TIDES

Lectures by G.J. Schiereck

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P4S/BTA-60
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CONTENTS

1. INTRODUCTION.

The aim of this course is to give insight into the tidal movement on earth, in Indonesia and in the P4S areas. To do so we start in chapter 2 with the origin of the tidal movement. Next, in chapter 3, we will see how tidal waves behave when they travel in seas and rivers. With this knowledge we will explain some tidal phenomena in Indonesia (chapter 4). A few other factors influencing the waterlevels will be discussed in chapter 5. Chapter 6 finally discusses measuring and computation of tidal waves, in relation to design aspects.

Four annexes are added. One with useful definitions of things that are often confused. One with available books on the subject in the BTA-60 library. A small vocabulary English-Indonesian is added for the most important words. Finally a copy from an Indonesian book on physics is added to remind you of things you learnt in the past.

Where necessary some formulas are used. They are very simple and the majority you know already from elementary physics.

Beside the text a lot of figures are included in these notes. They contain maybe even more information than the written text. When re-reading these notes after the course, please, study the figures very carefully.

2. ORIGIN AND COMPONENTS OF THE TIDAL MOVEMENT.

2.1 General.

All bodies in the space we live in (sun, planets, moons etc.) attract each other. The greater the mass of the bodies, the greater the attraction force and the greater the distance, the smaller the force. This principle was first suggested by Newton (1642-1727). These forces are also responsible for the tidal movement on earth.
Not only the water is affected by these forces, also the atmosphere and the earth's shell are influenced. Fig. 2.1 for example shows the fluctuation in air pressure in Jakarta due to the moon's attraction.

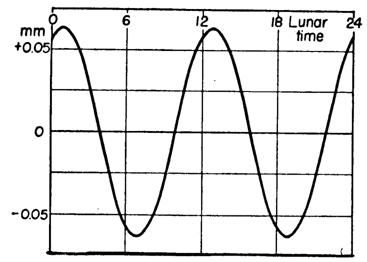


FIG. 2.1 Semidiurnal air pressure wave in Batavia (computed from observations over 40 years).

The planets rotate around the sun and the moons rotate around the planets. Because of this rotation the attraction forces are counterbalanced by centrifugal forces. These two forces make that the whole system is in a <u>dynamic</u> equilibrium. The movements that are made by the celestial bodies are sometimes very complex. This complexity is found back in the tidal movement on earth, giving the so-called tidal components.
In fig. 2.2 the system sun - earth is given as an example. Note that both bodies move around a common point of gravity.

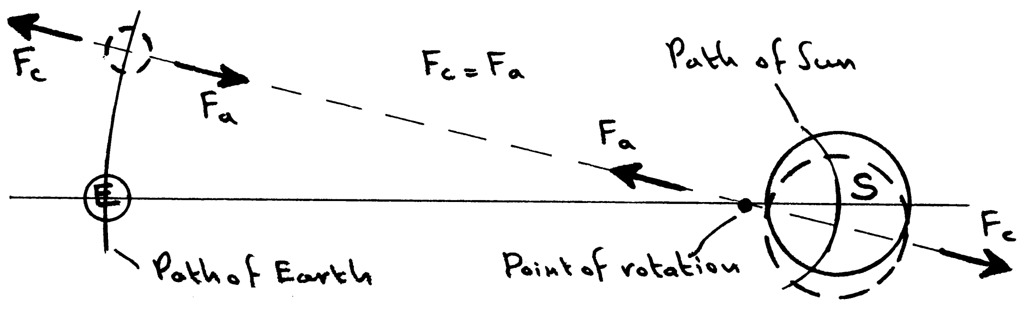


Fig. 2.2 Dynamic equilibrium between Sun and Earth
F_c = Centrifugal Force F_a = Centripetal Force = = Attraction Force.

Of all celestial bodies only the sun and the moon influence the tidal movement on earth. The sun has the greatest mass, but the distance to the moon is much smaller and so the influence of the moon is about twice as big as the influence of the sun. We start our thinking about tides however with the sun because this is somewhat simpler.

2.2 Principal tides.

To do so, we start with an earth completely covered with water. The two forces F_a and F_c , give the watersurface a shape like a mangga. See fig. 2.3.
The earth rotates around its own axis in 24 hours, so an observer in point A will notice twice a day high water and twice a day low water. So, the period of this tide is half a day and is therefore named a semi-diurnal (half daily) tide. This tidal component, the most simple of them all, is called: S2 (S for Sun, 2 for semi-diurnal).

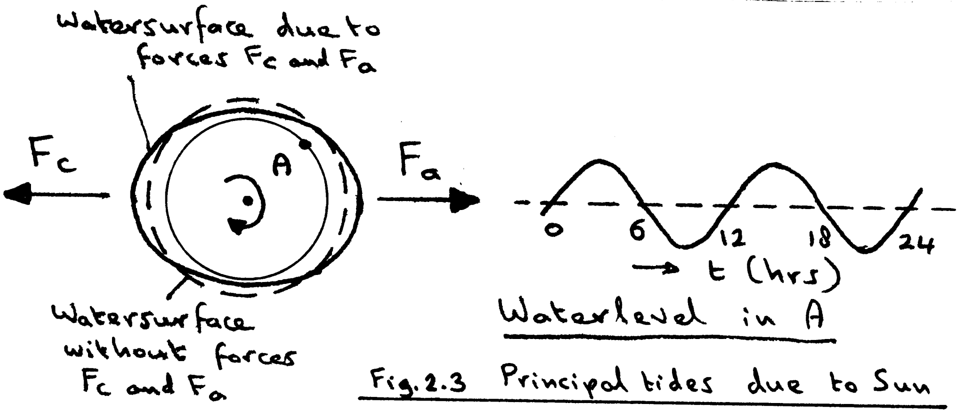


Fig. 2.3 Principal tides due to Sun

The influence of the moon is the same, but has a different period (fig. 2.4). While the earth rotates around its axis, the moon also moves: after one day about 13° (360° in 27.32 days). So, to reach the same position with regard to the 'moon-mangga', a point on earth has to turn about 13° more, which takes about 50 min.

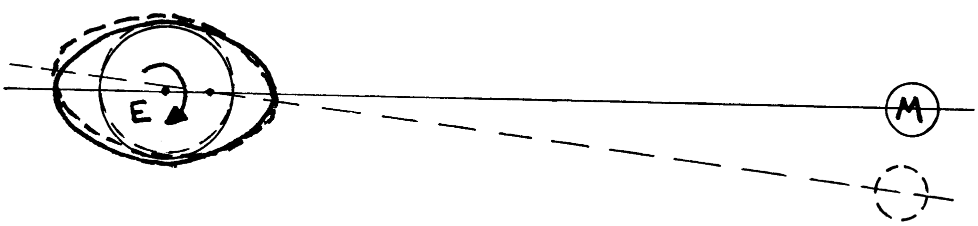


Fig. 2.4 Watersurface due to Moon

During this period of 24 hours 50 min. again twice high and low water occur. This gives us our second component, a semi-diurnal lunar component: M2, period 12 hr. 25 min.

M2 and S2 are named principal tides , because they represent the direct influence of attraction of the celestial bodies. All other components are in fact corrections on the principal tides. They come from the fact that the movement of sun, earth and moon are more complex than assumed when deriving S2 and M2.

M2 and S2 differ slightly in period. From elementary physics it is known that two waves (more in general: vibrations) with a small difference in frequency give so-called beats.

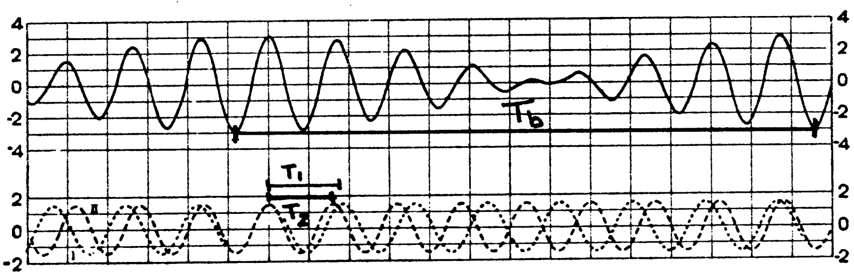


Fig. 2.5 Beats

This is the phenomena that the intensity of a wave changes slowly from strong to weak. In fig. 2.5 can be seen that the two waves have the same phase at a certain moment and are out of phase some time later. Sometimes these beats can be heard when two musical instruments produce the same tone, but not exactly equal. The period of a beat (defined from strong to strong or from weak to weak) is given by:

$$Tb = \frac{T1.T2}{|T1-T2|} \qquad (2.1)$$

Applying this for M2 and S2 we find that these components will have a beat with a period:

$$Tb = \frac{12 \times 12.42}{0.42} = 355 \text{ hr.} = 14.8 \text{ days}$$

This means that during these 14.8 days the tides will be strong and weak. This is what we call springtide and neaptide.

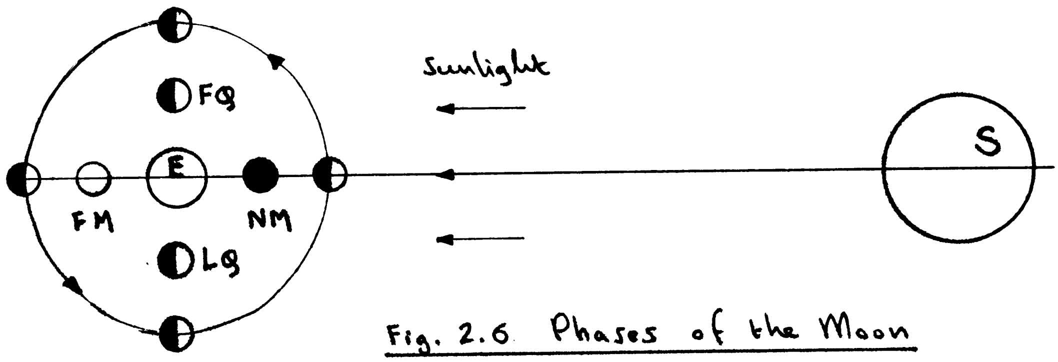


Fig. 2.6 Phases of the Moon

The cycle of spring and neap can also be explained directly from the movements of moon and sun. In fig. 2.6 the moon's path and the moon's phases, as they are seen on earth, are given (New Moon, First Quarter, Full Moon, Last Quarter). When the moon is in the line Earth-Sun (FM and NM), the two components work together. During FQ en LQ they work against each other (fig. 2.7).

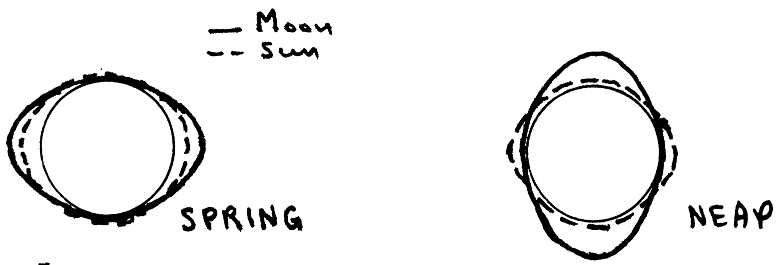


Fig. 2.7

The period can be found in the same way we found it for M2. The moon rotates around the earth in 27.32 days. During this revolution the earth moves around the sun about 27^{o}. Thus it takes the system about 29.5 days to complete a period from full moon to full moon.

(This is also the Islamic month, twelve of these months give a year which is 11 days shorter than a Christian year. Hence, Lebaran comes earlier in the season every year). During this period, spring and neap occur twice, so again we find: Tb = 14.8 days.

2.3 Declination tides.

Up to now we assumed the moon and the sun were situated in the plane of the earth's equator. But in fact they move in a plane that makes an angle with the equator, named declination (fig. 2.8a, b). This means that in a point the two daily high waters will have different heights (fig. 2.8b, c). When we analyse fig. 2.8c we see that it contains a semi-diurnal component and a diurnal one. These two each consist of several other components, which are not easy to understand physically. They follow from a mathematical analysis of the tidal forces; they are, as said before, corrections on the principal tides. We will make an attempt however to obtain some insight, using the already mentioned phenomenon of beats.

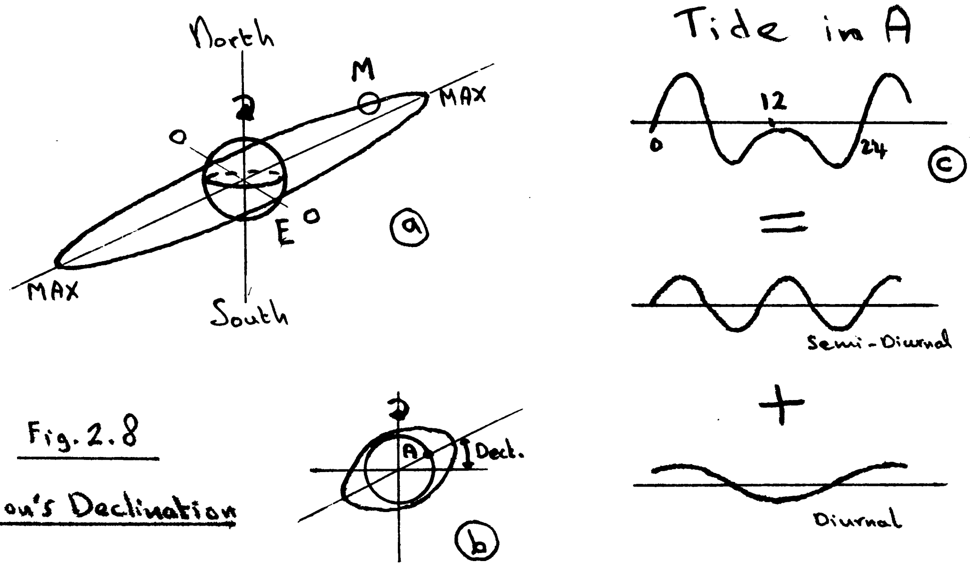
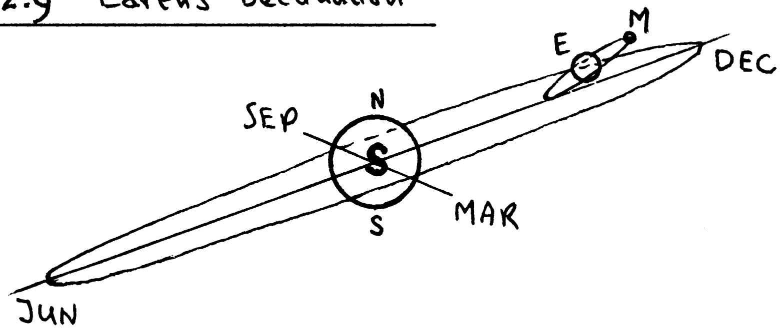


Fig. 2.8
Moon's Declination

The moon rotates in 27.32 days around the earth. During this period the declination is twice maximal and twice zero (fig. 2.8a). So, we can expect twice neap and twice spring due to declination. This means that the period of the beat is 13.66 days. This beat can be analysed in two diurnal components with periods of 23.935 and 25.820 hr. (Check for yourself with formula 2.1). The name of these components are K1 and O1 . Note that spring for these tides does not occur during FM and NM, but during maximum North and South declination.

The sun follows the same pattern. Now twice a year the declination is maximal and zero (fig. 2.9). This beat can be divided in two components with periods of 23.935 and 24.066 hr. (check again). These are named K1 and P1 respectively. We see that K1 is both of lunar and solar origin.

Fig. 2.9 Earth's Declination



Also the semi-diurnal components are influenced by the declination. For example: in June and December the declination of the sun is maximal. That means that the principal tide S2 is "disturbed" most. In March and September the sun has no declination, hence S2 is "undisturbed". So, S2 and another component have a beat with a period of a half year, which leads to K2, with a period of 11.97 hr. (K2 is, like K1, also from lunar origin, giving with M2 a beat of again 13.66 days).

2.4 Elliptic tides.

The orbits of the earth and moon are no circles but ellipses. For instance on fig. 2.10, the orbit of the moon is given. The earth is located in one of the focusses of the ellipse. This makes that once during a revolution the distance moon - earth is maximal (called apogee) and once minimal (called perigee). At perigee the moon forces are strongest, at apogee weakest. This gives, together with M2, a component N2 with a period of 12.66 hr, resulting in a beat with a period of 27.6 days.

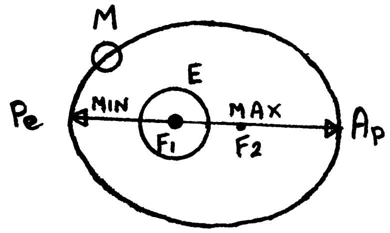


Fig. 2.10 Distance Moon-Earth

2.5 Shallow water tides.

When a tidal wave enters shallow waters, the shape will be changed. Components appear with periods 2,3,4.... times smaller than the astronomic components.

In chapter 3.5 this will be discussed further. Here we only mention two of these components: M4, period 6.2 hr and MS4, period 6.1 hr.

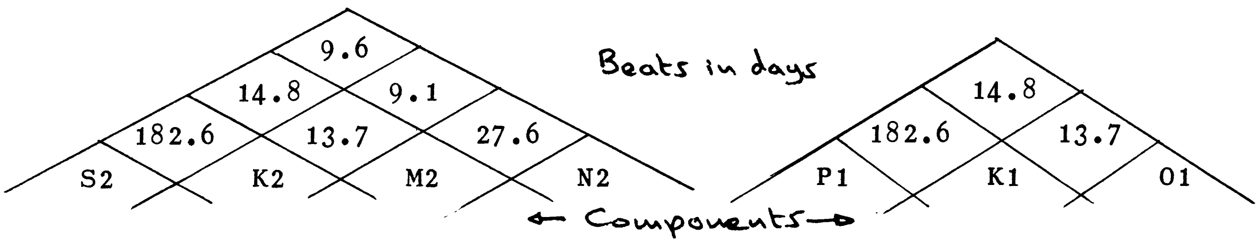
2.6 Final remarks on tidal components.

In the beginning we assumed the earth being covered completely with water. This is, as you probably know, not true. So in fact the whole situation is even more complicated. The tidal waves will propagate through the oceans and reflect against the continents, giving complex patterns. In fact, without these reflections, tides on earth would be very small. In chapter 3.7 - 3.10 we will discuss this matter more in detail. But, despite these complications, it is always possible to recognize the above-mentioned components in the waterlevel fluctuation on any place of the earth. Only the strength of the different components can vary very much from place to place, due to the above-mentioned behaviour of tidal waves.

The division of the waterlevel fluctuation in components is called harmonic analysis. Once the components for a place are analyzed, it is possible to make a prediction for the waterlevel at that place at any moment in the future (provided the situation does not change). This is what is done by Hidral who edits yearly tidetables (Daftar Pasang Surut) with hourly waterlevels for 60 stations in Indonesia. Recently the program Rampas (Ramalan Pasang Surut) became available for P4S/BTA-60, which also predicts waterlevels from known components. The components used by Hidral and in Rampas are the ones we discussed above:

Principal tides	:	M2, S2
Declination tides	:	K2, K1, O1, P1
Elliptic tides	:	N2
Shallow water tides	:	M4, MS4

In the next table the beats betweeen the various components are given.



There are of course, many more components. In fact the number is endless, because there are always corrections possible on the harmonic analysis. In Europe sometimes more than 100 components are used in tidal predictions. But the nine given here are normally enough to give a reasonable description for engineering purposes. (Except in very shallow water or when river discharges play an important role).

2.7 Character of tides.

There are places on earth with only semi-diurnal, only diurnal tides or a mixture of both. To classify the character of the tides the so-called f-number is introduced. f is given by the ratio between the amplitudes of K1 + O1 and M2 + S2 (being the four most important ones):

$$f = \frac{K1 + O1}{M2 + S2}$$

It will be clear that when f is great the character will be diurnal and when f is small it will be semi-diurnal.

The following (arbitrary) division can be made:

$f < 0.25$	semi-diurnal
$0.25 < f < 1.5$	mixed, mainly semi-diurnal
$1.5 < f < 3.0$	mixed, mainly diurnal
$3.0 < f$	diurnal

In fig. 2.11 the tidal registration for one month is given for 4 places, each one representative for one of the given groups. Also indicated are the phases of the moon, the declination and the distance moon - earth. Check fig. 2.11 for yourself with the foregoing.

