Mar. Res. Indonesia Vol.26, 1987: 13-28

THE SEMIDIURNAL M_2 TIDE IN THE SOUTHEAST ASIAN WATERS

by

KASTORO [1)]

ABSTRACT

The semidiurnal tides of the Pacific and Indian Oceans penetrate deeply into the Southeast Asian waters. The tides of the Pacific Ocean govern the whole of the China Sea, the Philippines waters and the Sulawesi Sea while the tides of the Indian Ocean govern the Timor Sea, the Banda Sea, the Andaman Sea and the Malacca Strait. The Maluku Sea, the Makassar Strait and the Java Sea are the boundary region between tides from the Indian and Pacific Oceans. In the Java Sea the semidiurnal tide is produced mainly by the tide from the Indian Ocean. At the boundary region, the amplitudes are generally very small. As an example of a boundary region, the tides of the Sunda Strait are considered in some detail. An analytical solution of two overlapping standing waves, one wave resulting from open mouth reflection of a wave incident from the Indian Ocean and the other standing wave from open mouth reflection of a wave incident from the Java Sea, adequately describe the M_2 tide in the Sunda Strait.

ABSTRAK

Pasang-surut harian ganda (M_2) berasal dari Samudera Pasifik dan Samudera Hindia menembus jauh ke dalam perairan Asia Tenggara. Pasang-surut Samudera Pasifik mempengaruhi seluruh Laut Cina, Perairan Filipina dan Laut Sulawesi sedangkan pasang-surut Samudera Hindia mempengaruhi Laut Timor, Laut Banda, Laut Andaman dan Selat Malaka. Laut Maluku, Selat Makasar dan Laut Jawa merupakan daerah batas antara pasang-surut dari Samudera Hindia dan Samudera Pasifik. Pasang-surut harian ganda di Laut Jawa terutama dihasilkan oleh pasang-surut Samudera Hindia. Amplitudo di daerah batas tersebut umumnya sangat kecil. Sebagai contoh dari sebuah daerah batas, pasang-surut Selat Sunda ditinjau agak rind. Suatu pemecahan analitis dari dua gelom-bang tegak, gelombang yang satu berupa gelombang refleksi pada ujung mulut selat sebagai akibat dari gelombang yang berasal dari Samudera Hindia dan yang lain adalah gelombang refleksi dari ujung mulut selat yang lain sebagai akibat dari gelombang yang berasal dari Laut Jawa, cukup menjelaskan sifat-sifat pasang surut M_2 di Selat Sunda**.**

INTRODUCTION

Tides within the Southeast Asian Waters result from tidal cooscillation of the Pacific and Indian Oceans. These tides are of special interest because the numerous large and small islands divide the region into different seas which are connected with each other by many passages and channels. Several deep basins are also found in this region, each with its own dimensions and hence its own natural period. Therefore, it could be expected that the tides in this region to be quite variable.

---

1) Centre for Oceanological Research and Development - LIPI, Jakarta.

DOI: 10.14203/mri.v26i0.405

It was concluded from the general topography described by WYRTKI (1961) that there are three entrances which are particularly important for the development of the tide in this region :

- The Bashi Channel, a wide strait between Formosa and Luzon, acting as an entrance from the Pacific Ocean into the China Sea.
- The area between Mindanao and Halmahera, which is an entrance from the Pacific Ocean into the Sulawesi and Maluku Seas.
- The strait between Timor and Aru Islands, connecting the Timor and Arafura Seas with the Banda Sea. The other entrances between the group Nusa Tenggara Islands in the south and through the Strait of Malacca seem to be only of minor importance.

In the present study broad scale details of the M_2 tide in the Southeast Asian waters is described. The M_2 tide in the Sunda Strait is then analysed in some detail.

MATERIALS AND METHODS

The area studied is that part of the Southeast Asian waters which lies between latitudes 24°00' S and 24°00' N and longitudes 90°00' E and 127°°' E (Fig. 1). Data consisting of tidal constants taken from the British Admiralty Tide Tables (HYDRO-GRAPHIC DEPARTMENT 1975, 1977) and relating to this region have been used to produce charts of amplitudes and co-tidal lines of the semidiurnal M_2 tide with a period of 12.42 hours. Isolines of phase were contoured mostly at 30 degrees intervals and isolines of amplitude at 0.1 m intervals.

RESULTS AND DISCUSSION

1. *The semidiurnal M_2 tide*

Figures 2 and 3 give distributions of amplitude and cotidal lines of the semidiurnal M_2 tide. On both sides of Formosa the wave is strongly refracted in the shallow water, so that it enters the Formosa Strait simultaneously from the south and north. Consequently high amplitudes (1 m) are found in the centre of shallow strait. The wave with a phase of about 160° enters the Luzon Strait and advances into the China Sea relatively slowly; here it has a small amplitude between 0.2 and 0.1 m. When this wave reaches the Sunda Shelf its phase has increased to 360°, that is, it takes about six hours to pass through the China Sea. A part of this wave enters the Gulf of Tonking and increases in phase from 30° to 360° around the coast of Hainan Island to form an amphidromic region with a clockwise circulation. The highest amplitude is about 0.3 m. Along the coast of China, between Hongkong and Hainan Strait the M_2 tidal amplitude increases towards the coast as an effect of the shelf. In this region the tidal wave is met by the other ones, almost under the same phase and causes a considerable increase of its amplitudes.

