ON THE TIDES AND TIDAL CURRENTS IN THE NAIKAI (INLAND SEA), JAPAN

by

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Translated from Japanese in the "*Toyô Gakugei Zassi*" (*The Oriental Sciences and Arts*), Vol. 46, 1930, pp. 214 to 229).

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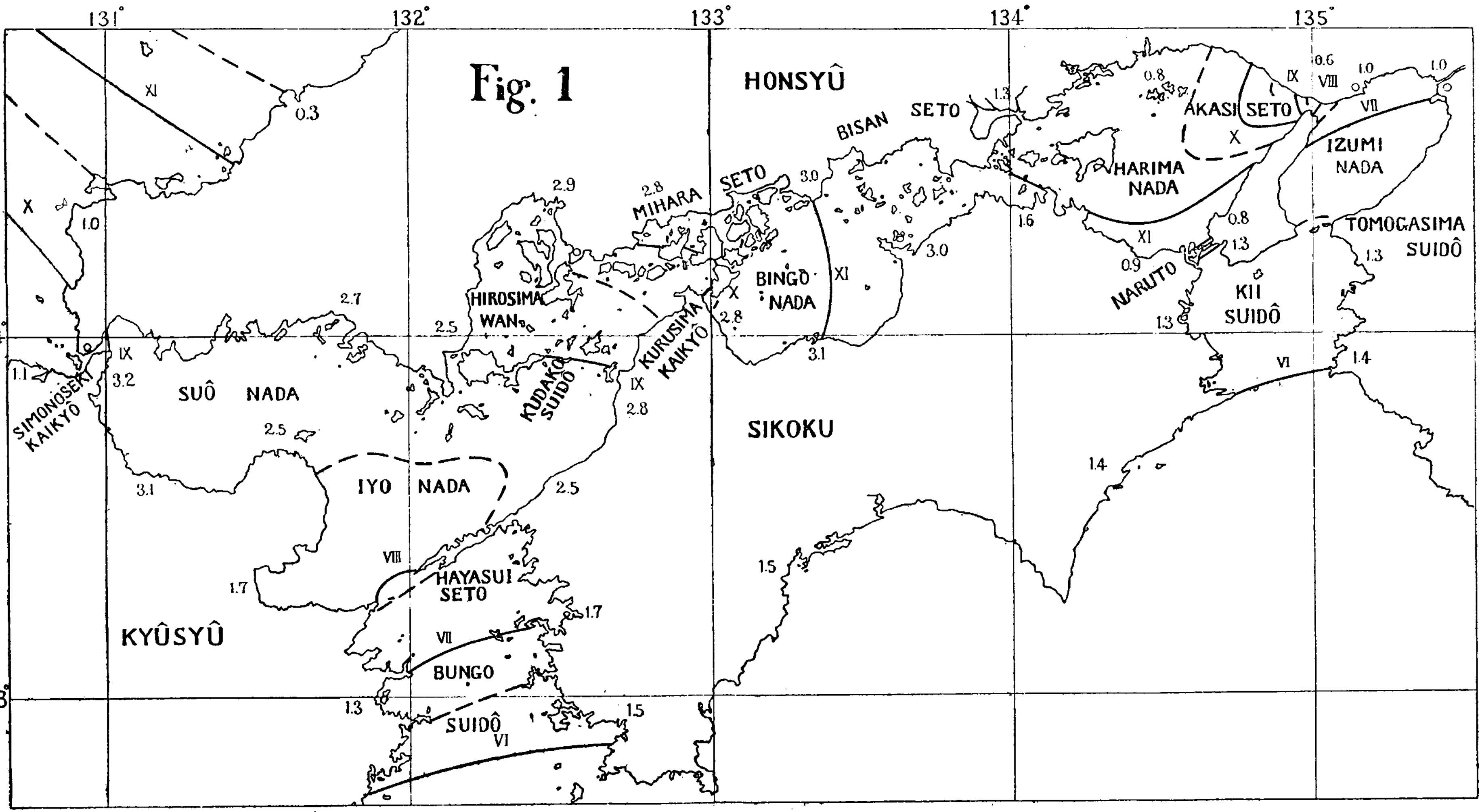
1. *INTRODUCTION.*

The writer's study on the tides and tidal currents in the Naikai (Inland Sea), Japan, was made by utilizing the data obtained mainly by the Hydrographic Department of the Japanese Navy. The Inland Sea is the most frequented sea in Japan; its topography is very intricate, with hundreds of islands scattered here and there; the tides are very complicated and the tidal currents are very strong in the narrows, always embarrassing navigators.