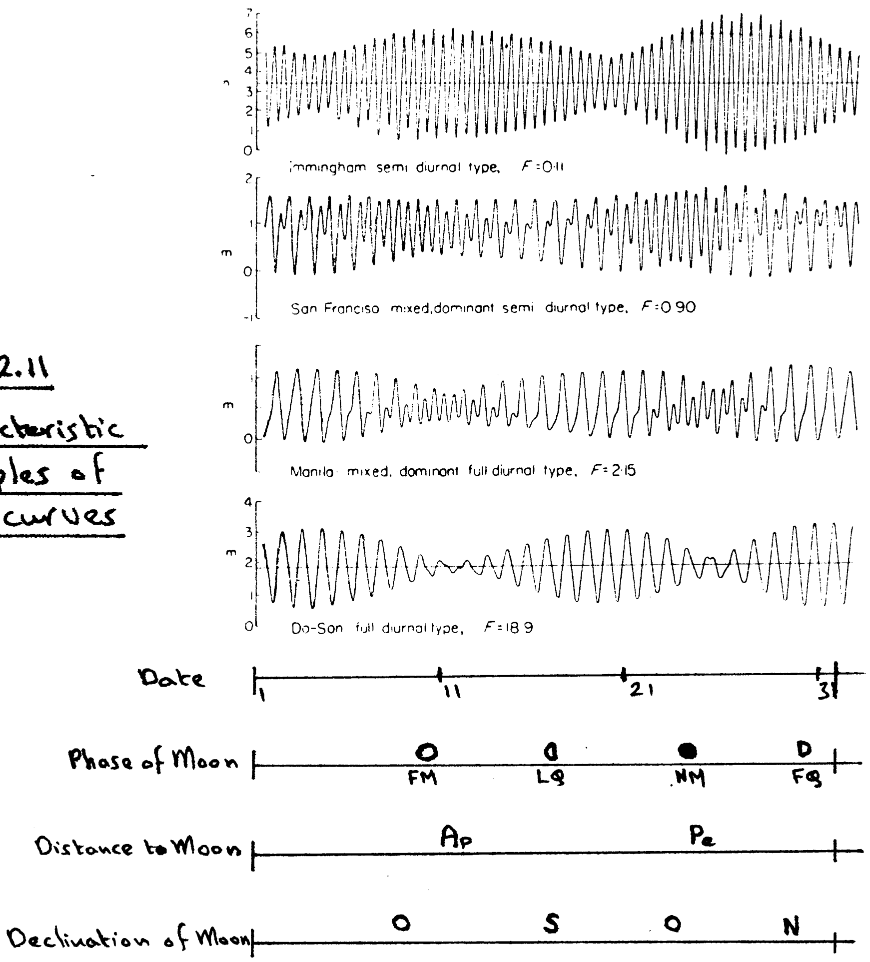
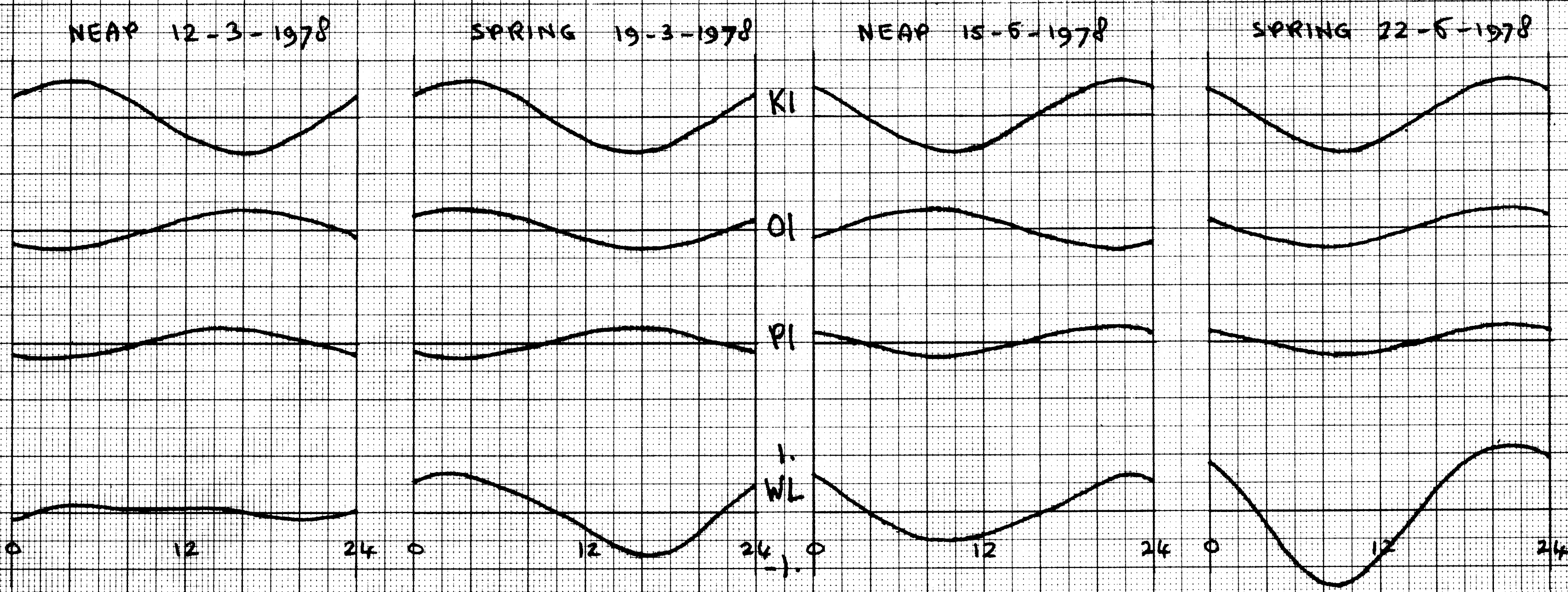


Fig. 2.11
Characteristic examples of tidal curves

Note that the springs and neaps come a few days later than follows from the theory. This is because of the inertia of the water masses on earth and is called the age of the tide.

In Indonesia all kinds of tides are present.
To illustrate once more the theory, in fig. 2.12a-d, waterlevels (computed with Rampas) are given for 4 places in different seasons, illustrating the half yearly variations. For a better understanding also the most important components are given. Check again for yourself.



Waterlevel prediction for Tanjung Pandan (Billiton) (f = 7.6)

Astronomical Data for: March

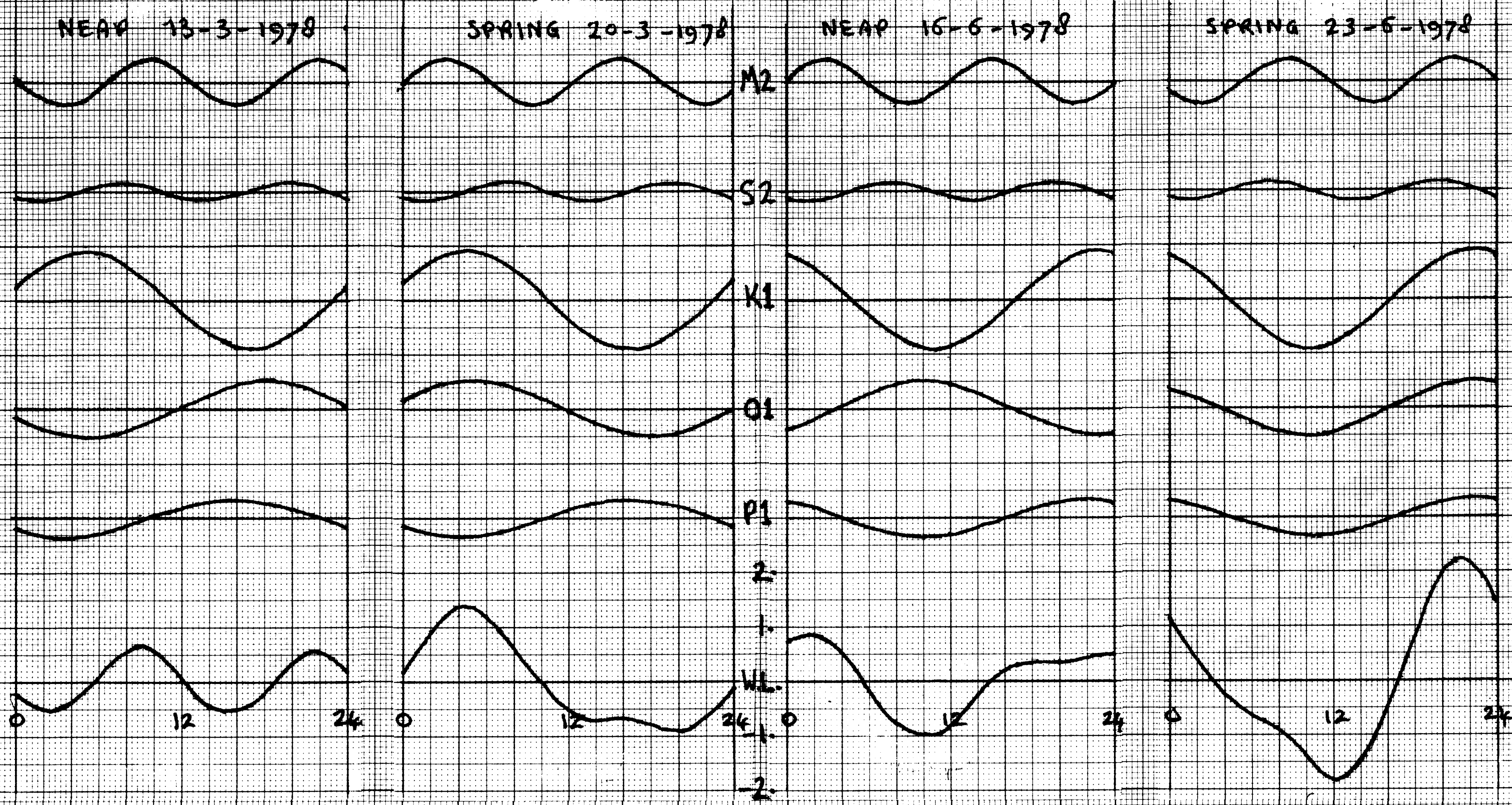
Date	1	11	21	31
Phase of Moon	LQ	NM	FQ	FM
Distance to Moon	Pe		Ap	Pe
Declination of Moon	S	O	N	O

June

Date	1	11	21	31
Phase of Moon	NM	FQ	FM	LQ
Distance to Moon	Ap		Pe	
Declination of Moon	N	O	S	O

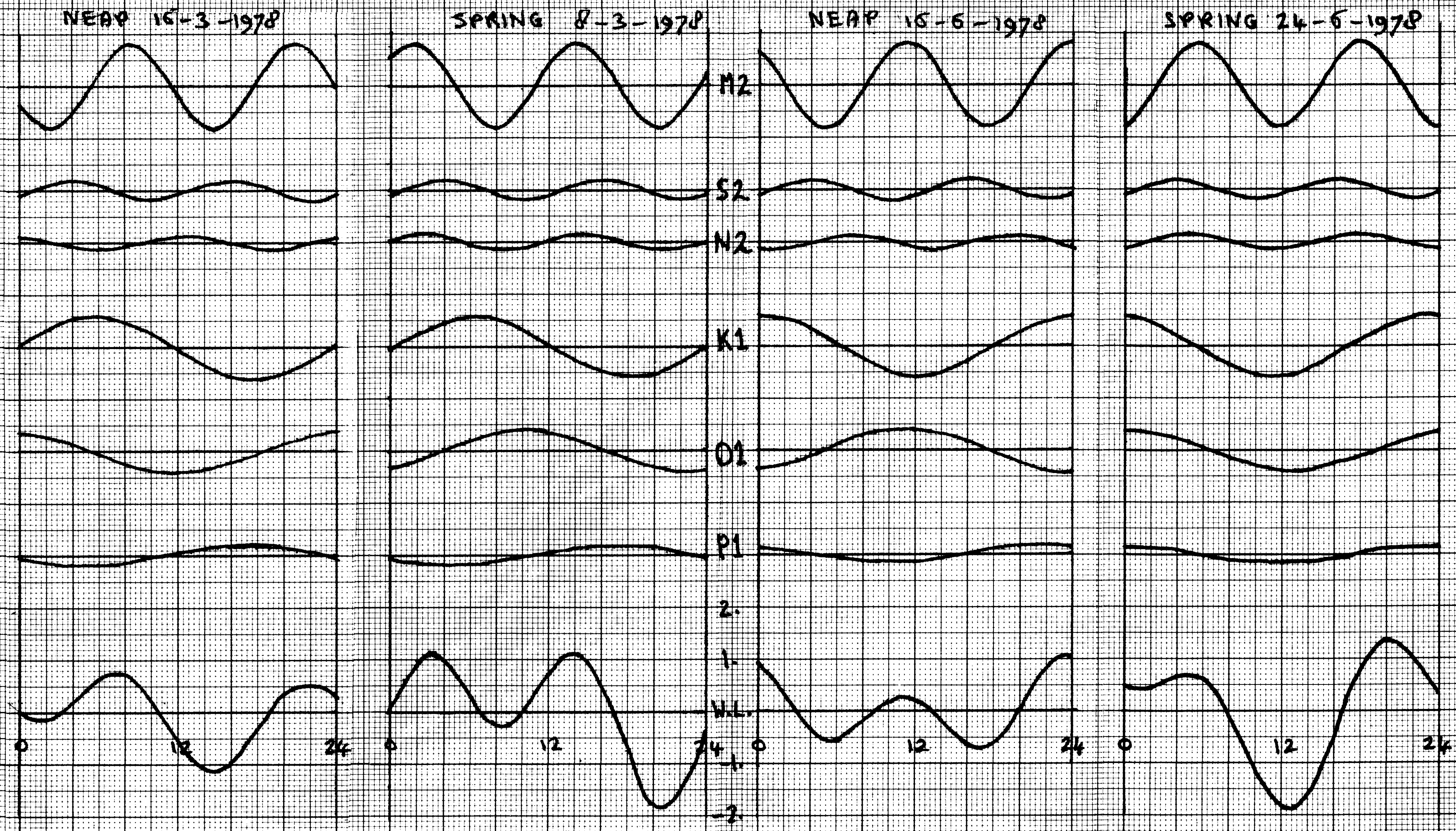
Note: Components smaller than .1 m are not drawn

Fig. 12a



Waterlevel prediction for Muara Banyuasin (f = 2.9)

Fig. 12b



Waterlevel prediction for Muara Batang Hari (f = 1.2)

Fig. 12c

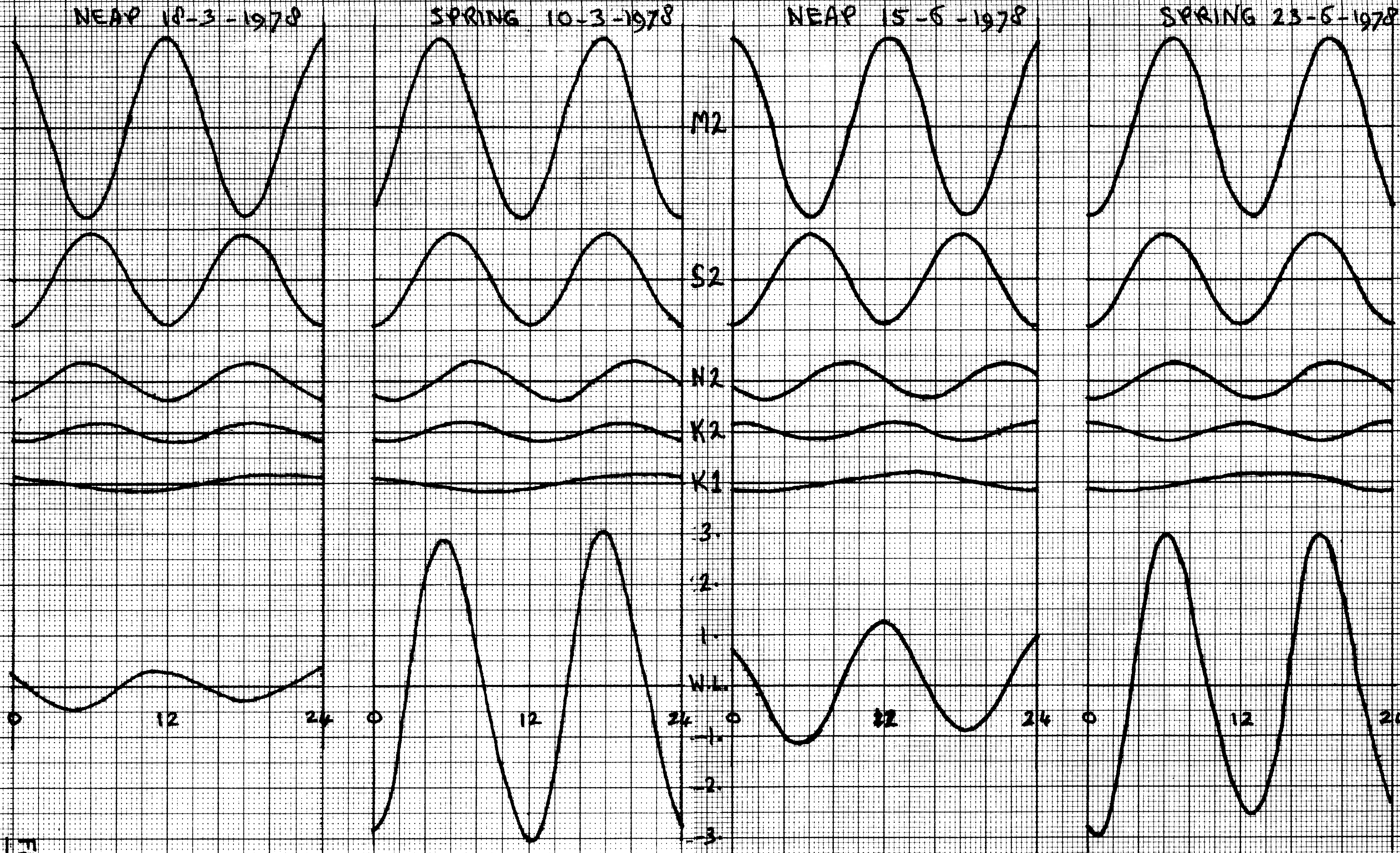


Fig. 12d

Waterlevel prediction for Bagan Siapi-api (F = 0.08)

3. BEHAVIOUR OF TIDAL WAVES.

3.1 General.

The force-components discussed in chapter 2 cause tidal waves primarily only in the oceans. Most seas and lakes are too small to have independent tides. In the oceans the waves reflect against the land-masses, penetrate the smaller seas and from there into the rivers and bays. Along this way many things happen with the various waves. They get smaller (damping) because of friction, become higher due to reflection, resonance or shoaling and their shape changes due to friction, shallowness and currents. In the following we will take a look at these phenomena. It is difficult to find good examples in nature which illustrate only one aspect, because these phenomena always occur in combinations of two or more.

3.2 Progressive waves.

First we consider the most simple case: a sine wave travels without friction in relatively deep water. This wave travels on with constant speed, constant amplitude and undistorted. This situation is approximately true in the deep oceans. The propagation speed of the wave is given by:

$$c = \sqrt{g.d} \qquad (3.1)$$

in which:

c = wavespeed (named celerity) (m/s)
g = acceleration of gravity (m/s^2)
d = depth (m)

In water of 4000 m depth this means:
c = 200 m/s = 720 km/hr. This is about the speed of a plane! Does this mean that the water also flows with that velocity? That would cause a lot of trouble for a ship sailing on that ocean. In fact there are two velocities in a wave: the propagation velocity or celerity, indicated by c and the water particle velocity, indicated by v. The celerity gives only

the speed with which the shape of the wave (or better: the energy) is moving. The particle velocity (the speed of the water mass) is much smaller. For a wave with amplitude = 1 m it can be calculated that the velocity will be 0.05 m/s in 4000 m deep water. If you have difficulties in imagining the difference between these two velocities, you may think of a rope lying on the ground in which you make a wave by moving the end. A wave will travel while the rope particles go up and down only.

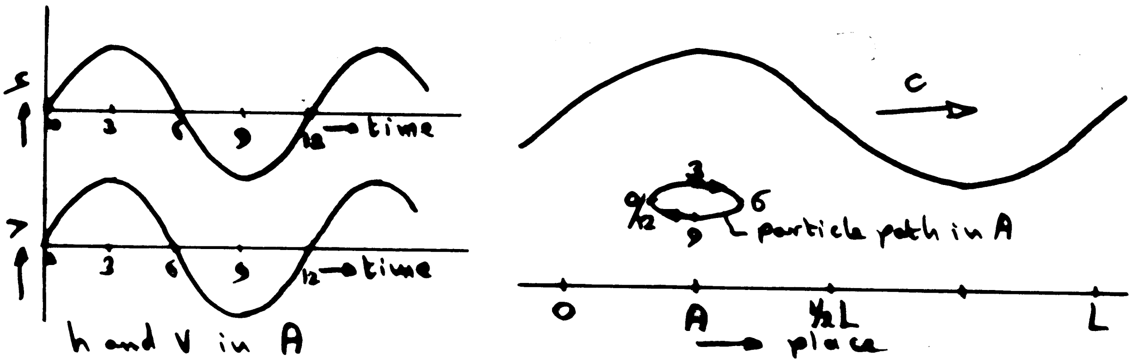


Fig. 3.1 Waterlevels and velocities in a progressive wave

In every point the situation is similar to point A

The velocity in a progressive wave is in phase with the wave profile (fig. 3.1). The water particles flow half the time in the direction of the wave celerity and half the time against it. After one complete period the particles are in the same position again. In one period the particles travel about 1.5 km to and fro, while the wave profile travels 18.000 km in the same time. (For a diurnal wave in the above-mentioned situation).

3.3 Effect of changes in cross-section on a progressive wave.

a. Depth.

When the waterdepth decreases the celerity will also decrease according to formula 3.1. From elementary physics you will remember that a wavelength is given by:

$$L = c.T \qquad (3.2)$$

in which: T = waveperiod (s).

The period will not change, so when c decreases, L gets smaller too. This means, when the energy remains constant, (we assume no friction) the wave will become higher. Popularly we can say that the wave is "crushed". (fig. 3.2).

Fig. 3.2

This process, of waves getting higher when travelling into shallow water, is named shoaling. In tidal waves this goes rather slowly, so only when there is considerable change of depth, shoaling will be visible. This is, for example the case when a wave comes from the ocean on the continental shelf. Fig. 3.3 gives the result of a theoretical study of this phenomenon.

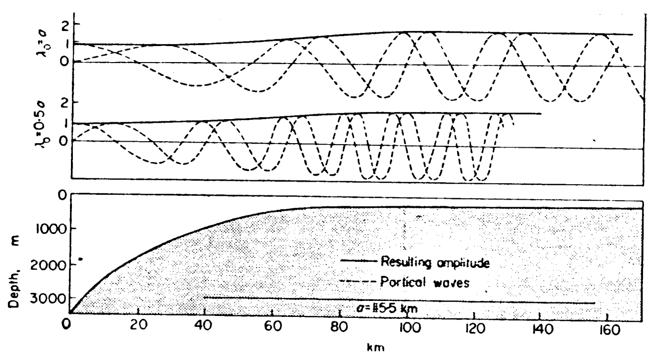


FIG. ~~69~~ 3.3

Shoaling of long waves

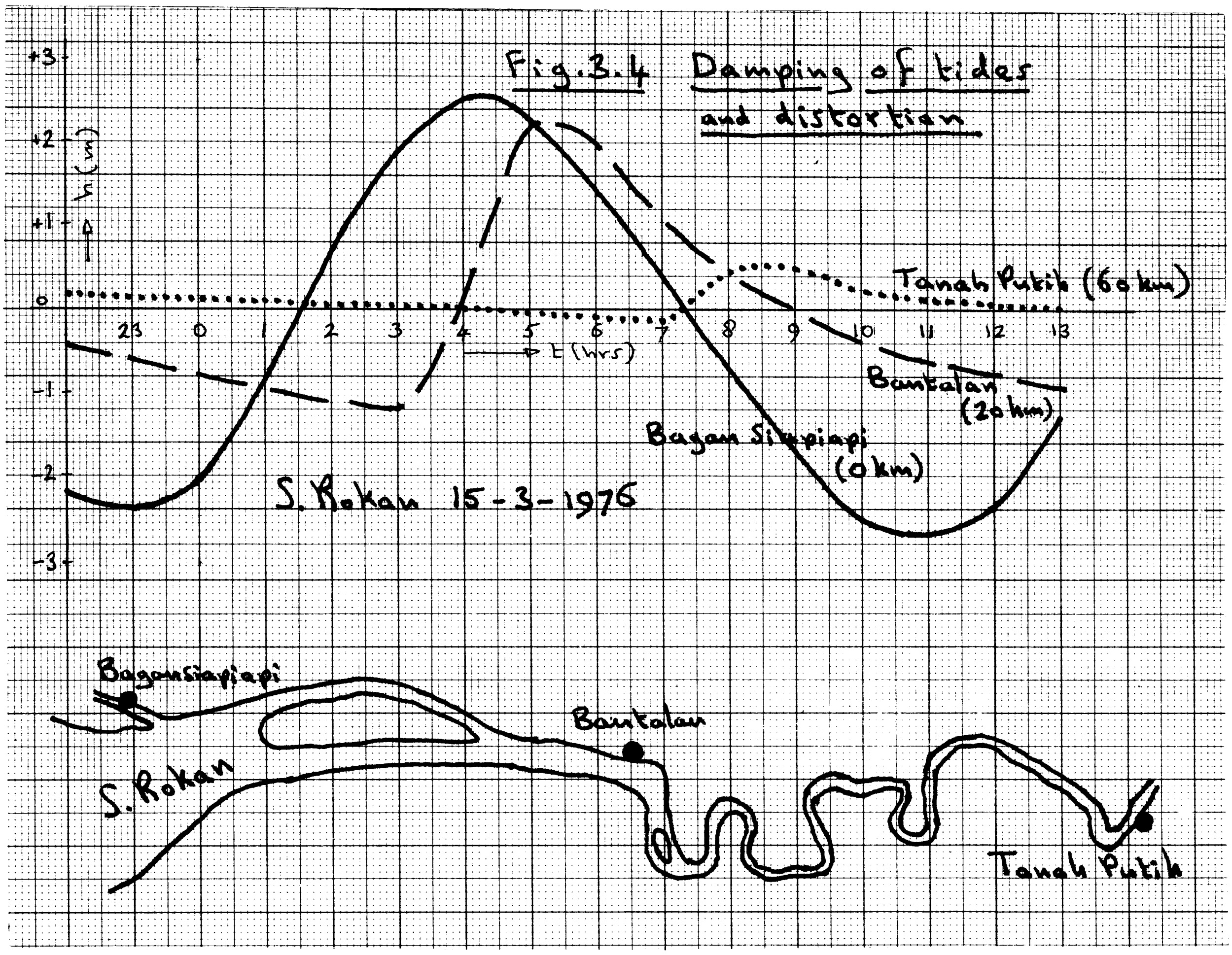
When the bottom rises steeply we will not only get shoaling, but also reflection (see 3.7).

b. Width.

