有明海における潮汐特性

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Characteristics of Tides in the Ariake Sea

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Summary

To clarify the characteristics of tides in the Ariake Sea, the tide levels observed at six tidal stations including the observation system installed by Saga University (Observation Tower) were analyzed, and the mean tide levels and harmonic constants were examined.

The following results were obtained.

(1) The monthly mean tide levels showed the maximum values in August and the minimum values in January at all stations. These difference extended about 40 cm. Furthermore, mean tide level became higher as the station moved to the inner area of the bay and the difference of mean tide level between Kuchinotsu and Observation Tower was about 30 cm.

(2) The harmonic constants, amplitude H and phase lag x in four major component tides, M_2, S_2, O_1 and K_1 were obtained by the harmonic analysis of tides using least square method. As the result, M_2 tide and S_2 tide contributed greatly to the change of tide level. In S_2 tide and K_1 tide, the monthly variations of H and x were large, relatively. Particularly, H of M_2 tide and S_2 tide increased remarkably as the station moved from the mouth to the head of bay.

Key words : the Ariake Sea, tide, mean tide level, harmonic analysis

Introduction

The Ariake Sea is an inland sea, which bends roughly at a right angle in the middle part and covers an area of 1,700 km^2. Sea water flows in and out mostly through the Hayasaki Strait. Because of its peculiar land formation, the tidal range is the largest in Japan and it increases as the position moves from the mouth to the head of the bay. At Suminoe located in the head of the bay, the tidal range attains to about 6 m in spring tide.

This is caused by the fact that the period of free vibration of water in the bay is about 12 hours and therefore, when semi-diurnal tide enters into the bay, they resonate each other, in addition to the fact that the tidal range at the mouth of the bay is large already.

The investigations of the tidal phenomena in such a bay is one of the fundamental researches to clarify the mechanism of tidal current, wave, diffusion of river water and distribution of bottom materials.

From such a viewpoint, this paper deals with the positional characteristics of the mean tide levels and tidal harmonic constants at six tidal stations including the observation system installed by Saga University (Observation Tower) in the Ariake Sea.

Tidal stations and location

The long-term data of the tidal level were obtained at six tidal stations and they were analyzed in order to clarify the characteristics of the tide in the Ariake Sea. The locations of these stations are shown in Fig. 1.

(Station)	(Observer)
1. Kuchinotsu	Nagasaki Marine Observatory
2. Misumi	Kumamoto Local Meteorological Observatory
3. Ohura	Saga Local Meteorological Observatory
4. Miike	Mitsui Mining Co., Ltd.
5. Observation Tower	Saga University
6. Suminoe	Kyusyu Regional Construction Bureau, Takeo Work Office

The five stations are located along the coast. But Observation Tower is located on the sea, 130°16′42″ of east longitude, 33°5′52″ of north latitude. The tidal data which were analyzed in this paper were sampled for six years (from 1981) at Kuchinotsu, Misumi, Ohura and Observation Tower, but for one year (1983) at Miike and Suminoe.

Harmonic analysis of tides

Tides are the phenomena in which the tide level rises and falls twice a day, in general. Such a motion of the tide level is closely related to the position of the moon and the sun.

By the equilibrium theory of tides, tides consist of the superposition of many component tides. Therefore, tide level is represented by following simple equation.