THE SEMIDIURNAL TIDE

When the tidal wave reaches the Sunda Shelf, its phase speed decreases. This is particularly noticeable off the coast of Vietnam. Off the coast of Vietnam and Kalimantan the v/ave is refracted and high amplitudes develop. The amplitude reaches 0.8 m on the coast of Vietnam and 1.2 m on the coast of Kalimantan. South from here the wave splits off into two branches, one moves northwards into the Gulf of Thailand and the other moves southwards and enters the Malacca Strait (Riau Archipelago). In the Gulf of Thailand the wave forms an amphidromic region, with an anticlockwise rotation having amplitudes less than 0.2 m. Its centres is at 9°18'N, 103°28'E. The other wave moving southwards in the South China Sea turns anticlockwise around an amphidromic point at 0°43'S, 103°28'E. The cotidal lines are all concentrated west of the amphidrome. The phase of the wave entering the Strait of Malacca from the south is from 330° to 30°. It produces a strong tide with amplitudes greater than 0.8 m. Southwest of Bangka the amplitudes are small, about 0.2 m. Here it joins with the wave coming from the Java Sea and the amplitudes decrease. Within the entrance of Malacca Strait the amplitudes increase; this seems to be partly an influence of tidal wave entering through Malacca Strait from the Indian Ocean.

In the region between Kalimantan and Sumatra the influence of the tidal wave coming from the Pacific Ocean practically ends. In the Java Sea, before meeting the wave from the South China Sea, it also forms an amphidromic region with the anticlockwise circulation. Its centre is in 5°53'S, 110°25'E. Low amplitudes, around 0.1 m, are observed on the north coast of Java and the west coast of Makassar. These low amplitudes are probably caused by superposition of two waves which are out of phase.

South of Mindano another branch of tidal wave coming from the Pacific Ocean enters the Sulawesi Sea with a phase of 160°. In the northern entrance of Makassar Strait part of this wave joins with the wave coming from the Indian Ocean. The resulting has a phase of 180° and an amplitude of 0,6 a. The other part of the wave enters the Sulawesi Sea then moves towards the north and enters the Sulu Sea. The phase is nearly the same as that in the Philippines Waters indicative of a standing wave with an average amplitude of about 0.4 m. A wave from China Sea also enters the Sulu Sea passing the north and south of Pahlawan islands. Its amplitude is small, 0.2 m, and therefore does not have a strong influence on the tides in the Sulu Sea. The direct effect of the tidal wave from the the Philippines Waters on the Sulu Sea seems to be shielded by small shallow strait between Luzon and Mindanao. In this strait the tidal phase changes rapidly. Consequently the tidal currents are relatively strong.

The tidal wave of the Indian Ocean enters a region between Jawa and Australia with a phase of 180° at around Christmas Island. It moves towards the east and reaches the Timor Sea with a phase of 300°. In the Timor Sea high water occurs simultaneously, the amplitudes from the north to the south region vary from 0.6 to 2.8 m. The high amplitudes are found along the north coast of Australia. This indicates that a characteristic of standing wave is well developed in this region. The tidal wave from this region moves towards the Banda Sea. It then meets the tidal wave from the Pacific Ocean in the Maluku Sea. The resulting wave has a phase of 120°. Low tidal amplitudes,

Mar. Res. Indonesia Vol.26, 1987: 13-28

0.2 to 0.4 m, are found axound the northern part of the east coast of Sulawesi extending to the east.

The tidal wave of the Indian Ocean entering the Andaman Sea produces large amplitudes in the whole region with a phase of 270° except near the southern coast towards the mouth of Saluen River where the phases increase rapidly. This wave causes a large tide along the coast of Burma. Around the mouth of Saluen River the amplitude reaches 1.70 m. Part of the tidal wave from the Andaman Sea enters the Malacca Strait, where it advances slowly. The contraction of the strait causes the amplitude to rise from 0.6 m at the entrance to more than 1.2 m in the narrow strait. The amplitude then decreases again to 0.8 m at other end of the strait. The tidal wave phase changes rapidly. At the western entrance it is 300° and at the eastern entrance it is also 300° near the South China Sea. Thus, it takes 12 hours to pass through Malacca Strait.

The Nusa Tenggara Islands are reached by semidiurnal tidal wave of Indian Ocean with a phase of 300°, and an amplitude between 0.3 and 0.6 m. A part of this wave passes the various straits between the islands; another enters the Banda Sea through the Timor Sea. In the whole Banda Sea high water occurs with a phase of 30°; the amplitude is about 0.5 m. Between the islands in the Flores Sea the wave moves slowly northwards, one part is deflected to the west and enters the Java Sea. A smaller part moves further into the Macassar Strait, where it meets the wave of the Pacific Ocean with a phase of 160°. The wave entering Java Sea is weak. Here the wave forms an amphidromic circulation as discussed above.