Narrowing, too, will result in a higher wave. Here the same applies as for the shallowing: when it goes too fast, the wave will partly reflect against the walls.

3.4 Friction.

Friction takes energy out of a wave, like it takes energy out of any movement, converting it into warmth. Because of this the wave amplitude becomes smaller. This is called damping. Fig. 3.4 gives a very strong damping on the Rokan.



3.5 Distortion.

From formula 3.1, we learnt that the greater the depth, the greater the celerity. This also means that a wave crest will travel faster than a wave trough. In shallow water this difference can become important (fig. 3.5).

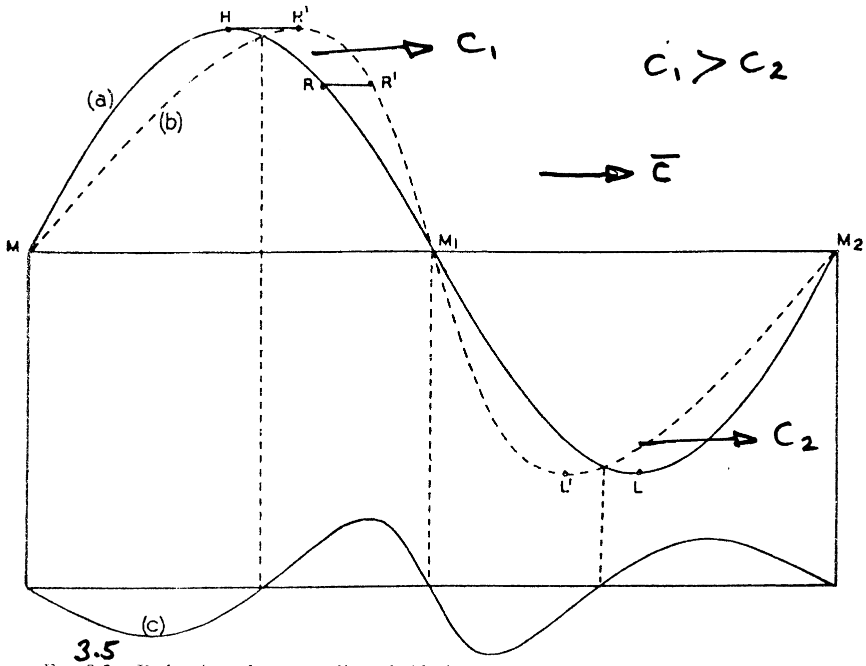
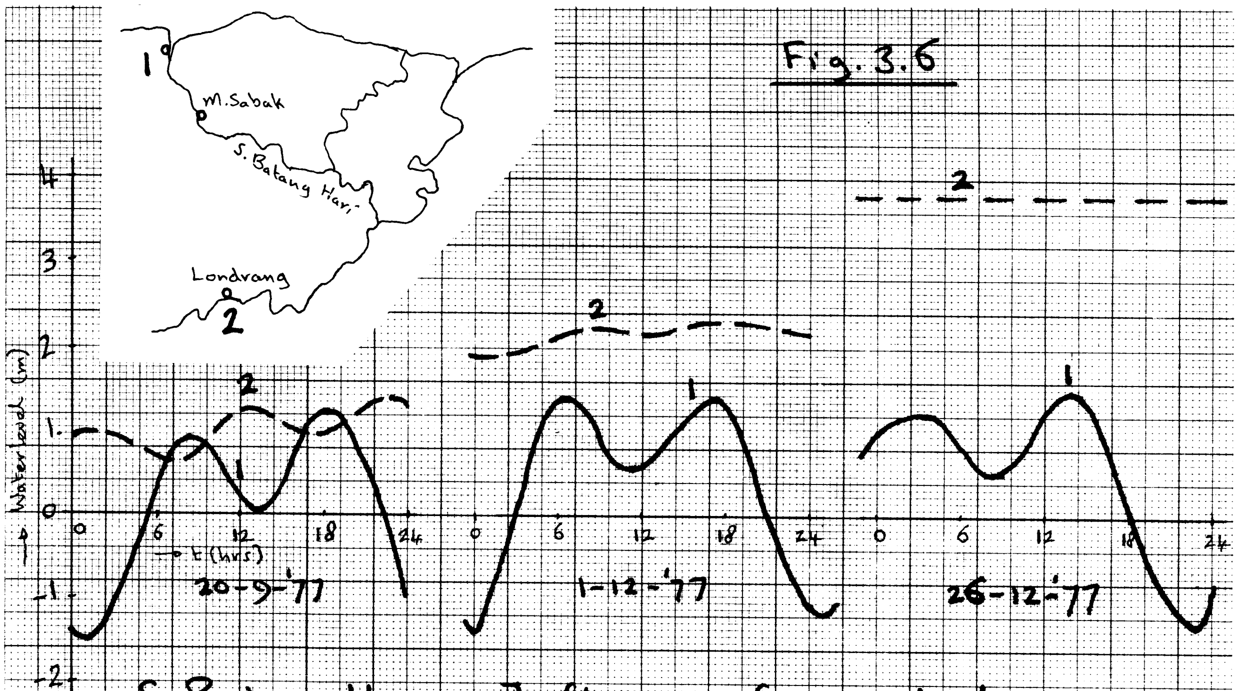


FIG. 3.5. Deduction of quarter-diurnal tide from change of shape of progressive wave.

This will change the shape, the profile of the wave. Also friction will change the profile, but it is of course difficult to separate this from the first reason. Fig. 3.4 gives also a nice picture of distortion.

3.6 River discharge and river bottom slope.

When a tidal wave enters a river it will meet the water flowing from the upland. This will influence the celerity, the amplitude and shape of the wave. The average water-level also changes, which is in fact a wave phenomenon itself (see chapter 5.4). In fig. 3.6 tidal registrations on the Batang Hari are given for three different days (from almost dry till wet season). The waterlevel near the sea is hardly influenced by the discharge. The change in average level in the mouth is mainly due to wind. See also chapter 5.1.



S. Batang Hari Influence of river discharge on tidal propagation

In fig. 3.7 some computational results are given for three cases, in which the discharge and bottom slope was varied.

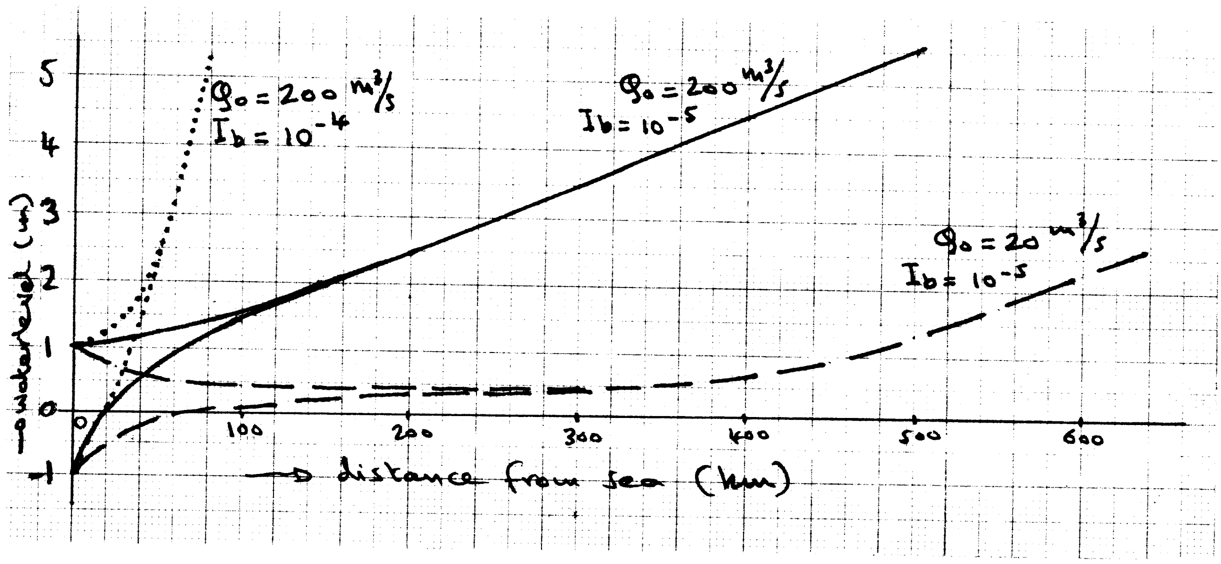


Fig 3.7 a Maximum and minimum waterlevels in various tidal rivers

Fig. 3.7a shows that tidal penetration depends much on river discharge and bottom slope. The greater the river-velocity, the more difficult for a wave to penetrate. And from elementary hydraulics you know that the greater the discharge, the greater the velocity (with a constant slope). Also, for a certain discharge, the velocity is greater at a greater slope. This may explain fig. 3.7a. Fig. 3.7b. shows the waterlevel and discharges in the rivermouth. Note the relation between water-level and velocity.

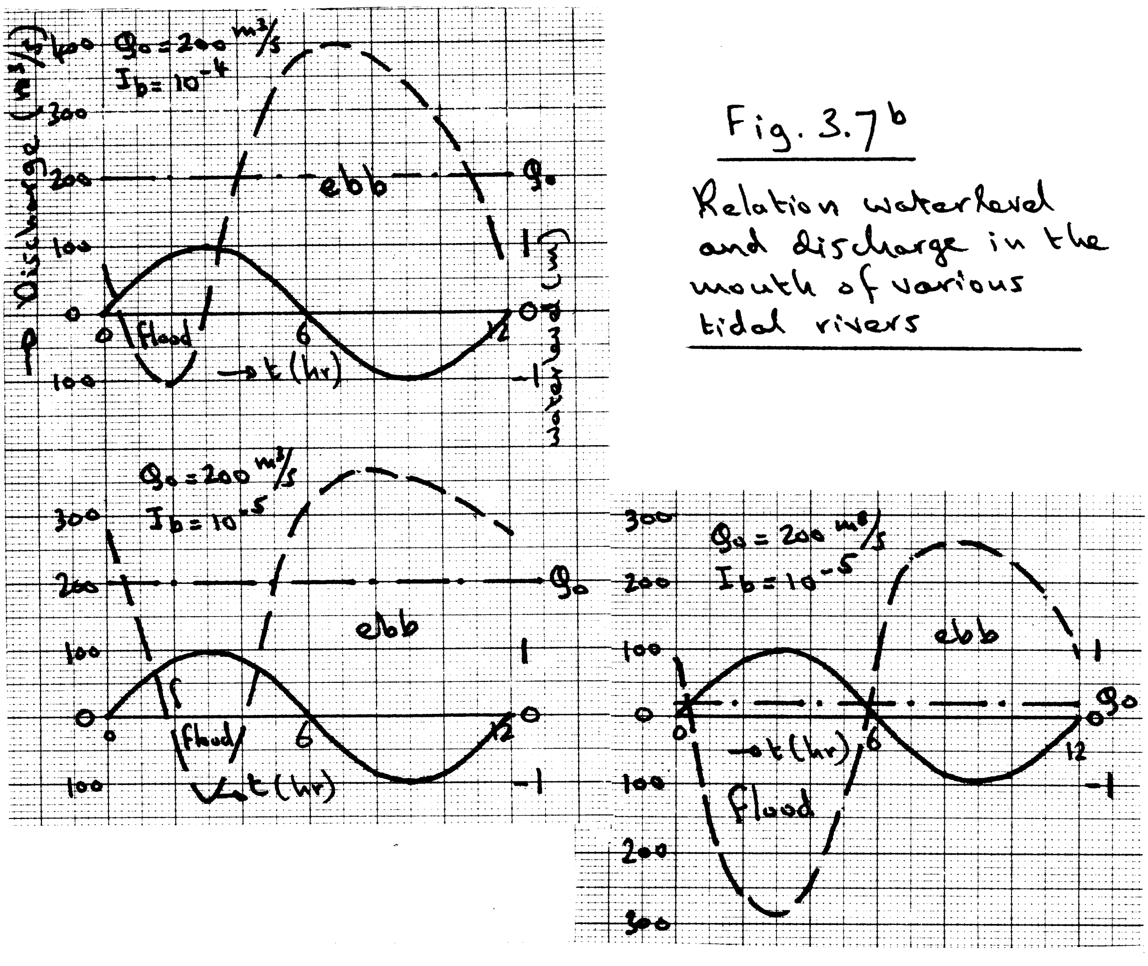
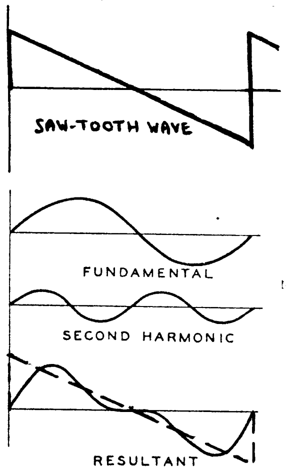


Fig. 3.7b
Relation waterlevel and discharge in the mouth of various tidal rivers

We return for a moment to tidal analysis. When the waterlevel is distorted like in fig. 3.4, we cannot describe it sufficiently with the nine components from chapter 2.5. Fig. 3.8 gives an example for a so-called saw-tooth wave, which can only be described sufficiently by taking more then 4 or 5 higher harmonics into account.



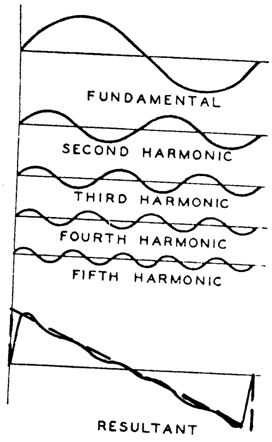


Fig. 3.8 Components in a saw-tooth wave

So, components like M6, M8, M10 etc. are also necessary. River discharge gives similar problems, but now the influence also changes with the season.

As a conclusion we can say that a tidal analysis as in chapter 2.6 should be applied for rivermouths only. Upstream we better use a computational method a described in chapter 6.4.

3.7 Reflection, standing waves.

When a progressive wave comes to a wall it will be reflected, like any wave (sound, light). The reflected wave will travel in an opposite direction with the same speed.

The reflected wave can be constructed, thinking of the wall being a mirror (fig. 3.9a). The result is a so-called standing wave (fig. 3.9b). Celerity is now zero (+ c - c), hence the name standing. The water goes up and down only in the so-called anti-nodes, while in the nodes there is no vertical movement, but here the horizontal velocity is maximal. Now velocity and water-level are 90° out of phase (fig. 3.10).

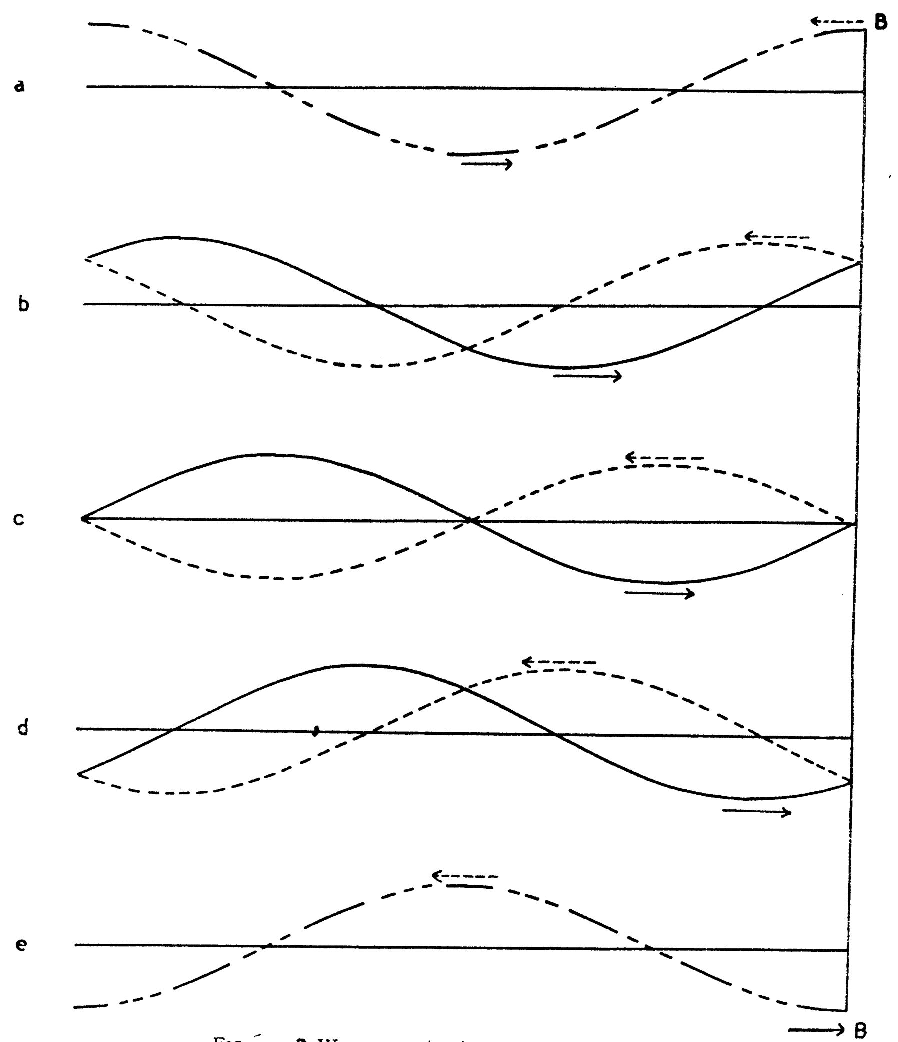


FIG. , Waves moving in opposite directions.

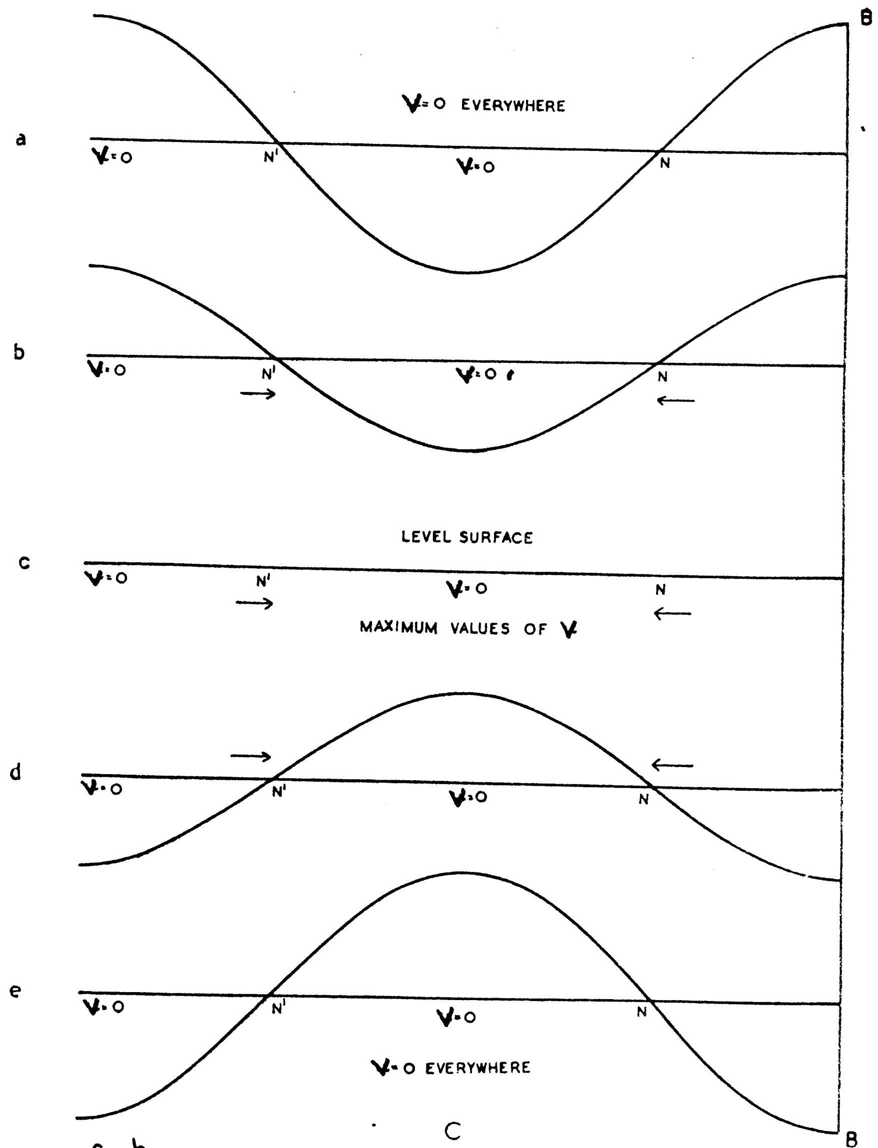
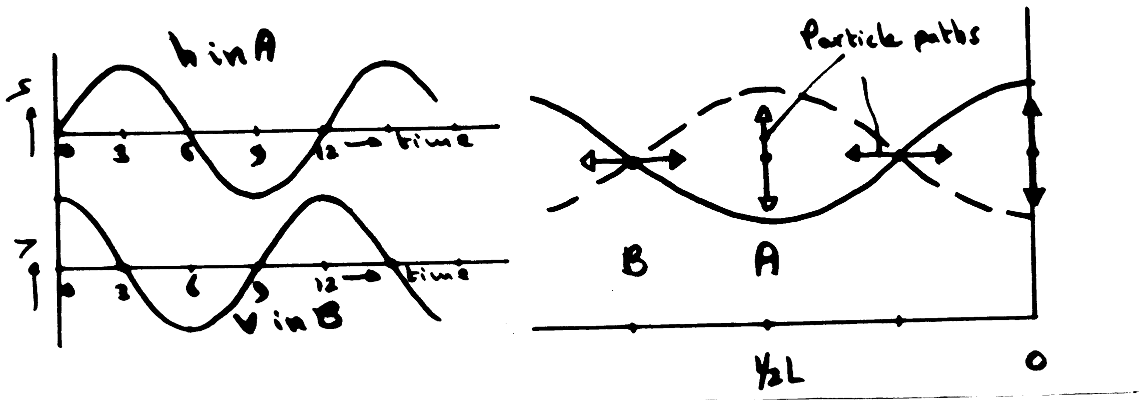


FIG. , Standing oscillations resulting from primary and reflected waves.