$$\bar{\eta}=G_1\sum_i G_2 \cdot C_i \cdot \cos(V_i+u_i), \quad (1)$$

where

$\bar{\eta}$; tide level

G_1 ; constant value all over the earth

G_2 ; coefficient related to latitude

C ; coefficient related to eccentricity of orbit of celestial body

V ; factor varing uniformly with time

u ; factor related to orbit of celestial body

Namely, each component tide level η is given by

$$\eta=G_1 \cdot G_2 \cdot \cos(V+u). \quad (2)$$

and Eq.2 shows that a component tide becomes high tide level at $V+u=0°$ and

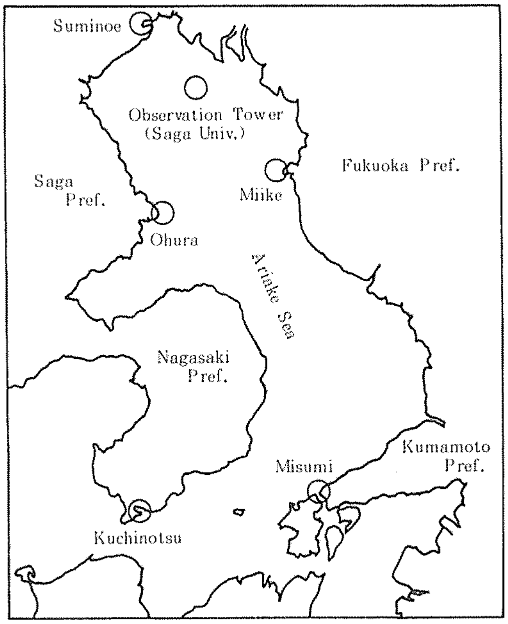

Fig. 1 Location of tidal stations.

low tide level at $V+u=180°$. But in practice, the change of amplitude or the phase lag caused by the bottom friction or the lay of the land occur, and therefore these caluculated values require some adequate corrections or translations.

The practical component tide level is written in the form

$$\eta=R\cdot\cos(V+u-x) \tag{3}$$

or

$$\eta=f\cdot H\cdot\cos(V+u-x), \tag{4}$$

in which

R ; amplitude of component tide
H ; tidal harmonic constant (amplitude)
x ; tidal harmonic constant (phase lag)
f ; ratio of R to H
V ; factor of component tide including the term varing with time and the constant term
u ; factor of component tide varing periodically in the narrow range

Furthermore, the tide level of a certain component tide is expressed by

$$\eta=A\cdot\cos\omega t+B\cdot\sin\omega t \tag{5}$$

$$=\sqrt{A^2+B^2}\cdot\cos(\omega t-\zeta)$$

$$=R\cdot\cos(\omega t-\zeta). \tag{6}$$

where

A, B ; coefficient (amplitude)
t ; time counted from an epock
ω ; angular velocity of component tide
ζ ; phase lag from an epock ($t=0$) to the high tide level of component tide

As Eq.4 and Eq.6 are simultaneous, the following equations are obtained.

$$R=f\cdot H \tag{7}$$

$$V+u-x=\omega t-\zeta \tag{8}$$

Assuming that u is constant in short-term, x is expressed as follows,

$$x=V_0+u+\zeta \tag{9}$$

in which V_0 is V at $t=0$.

Therefore, the level of practical component tide is written in the form

$$\eta=f\cdot H\cdot\cos(V_0+u+\omega t-x). \tag{10}$$

The component tides considered in this paper are four major tides which influence remakably the variations of the tide level. These angular velocities and symbols are shown in Table 1.

Table 1 Four major component tides

component tide	symbol	Angular velocity (°)
principal lunar diurnal tide	O_1	13.943036
solar and lunar composite diurnal tide	K_1	15.041069
principal lunar semi-diurnal tide	M_2	28.984104
principal solar semi-diurnal tide	S_2	30.000000

The harmonic analysis of tides by least square method

Assuming that the tide level at time t is represented by the superposition of n component tides, it is expressed by

$$\bar{\eta}=R_0+R_1\cdot\cos(\omega_1 t-\zeta_1)+R_2\cdot\cos(\omega_2 t-\zeta_2)+\cdots\cdots+R_n\cdot\cos(\omega_n t-\zeta_n). \tag{11}$$

Furthermore, Eq.11 is rewritten as follows

$$\bar{\eta}=a_0\cdot\cos(\omega_0 t)+a_1\cdot\cos(\omega_1 t)+\cdots\cdots+a_n\cdot\cos(\omega_n t)+b_1\cdot\sin(\omega_1 t)+\cdots\cdots+b_n\cdot\sin(\omega_n t). \tag{12}$$

In this case, $\omega_0=0°$.