The physical oceanography of the Southeast Asian Waters has been studied by WYRTKI (1961). His studies included a discussion of the semidiurnal M_2 and $M_2 + S_2$ tides. DEFANT (1961) in his studies of tide of the East Indian Archipelago, also discussed a chart of co-tidal lines of the M_2 tide prepared by DIETRICH (1944). The present chart of the M_2 amplitudes is similar to the values given by WYRTKI. However, the chart of the M_2 tidal phase (Fig. 3) differs slightly from that given by him. WYRTKI'S chart shows an amphidromic region with a clockwise rotation in the Gulf of Thailand, whereas the present study shows an anticlockwise rotation for this amphidromic region. The occurrence of the amphidromic region in the north of Bangka island is in good agreement with WYRTKI'S and DEFANT'S charts. The present amphidrome in the Java Sea agrees with DEFANT. However, here WYRTKI'S chart does not show an amphidrome. This difference is probably a consequence of the recent increase in the number of obsevations.

2. *Tidal elevation in Sunda Strait*

Sunda Strait is a good example for further study of the characteristic of semidiurnal M_2 tide for it connects the Indian Ocean and the South China Sea (Fig. 4). For this purpose the shape of the Sunda Strait is simplified as shown in Fig. 5. *O* is an origin point at one end of the strait and distance *x* increases towards the Java Sea. Now the wave advancing from the Java Sea and reflected at the opening to the Indian Ocean at $x = O$ can be represented by

$$n_1 = A \sin (wt + \theta + kx) + RA \sin (wt + \theta - kx)$$

THE SEMIDIURNAL TIDE

While the wave advancing from the Indian Ocean and reflected at $x = L$ is given by

$$n_2 = B \sin (wt - \emptyset + \theta - k (x - L)) + RB \sin (wt - \emptyset + \theta + k (x - L))$$

The elevation, n, arising from the superposition of these waves are

$$n = n_1 + n_2 = A \sin (wt + \theta + kx) + RA \sin (wt + \theta - kx) + B \sin (wt - \emptyset + \theta - k (x - L)) + RB \sin (wt - \emptyset + \theta + k (x - L)) \quad (1)$$

Where A and B are amplitudes of the wave advancing from the Java Sea at $x = 0$ and from the Indian Ocean at $x = L$ respectively, with phase $-\theta$ and $\emptyset - \theta$, k is the wave number, R is the reflection coefficient which can take values from -1 to 1 ($R = 1$ for solid wall reflection, $R = -1$ for open mouth reflection, and $R = 0$ for no reflection), w is the angular frequency. Such methods have been used by HEATH (1974, 1978).

Some measure of the actual bathymetry and the shape of the Sunda Strait can be accounted for by considering the constraint imposed by the conservation of energy. For a wave of elevation n and group velocity $(gh)^{1/2}$ travelling in a channel of width b and the depth of h, conservation of energy flux imposes the condition

$$n^2 (gh)^{1/2}\, b = \text{constant}$$

or $n \alpha b^{-1/2} h^{-1/4}$ (*see* e.g., LAMB 1932)

A plot of $b^{-1/2} h^{-1/4}$ for the Sunda Strait is shown in Fig. 6 together with the observed amplitude and phase. The observed M_2 amplitude decreases towards the northeast (increasing x) through the strait. For $R = 1$, solid wall reflection, however, the amplitude would increase with x. Further the observed M_2 amplitude differs from $n \alpha b^{-1/2} h^{-1/4}$, indicating that the reflection condition $R = 0$ is not applicable.

For $R = -1$, equation (1) becomes

$$n = 2A \cos (wt + \theta) \sin kx - 2B \cos (wt + \theta - \emptyset) \sin k (x - L)$$

At $x = 0$ (Tanjung Layar), where

$$n = 2B \cos (wt + \theta - \emptyset) \sin kL$$

the elevation amplitude is set equal to the observed value (Stn 2, Fig. 4) of 0.40 m, i.e.,

$$2B \sin kL = 0.40 \quad (2)$$

Similarly, at $x = L$ (Merak),

$$n = 2A \cos(wt + \theta) \sin kL$$

the elevation amplitude is set equal to 0.16 m (Stn 5), i.e.,

$$2A \sin kL = 0.16 \qquad (3)$$

At $x = 0, L$, we set the model phases $\phi - \theta, -\theta$ equal to those observed $\phi - \theta = 200$ $(x = 0)$, $-\theta = 205^{\circ}$ $(x = L)$.