Fig. 3.10 Waterlevels and velocity in a standing wave



3.8 Influence of earth rotation on a standing wave.

A particle moving on the earth's surface will get an acceleration perpendicular to its movement. This is called the gyroscopic acceleration. This acceleration is maximal on the poles and zero on the equator. On the northern hemisphere it works to the right, on the southern to the left. You are familiar with this acceleration from the trade winds (NE and SE trade wind, check with the foregoing). In fig. 3.11 we see the effect of gyration on a standing wave in a closed basin. (Question: is this on the northern or southern hemisphere?).

Looking to the wave crest in the right of fig. 3.11 we see that it no longer goes to and fro, but it circles around.

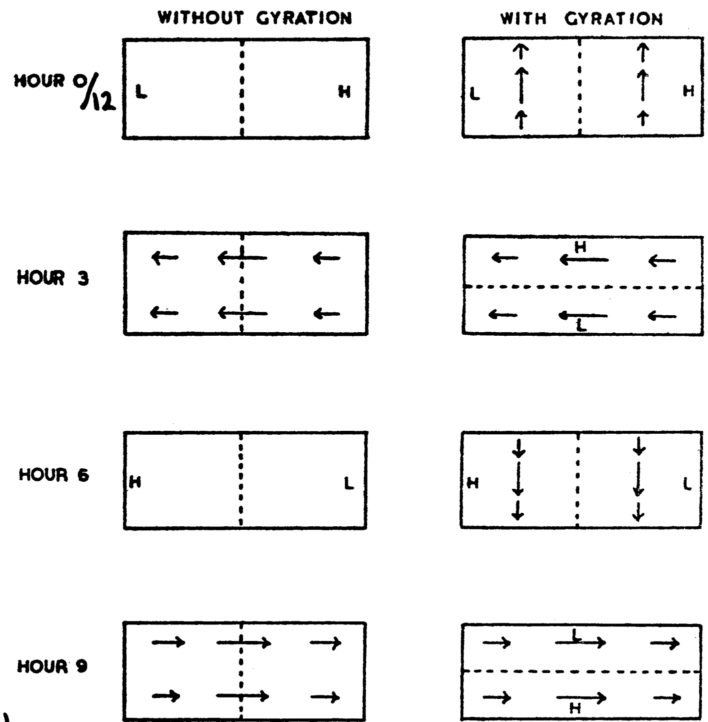
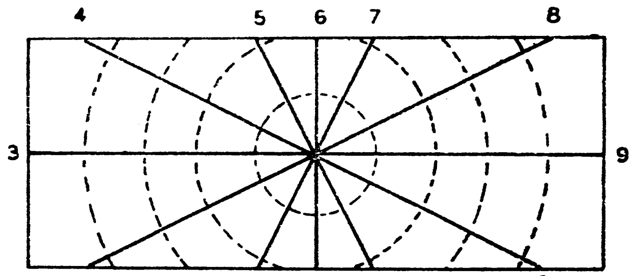


Fig. 3.11. Effects of gyration on standing oscillation in rectangular basin. (The components of the streams are drawn at their maximum rates; the broken lines join points at mean level.)

The result is a rotating wave (fig. 3.12). The co-tidal lines indicate the position of the wave crest every hour. The co-range lines connect points with equal amplitude. In the middle is a point with zero amplitude; this is called an amphidromic point.

— Co-tidal lines
- - Co-range lines



3.12 FIG. ~~[illegible]~~. Amphidromic system in small seas, directly due to lunar semidiurnal tide-generating forces.

3.9 Natural periods, Free oscillations.

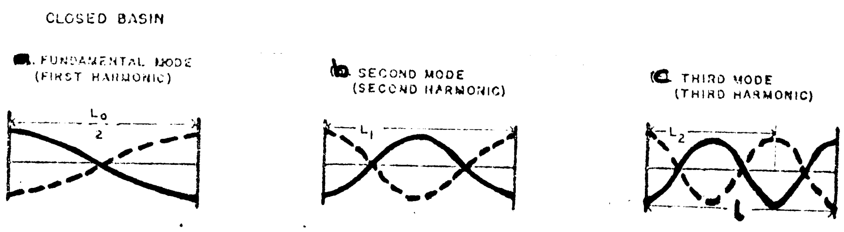
Bays and seas have natural periods, which is the period of a free oscillation of water in that bay or sea. This is easily seen when you lift a tank, partly filled with water at one side and put it down again. A standing wave will be visible now with a certain period. This period is the first natural period or first harmonic or fundamental mode. The period can be calculated from:

$$Tn = \frac{2.1}{\sqrt{gd}} \qquad (3.3)$$

in which: 1 = lenght of tank

$\sqrt{gd}$ is, as you remember, the wave celerity. So, formula 3.3 is in fact just the time needed for a wave to travel to and fro once. At the ends of the tank the water velocity must be zero, so here an anti-node will occur. In the middle there is a node (fig. 3.13a).

Fig.3.13



Like in musical instruments there are many more harmonics, (see fig. 3.13b, c). This means that formula 3.3 should be extended to:

$$Tn = \frac{2.1}{n\sqrt{gd}} \qquad (3.3)$$

in which: n = 1, 2, 3, 4 ....

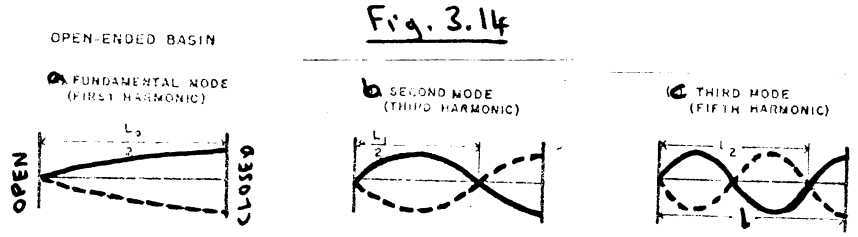
In open bays the situation is different. A node will occur at the opening (fig. 3.14a) and the fundamental mode is given by:

$$Tn = \frac{4.1}{\sqrt{gd}}$$, or more in general

$$Tn = \frac{4.1}{n\sqrt{gd}} \qquad (3.4)$$

in which: n = 1, 3, 5, 7 ....   (fig. 3.14 bc)

Fig. 3.14



3.10 Forced oscillations.

The natural periods derived in 3.9 were for free oscillations. When there is a force from outside, the movement will have the period of that force (forced oscillation). This force can be the direct influence of the moon or sun, or a wave coming from the ocean. For example: a bay with a length of 9 km and a depth of 10 m has natural periods of 1, 1/3, 1/5 hr. But the tide in that bay will just follow the periods of the components derived in chapter 2.

3.11 Resonance.

A very interesting phenomenon occurs when the period of the forced oscillation is equal to one of the natural periods of a system. Then the movements become theoretically infinite; this is what we call resonance. Due to friction they never become infinite, but they can be very spectacular.

Forced oscillation (or excitation) in a closed basin can come only from the moon or sun directly, because no other waves can enter the basin. This is also true for all our oceans. Real resonance nowhere occurs on earth; but for example, Lake Erie in the USA has a fundamental period of 14 hours, which is not very far from the 12.4 hours of the M2 component. Due to this, the relatively small lake has a tidal range of 8 cm. Not spectacular, but the lake beside it, Lake Michigan which is much bigger, has hardly noticeable tides.

Resonance in open bays happens more frequently. The most famous case is the Bay of Fundy in Canada. But Indonesia too has a resonance bay to be proud of. It is the Teluk Berau or Bentoni in Irian Jaya.

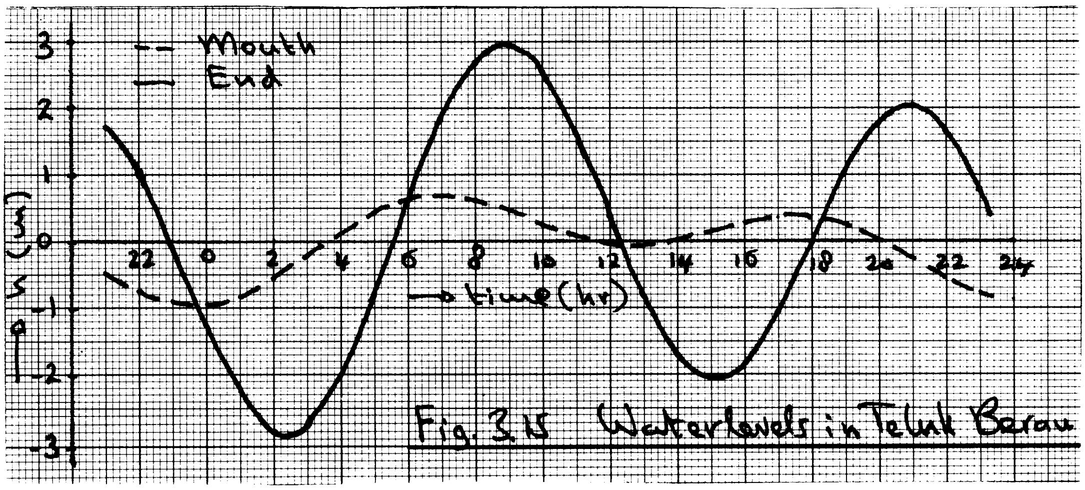


Fig. 3.15 Waterlevels in Teluk Berau

In fig. 3.15 the tides at the entrance and at the end during springtide are given.
With a length of about 180 km and an average depth of 25 m, the first natural period becomes about 12.8 hr. So, very near the 12.4 hr of M2. Indeed M2 is the component which is amplified most (fig. 3.16).

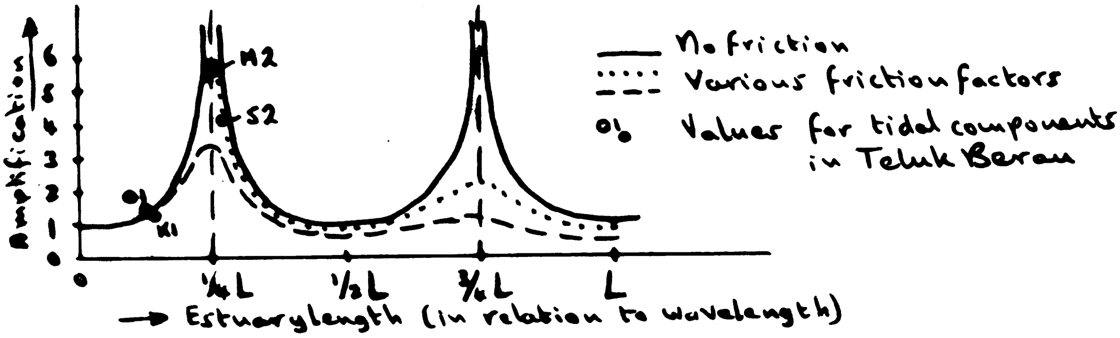
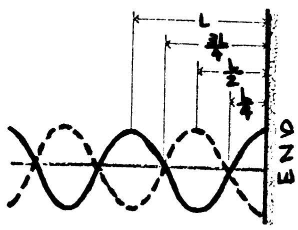


Fig. 3.16 Amplification of tidal waves in open estuaries

Formula 3.4 can also be given in terms of wave length. When the length of a bay is 1/4, 3/4, 5/4 ...... etc. of the length of a progressive wave there will be resonance. In other cases the amplification can be derived from fig. 3.17 by comparing the amplitude at the closed end and at the location of the open end. From this we get a picture like 3.16.

Fig. 3.17



4. EXPLANATION OF SOME TIDAL PHENOMENA IN INDONESIA.

4.1 The character of the tides in Indonesia.

In chapter 2.7 we saw already that the character of the tides in Indonesia ranges from purely diurnal to purely semi-diurnal. Fig. 4.1 gives a picture of the diversity of the tides in the Indonesian archipelago. This is indeed a very complex picture; with the knowledge gathered in chapter 3 we will try to explain this picture.

In fig. 4.2 the sum of amplitudes of K1 and O1 are given and in fig. 4.3 the same for M2 and S2. Laying these pictures above each other, figure 4.1 appears (remember that f = K1 + O1/M2 + S2). So, for our explanation we must look into the behaviour of the semi-diurnal and diurnal tidal waves.

To do so, we first take a look at the depth contours of the archipelago (fig. 4.4). This looks too complex for any explanation, but we can simplify the picture very much. In fig. 4.5 the system is simplified to three channels with three openings to the oceans. The smaller entrances like Malacca strait, Sunda strait etc. have been neglected, which is justified as we will see later (chapter 4.2).

Fig. 4.6a and b give the co-tidal lines of the K1 and M2 tides on the adjacent oceans.

Note the amphidromic systems. From these figures we see that the tidal waves penetrate the Indonesian waters from opposite directions. Fig. 4.7 gives the depths along the three channels. First we look at channel a. Waves entering the channel first travel in very deep water. Then they come in the shallow Java Sea and South China Sea, with a depth of about 50 m. This is a change in depth of a factor 100. From chapter 3 we know that the waves will become higher due to shoaling, but the change in depth is so sudden that the shallow middle part (almost an island) will also act as a reflecting body.

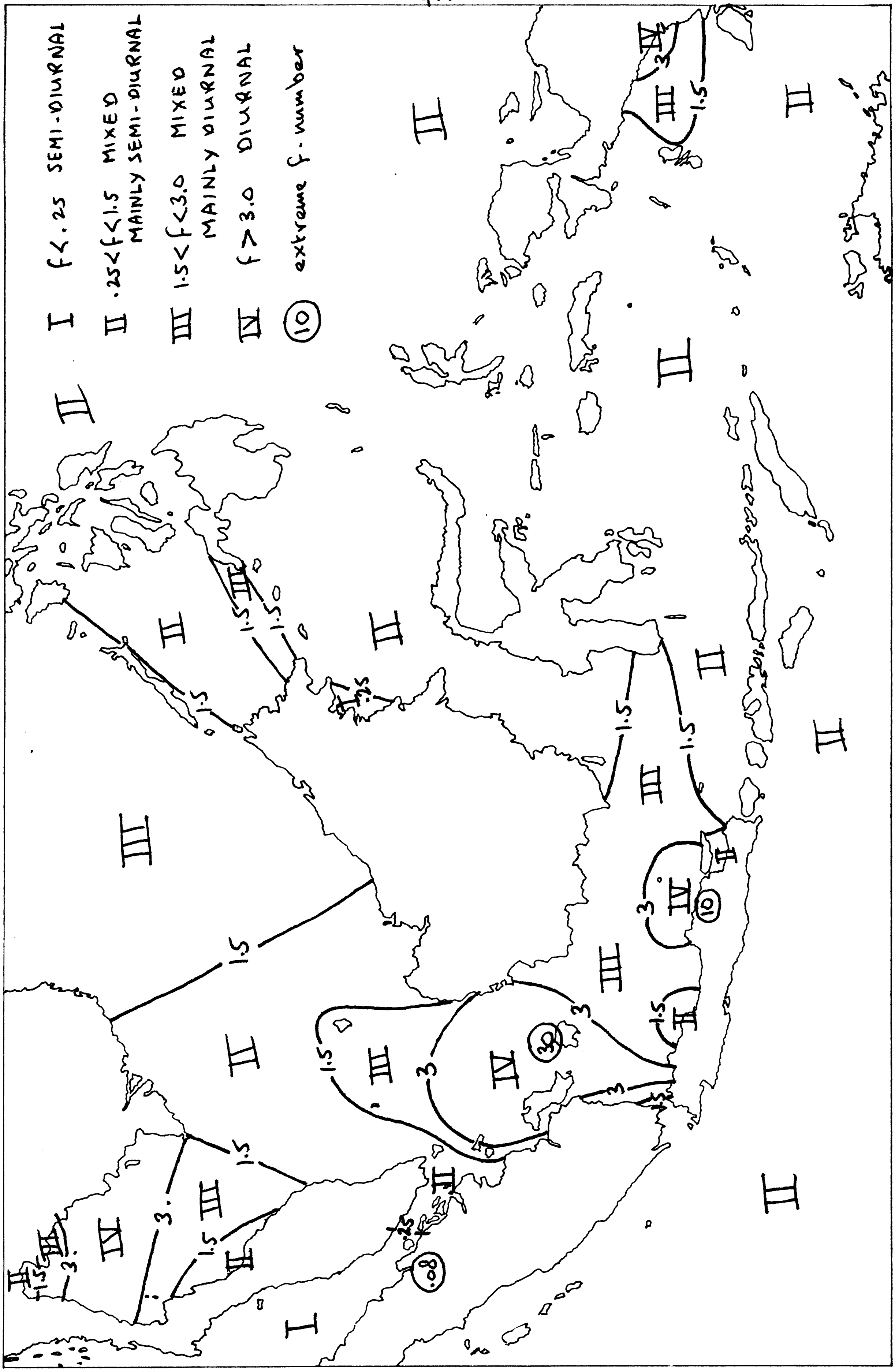


Fig. 4.1 Character of tides in Indonesia

Fig. 4.2 of equal diurnal amplitudes (K1 + O1)

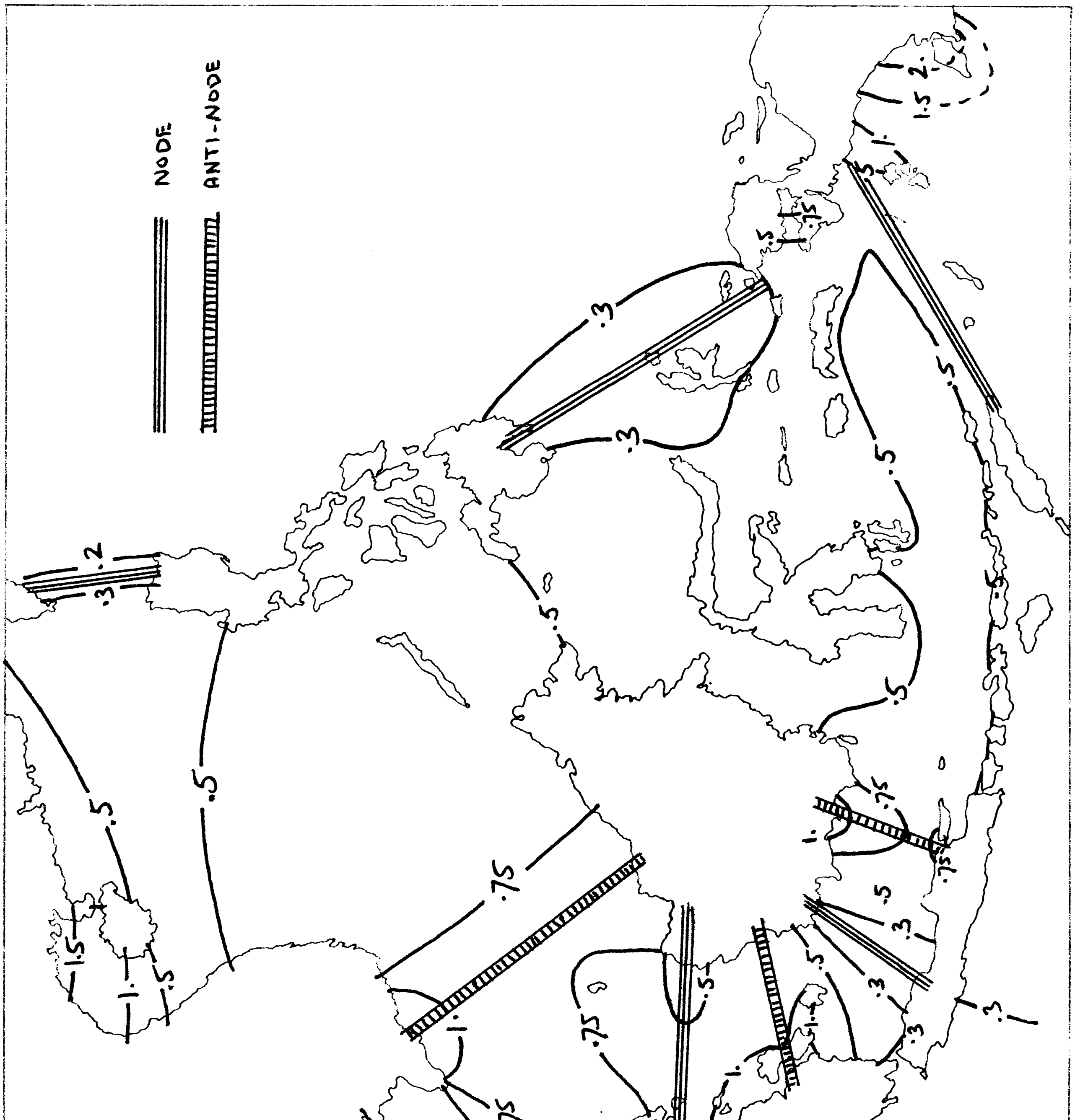
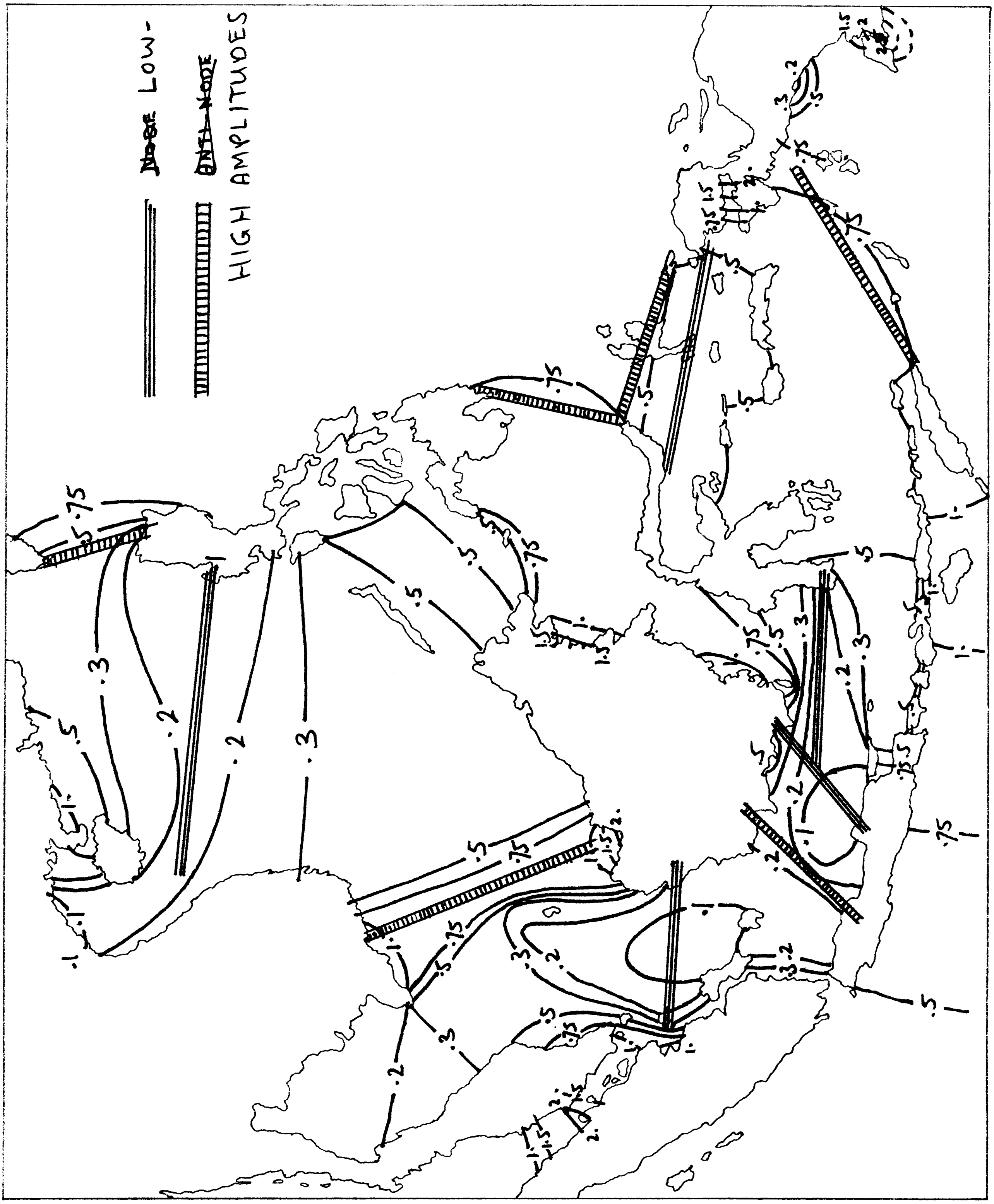