Coefficients a_r, b_r in Eq.12 are obtained from the simultaneous equations obtained by partially differentiating the following Eq.13 with respect a_r and b_r and then equating the results to zero.

$$S=\sum_{i=1}^{N}\left\{\eta-\sum_{r=0}^{n}(a_r\cdot\cos\omega_r t_i+b_r\cdot\sin\omega_r t_i)\right\}^2 \tag{13}$$

N denotes the number of the data and n the number of component tides.

Showing the simultaneous equations by the form of matrix, Eq.14 is obtained,

$$\begin{pmatrix} CC_{00}, & CC_{01}, & \cdots, & CC_{0n}, & SC_{01}, & \cdots, & SC_{0n} \\ CC_{01}, & CC_{11}, & \cdots, & CC_{1n}, & SC_{11}, & \cdots, & SC_{1n} \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ CC_{n0}, & CC_{n1}, & \cdots, & CC_{nn}, & SC_{n1}, & \cdots, & SC_{nn} \\ CS_{10}, & CS_{11}, & \cdots, & CS_{1n}, & SS_{11}, & \cdots, & SS_{1n} \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ CS_{n0}, & CS_{n1}, & \cdots, & CS_{nn}, & SS_{n1}, & \cdots, & SS_{nn} \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \\ b_1 \\ \vdots \\ b_n \end{pmatrix} = \begin{pmatrix} \bar{\eta}C_0 \\ \bar{\eta}C_1 \\ \vdots \\ \bar{\eta}C_n \\ \bar{\eta}S_1 \\ \vdots \\ \bar{\eta}S_n \end{pmatrix} \tag{14}$$

in which

$$\bar{\eta}C_m=\sum_{i=1}^{N}(\bar{\eta}_i\cdot\cos\omega_m t_i) \qquad (m=0\sim n)$$

$$\bar{\eta}S_m=\sum_{i=1}^{N}(\bar{\eta}_i\cdot\sin\omega_m t_i) \qquad (m=1\sim n)$$

$$CC_{m,\ell}=\sum_{i=1}^{N}(\cos\omega_\ell t_i\cdot\cos\omega_m t_i) \qquad (\ell,\ m=0\sim n)$$

$$SS_{m,\ell}=\sum_{i=1}^{N}(\sin\omega_\ell t_i\cdot\sin\omega_m t_i) \qquad (\ell,\ m=0\sim n)$$

$$SC_{m,\ell}=\sum_{i=1}^{N}(\sin\omega_\ell t_i\cdot\cos\omega_m t_i) \qquad (m=0\sim n),\ (\ell=1\sim n)$$

$$CS_{m,\ell}=\sum_{i=1}^{N}(\cos\omega_\ell t_i\cdot\sin\omega_m t_i) \qquad (\ell=0\sim n),\ (m=1\sim n)$$

Therefore, the amplitude R_m and the phase angle ζ_m of the component tide m are expressed by the following equations using coefficients a_m, b_m.

$$R_m=\sqrt{a_m^2+b_m^2} \tag{15}$$

$$\zeta_m=\tan^{-1}(b_m/a_m) \tag{16}$$

Finally, by using these values and the factor f in Eq.7 and V_0+u in Eq.9 which depend on the observed date or the longitude of station, the harmonic constants of each component tide H_m and $\varkappa_m$ can be obtained.

$$H_m = R_m / f \tag{17}$$

$$\varkappa_m = V_0 + u + \zeta_m \tag{18}$$

Mean tide level

Mean tide level is affected in space and time by atmospheric pressure, lay of the land, wind and density of sea water, etc. And, it is also affected remarkably by river discharge in the area of the mouth of a river.