The Hydrographic Department had collected data on the tides and tidal currents in the Inland Sea obtained in the course of the survey of the coast but these were insufficient for the thorough study of such complicated tides and currents. Consequently, the same Department undertook a closer survey of the currents in the principal narrows of the Inland Sea in order to obtain the data necessary to make navigation safer. The survey was commenced in 1913 and finished in 1924, the principal narrows being surveyed from year to year by Messrs T. OGAWA, Y. ARAI, T. TAKENOUTI, K. KOBAYASI, K. KUDÔ and many others with the greatest care. When the currents in a particular area were surveyed, current charts of that area were published by the Hydrographic Department for the use of navigators. Such charts have been published for Tomogasima Suidô, Akasi Seto, Simonoseki Kaikyô, Kudako Suidô and its vicinity, Kurusima Kaikyô, Mihara Seto and their vicinities. All these charts, together with those for Naruto which had been published earlier, and those for Obatake Seto, which was surveyed later, were bound together in a single volume entitled "*Current Charts for the Naikai*" and this volume was issued in 1929.

Previous to this, in about 1910, the present writer had begun a study of the tides in Japanese waters, which problem had hitherto hardly been touched, using the data obtained by the Hydrographic Department. The result of his study was published in Japanese by this Department in 1914 as a report, under the title of "*Tides in the Adjacent Seas of Japan*". A preliminary study of the tides in the Inland Sea is included in this report. Since then, the results of the author's study on tides and currents in the various parts of the Inland Sea have been published from time to time in the "*Suiro Zasso*" (*Miscellaneous Reports on Hydrography*) in Japanese. The present paper is a popular summary of his work.

Fig. 1



Co-tidal chart for semi-diurnal tide, referred to the meridian of 135° E.

$$\text{Co-tidal hour} = \frac{M_2^{\circ}}{30^{\circ}} + (9\text{ h} - \text{E. Long in time}).$$

Numerals denote $2\ (M_2 + S_2)$ in metres.