Fig. 4.3 Lines of equal semi-diurnal amplitudes ($M_2 + S_2$)



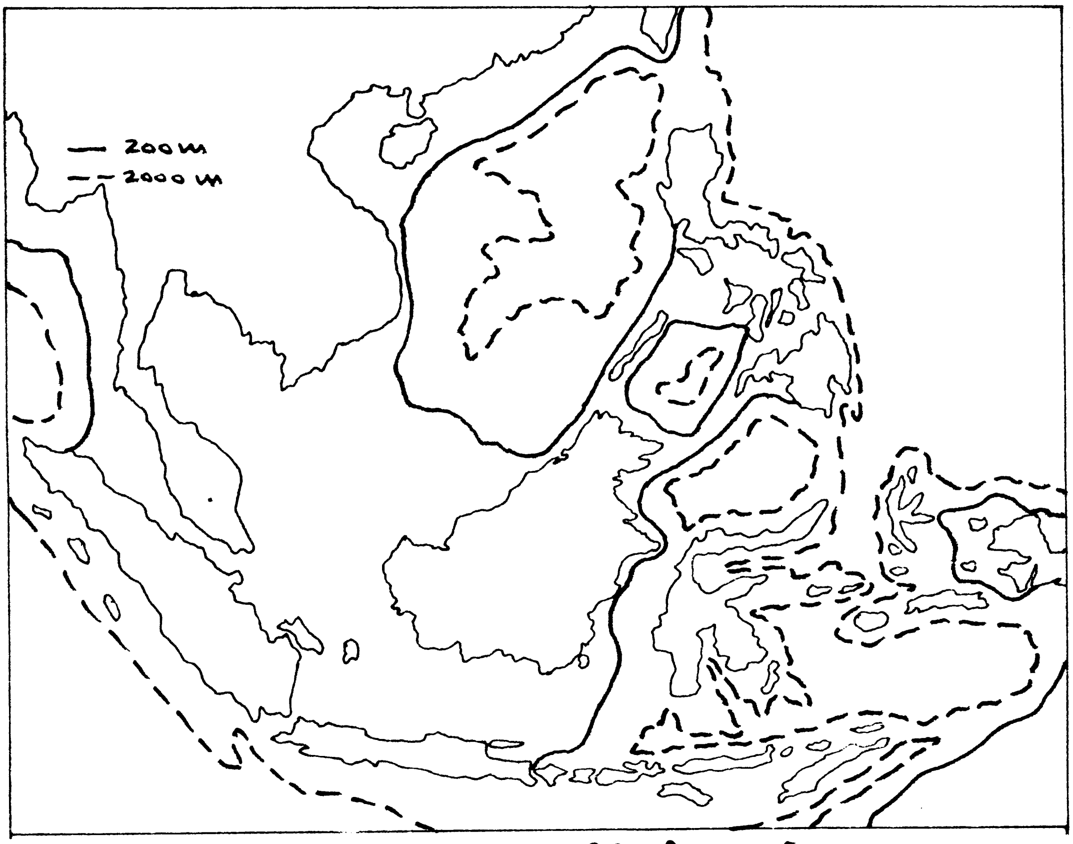


Fig. 4.4 Contourlines SE. Asian Seas

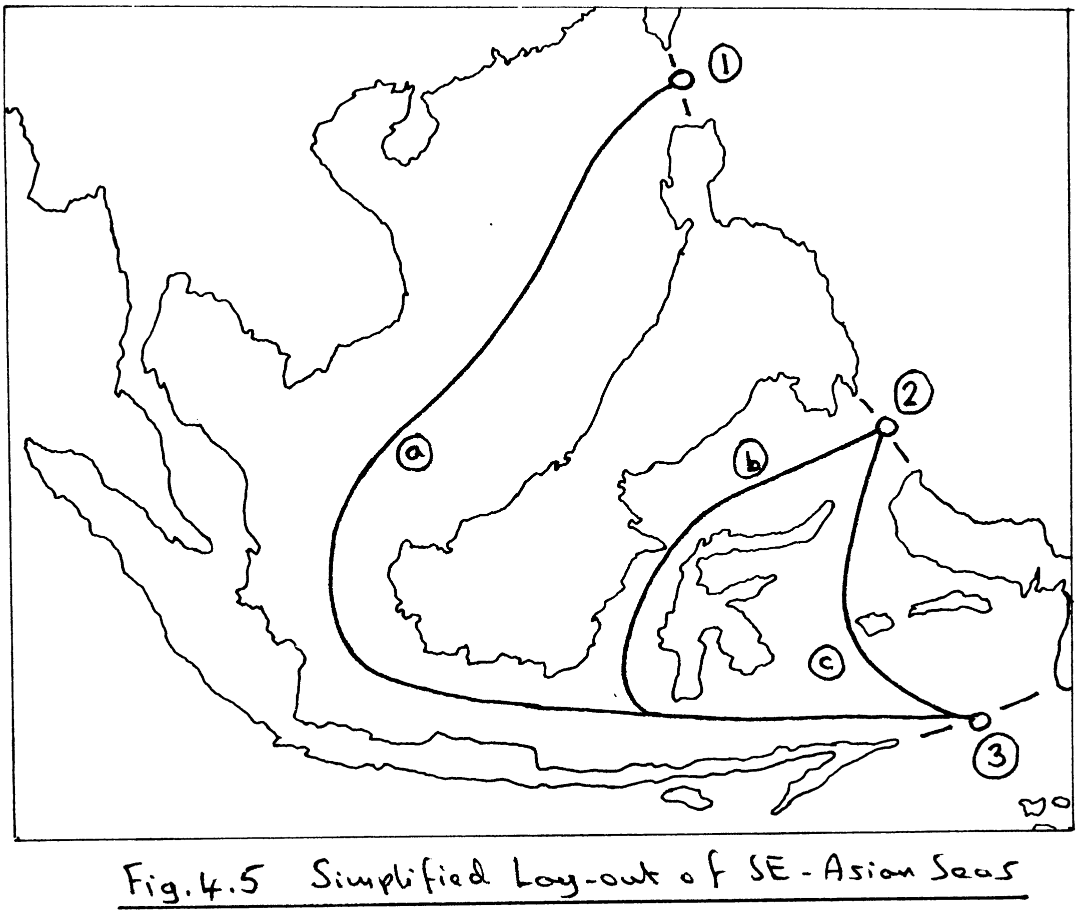


Fig. 4.5 Simplified Lay-out of SE-Asian Seas

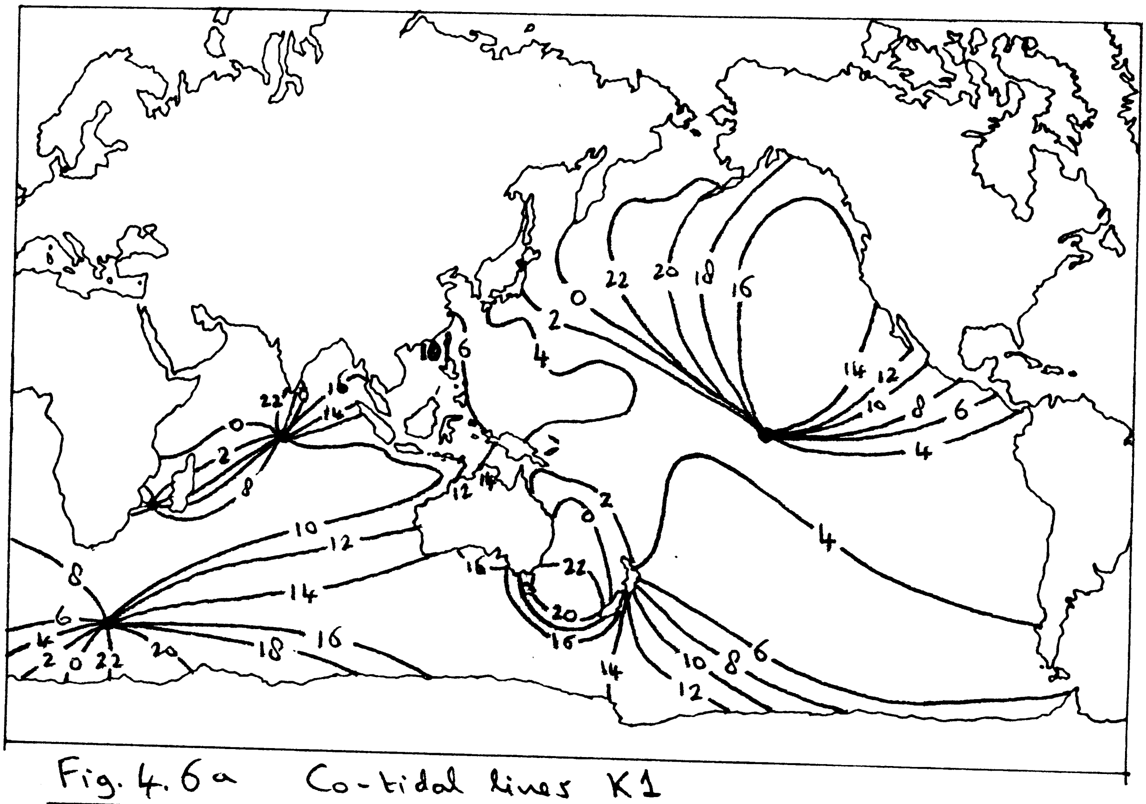


Fig. 4.6a Co-tidal lines K1

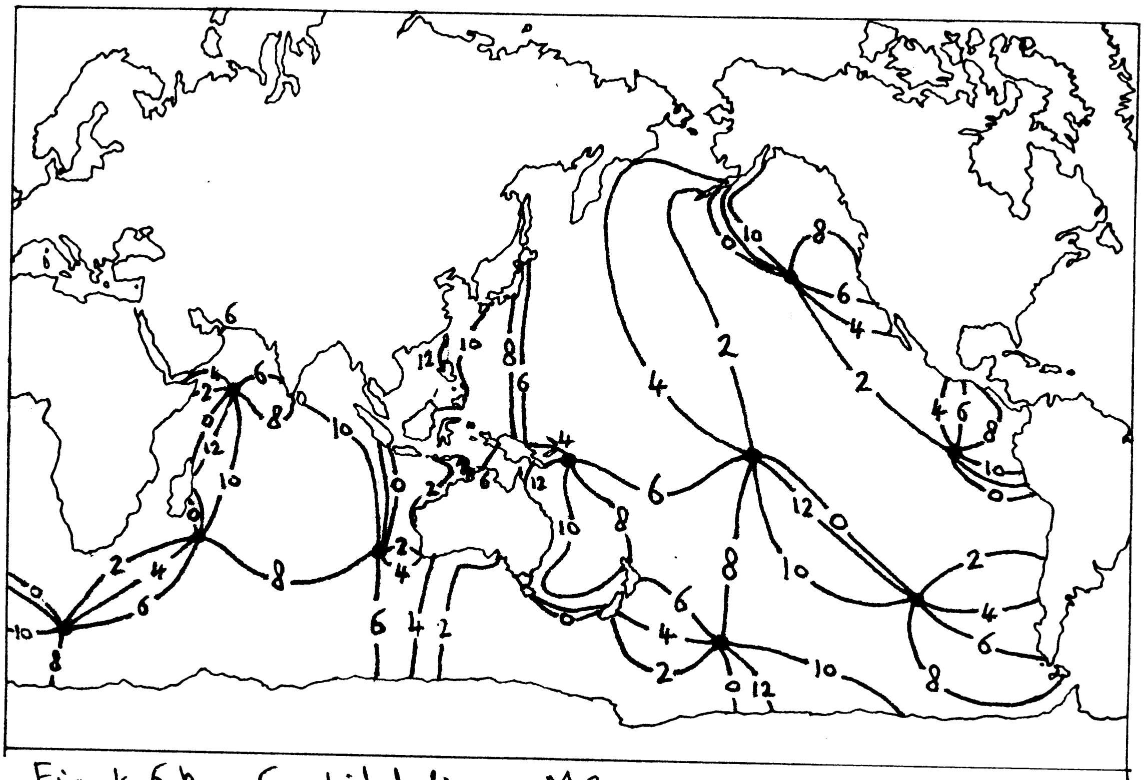


Fig. 4.6b Co-tidal lines M2

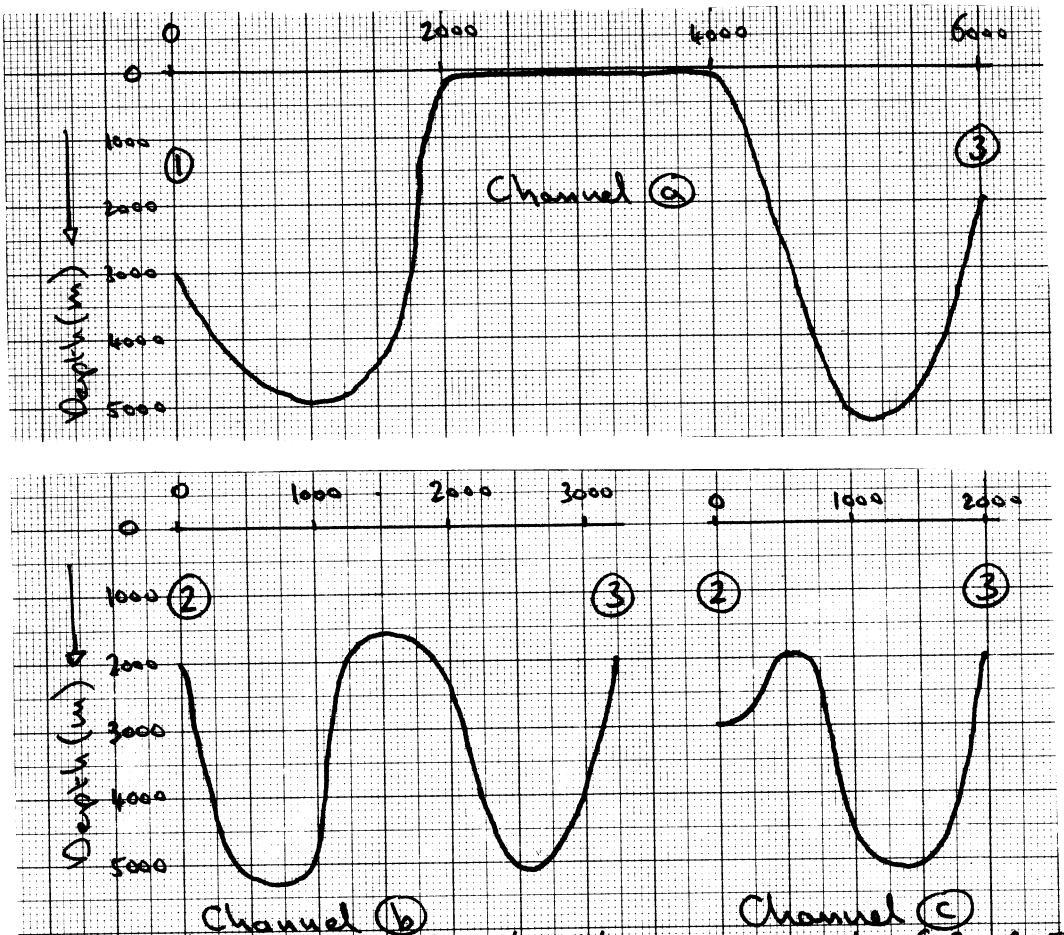


Fig. 4.7 Depths in the three channels of fig. 4.5

Starting with the diurnal tides we see from depth and length of the deep parts that the length is shorter than one quarter of the wavelength. From fig. 3.17 we learn that there will be no node in the deeper parts. The shallow part will now act as a closed basin between the two incoming waves travelling in opposite direction. The fundamental period of this part is, according to formula 3.3 about 50 hr, so we can expect two nodes in the basin (see also fig. 3.13b). We can obtain the same result from fig. 3.17 when we say that the length is equal to the wave length. The wave pattern in channel a finally looks like fig. 4.8. Looking again at fig. 4.2 we recognize this pattern clearly. Channels b and c have no internal reflection points; the tides will follow the incoming waves. Based on length and depth no nodes can be expected, which is indeed the case in fig. 4.2.

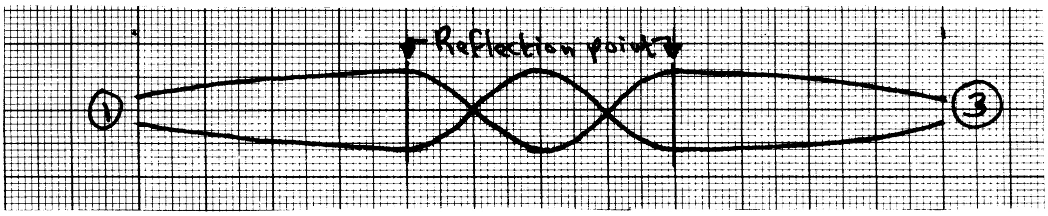


Fig. 4.8 Standing wave pattern for diurnal tides in channel a

For the semi-diurnal tides the picture is much more complicated. The length of the deeper parts is such that one node can be expected near the openings to the oceans. On the shallow part there should now be 4 nodes (fig. 4.9). But looking at fig. 4.3 we only see a node in the northern deep part and not in the south-east part. In the Java Sea we do not recognize anything of the picture we expect.
The tides at the entrances of channels b and c are 180^o out of phase and we can expect one nodal line in these basins (fig. 4.9). They are indeed visible on fig. 4.3 near South Sulawesi and Halmahera.

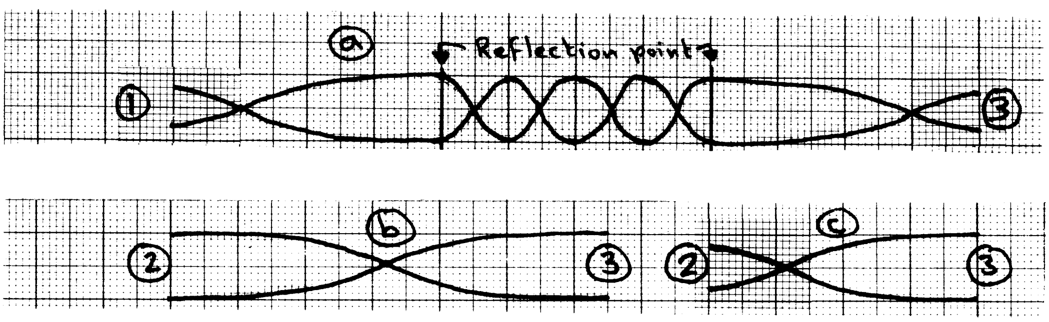


Fig 4.9 Standing wave pattern for semi-diurnal tides in the three channels

But how about channel a? To understand this we take a closer look at the expected wave patterns in the three channels. Fig. 4.10 is an attempt to draw them in bird's-eye view. We see that channel a in the South-east has a node where b and c nearly have an anti-node. And channel b has a node where channel a wants an anti-node.