Mean tide level is represented by the arithmetical mean of the hourly tide level for a day, a month or a year. In this paper, the monthly mean tide levels were calculated at the four stations, Kuchinotsu, Misumi, Ohura and Observation Tower, where the measured tide levels were obtained for six years since 1981. And as the tide levels obtained at each station were expressed in values relative to the respective different datum level, they were transformed into the mean tide level in Tokyo Bay (T. P.). As the results, in all stations, the monthly mean tide level showed the maximum values in August and the minimum values in January. And these differences extended about 40 cm. These yearly variations shown in Fig. 2 corresponded to the yearly variations of atmosperic pressure measured at Saga University in Fig. 3. Futhermore, mean tide level became higher as the station moved to inner area of the bay, and the difference of mean tide levels between Kuchinotsu and Observation Tower was about 30 cm.

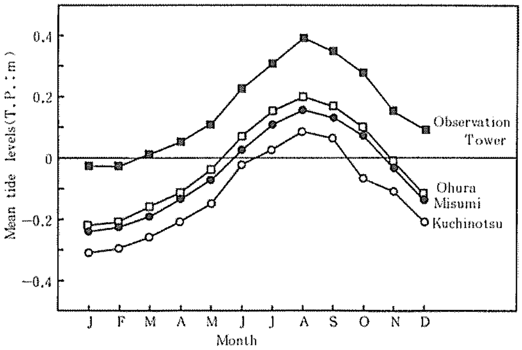

Fig. 2 Monthly variations of mean tide levels at six tidal station (1981-1986).

The characteristics of tides

1. Tide level and tidal range

The variations of the tide levels observed at six stations in the Ariake Sea are shown by the case of March, 1983 in Fig. 4.

In every stations, the diurnal inequality exists and high water and low water occurred twice a day, respectively. Moreover, spring tide and neap tide occurred twice a month reciprocally. Fig. 5 shows the relations of tide levels at same time between Observation Tower and the other stations, Kuchinotsu, Ohura and Suminoe. As the station moved to an inner area, it was recognized that the inclines of the group of dots in Fig. 5

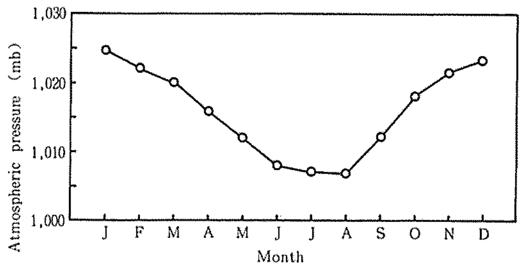

Fig. 3 Monthly mean atmospheric pressure at Saga University (1981-1986).

became steeper and the tidal ranges gradually increased. Then, the yearly statistics of these tidal ranges at all stations in 1983 are summarized in Table 2. In consequence, the ratios of mean tidal range at other stations to the one at Kuchinotsu were 1.21 at Misumi, 1.52 at Miike, 1.53 at Ohura, 1.58 at Tower and 1.64 at Suminoe. Furthermore, the relations of tidal ranges at same tide between Observation Tower and the other stations, Kuchinot-

Table 2 Yearly statistics of tidal ranges (1983)

Station	Maximum (m)	Mean (m)	Minimum (m)
Kuchinotsu	3.83	2.18(1.00)	0.21
Misumi	4.49	2.64(1.21)	0.30
Miike	5.44	3.30(1.52)	0.39
Ohura	5.55	3.34(1.53)	0.37
Observation Tower	5.65	3.45(1.58)	0.41
Suminoe	5.34	3.56(1.64)	0.54