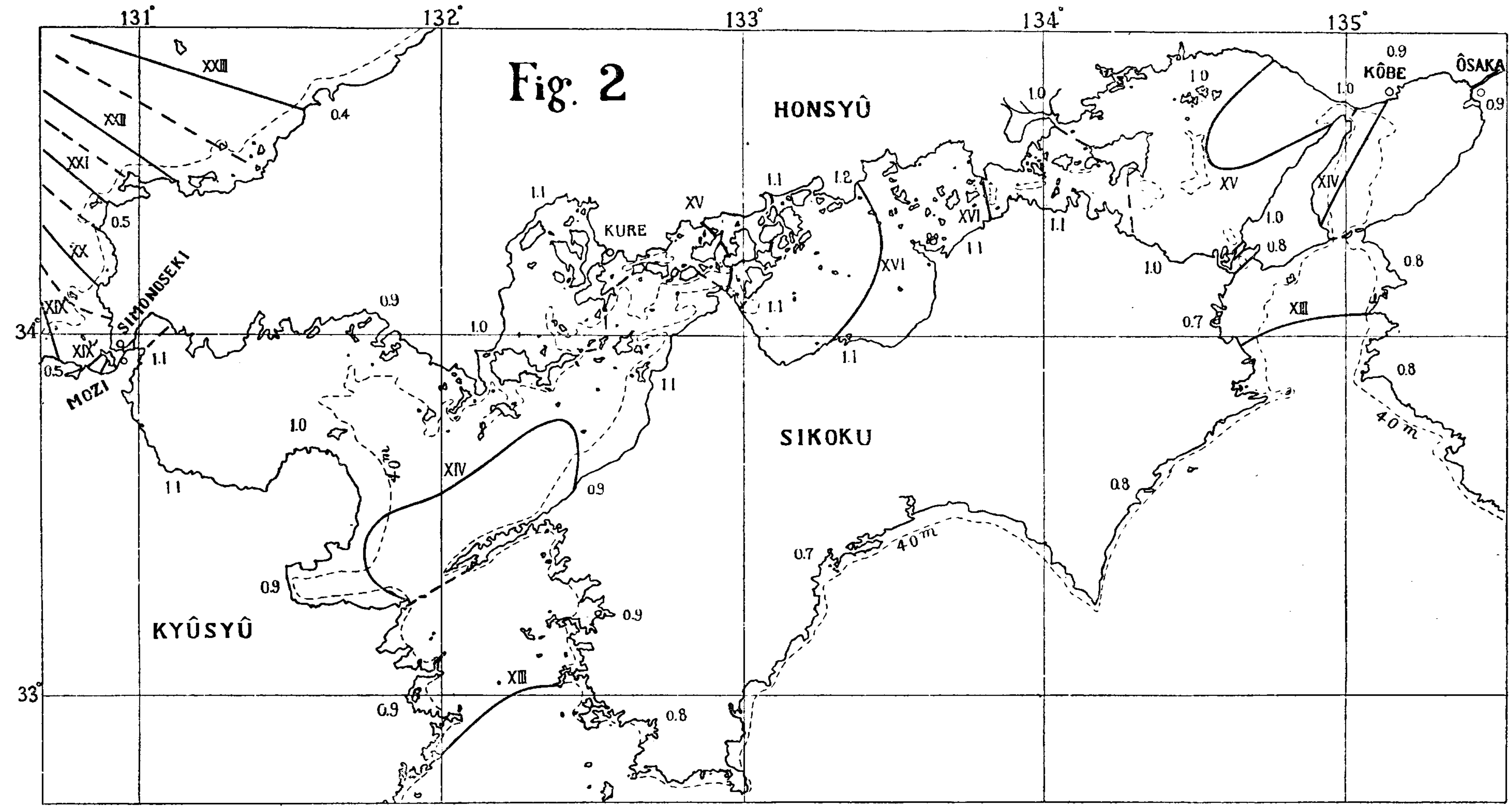
2. *PROGRESS OF TIDAL WAVES.*

For the study of tides and currents in the seas it is highly preferable to show the progress of the tidal wave and the range of the tide by means of a map. Therefore cotidal charts, containing tidal ranges as well, have been prepared for the Inland Sea. The diurnal inequalities of tides in the Inland Sea are very noticeable, especially in its eastern part, the heights and times of successive high waters and successive low waters differing from each other, and, at some places in the eastern part, one high water and one low water only in a day may frequently be observed. Consequently, it is advisable to treat semi-diurnal and diurnal tides separately. The writer is pleased that harmonic constants of the tides have been deduced by the Hydrographic Department for about 70 stations in the Inland Sea and its vicinity, and therefore co-tidal charts for semi-diurnal and diurnal tides can be drawn with reliable accuracy. The co-tidal chart for the M_2 tide, representing the semi-diurnal tides, and that for the K_1 tide, representing the diurnal tides, are shown in figures 1 and 2 respectively. In Fig. 1 the value of 2 $(M_2 + S_2)$ and in Fig. 2 the value of 2 $(K_1 + O)$ are shown in numerals at several places, so that the geographical distribution of tidal ranges can easily be seen. M_2 and S_2 are the tides caused by the action of the mean moon and the mean sun and their periods are 12.42 hours and 12 hours respectively. K_1 and O are the principal components of diurnal tides, the period being equal to 23.93 hours and 25.82 hours respectively. The range of semi-diurnal tides at mean syzygy is nearly equal to 2 $(M_2 + S_2)$, and that of diurnal tides at the moon's maximum declination (twice a month) to 2 $(K_1 + O)$.

It is to be observed, from Figures 1 and 2, that the waves of M_2 and K_1 tides generated in the Pacific Ocean come into the Inland Sea mainly through two channels, *viz.*, Kii Suidô in the east and Bungo Suidô in the west. The wave coming through Kii Suidô proceeds to the west and that coming through Bungo Suidô divides into two parts after entering the Inland Sea, one part proceeding westward to Simonoseki Kaikyô, the other eastward to meet the wave coming from Kii Suidô in the vicinity of Bisan Seto. The range of semi-diurnal tide is smaller in the eastern part of the Inland Sea and greater in the western than along the Pacific coasts. The range of the diurnal tide is nearly equal all over the Inland Sea and is a little greater than on the Pacific coasts. A detailed study of semi-diurnal and diurnal tides is given in the following articles.