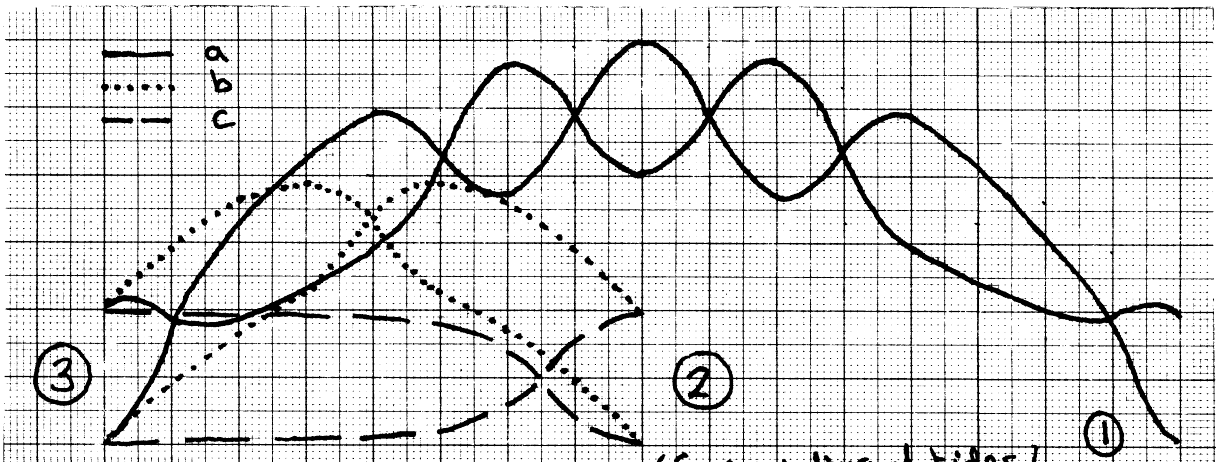
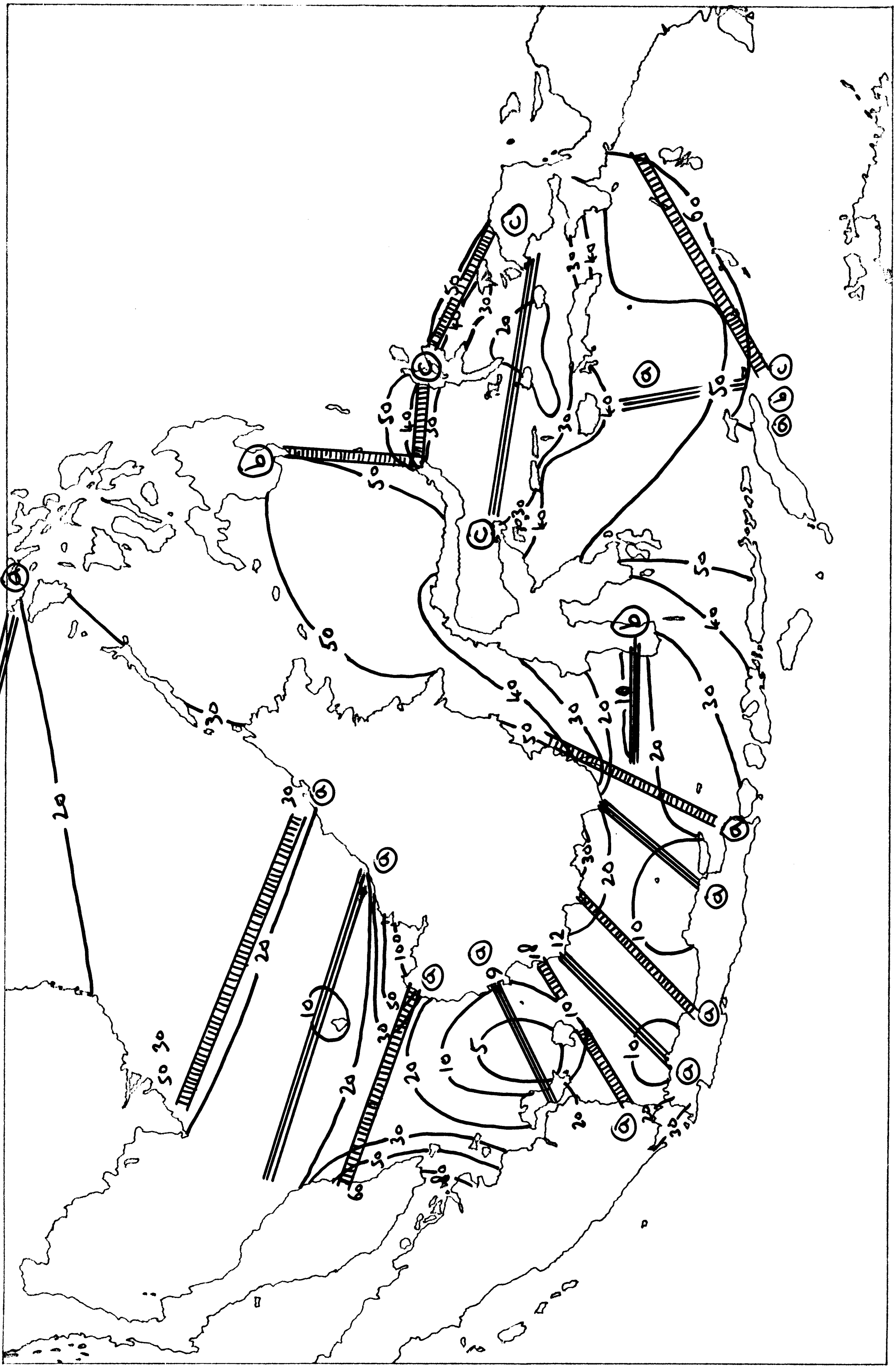


Fig. 4.10 Standing wave patterns (for semi-diurnal tides) in the three main channels (numbers refer to fig. 4.5)

So the systems are disturbing each other. To check this we must take a closer look into the tidal amplitudes and it is better to do it for each component separately. In fig. 4.11 co-range lines are drawn every dm for M2. With some imagination we can now see the picture we expected. In the Java Sea it looks like there are some amfidromic systems. A further study of the co-tidal lines will have to clarify this.

Despite the complexity of the tidal system in the Indonesian waters, we can see that the diversity in the character of the tides is not some mystic happening, but is governed by the elementary laws of physics.

Fig. 4.11 Co-range lines for M_2



4.2 The situation in Surabaya channel.

Going from the Java Sea to Madura Strait the f-number of the tide goes from 8 to less than 1, so from purely diurnal to dominantly semi-diurnal, within 40 km. (Fig. 4.12). At the northern entrance the diurnal tides have an anti-node (fig. 4.2).
The semi-diurnal tides entering from the east (having a weak anti-node east of Madura, fig. 4.11) are amplified in the Madura Strait (l ≈ 0.2L). This explains the difference in character.

When explaining the tidal characters in Indonesia, we neglected the influence of narrow straits. Here we see this is justified, because the tides hardly influence each other on both sides of Surabaya channel. This also means completely different waterlevels on both sides and, hence we expect high velocities. This is shown in fig. 4.13.
The maximum velocity is about 2 knots (= 1 m/s) while the velocity on the Java Sea will be not more than 0.1 m/s. Narrow straits all over the world have often high velocities because of this.

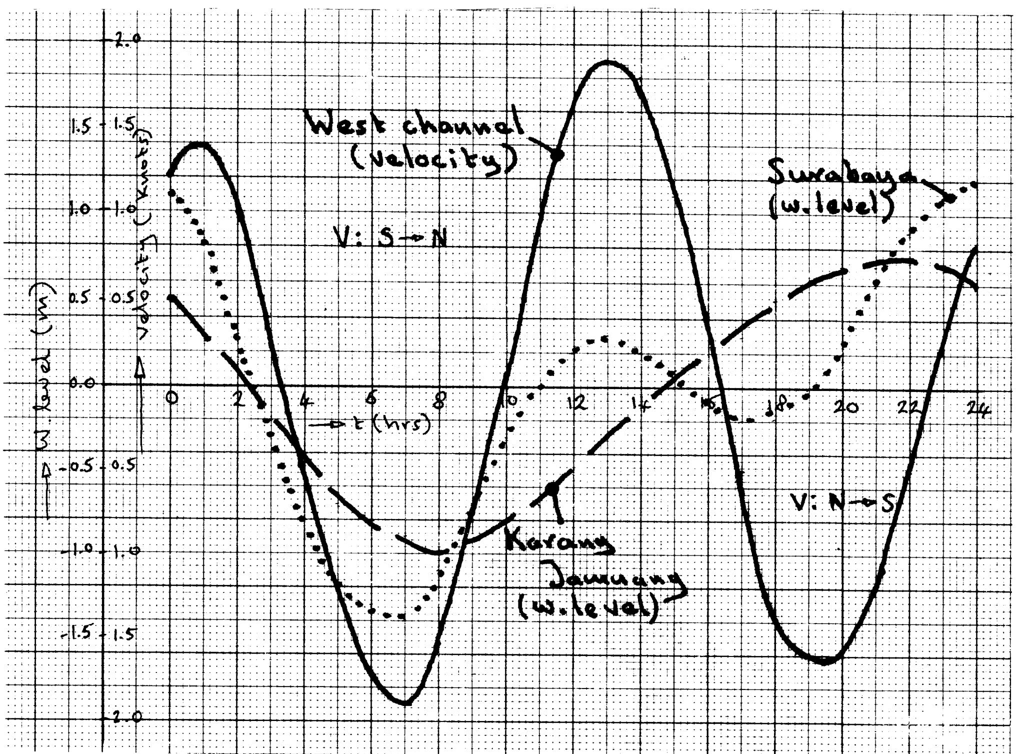


Fig. 4.13 Waterlevels and velocity in Surabaya channel

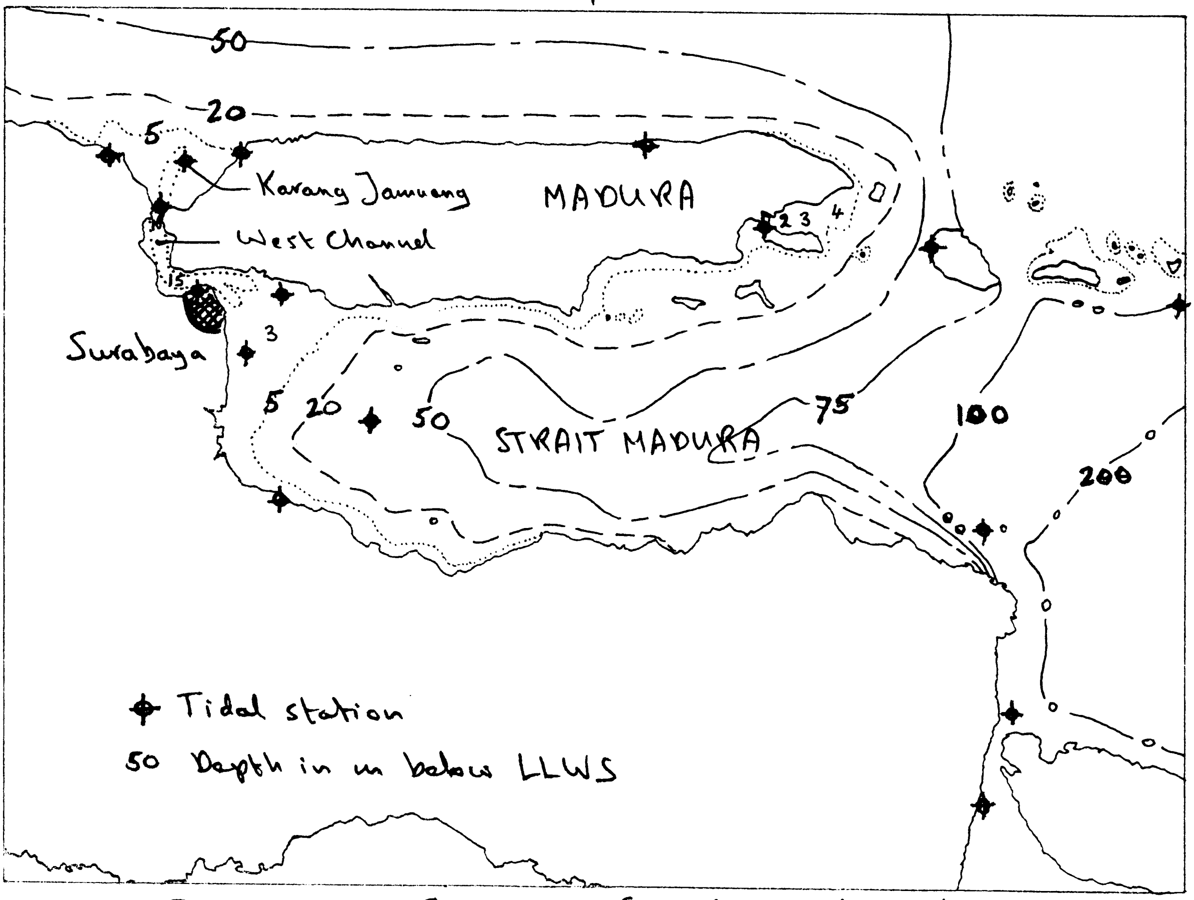


Fig. 4.12 a Situation Surabaya channel

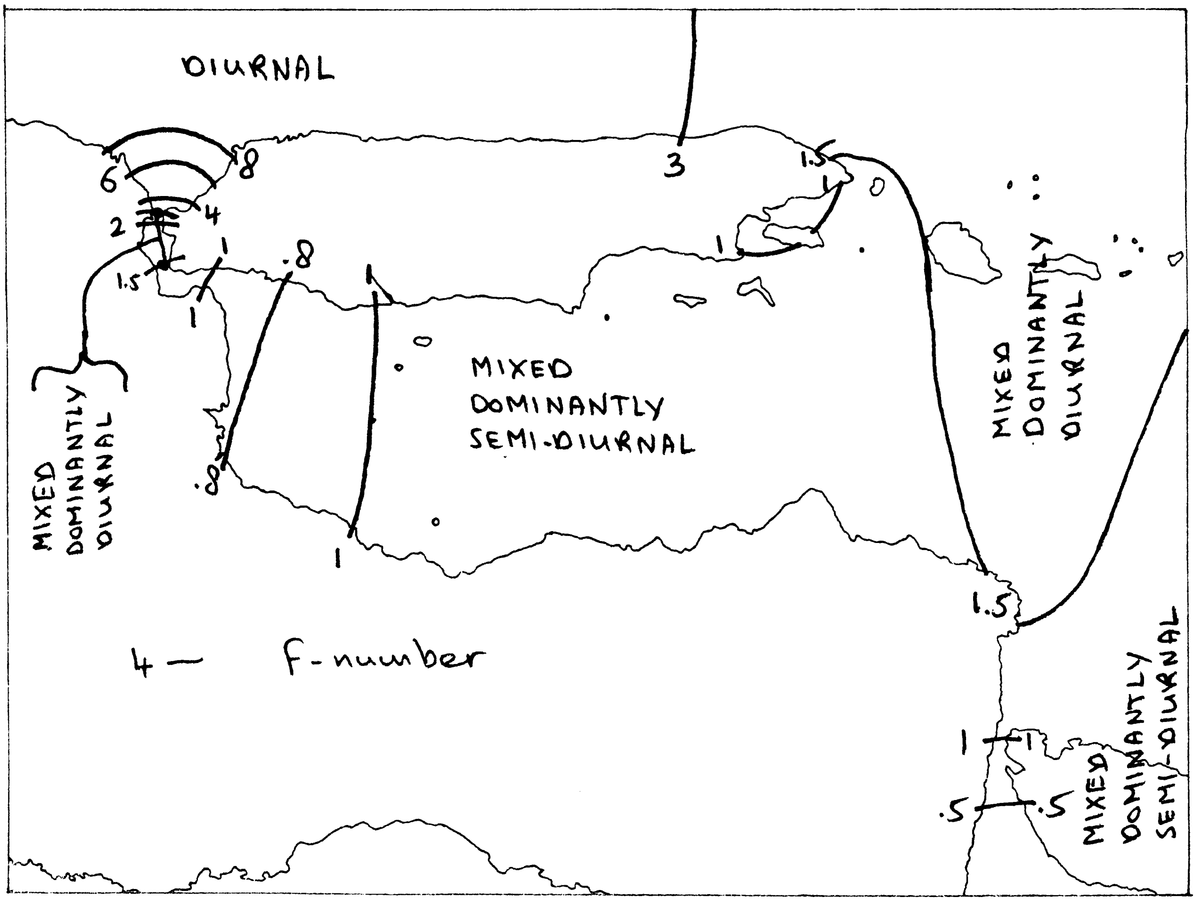


Fig. 4.12 b Character of tides

4.3 The tides on the Siak Besar.

Going inland, the tide on the Siak Besar gets stronger than at the mouth, while the cross-section does not change very much (fig. 4.14). So, there must be some reflection but, since the Siak runs on through the Sumatra plains for more than 250 km up to the origin, from where? Taking a closer look at the map we discover some small hills at about 160 km from the mouth, while 1/4L would be about 135 km. In these hills the river bottom will have a steeper slope, which probably acts, although weakly, as a reflector.

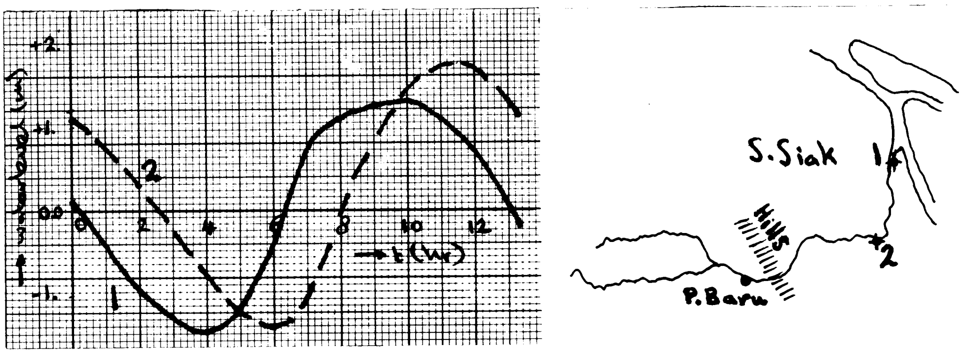


Fig 4.14 Tides on Siak Besar

4.4 The tidal bore on the Rokan and Kampar.

Finally we come to a rather spectacular tidal phenomenon: the bore. Without knowing, probably everybody has seen many bores in his life. For, when a wave breaks on a beach we also see a bore. As we know the wave celerity c decreases when the depth decreases. At a certain moment c becomes even lower than the water particle velocity v (remember again the two speeds in a wave). This means that the water is going faster than the wave itself, the wave cannot exist anymore, gets unstable; in other words: the water "comes out of the wave". This is the breaking of a wave (fig. 4.15).

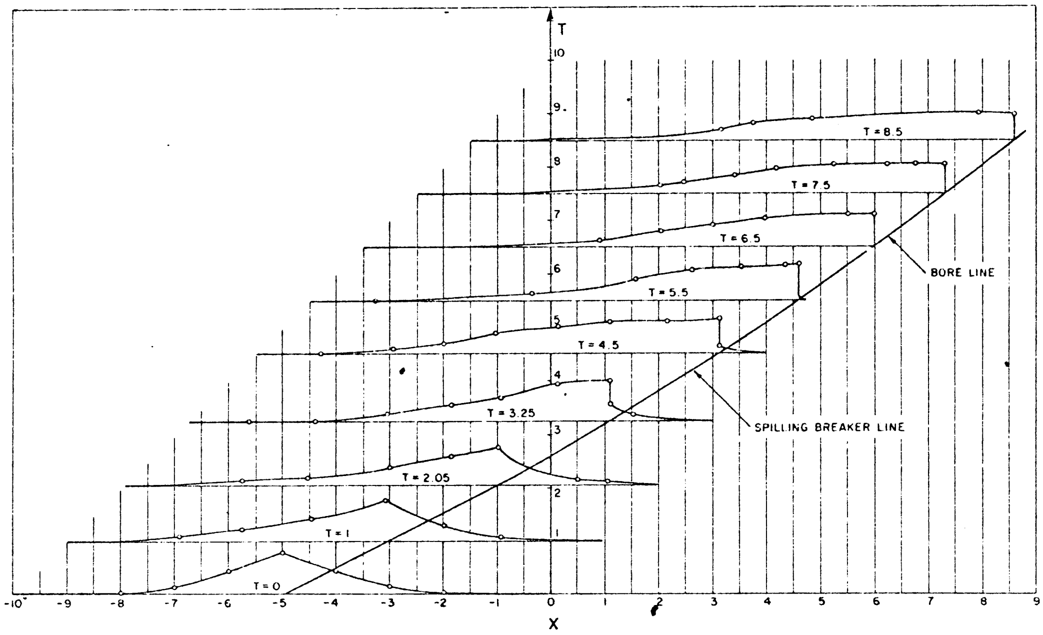


FIGURE
TIME-HISTORY OF THE WAVE PROFILES BREAKING ON A 1/10 BOTTOM SLOPE

Tidal bores however, are very rare in the world; there are hardly more than ten. The biggest is in the Chien Tan Kiang in China, where the bore can have an almost vertical waterfront of several meters.
In Indonesia tidal bores occur on the Rokan and the Kampar; in Malaysia there is one on the Serawak.
Tidal bores are rare because a special combination of conditions are necessary to break a tidal wave.

1 - First we need strong tides. All bores are located in areas with tides having ranges of many meters (more than about 4 m average).
Even then bores usually exist only during spring-tide.

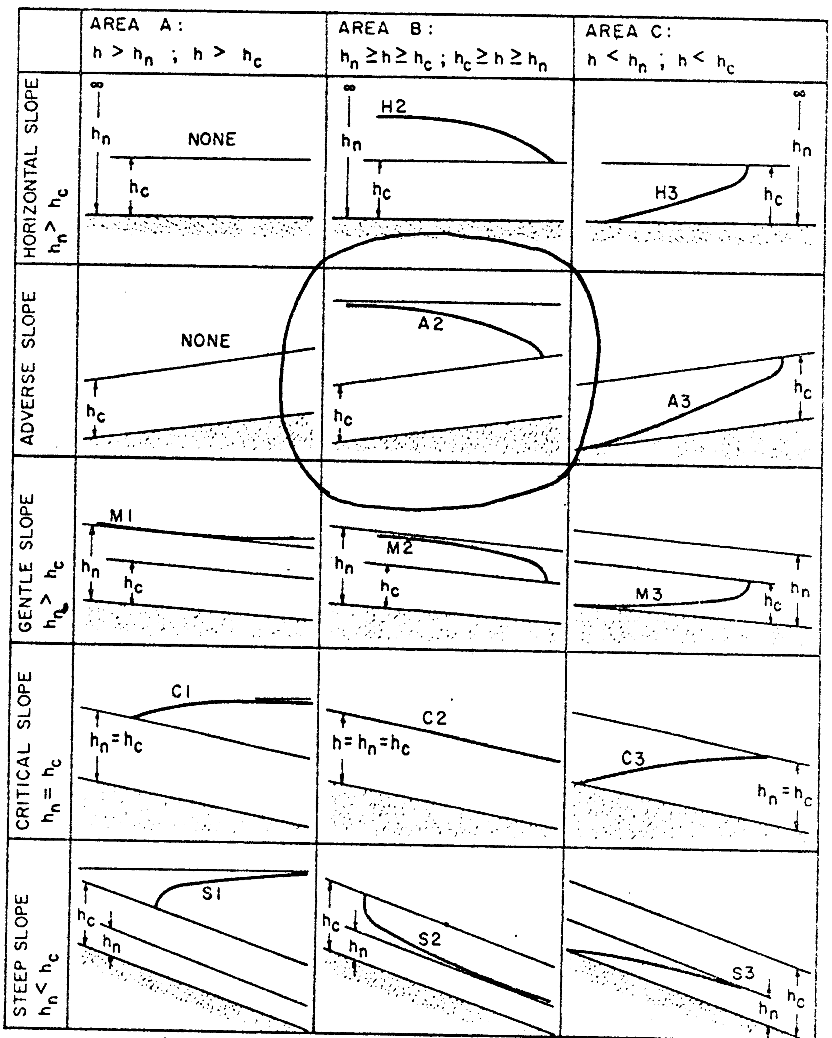
2 - Secondly we need shallow water to decrease the celerity and to distort the wave (make it steeper, see also chaper 3.5).