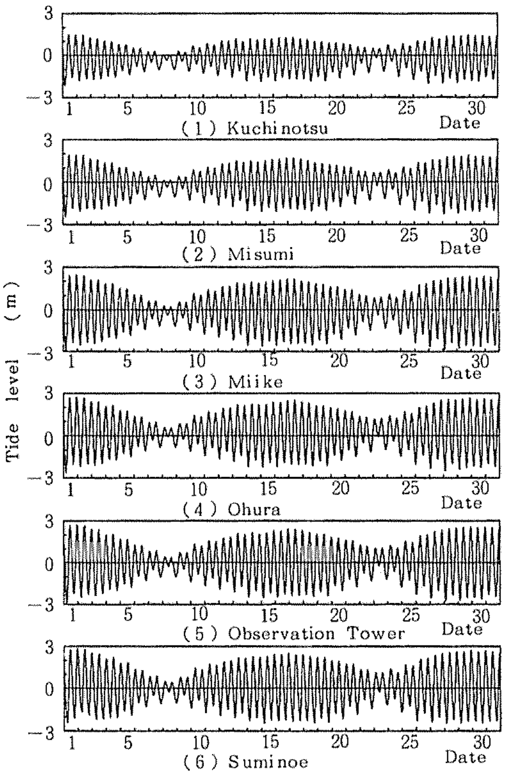

Fig. 4 Variations of tide level at six tidal stations (March, 1983).

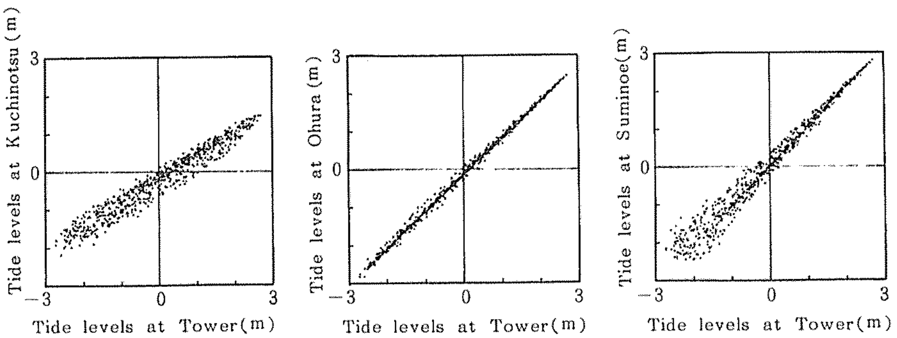

Fig. 5 Relations of tide levels between Observation Tower and other stations, Kuchinotsu, Ohura, Suminoe (March, 1983).

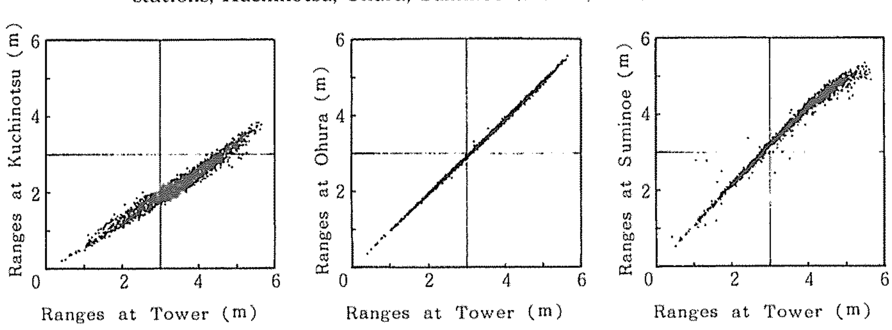

Fig. 6 Relations of tidal ranges between Observation Tower and other stations, Kuchinotsu, Ohura, Suminoe (1983, N=1409).

su, Ohura and Suminoe are shown in Fig. 6. At Ohura which is the nearest to Observation Tower, tidal ranges at both stations were roughly equal and had straight-line relation. But, the relations between Observation Tower and Kuchinotsu or Suminoe were curved to some extent. This is caused by the fact that the water depth decreases as the station moves from the mouth to the head of bay.

2. Harmonic constants of tides

In harmonic analysis of tide, many component tides have been obtained. Among them,