The phase difference between the two waves advancing from the Java Sea (at $x = 0$ and Indian Ocean (at $x = L$) is $\phi = -5^{\circ}$. To determine A, B we need to compute kl where

L = distance between Stn 2 and Stn 5
= 68 nautical miles = 125 km

For the computation of k, wave number, we use the relation

$$k = \frac{W}{(gh)^{1/2}} \quad \text{where} \quad w = \frac{2\pi}{T}$$

where

T is the M_2 tidal period (12.42 hours), g the gravitational acceleration = 9.8 m s^{-2}, $(\bar{h})^{1/2}$ = average $(h)^{1/2}$ of depth (h) of the Sunda Strait, 14.15, i.e.,

$$w = \frac{2\pi}{12.42 \times 60 \times 60} = 1.4 \times 10^{-4}\ s^{-1}$$

$$k = \frac{w}{(gh)^{1/2}} = 2.95 \times 10^{-6}\ m^{-1}$$

Therefore $kL = 2.95 \times 10^{-6}\ m^{-1} \times 125 \times 103\ m = 21^{\circ}\,15'$

From equations (2) and (3)

$$B = \frac{0.40}{2 \sin kL} = 0.55 m$$

$$A = \frac{0.16}{2 \sin kL} = 0.22\ m$$

THE SEMIDIURNAL TIDE

Superposition of waves given by equation (1) can be expressed by

$n = F \cos(wt - a)$ where

$F = (p^2 + q^2)^{1/2}$ is the amplitude and

$a = \tan^{-1} \frac{q}{p}$ is the phase

$$q = 2A \sin\theta \sin kx + 2B \sin k(x - L) \sin(\theta - \phi)$$

$$p = 2A \cos\theta \sin kx - 2B \sin k(x - L) \cos(\theta - \phi)$$

From the above results : $A = 0.22$ m

$B = 0.55$ m

$\theta - \phi = -200^\circ$

$\theta = -205^\circ$

$kL = 21^\circ 16'$

Therefore we have

$$p = 0.56 \sin kx - 0.37 \cos kx$$

$$q = 0.16 \sin kx - 0.15 \cos kx$$

and the amplitude is

$$F = (0.18 \sin^2 kx - 0.23 \sin 2(kL) + 0.16)^{1/2}$$

while the phase is

$$a = \tan^{-1} \left(\frac{0.16 \sin kx - 0.14 \cos kx}{0.56 \sin kx - 0.37 \cos kx} \right)$$

The elevation amplitude and phase plotted against distance (x), with intervals of 10 miles, are shown in Figure 7.

The following tables show the analytical values of the amplitudes and phases and the observed values at the various distances and stations.

If the analytical results are compared with the observed values, they generally show a good agreement (Figs. 6 and 7, and Table 2). Slight differences appear at Stn 3. Here both the differences may, however, be caused by the errors made in the geometrical measurements of the Sunda Strait chart.

It is concluded that the model with reflection coefficient, $R = -1$ (an open mouth reflection) fits the observed values reasonably well.

Other reflection condition (R = I, solid wall reflection and $R = 0$, no reflection) give amplitude distributions which differ from the observed ones.

Table 1 : Analytical values of the amplitudes and phases at various distances.

Distance, x (miles)	Amplitude, F (metres)	Phase, a (degrees)
0	0.40	200
10	0.36	201
20	0.33	201
30	0.30	202
40	0.26	203
50	0.22	203
60	0.20	205
70	0.17	207

Table 2 : The observed and the analytical values at each station

	OBSERVED VALUES		**ANALYTICAL VALUES**	
Station Number	Amplitude (metres)	Phase (degrees)	Amplitude (metres)	Phase (degrees)
2	0.40	200	0.40	200
3	0.35	207	0.26	203
4	0.24	202	0.20	204
5	0.16	205	0.18	204

THE SEMIDIURNAL TIDE

ACKNOWLEDGMENTS

The author would like to thank Dr. R. A. Heath of the New Zealand Oceanographic Institute, for his comments, and also to Prof. F.F. Evison, Chairman of the Institute of Geophysics of the Victoria University of Wellington, for his advice.

REFERENCES

DEFANT, A 1961. *"Physical Oceanography,* Volume 2". Pergamon Press, Oxford. 598 pp, 4 charts.

DIETRICH, G. 1944. Die Schwingungssysteme der holb - und entagigen Tiden in den Ozeanen. *Veroff. Inst. Meeresk. Berlin N.F.R.A., Heft 41.*

HEATH, R.A 1974. The lunar semidiurnal tide in Cook Strait, New Zealand. *Dt. hydrogr. Z. 27, 5/6 :* 214 - 224.

HEATH, RA 1978. Semidiurnal tides in Cook Strait. *N.Z. J. mar. Freshwat. Res. 12 (2)* : 87 - 97.

HYDROGRAPHIC DEPARTMENT, 1977. *"The Admiralty Tide Tables,* Volume 3 - Pacific Ocean and Adjacent Seas". London.

HYDROGRAPHIC DEPARTMENT, 1975. *"The Admiralty Tide Tables,* Volume 2 - Atlantic and Indian Oceans". London.

LAMB, H. 1932. *"Hydrodynamics"*. 6th Edition. Cambridge University Press. 738 pp.

WYRTKI, K 1961. Physical Oceanography of the Southeast Asian Waters. *Naga Report 2, Scripps Institution of Oceanography,* California : 1 - 163, 44 pis.