3 - Thirdly we need a slope from deep water to the shallow part. This slope has three functions:
- it will cause shoaling (chapter 3.3)

- when the slope is not too long, the friction does not get much chance to take energy out of the wave.
- the velocity will increase when water is flowing upto the slope, because the cross-section decreases.

  Hence the velocity-head will increase rapidly and the wave front will get steeper (more than the distortion mentioned under 2).
  Probably you remember this from basic hydraulics, where this was mentioned with backwater curves (fig. 4.16).

4 - It helps when there is a narrowing at the end of the slope, for example a river entrance.



FIGURE

DIFFERENT KINDS OF BACKWATER CURVES, A2 is bore.

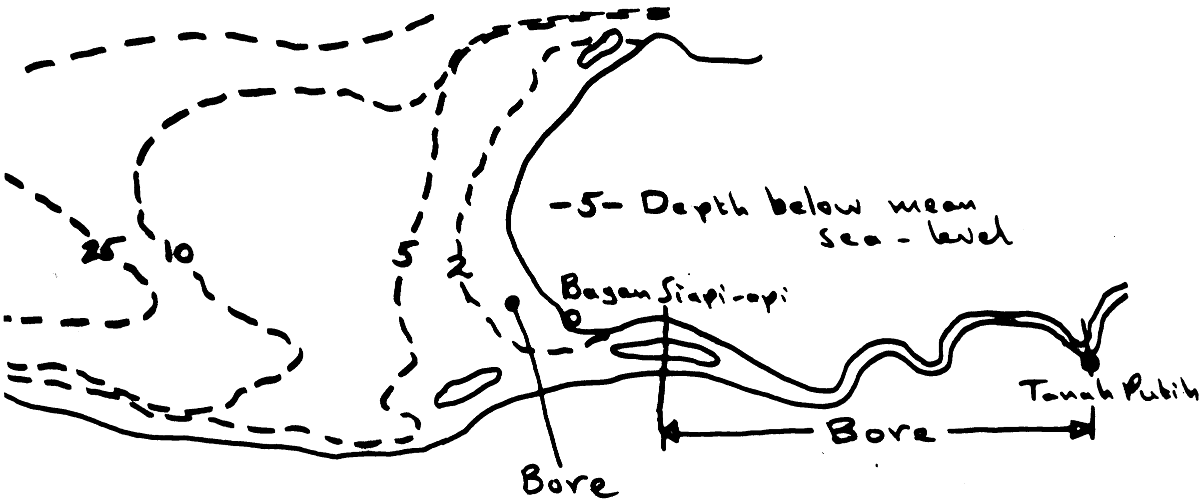


Fig. 4.17 Situation and location of Bores in the Rokan

On fig. 4.17 and 4.3 we see that these conditions are indeed present at the Rokan. It is reported that a bigger river discharge on the Rokan also helps to create a (greater) bore. This also decreases the celerity.

Since the watervelocity in the bore-front is about equal to the celerity we can expect high velocities with a lot of turbulence, because of the breaking. Together with the almost vertical wave-front, this makes a bore dangerous for small ships. It also causes intensified sediment transport making the gullies and riverbanks in the area rather unstable.

After the passage of the bore, the velocities will decrease again. The high turbulence together with the bottom friction take a lot of energy out of the wave. This results in a strong damping and gradually the bore dies out.

Unfortunately there are no registrations of the bore on the Rokan or Kampar. Fig. 4.18 gives waterlevels on the Hooghly river in India. h_o is at the mouth, h_1 halfway and h_2 at Calcutta where a bore exists. The increase of the tide between h_o and h_1 is probably due to shoaling. Fig. 4.18 also gives a velocity registration in the Hooghly bore.

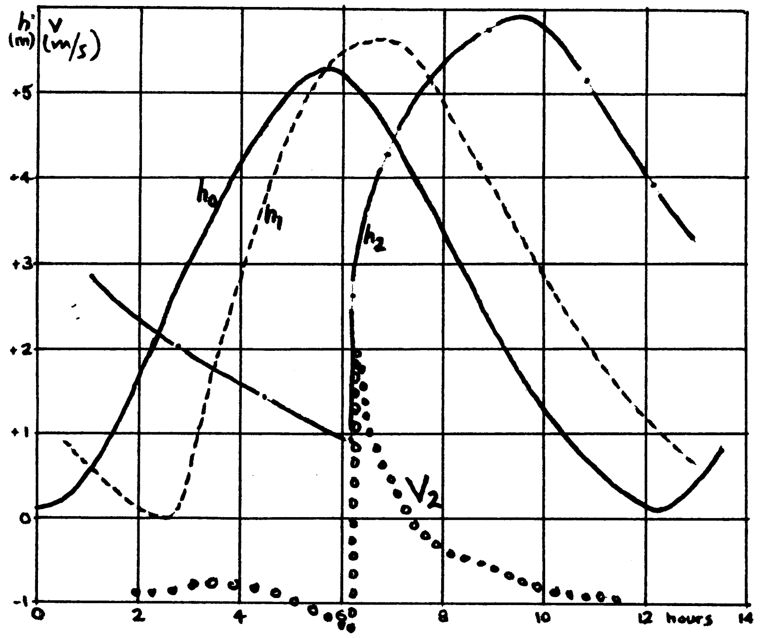


Fig.4.18 Waterlevels and velocity in the Hooghly river

Since the conditions necessary for a bore are so strict, relatively small changes can make a bore disappear. On the Seine in France there used to be a bore which almost disappeared due to dredging. To kill the Rokan bore this would be a very expensive solution, but it is probably possible to avoid bores in the canals of units along the Rokan. By making them deep enough it is possible to decrease v and increase c such that a bore coming from the Rokan will die out quickly in the unit. Calculations will be necessary to establish the required depth. Another solution is to situate the bottom of the canal high enough to prevent the bore to enter; in other words: the canal bottom must be above bore-level. (See fig. 4.18, a bore occurs at relatively low level). In this solution the canals will be completely dry during low water.

5. OTHER MOVEMENTS OF THE WATERSURFACE.

There are movements of the watersurface not caused by sun and moon. Wind (indirectly caused again by the sun), seismic forces etc. can also result in waves. Some of them will be mentioned here. Partly because they are closely related to tidal registrations, partly to get a better understanding of waterwaves in general.

5.1 Wind surges.

Wind blowing over a watersurface gives a slope to this surface and causes a current. This slope makes equilibrium with the bottom friction of the current (fig. 5.1).
From this figure you can understand that the slope will be greater when the waterdepth is smaller (more friction).
In the deep ocean we will therefore not notice any slope, only in shallow seas.

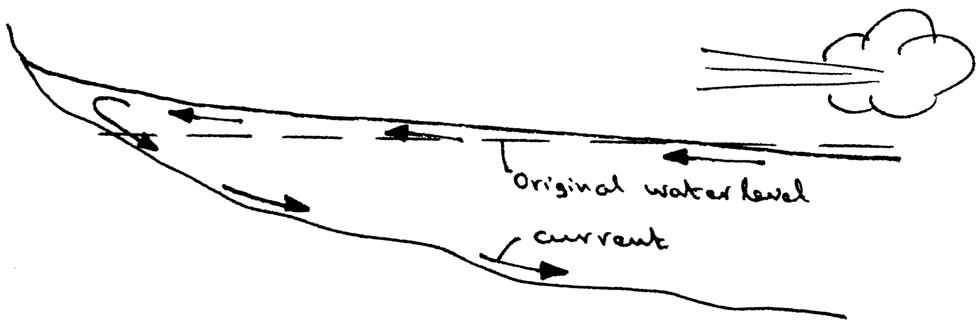


Fig. 5.1 Effect of wind blowing over water

Winds of short periods, storms etc., give non periodic movements of water (inpredictable on long term, because the winds are inpredictable). Monsoon winds can be predicted more or less. Fig. 5.2a and b give predictions for mean waterlevels in January and July, together with the prevailing wind direction.
Check again.Fig. 5.3 gives the predicted and registrated mean waterlevel in the mouth of the Banyuasin (Sumsel). Beside the periodic movement there are also non-periodic movements of some days. These non-periodic "waves" are often called: wind surges.

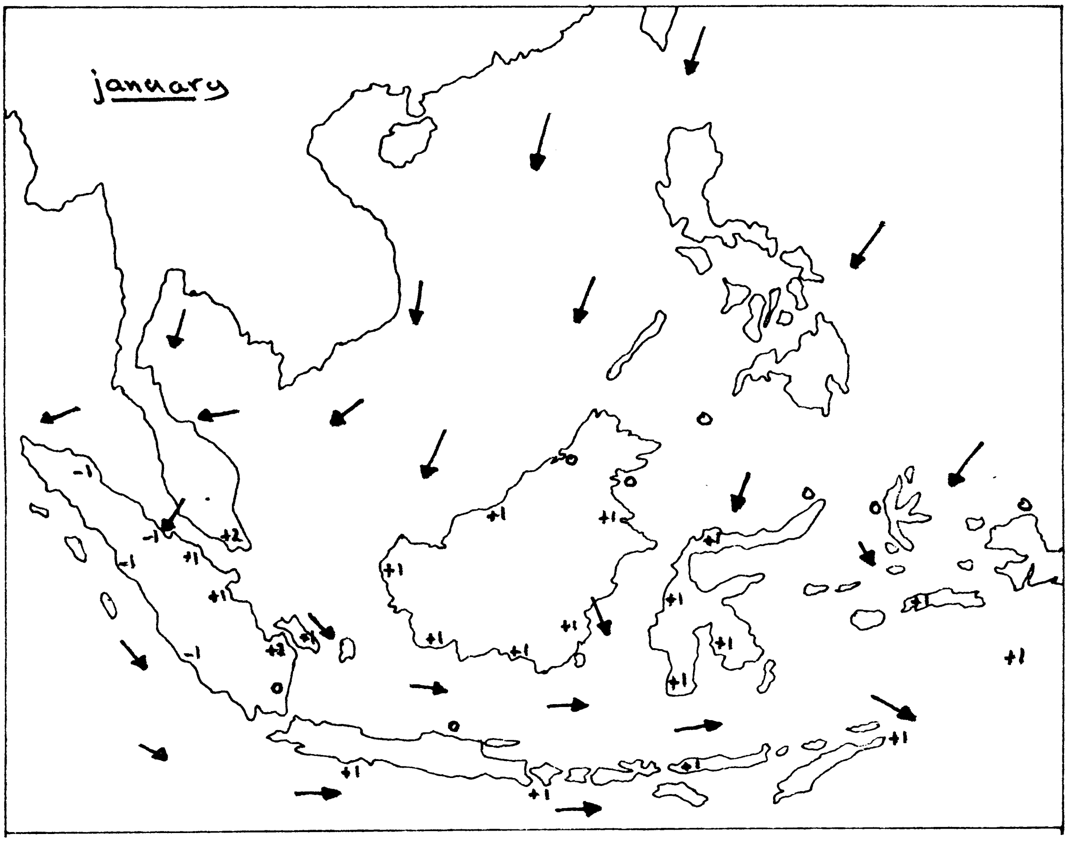


Fig. 5.2a

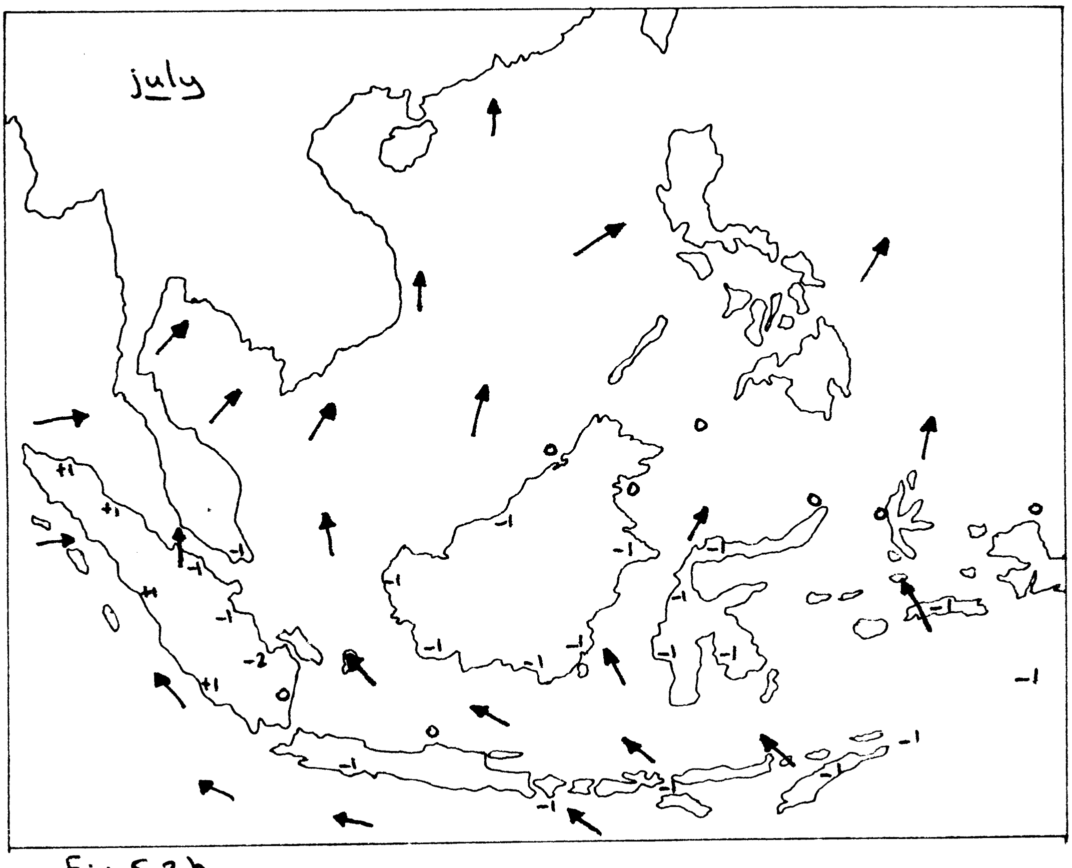
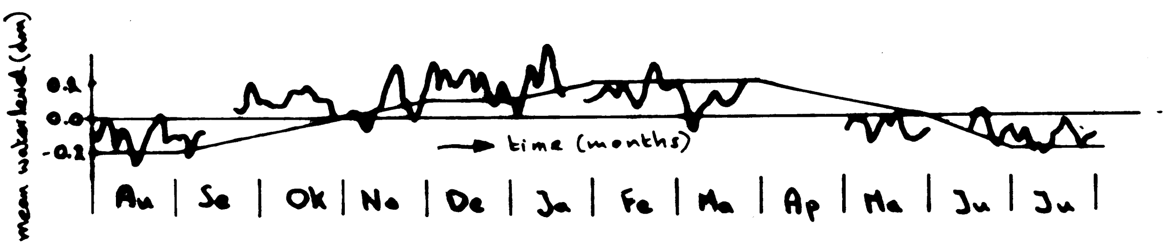


Fig. 5.2b

Fig. 5.2 Monsoon winds and predicted effect on average waterlevels



Influence of wind on daily mean waterlevels

—— registration mouth Banyuasin

—— prediction mouth Musi

Fig.5.3 Predicted and registrated average waterlevel

5.2 Wind waves.

Wind also causes waves. Although these waves are outside the scope of this course, some remarks are made to indicate the differences with tidal waves.

Tidal waves are so-called long waves, while wind waves (off-shore) belong to the short waves. Long and short are relative to the depth:

Long wave	:	$L/d > 25$
Intermediate wave	:	$2 < L/d < 25$
Short wave	:	$L/d < 2$

The movements in these waves are different.
In short waves the water particles describe circles, in intermediate waves ellipses and in long waves (almost) straight lines. Fig. 5.4 give the movement of water-particles on the surface of a short wave. (Note again the difference between V and C). These circles get smaller under the surface and below $\frac{1}{2}L$ there is no movement at all. (fig. 5.5). (Because of this, a cook on a submarine has a much easier job than his colleagues on normal ships).

When a short wave comes in shallow water, the wave starts to "feel the bottom" and the circles become ellipses, while at the bottom they are forced to be straight lines (fig. 5.6). In very shallow water, or in a very long wave, the ellipses become almost straight lines. In a tidal wave for example, the ellipse on the water-surface is about 1 or 2 m high and may be 50 km long.

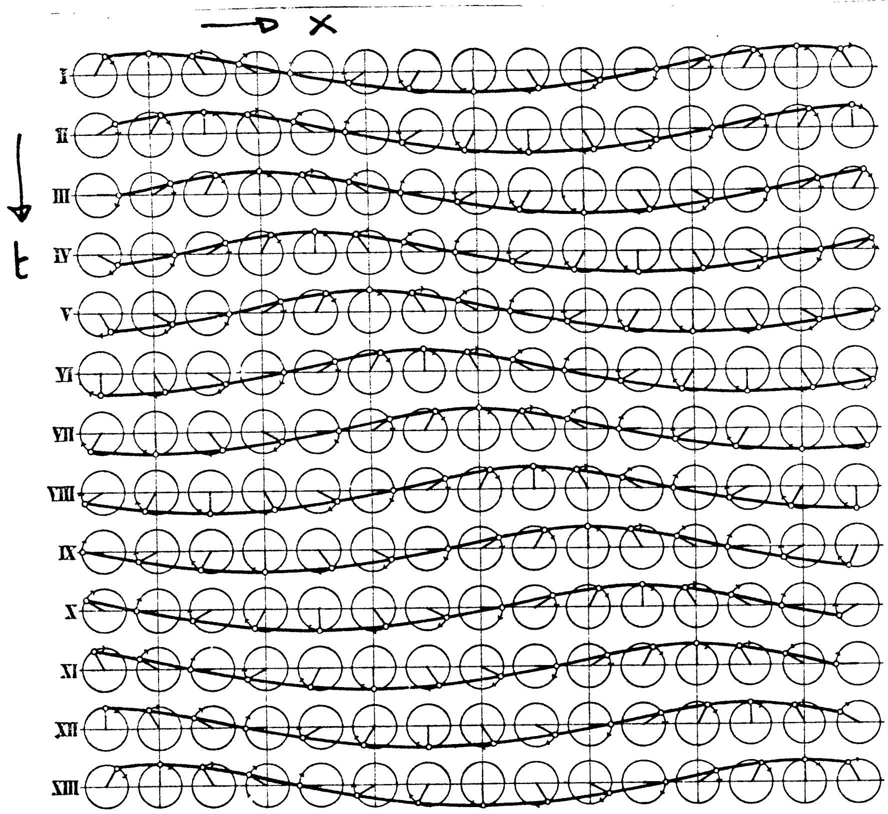


Fig. 5.4 Movement of surface particles in a short wave

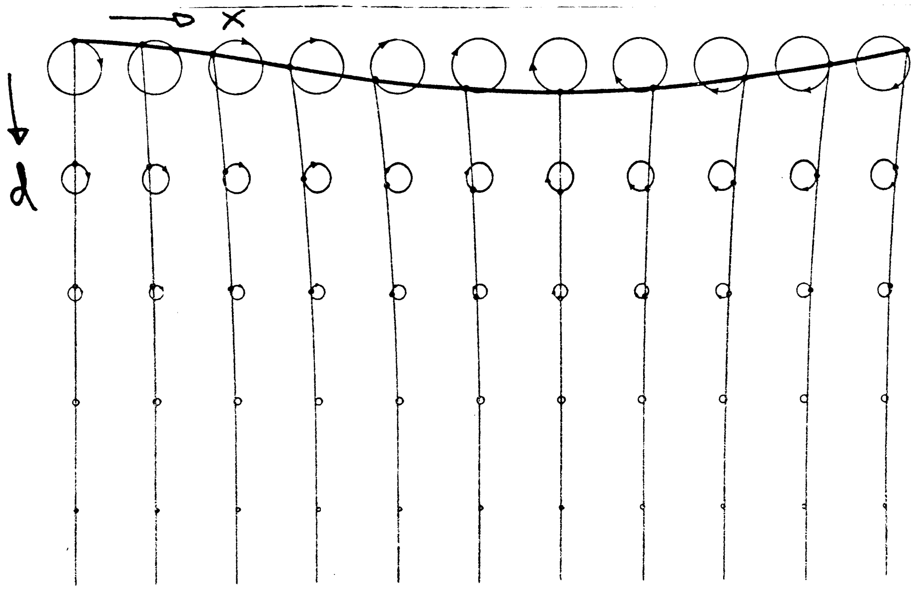


Fig. 5.5 Movement of particles in a short wave

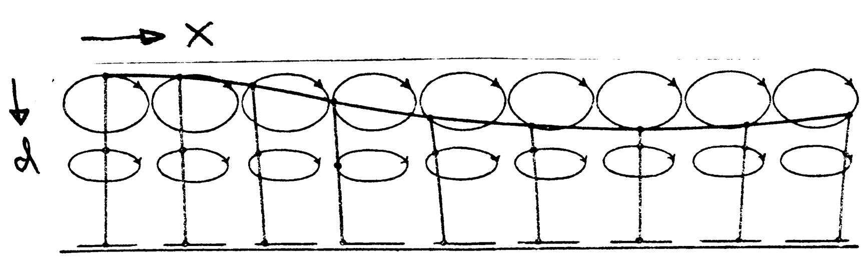


Fig. 5.6 Movement of particles in intermediate and long waves

The same difference as in particle paths can be seen in the pressure under a wave (fig. 5.7). The increase and decrease in pressure is felt over the full depth in a long wave, so we can assume normal hydrostatic pressure. This facts makes tidal computations easier than short wave computations.