3. *SEMI-DIURNAL TIDE AND CURRENT.*

The area of the Inland Sea being very small, the effect of the tide-generating forces of the moon and the sun acting directly on the water of the Inland Sea may be neglected. The tides generated in the Pacific Ocean propagate into the Inland Sea as a progressive tidal wave the velocity of which varies with the form of the sea, the depth, the friction between sea bottom and the water, *etc.* A tidal wave in a very long straight canal of uniform cross section progresses under the action of gravity alone as a free



Co-tidal chart for diurnal tide, referred to the meridian of 135° E.

$$\text{Co-tidal hour} = \frac{K_1{}^\circ}{15^\circ} + (9\,\text{h} - \text{E. Long. in time}).$$

Numerals denote $2\,(K_1 + O)$ in metres.

wave with a velocity given by $\sqrt{gh,}$ where g and h are the acceleration due to gravity and the mean depth of the canal respectively. Supposing a tidal wave progresses in the Inland Sea with a velocity given by $\sqrt{gh,}$ the time required for such progression over certain areas of the sea is calculated and this is then compared with the actual time required, with the results shown in the following table.

TABLE I. — TIME REQUIRED FOR TIDAL WAVE TO PROGRESS.

AREA.	*Mean depth*	*Distance*	TIME REQUIRED *Calculated*		TIME REQUIRED *Observed*	
	metres	miles	h	m	h	m
(1) S. end of Bungo Suidô-Hayasui Seto	90	30	0	30	2	0
(2) Hayasui Seto-Hime Sima, Suô Nada	55	35	0	50	0	50
(3) Hime Sima-W. side of Suô Nada	20	35	1	30	0	0
(4) Hayasui Seto-Kudako Suidô	40	50	1	20	1	0
(5) Kudako Suidô-W. end of Mihara Seto	45	20	0	30	0	40
(6) W. end of Mihara Seto-E. end of Mihara Seto	35	20	0	30	1	0
(7) E. end of Mihara Seto-W. end of Bisan Seto	20	15	0	30	0	20
(8) W.end of Mihara Seto-S. end of Kurusima Kaikyô	40	10	0	15	0	50
(9) S. end of Kurusima Kaikyô-W. end of Bisan Seto.	20	30	1	0	0	30
(2) + (3)		70	2	20	0	50
(1) + (2) + (3)		100	2	50	2	50
(4) + (5) + (6) + (7)		105	2	50	3	0
(4) + (5) + (8) + (9)		110	3	5	3	0
(10) S. end of Kii Suidô-Tomogasima Suidô	55	25	0	30	0	20
(11) Tomogasima Suidô-Akasi Seto	35	20	0	30	0	40
(12) Akasi Seto-S. side of Syôdo Sima	30	40	1	10	4	0
(13) S. side of Syôdo Sima-W. end of Bisan Seto	15	40	1	40	0	10
(10) + (11)		45	1	0	1	0
(12) + (13)		80	2	50	4	10

From the above table, as well as from Fig. 1, the following facts are to be observed :

1. The velocity of the tidal wave in Bungo Suidô is considerably less than that of a free tidal wave.

2. The velocity of the tidal wave in Suô Nada is considerably greater than that of a free tidal wave.

3. In the seas between Hayasui Seto and the western end of Bisan Seto, the velocity of the tidal wave is far greater in open seas such as Iyo Nada and Bingo Nada than that of a free wave, and is far less in the narrows such as Mihara Seto and Kurusima Kaikyô.

4. The velocity of the tidal wave compared with that of a free wave is greater in Kii Suidô, less in Tomogasima Suidô, and slightly greater in Izumi Nada.

5. The velocity of the tidal wave at Akasi Seto is considerably less than that of a free tidal wave.

6. The velocity of the tidal wave in the western part of Harima Nada and in Bisan Seto is considerably greater than that of a free wave.

We now proceed to give some facts on tidal currents derived from observations. For the study of currents the present writer deduced the harmonic constants of tidal currents for several narrows of the Inland Sea. From such harmonic constants, as well as from direct observations, the times of turns of currents referred to high and low waters are obtained for various narrows as shown in the following table:

TABLE II. — TIMES OF TURN OF CURRENT.

PLACE.	Turn of current from			
	Local H. W.		*Turn at Hayasui Seto*	
	h	m	h	m
South end of Bungo Suidô	3	0	−0	30
S. end of Hayasui Seto	2	0	0	0
N. end of Hayasui Seto	1	20	0	0
W. part of Suô Nada	0	40	0	0
Central part of Iyo Nada	2	0	1	0
Turusima Suidô and Kudako Suidô	1	50	1	30
E. part of Aki Nada	2	0	1	30
E. part of Mihara Seto	1	10	2	0
Kurusima Kaikyô	1	40	2	0
Tomogasima Suidô	4	30	0	0
Akasi Seto	3	0	0	20
Central part of Harima Nada	0	0	0	0
E. part of Bisan Seto	−0	50	−0	20
W. part of Bisan Seto	−1	0	−0	30

Bingo Nada being the area where the currents coming from the east and west meet and separate into the opposite directions, the positions of meeting and separation change from the east end to the west end of the Nada with the time of tides.