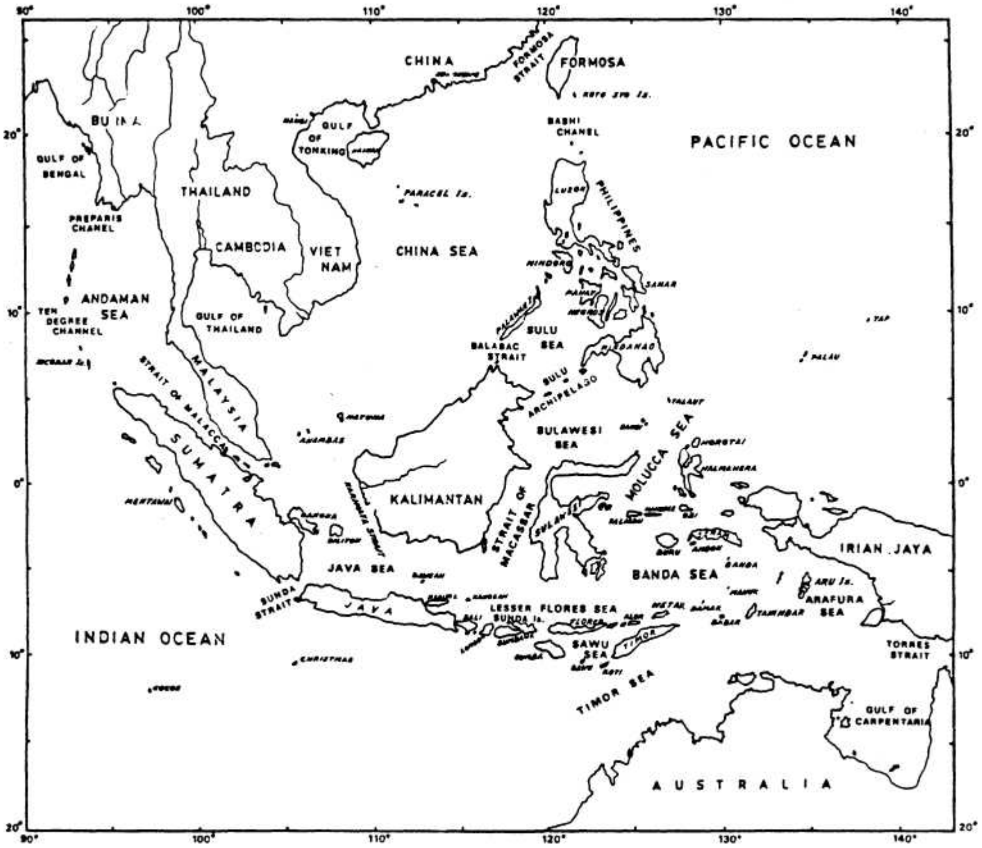

Figure 1. Map of the Southeast Asian Waters

THE SEMIDIURNAL TIDE

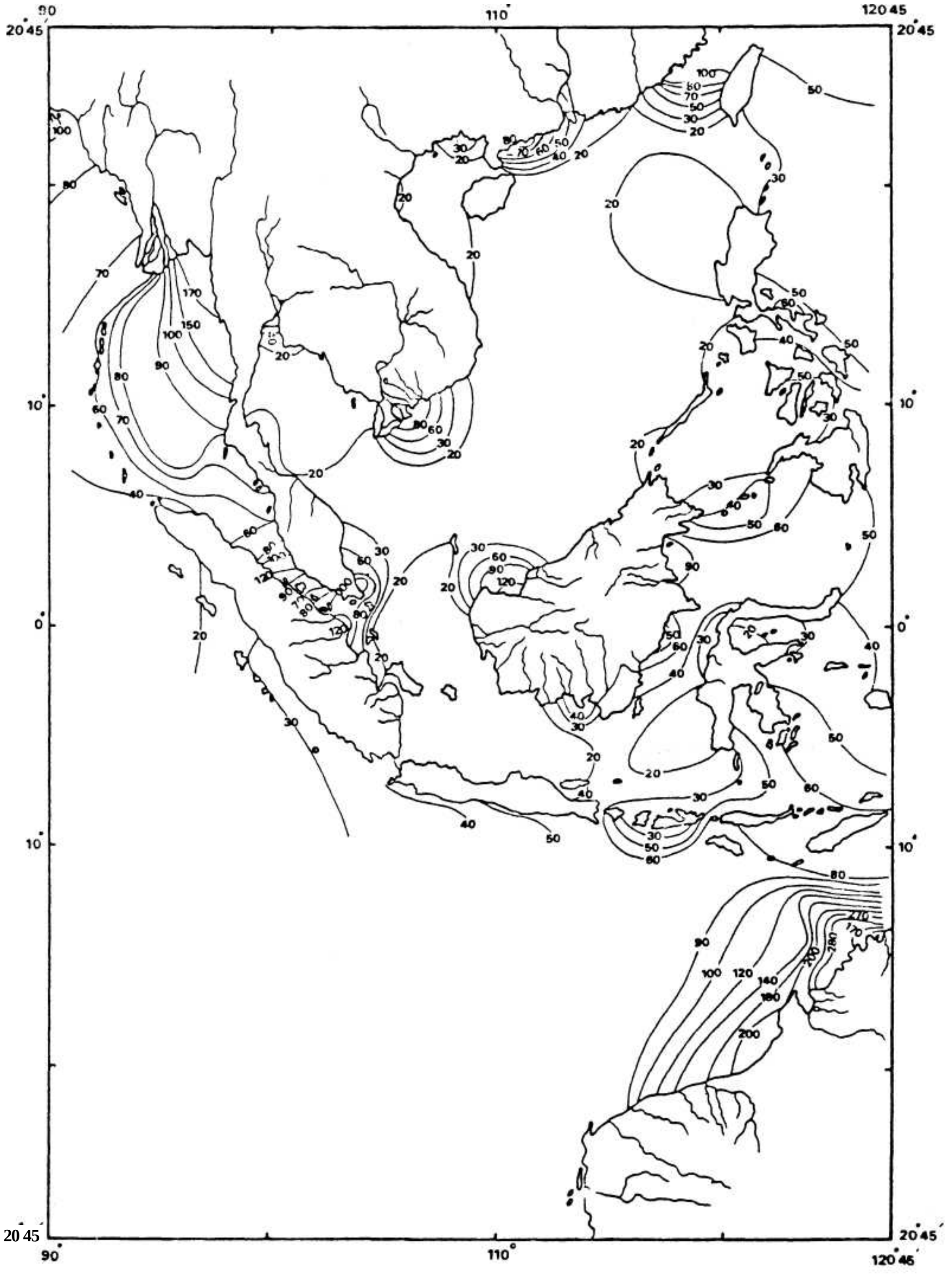

Figure 2. Amplitude (cm) of the semidiurnal M_2 tide.

