuration from the chart (12), and the cross-section of the mouth was found out by calculation under the assumption that the relief of the bay sloped uniformly from one isobath to the other.

Table I.

Basin Desi-gnation	A r e a F	Area of the Mouth Cross-section, S_o	Length of Axis. l	Breadth of Mouth, bo	Mouth Correction	
					$k = \sqrt{1+2\frac{\alpha}{l}}$	$k = 1 + \frac{\alpha}{l}$
I	$57{,}5\times10^6\,m^2$	89269 m^2	8165 m	2075 m	1,18	1,21
II	$61{,}0\times10^6\,m^2$	133838 m^2	9125 m	3100 m	1,21	1,24

The following periods were obtained by means of these values:

$$T_I = 53{,}6 \ min.$$
$$T_{II} = 47{,}7 \ min.$$

Through its mouth the bay can either emit an oscillatory energy of its own or receive an outside one. As the length of the periods is affected by the emission of the oscillatory energy, it must undergo a correction, the so called mouth correction.

The Japanese (10), (11), were the first to employ this correction by applying to bays the analogy of an organ pipe open at both ends according to results obtained by Rayleigh (13). The corrected period has the following value

$$T_k = T\sqrt{1 + 2\frac{\alpha}{l}} \quad \ldots\ldots\ldots \quad (2)$$

and the correction is

$$k = \sqrt{1 + 2\frac{\alpha}{l}} \quad \ldots\ldots\ldots \quad (3)$$

where $\alpha = \frac{b_0}{\pi}\left(\frac{3}{2} - 0{,}5772 - ln\ \frac{b_0\,\pi}{4\,l}\right)$ and b_o is the breadth of the mouth (7. page 185).

The correction may be obtained in another way also if we suppose that the period of the bay's oscillation is not based on the real length of the course of the basin l, but on the reduced length $l + \alpha$. In accordance with this (7. page 187) we have

$$T_k = T\left(1 + \frac{\alpha}{l}\right) \quad \ldots\ldots\ldots \quad (4)$$

and the correction is

$$k = 1 + \frac{\alpha}{l} \quad \ldots\ldots\ldots \quad (5)$$

By applying the first of the above two ways for the correction we obtain

$$T_I = 63{,}2 \ min.$$
$$T_{II} = 57{,}7 \ min.$$

These values confirm that the value established by means of observation represents the mean of the results obtained for both mouths, and show that the real mouth is likely to be found between the assumed two extreme mouths. The use of the correction $k = 1 + \frac{\alpha}{l}$ results in periods

$$T_I = 64{,}9 \ min.$$
$$T_{II} = 59{,}1 \ min.$$

The value T = 59,1 min. is the nearest of all to the results of observation, from which we can deduce that the second variant of limitation of the bay is better.

These results provide theoretical confirmation of the earlier conclusions that the 60 minutes' period really belongs to the basic seiche of Kaštela Bay, while the seiches of periods 150 and 104 minutes belong to another basin causing the forced oscillations of the bay.

Owing to the assumption that there are bay's own oscillations in its inner basin, its lake type seiche was calculated according to Merian's formula:

$$T = \frac{2\,l}{\sqrt{g\,h}}$$

where l is the length of axis, and h the average depth of the basin.

The average depth of the inner basin — amounting to 22 m — was calculated on the basis of isobaths, by taking into consideration the area comprised by each of the isobaths.

The length of the axis amonuts to 18 240 m. These values yielded a period

$$T = 41 \ min.$$

As no period of this order of magnitude was found in marigrams at all, we are right to conclude that independent oscillations do not develop in the inner basin.

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O SEŠIMA U KAŠTELANSKOM ZALJEVU

Mira Zorè

Institut za oceanografiju i ribarstvo FNRJ, Split

Kratak sadržaj

Za istraživanje seša u Kaštelanskom zaljevu upotrebljeni su tjedni mareogrami s rta Marjana, petodnevni mareogrami iz Divulja, jednodnevni mareogrami iz Divulja i s rta kod Sv. Kaje, te registracije strujomjera s rta Marjana.

Periodi seša određeni su tako, da su na mareogramima traženi nizovi oscilacija istog perioda, a za svaki niz određen je srednji period. Ovi su periodi skupljeni u grupe s istim stupnjem veličine i traženi su srednjaci tih grupa.

S mareograma s rta Marjana dobiveni su periodi od 150 min., 104 min. i 60 min. Nađene su još i oscilacije s kraćim periodom, koji se nije mogao odrediti. S mareograma iz Divulja dobiveni su periodi, koji se neznatno razlikuju od gornjih.

Ispitivanjem mareograma iz Bračko-Splitskog kanala utvrđeno je, da je period od 60 min. period slobodne oscilacije Kaštelanskog zaljeva, dok su periodi od 150 i 104 min. periodi većeg basena s kojim taj zaljev prisilno oscilira.

Zbog oblika zaljeva bilo je potrebno ispitati, da li postoje lateralna gibanja, koja bi se ispoljila kao jezerski seš unutarnjeg korita. Ispitivanjem mareograma iz Divulja i kod Sv. Kaje utvrđeno je za seš s periodom od 60 min. da na oba kraja zaljeva ima istovremeni nastup maksimuma, odnosno minimuma denivelacija, što odgovara osnovnom sešu cijelog zaljeva. Lateralna gibanja nisu, dakle, utvrđena.

Ispitivanje registracija strujomjera potvrdilo je ranija zaključivanja, da je period od 60 min. zaista osnovni period zaljeva.

Za račun osnovnog perioda upotrebljena je formula (1), s tim da su uvažene dvije varijante ograničenja zaljeva. Dobiveni periodi korigirani su još t. zv. korekcijom za ušće (3) odnosno (5). Računski dobiveni rezultati dobro se slažu s vrijednostima dobivenim iz mareograma. Pokazalo se, da je druga varijanta ograničenja zaljeva vjerojatnija.

This paper was submitted to the Scientific Board of the Institute on the February 20th, 1954.