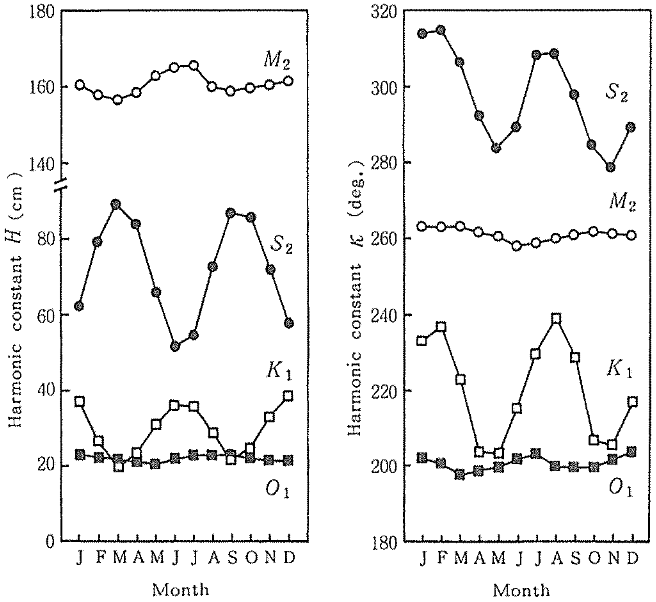

Fig. 7 Monthly mean harmonic constants in four major component tides at Observation Tower (1980-1986, except 1985).

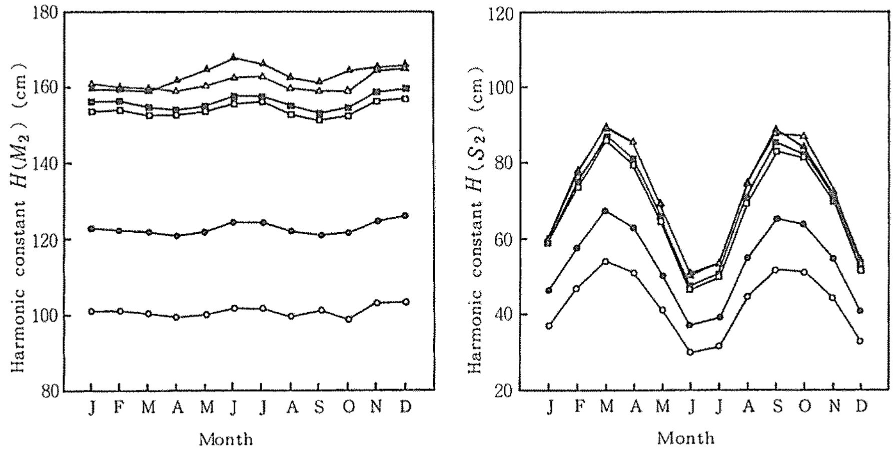

Fig. 8 Variations of harmonic constant H in M_2 and S_2 tides at six tidal stations (1983).
(○ : Kuchinotsu, ● : Misumi, □ : Miike, ■ : Ohura, △ : Tower, ▲ : Suminoe)

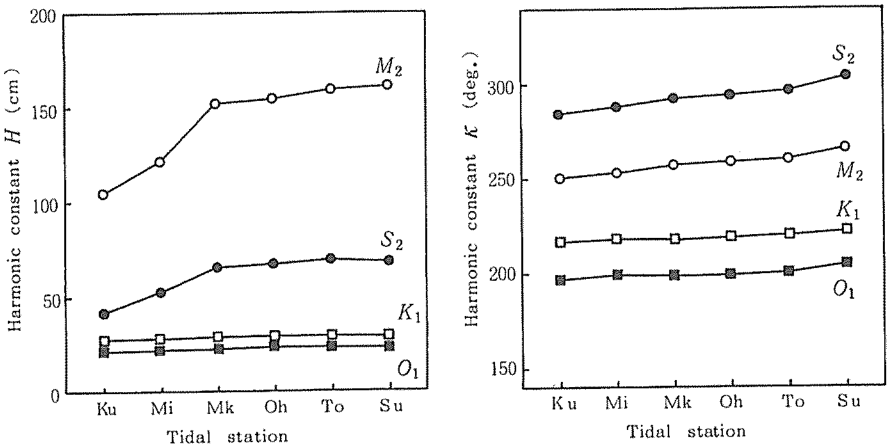

Fig. 9 Variations of harmonic constants H and κ in four component tides at six tidal stations (1983).
(Ku : Kuchinotsu, Mi : Misumi, Mk : Miike,
Oh : Ohura, To : Tower, Su : Suminoe)

the most important tides are four major tides, that is, principal lunar semi-diurnal tide M_2, principal solar semi-diurnal tide S_2, principal lunar diurnal tide O_1 and solar and lunar composite diurnal tide K_1. Therefore, hamonic constants H and κ for four component tides at each station were calculated by least square method.