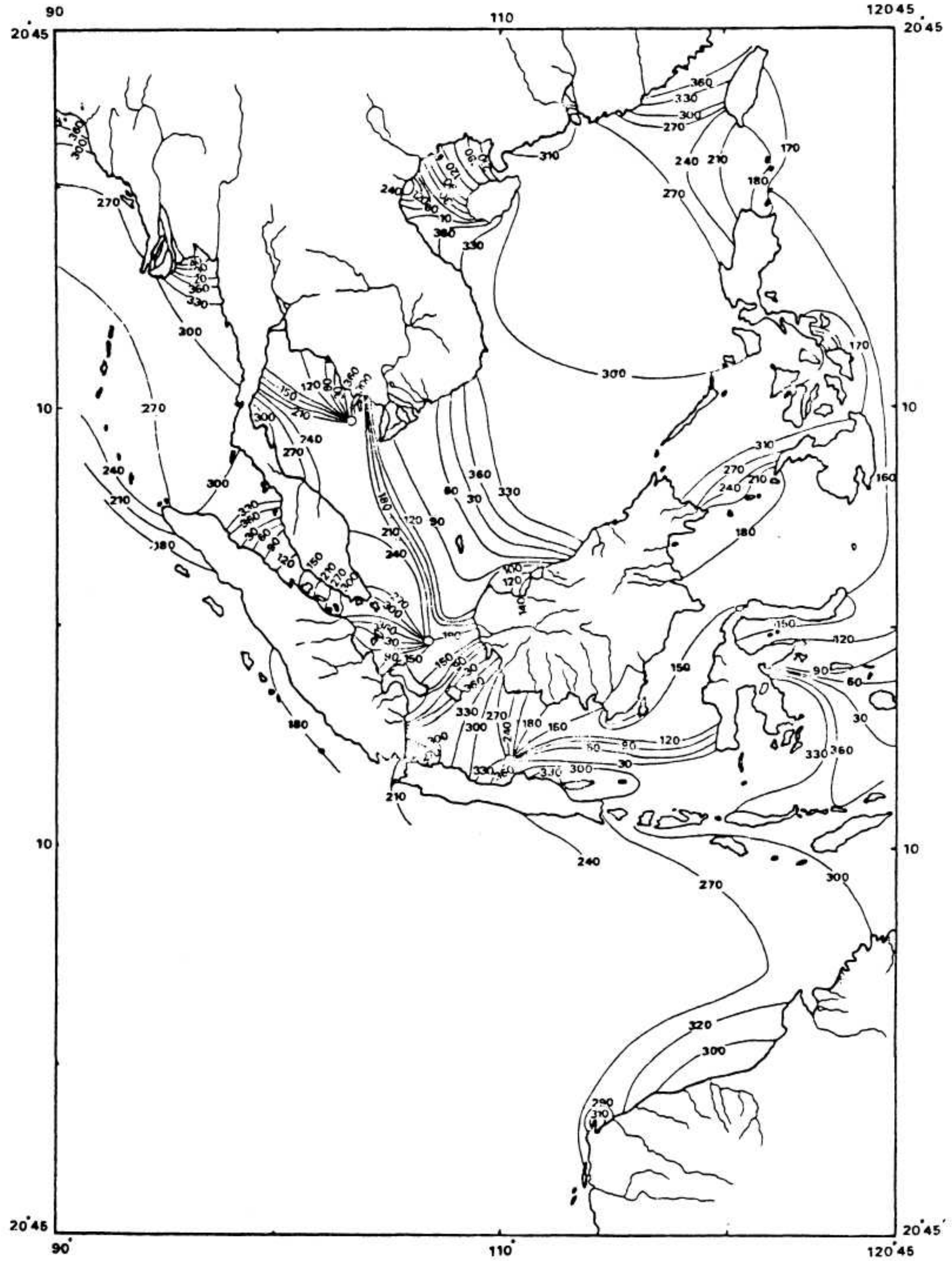

Figure 3. Co-tidal lines of the semidiurnal M_2 tide in degrees

THE SEMIDIURNAL TIDE

Figure 4. Chart of Sunda Strait and positions of Station