The following facts result from the above table.

1. In the area from Bungo Suidô to the west side of Suô Nada the time intervals from high and low waters to the turns of currents decrease as the head of the sea is approached, but the actual time of turns is nearly simultaneous all over the area.

2. In the area between Iyo Nada and Bingo Nada the time interval

from high and low waters to the turns of currents slightly decreases and the times of turns become later to the east.

3. In the area between Kii Suidô and the western part of Bisan Seto the time interval from high and low waters to the turns of currents rapidly decreases, while the actual times of turns remain nearly the same all over the area.

What is the cause of this complexity of the tides and currents ? This is a problem which may be solved by hydrodynamics. It is very difficult to treat theoretically the tides of the Inland Sea as a whole, for here the topography is very intricate, especially when the tidal wave coming from Bungo Suidô divides into two parts, one entering a long canal eastward of Iyo Nada and the other going into Suô Nada three sides of which are nearly enclosed by land. It is possible, however, to explain the tides in the Inland Sea at least qualitatively, though not quantitatively, by applying the theories on tides which have been solved theoretically in the cases of small canals and bays of simple form. The tides in the Inland Sea may be explained as follows, though the writer is still in course of studying them :-

The Inland Sea communicates with the outer seas by three mouths: Kii Suidô in the east, Bungo Suidô and Simonoseki Kaikyô in the west. The tides in the outer seas propagate into the Inland Sea as tidal waves. Simonoseki Kaikyô having a very small cross section, the tidal wave passing through that strait has but little influence on the tides of the Inland Sea except in a limited area near the strait. Kii Suidô communicates with the Inland Sea by Tomogasima Suidô, Naruto and Muyano Seto, adjacent to the west of Naruto, the cross sections of the second and last being very small compared with the first. Consequently, the tides in the Inland Sea are principally governed by the tidal waves coming in from the Pacific Ocean passing through Bungo Suidô, and Tomogasima Suidô. Not only has Bungo Suidô a greater cross section than Kii Suidô, but the tidal wave coming into the Inland Sea through the latter, having to pass through narrows such as Tomogasima Suidô and Akasi Seto, the volume of water passing through Bungo Suidô is considerably greater than that passing through Kii Suidô. Thus Bungo Suidô has the greatest influence on the tides in the Inland Sea. If we take cross sections at many places of the Inland Sea and calculate the mean volume of water passing through each cross section during about 6 hours from a turn to the next turn of current at springs, we obtain the results shown in the following table : -

TABLE III.— VOLUME OF WATER PASSING THROUGH IN 6 HOURS AT SPRINGS

PLACE.	*Volume*	PLACE	*Volume.*
	cub. mile		cub. mile
E. end of Suô Nada	1.50	Kurusima Kaikyô....................	0.28
Simonoseki Kaikyô	0.04	Tomogasima Suidô..................	0.34
Kudako Suidô and eastern channels	0.76	Akasi Seto	0.49
Entrances of Hirosima Wan........	0.47	W. end of Bisan Seto	0.33
Central part of E. Aki Nada......	0.65	Naruto	0.18
W. end of Mihara Seto.............	0.20		

Let us now consider the tides in the seas from Bungo Suidô to Suô Nada. This area forms a long and narrow canal divided into two parts by a narrows, Hayasui Seto, formed by a long promontory, Mi Saki, projecting westwards from Sikoku and a promontory of Kyûsyû. Moreover, this canal communicates, at its central part, and nearly perpendicularly to its length, with a long canal east of Iyo Nada. If we suppose that there is no Mi Saki promontory and that Iyo Nada is divided centrally into two parts by an embankment extending in a south and north direction, the sea area from Bungo Suidô to Suô Nada forms a long canal closed by land except at its south end, where it communicates with a large tided sea. In such a canal a stationary wave, though not in strict sense, is formed by a wave coming into the canal and a wave reflected at its head. As can be seen from Table I, a free tidal wave requires 2 hours 50 minutes to travel from the mouth of Bungo Suidô to the head of Suô Nada; probably a little more than 3 hours in actual fact because the velocity of the wave will be reduced at the narrows of Hayasui Seto. In such case, a stationary wave is produced with a node at the mouth and the tides in the canal become considerably greater than those outside of the canal, the currents running towards the head from low water to high water at the head of the canal. As a matter of fact, however, a part of the wave is reflected by the Mi Saki promontory and no longer exists as a stationary wave in Bungo Suidô, the wave becoming a progressive one. The times of turns of currents in Bungo Suidô become early by this effect.