Fig. 7 showed the monthly variations of mean harmonic constants for six years from 1980 to 1986 except 1985 at Observation Tower. As the result, M_2 tide and S_2 tide contributed greatly to the amplitude H and phase lag κ in the change of tide level. Furthermore, in S_2 tide and K_1 tide, the monthly variations of both of H and κ were large relatively. Namely, these constants showed the maximum values in spring or autumun and the minimum values in summer or winter. On the contrary, in M_2 tide and O_1 tide, these constants H and κ did not vary almost through a year. Moreover, though Fig. 8 showed the yearly variations of the constants H in M_2 tide and S_2 tide calculated by the data of 1983, such an inclination of the variations corresponded to the results of Fig. 7 at all stations.

On the other hand, the harmonic constants H and κ of four component tides obtained for the data of 1983 at six stations are showed in Fig. 9. According to the results, generally, both of κ became larger, as the station moved to the head of the bay. Particularly, the amplitudes H of M_2 tide and S_2 tide increased remarkably from Kuchinotsu to Ohura.

Table 3 Ratios of H of diurnal tides to semi-diurnal tides

Station	$\frac{H(K_1)+H(O_1)}{H(M_2)+H(S_2)}$	$\frac{H(K_1)+H(O_1)}{H(M_2)}$
Kuchinotsu	0.343	0.486
Misumi	0.287	0.410
Ohura	0.237	0.340
Miike	0.235	0.336
Observation Tower	0.230	0.330
Suminoe	0.207	0.296

Types of tide are divided into the three, semi-diurnal, diurnal and mixed type according to the following standards. Equating the ratios of H of diurnal tides to semi-diurnal tides to F or f,

$$F=[H(K_1)+H(O_1)]/[H(M_2)+H(S_2)]$$

$$f=[H(K_1)+H(O_1)]/H(M_2)$$

In France, $F<0.25$: semi-diurnal type, $0.25<F<1.25$: mixed type, $1.25<F$: diurnal type.

In America, $f<0.5$: semi-diurnal type, $0.5<f<2.0$: mixed type, $2.0<f$: diurnal type.

Table. 3 showed the values of F and f caluculated on the basis of these standards at six stations. As the results, it was recognized that both F and f became smaller with the move to the inner area of bay, and that semi-diurnal tides were more excellent.

有明海における潮汐特性

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摘　　要

有明海における潮汐の変動特性を明らかにするため，有明海の湾奥部に設置している佐賀大学の海象観測装置と，口之津，三角，大浦，三池および住ノ江の湾内6か所の験潮所における潮位の観測データより潮汐の調和分解を行った．

長期の潮位データを収集・解析することによって，次のようなことが明らかになった．

1）平均海面：1時間間隔で観測された潮位を1か月ごとに平均して求めた平均海面は，各地点とも8月に最高，1月に最低を示し，その差は約40cmにも及ぶ．これは気圧の年間変動とよく対応している．また，平均海面は湾口から湾奥へと進むにつれて高くなり，ロノ津と観測塔での差は約30cmである。

2）調和常数：潮汐の調和分解によって主要4分潮（M_2，S_2，K_1，O_1）の調和定数（振幅H，遅角κ）を求めた．潮汐変動における振幅に最も大きく寄与するのはS_2潮とM_2潮である．また計算期間を1か月間として，月ごとのこれらの定数の変化をみると，S_2潮とK_1潮はH，κともに変動が大きいが，M_2潮とO_1潮のそれはほぼ一定している。さらに，定数値を地点別にみると，S_2潮とM_2潮についてはH，κともに湾奥の方が大きくなる．