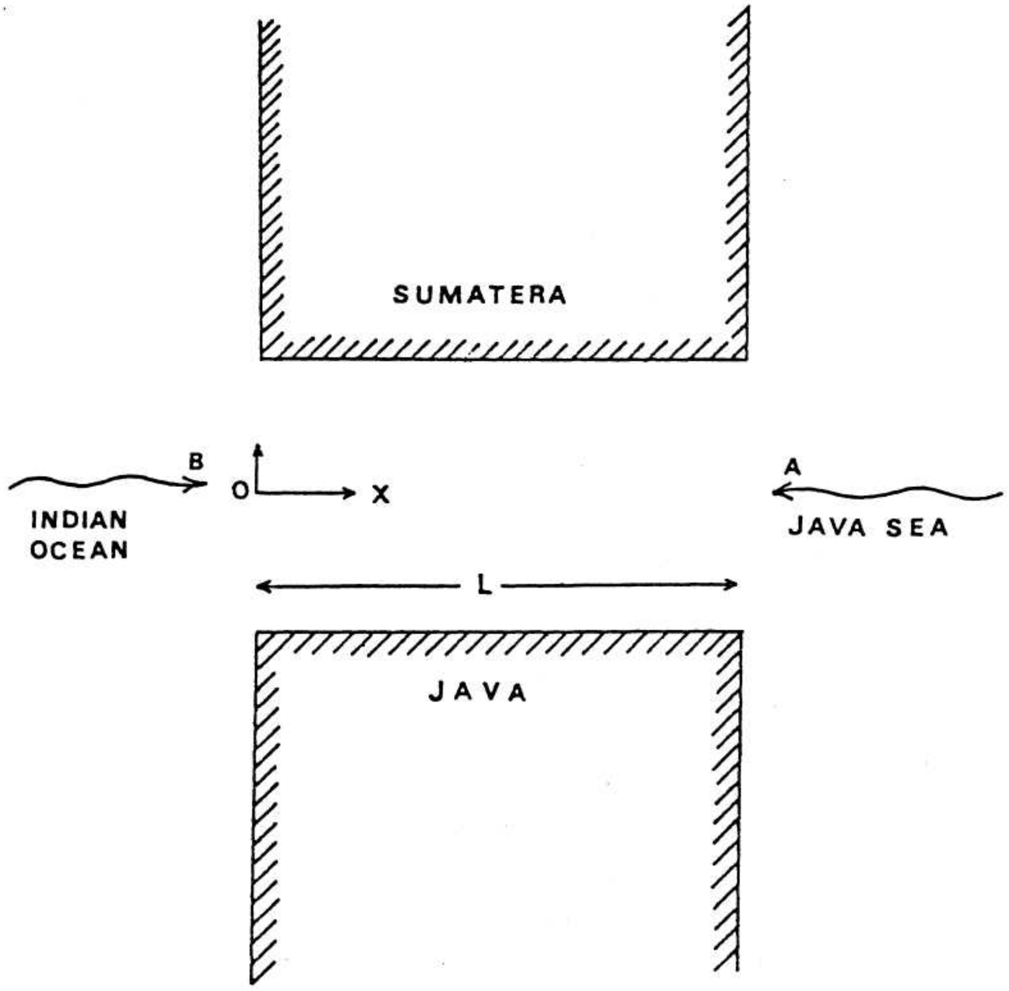

Figure 5. Simplification of the Sunda Strait in the form of the rectangular canal with constant depth.