The area East of Iyo Nada forms a long canal with numerous islands in it and tided at its west end. Consequently, the tidal wave in this canal is partly reflected by islands, and the turns of currents occur some time after high and low waters. But the sea area on the north side of Bungo Suidô not being sufficiently great, the tides to the east of Iyo Nada affect the tides in Bungo Suidô and Suô Nada, and the wave in Bungo Suidô becomes more progressive.

The tides and currents in Bingo Nada are principally governed by the tidal wave coming from Bungo Suidô, but they have close relation with the wave coming in from Kii Suidô. We can consider two independently tided seas, *viz.*, Bingo Nada and the south side of Kii Suidô, which are connected by a long canal consisting of Kii Suidô, Izumi Nada, Harima Nada and Bisan Seto. The tides in a long straight canal of uniform cross section connecting two independently tided large seas are solved theoretically neglecting the effects of the earth's rotation and friction. We take the origin at the sea bottom at one end of the canal, the x axis to the direction of the canal and the y axis vertically upwards. Assume that the tides at the two ends of the canal, the length of which is L, are given by the following expressions :-

$$\text{At} \quad x = 0 \qquad \eta_1 = H_1 \cos(\sigma t - \varkappa_1) \quad , \quad \sigma = \frac{2\pi}{period}$$

$$\text{At} \quad y = L \qquad \eta_2 = H_2 \cos(\sigma t - \varkappa_2)$$

Then the horizontal and vertical displacements ξ and η of a particle of water at a point x on the surface of the sea are given by the following expressions :

$$\xi = -\frac{H_1}{h}\frac{c}{\sigma}\frac{\cos\frac{\sigma}{c}(L-x)}{\sin\frac{\sigma}{c}L}\cos(\sigma t - \varkappa_1) + \frac{H_2}{h}\frac{c}{\sigma}\frac{\cos\frac{\sigma}{c}x}{\sin\frac{\sigma}{c}L}\cos(\sigma t - \varkappa_2)$$

$$\eta = H_1\frac{\sin\frac{\sigma}{c}(L-x)}{\sin\frac{\sigma}{c}L}\cos(\sigma t - \varkappa_1) + H_2\frac{\sin\frac{\sigma}{c}x}{\sin\frac{\sigma}{c}L}\cos(\sigma t - \varkappa_2)$$

where h is the depth of the sea, and $c = \sqrt{gh}$.

In the case of the eastern part of the Inland Sea, the area of Bingo Nada being comparatively small, the tides in this sea are more or less affected by the tides in the seas east of it, and the sectional area of the canal connecting Bingo Nada and the sea south of Kii Suidô differs considerably from place to place, with narrows such as Tomogasima Suidô and Akasi Seto.

Consequently, it is clear that the tides in the eastern part of the Inland Sea cannot be treated as a case of a straight and uniform canal connecting two independently tided large seas ; but if we take cross sections at several places of the canal and calculate the tides and currents at each cross section by the formula given above, giving to L and h the values derived from the depth of the sea at each section, they coincide approximately with the observed values.

4. *DIURNAL TIDES.*

We can observe from Fig. 2, the co-tidal chart for the diurnal tide, that the progress of the diurnal wave is somewhat similar to, but simpler than, that of the semi-diurnal wave, without retardation in Bungo Suidô and Akasi Seto, that the time required for the diurnal wave to reach the meeting at Bingo Nada after entering into Bungo Suidô in the west and Kii Suidô in the east, being about 3 hours, is considerably shorter than 5 hours for the semi-diurnal wave, and that the range of the diurnal tide is nearly equal to and a little greater than that on the Pacific coasts all over the Inland Sea, while that of the semi-diurnal tide differs considerably according to the place.

For the places where the harmonic constants of tidal currents have been derived the following values are obtained :

TABLE IV. — DIURNAL TIDAL CURRENTS.

PLACE.	*H.W. to turn of current.*		$(K_1+O)/(M_2+S_2)$	
			Tide.	*Current.*
	h	m		
Kudako Suidô	0	0	0.39	0.20
Turusima Suidô	3	40	0.39	0.35
Kurusima Kaikyô	0	40	0.37	0.20
Akasi Seto	1	10	2.05	0.41
E. part of Bisan Seto	−1	30	0.67	0.18

The diurnal tides and currents can be explained in a similar way to the semi-diurnal tides and currents.