THE SEMIDIURNAL TIDE

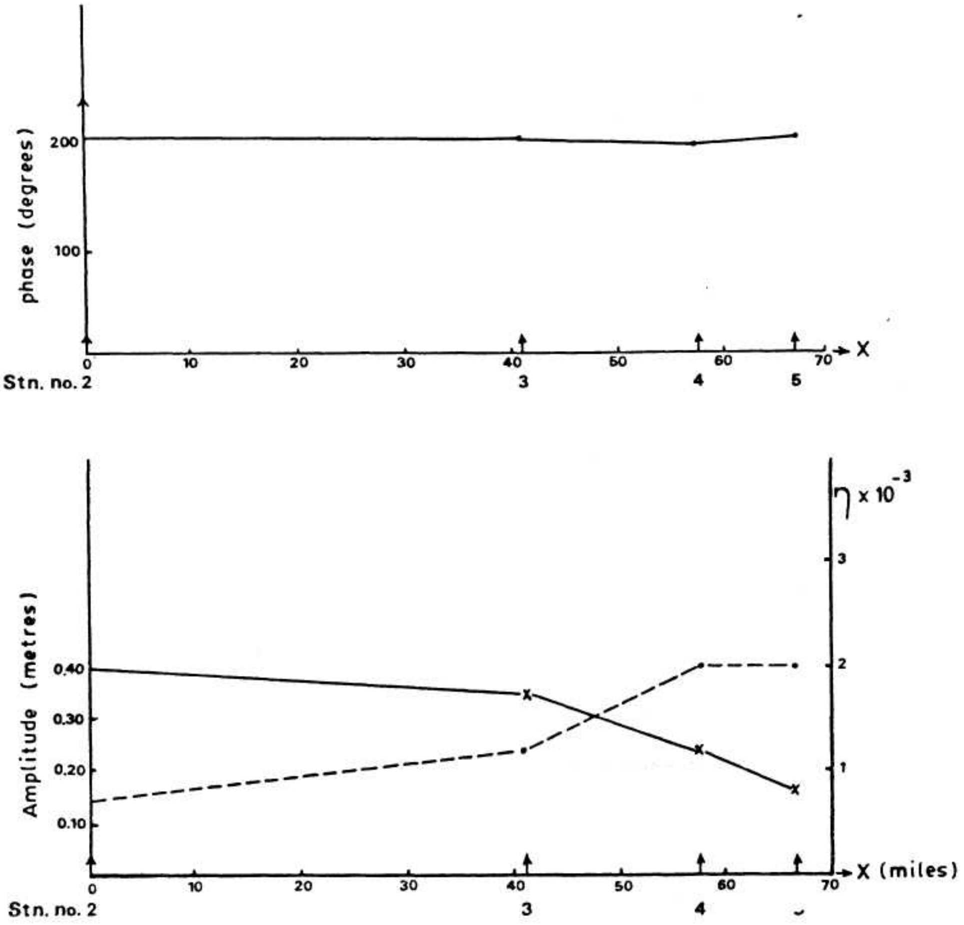

Figure 6.

—•— Plot of the observed phase against distance, x

×—×—× Plot of the observed amplitude against distance, x

-----•----- Plot of $\eta \propto b^{-\frac{1}{2}} h^{-\frac{1}{4}}$ against distance, x

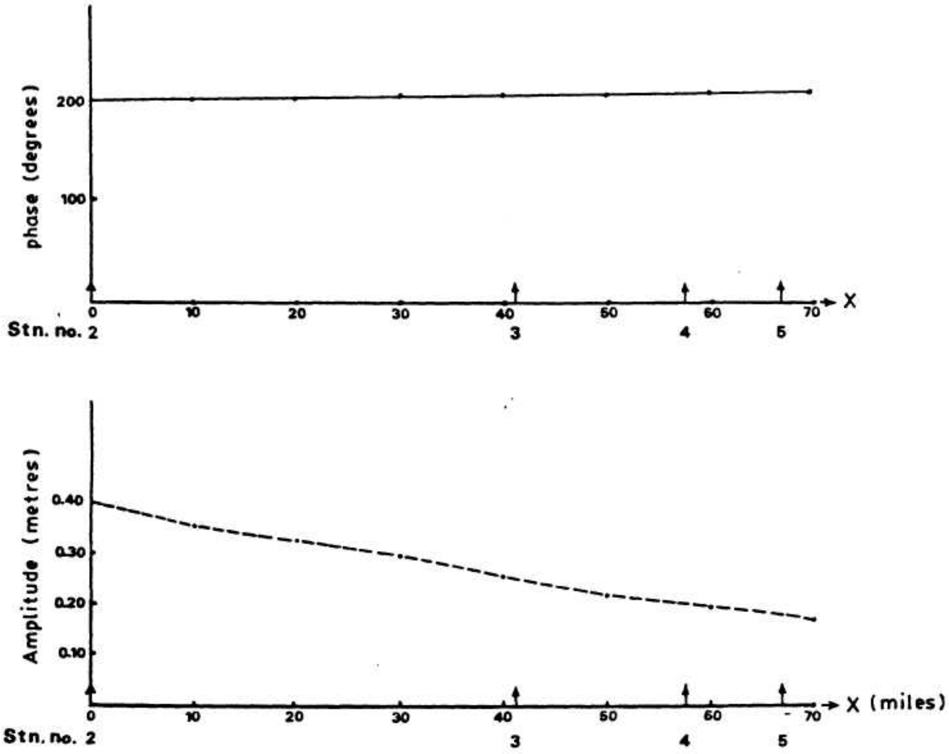

Figure 7. ——— : Plot of the analytical values of the phase against distance, x

-•-•- : Plot of the analytical values of the amplitude against distance, x