In Bungo Suidô and Suô Nada a partially stationary wave is formed, but the time required for a free diurnal wave to travel from the mouth of Bungo Suidô to the head of Suô Nada (3 hours nearly) being very short compared with the period of the diurnal wave (24 hours nearly), the range of tides is nearly equal everywhere, without a node as in the case of semi-diurnal tide. In the long canal with numerous islands to the east of Iyo Nada the diurnal wave progresses to the east in the same way as the semi-diurnal wave, and the currents turn some time after high water and low water.

The tides in the sea from Bisan Seto to Kii Suidô can be explained approximately as the case of a long canal connecting two independently tided large seas, in the same way as the semi-diurnal tide.

5. *TIDES AT NARUTO, SIMONOSEKI KAIKYO AND HIROSIMA WAN.*

In the discussion of tides in the Inland Sea in the two preceding articles we have neglected the effects of Naruto and Simonoseki Kaikyô, of very small cross actions, and of Hirosima Wan situated at the side of the propagation of the principal tidal waves. Let us now consider the tides and currents in these places.

Naruto being a very narrow and short strait connecting Kii Suidô and Harima Nada, the currents in this strait are caused by the differences in heights of sea levels in the two seas on the south (Kii Suidô) and the north (Harima Nada) of the strait, the current running from the higher level to the lower with a velocity given by $\sqrt{2gh}$ and slacks when the difference in level is zero. In the above expression g and h are the acceleration due to gravity and the difference in heights of sea-level respectively. The observed velocity of currents at the narrowest part of the strait agrees very well with the theoretical value. About ten years after the observations of currents were made at Naruto, the tides were observed for one year at two stations, one on the south and the other on the north of the strait, and harmonic constants of the tides at these stations were derived. From these constants, the harmonic constants of level difference for each component tide were obtained and the actual level difference at the time of current observation was calculated by using Kelvin's tide predictor. With these calculated level differences the velocity of current was evaluated by the formula $\sqrt{2gh}$ and it was found that it coincides fairly well with the observed velocity. The difference of the times of high waters in the two seas north and south of Naruto being about 5 hours (semi-diurnal tide), the maximum level difference occurs at about the time of high water in Kii Suidô, the maximum difference of 1.4 metres at springs giving rise to a current of over 10 knots. Naruto is noted for its currents being the strongest in Japanese seas.

Very near to the west of Naruto there is a long narrow canal, Muyano Seto, connecting Kii Suidô and Harima Nada. The currents in this strait are also caused by the differences in heights of the sea levels and the velocity is given by 0.5 $\sqrt{2gh}$ at the narrowest part of the strait. Such current corresponds to that in a small and long tube connecting the lower parts of two water tanks in which the water surfaces are at different heights.

Simonoseki Kaikyô is a narrow and long strait of varying width connecting two independently tided seas, the Inland Sea and Tusima Kaikyô, with two narrows, Hayatomo Seto in the east and O Seto in the west. Moreover, a very narrow strait, Ko Seto, connects Simonoseki Kaikyô to Tusima Kaikyô toward the northwest. The tides and currents in this strait are caused by the differences of heights in the two seas. The surface of the sea at any given time forms nearly a single plane inclined from one end of the strait to the other, and the water flows from the higher level to the lower. The range of tide, both semi-diurnal and diurnal, is greater in the east than in the west and the time of high water is earlier at the east end that at the west, by about one hour for semi-diurnal tides and about 5 hours for diurnal tides. Therefore the waves, both semi-diurnal and diurnal, progress towards the west through the strait and the range of tides becomes smaller to the west. The maximum difference of height between the sea levels at the east and west ends occurs at about the time of high water and low water at the east end, the current going towards the west at maximum velocity at about the time of high water and towards the east at about the time of low water. The strait being long and narrow, the velocity of current at the time of its maximum strength is not represented by $\sqrt{2gh}$, as in the case of a very short and narrow strait, but by $c\sqrt{2gh}$, in which c is a constant smaller than unity, and the turn of current in the strait occurs some time after the heights of sea-levels at the two ends become equal. If we take Hesaki as representing the level of the Inland Sea and Takenoko Sima the level of Tusima Kaikyô, both stations being situated very near to the ends of the strait, the constant c was found to be about 0.70 and the lag of turn of current about 50 minutes at the place of maximum strength of current at Hayatomo Seto (a little lower reach of the narrowest part and along the central line). Along the coasts the turn of current takes place earlier than along the central line. Ko Seto being very short and narrow, the currents in this strait are caused by the difference of level at the two ends and turn at about the time when the level-difference is zero. In the three narrows in Simonoseki Kaikyô the turn of current occurs first at Ko Seto, then at Hayatomo Seto and finally at O Seto. This relation can be explained by calculating the volume of sea water passing through the three narrows and that required for the rise and fall of sea level in the strait.

According to hydromechanics, at every section of a continuous and steady stream of frictionless fluid, the sum total of velocity head, pressure head and potential head is a constant. At the free surface of the fluid the pressure head is zero and therefore the potential head will decrease with increasing velocity. Consequently, if the tidal current flows with a great velocity the surface of the sea will become lower. If the tidal current attains its maximum velocity at about the time of high and low waters the marigram will be flat at high water and sharp at low water. As the time of high water and low water coincides nearly with that of the M_2 tide, an M_4 tide will result with half the period of M_2, the times of high waters of the two tides occuring at about the same moment. This is the case in Akasi Seto and Simonoseki Kaikyô. At Ezaki, on the south side of Akasi Seto, the effect of currents on tides is most conspicuous and high water consists of two maximums instead of one, as in the ordinary case; the level of the sea falls a little after the first high water and then rises to a second high. The values of the semi-ranges of M_2 and M_4 tides at Ezaki, on the south side of Akasi Seto, and at Myôzin Bana, on the south side of Hayatomo Seto in Simonoseki Kaikyô, are as follows :-

	M_2	M_4
	metres	metres
Ezaki	0.13	0.05
Myôzin Bana	0.80	0.07

The currents in Simonoseki Kaikyô can be calculated by using harmonic constants for each component of tide expressing the difference of level at the two ends of the strait, as derived from harmonic constants of the tides at the two ends. In the Tyôseki Hyô (Tide Tables) published annually by the Japanese Hydrographic Department daily predictions of tidal currents are given for 4 straits in the Inland Sea, *viz.*, Akasi Seto, Naruto, Kurusima Kaikyô and Simonoseki Kaikyô. The currents at Naruto and Simonoseki Kaikyô are calculated by using harmonic constants of each component of the tide expressing the difference of level at the two ends of the strait, and those for Akasi Seto and Kurusima Kaikyô are calculated directly by means of harmonic constants of tidal currents. The calculations were made by using a tide predictor provided with 15 components.

Hirosima Wan is a bay nearly enclosed by land except on its southeastern part. In addition to this entrance the bay communicates with Iyo Nada by a narrow strait, Obatake Seto, in the southwest, and with Aki Nada by a very narrow strait, Ondo Seto, in the east (to the south of Kure). The tides in this bay are principally governed by tides in the southeastern entrance and are almost simultaneous all over the bay, the currents running into the bay while the level of the bay is rising. Morosima Suidô, a strait to the west of the southeastern entrance of the bay, being very narrow, the currents flow from the higher level to the lower. The currents at Obatake Seto also run from a sea of higher level to a lower and attain a maximum velocity of about 7 knots.

The tidal current at Ondo Seto is peculiar. In an ordinary strait the tidal currents run for about 6 hours in one direction and, during the succeeding 6 hours, in the opposite direction, the maximum velocity being attained about 3 hours after the turn of the current. At Ondo Seto, however, the current gradually increases its velocity after the turn and the maximum velocity is reached about 1.5 hours after the turn; then the velocity gradually decreases (sometimes the current runs in the opposite direction), the minimum being attained about 3.5 hours after the turn; then the velocity increases again and, after attaining a second maximum, the velocity gradually decreases till it reverses its direction about 6 hours after the preceding turn. In this strait, being very short and narrow, the currents flow from the sea of higher to that of lower level, as in Naruto, and a velocity of several knots is caused by a level difference of a few decimetres. The tides in the north of Ondo Seto, Hirosima Wan, are of somewhat different character from that in the south. As explained above, the currents at Obatake Seto and Morosima Suidô run at a velocity proportional to the square root of the level difference and, therefore, the rise and fall of the sea level in the bay is not expressed by the cosine with a half day period if such tide occurs outside, but by the sum of tides to be expressed by the cosine with a half day period and the other tide with a quarter day period (not given by the cosine). It follows that the difference between the heights of sea-levels in the seas north and south of Ondo Seto consists of variations with half day and quarter day periods. A range of quarter-diurnal tide not greater than 10 centimetres is sufficient to give rise to peculiar currents such as are observed at Ondo Seto.