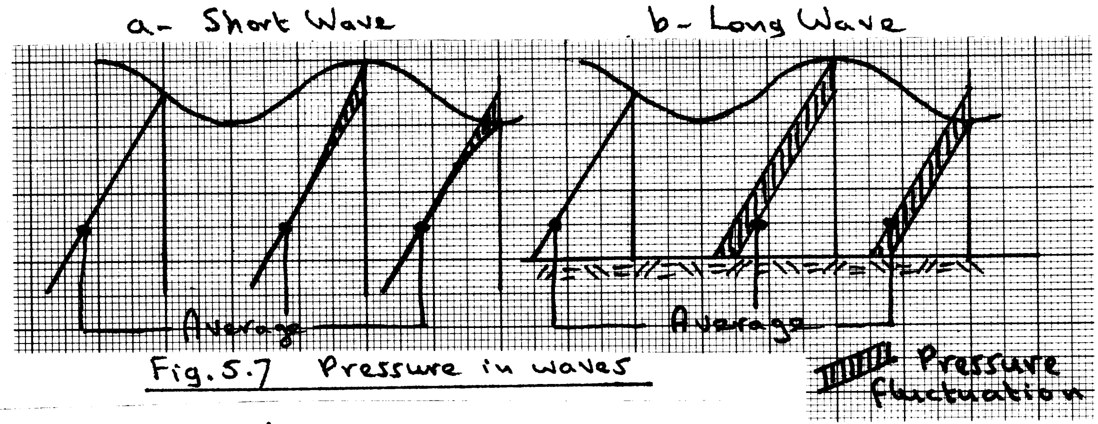


Fig. 5.7 Pressure in waves

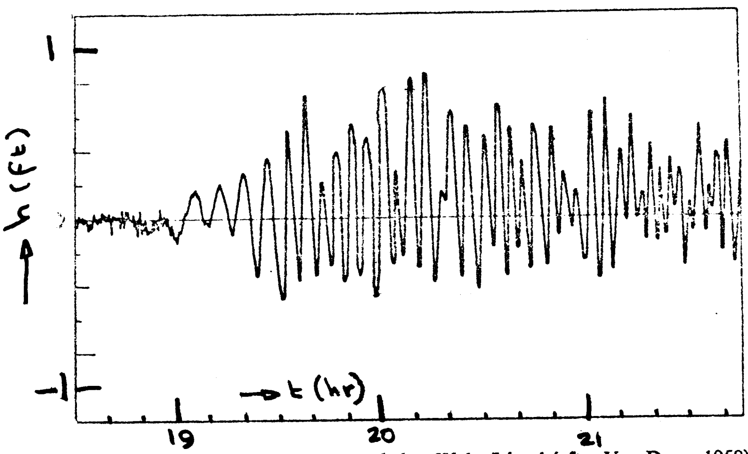
5.3 Tsunamis.

Tsunamis are waves with a period of about 10 to 50 minutes. Much shorter than tidal waves, but still long waves in the sense of chapter 5.2.

Of the about 200 tsunamis known up to 1950, 25% occured in Indonesia. So it is reasonable to spend a few words on this phenomena in this course.

A tsunami can originate from a volcanic eruption under water or sudden seismic movements, or a big piece of land sliding in the sea etc. A very big tsunami occured when the Krakatau exploded in 1883. The last one was in the summer of 1977 which caused much damage on Sumbawa. At the origin tsunamis are rather small waves, only a few decimeter high. Due to shoaling etc. they can get much higher. As an example is given a registration of a tsunami in 1957 given in two locations, one in deep water, one in Hilo bay on Hawai (fig. 5.8).

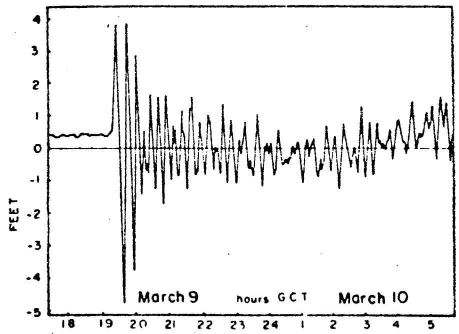
There is not much you can do about tsunamis. They travel very fast through the deep seas ($c = \sqrt{gd}$) and it is difficult to say where they will cause problems.



(a) Tsunami of March 9, 1957, as recorded at Wake Island (after Van Dorn, 1959)

Fig. 5.8

Tsunami records



(d) Record of the tsunami of March 9, 1957, from the Hilo tide gage. Time is 10 hours ahead of Hawaiian time. Period 1st to 2nd crest; 19 minutes. 1st wave highest (Courtesy, U.S.C. & G.S.)

5.3 Flood waves.

When heavy rainfall occurs during a certain period on an area, the rivers in that area will have to carry this water to the sea. This can result in an increase of the discharge and the waterlevel in the river. When the rain has stopped again the situation returns to normal (whatever that may be). This is called a flood wave (fig. 5.9). In fact the same applies as for wind-surges: inpredictable on long term. Again however monsoon influences have periods of one year. To predict these monsoon flood waves a lot of data are needed over many years. See also fig. 3.6 in these lecture notes and chapter 3.4 Hydrographs in "General aspects of rivers and deltas" by D. Gersie.

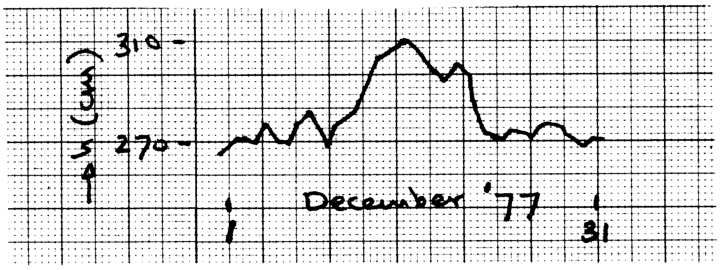
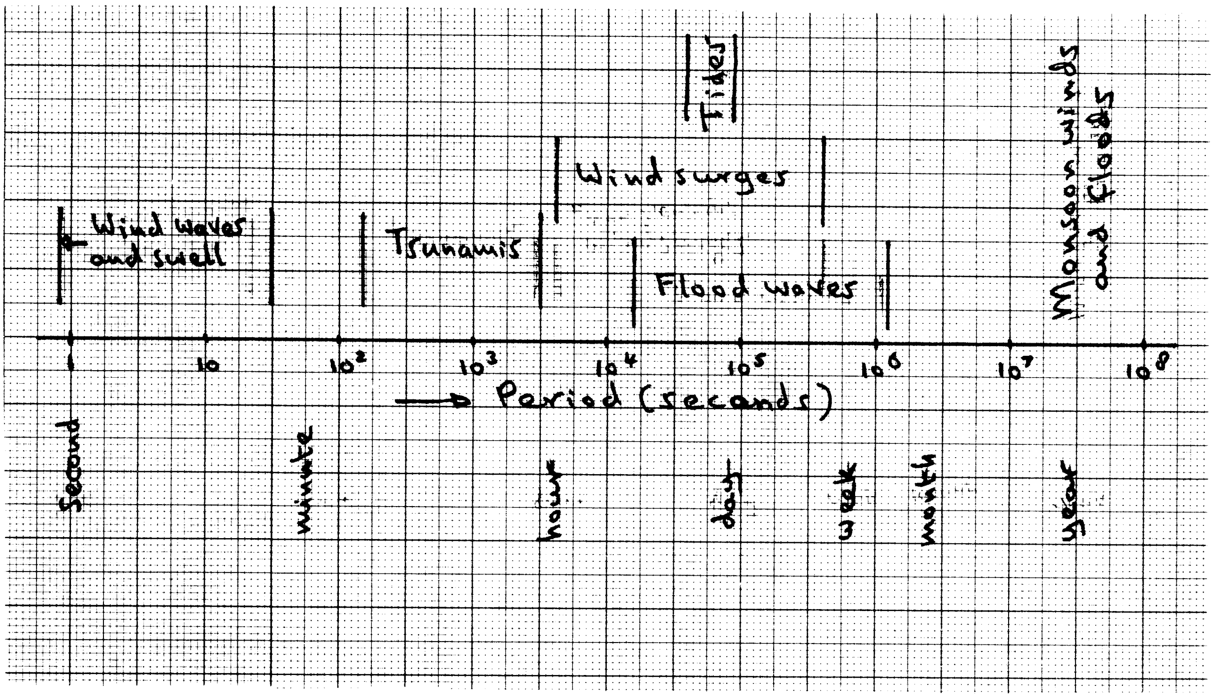


Fig. 5.9 Daily average of water level on the Lalang

5.4 The family of water waves.

In fig. 5.10 a simple division is made between the different kinds of waves , ranging from 1 second to 1 year. These very long waves we hardly recognize as waves any more, but in fact they are.



6. MEASURING AND USE OF TIDAL DATA.

It is clear that when a design is made for an agricultural unit in a tidal area, data about the tidal movement are necessary. These data can either be used directly for design purposes or after a more or less complicated elaboration, like a mathematical model. We will shortly review the problems and possibilities.

6.1 Waterlevel registrations in relation to design.

Basis for everything are waterlevel registrations. Possibilities for drainage and irrigation depend heavily on waterlevels. This also means that waterlevel registrations are useless if there is no relation with the level of the soil in the area.

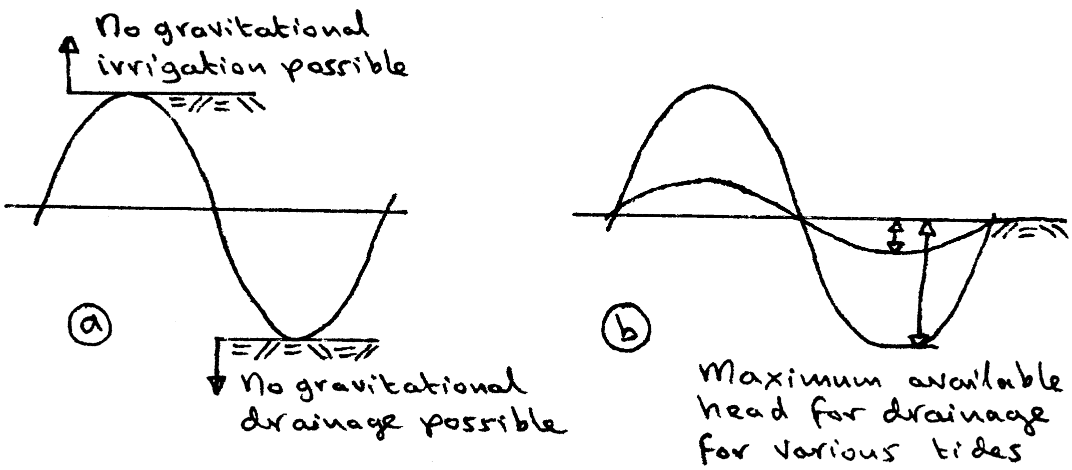


Fig. 6.1

Fig. 6.1a indicates this very clearly and simply for the extremes. In between it is not so easy to tell. In the case of drainage, when it is possible to keep the flood outside by means of some construction, a high amplitude is better than a small one, because the available head is bigger (fig. 6.1b).
In the following some examples will be given.

At the Punggur river in Kalbar a unit of 80 ha will be made (we start small). The land is situated about 0.2 m above the average waterlevel in the wet season (which is different every year, but we also start simple).

With small dikes a waterlevel of 0.25 m is maintained on the sawahs. For the design of the drainage-system we take a rainfall of three days, the shape of which is given in fig. 6.2.
The waterlevel on the sawahs should not become too high and not too long above the ideal level of 0.25. (These criteria should be well defined by an agricultural expert. The author of these notes does not claim any knowledge).

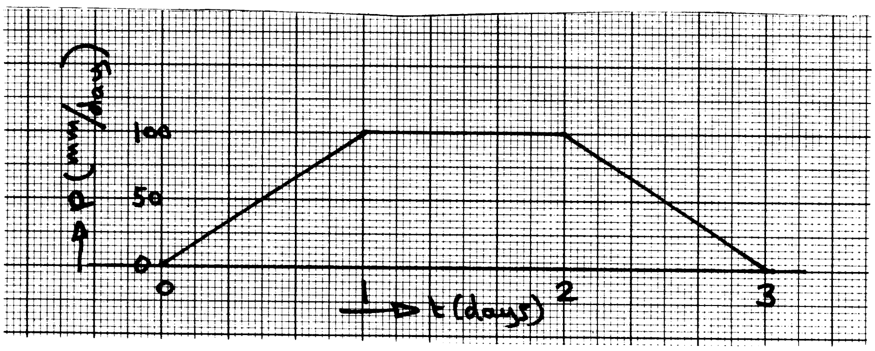


Fig. 6.2 Assumed rainfall for design

First we consider a drainage canal of 1 x 1 m^2. In fig. 6.3a are given the waterlevel on the Punggur, the waterlevel at the end of the canal and on the sawahs. (Changes due to neap and spring are also neglected for the sake of simplicity). We see that when the rain starts there is no longer a difference between the waterlevel on the sawah and at the end of the canal. This means the resistance is too big, the waterlevel on the sawah becomes very high and remains high during three days. This is probably too bad. A canal of 3 x 1 m^2 makes the situation better (fig. 6.3b). (These examples should not exactly be used for a design. They are only meant as an illustration).

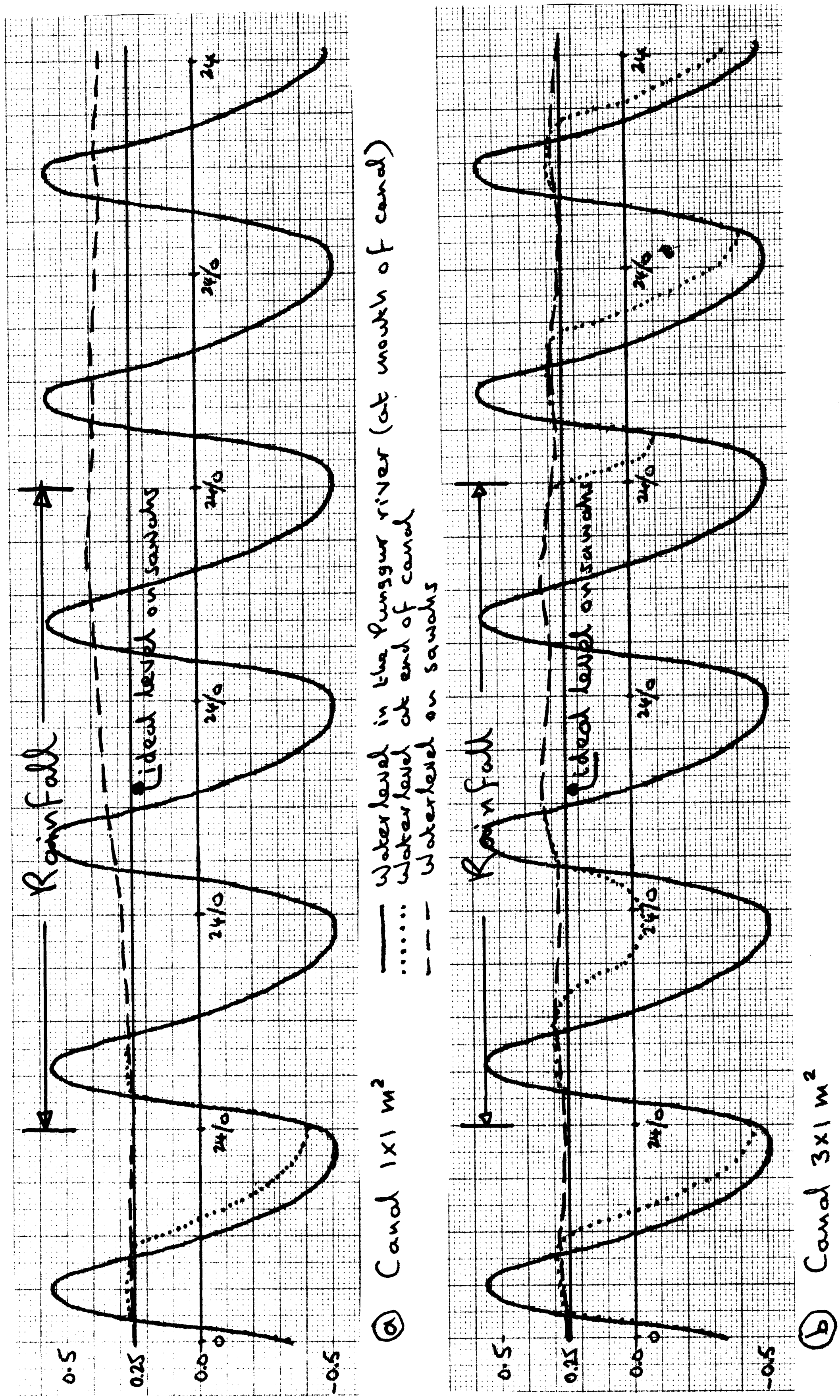


Fig. 6.3 Drainage design 1

At a nearby location the sawah-level is 0.25 m lower. Fig. 6.4a gives the result for a canal 3 x 1 m^2. Now the drainage is not enough, while it looked okay for the previous case. We again enlarge the canal and make it 6 x 1 m^2 (fig. 6.4b). But this does not help very much either.

The soil level is so low that the average waterlevel on the sawahs remains relatively high. In a bigger canal the water does not only flow out more easily, but the flood can enter easily too. To understand this, you can think of a sawah laying on LW-level. Even with a very big canal the average waterlevel on the sawah will be about equal to the average level on the river, only the tide is damped somewhat. So, the waterlevel on the sawah is always (too) high.

A better solution in this case is when we make a construction in the canal through which water can flow out, but not flow in. (Aeroflap-gates or something the like).
A canal of 3 x 1 m^2 with such a construction is enough to give sufficient drainage (fig. 6.4c).
When the sawah level is much lower, like LW-level, the only solution is pumping.

The same approach, but in the other direction can be applied for irrigation. Now the water supply from the river must be enough to compensate the losses due to evaporation.

What can we learn from chapter 6.1?

1 - Waterlevel data (in all seasons, for drainage and irrigation) are very important.

2 - Relation between waterlevels and soillevels are equally important. So, accurate levelling of the soil and the staff-gauge should be done.

3 - In fact a general design, independent from waterlevels and soillevels is impossible.

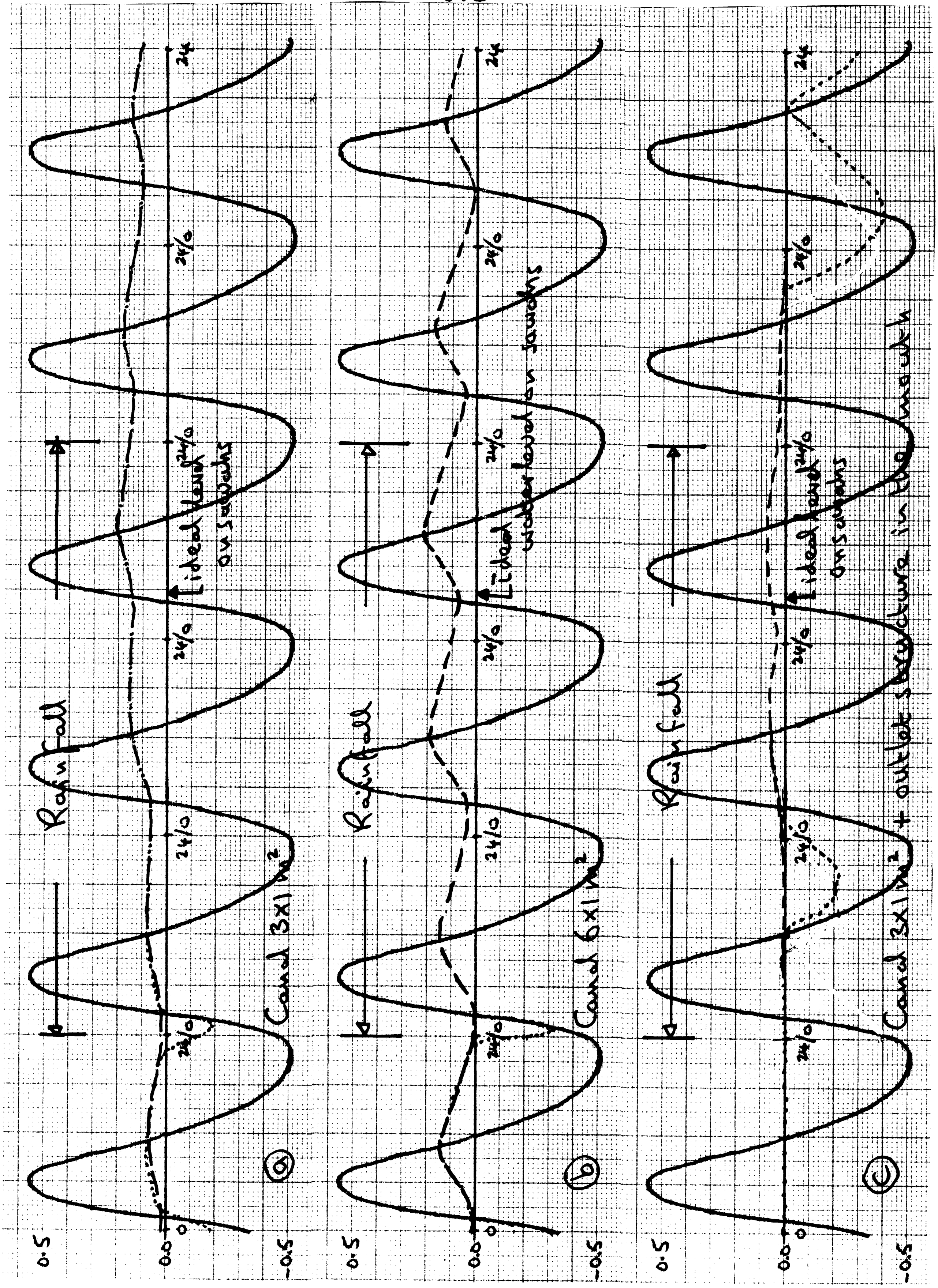


Fig. 6.4 Drainage design 2

Explanation see fig. 6.3

Because of this, waterlevel data are collected in the fråmework of the P4S/BTA-60 project. The registrations should preferably cover several years. In the central office the registrations are corrected and elaborated, giving averages, maxima and minima etc. In addition levelling of the soil surface should be done. It is better to have some reliable results than a lot of measurements that cannot be trusted.

6.2 Something more about levelling

1 - Water that is not flowing has a horizontal level, hence the name "waterpas". So, when we have a situation like in fig. 6.5 and we dig a canal that has a fixed depth below soillevel instead of a horizontal bottom, we get parts which have no drainage at all. (Only through the soil, which goes very slowly.) This shows again the importance of waterleveldata combined with soillevelling.

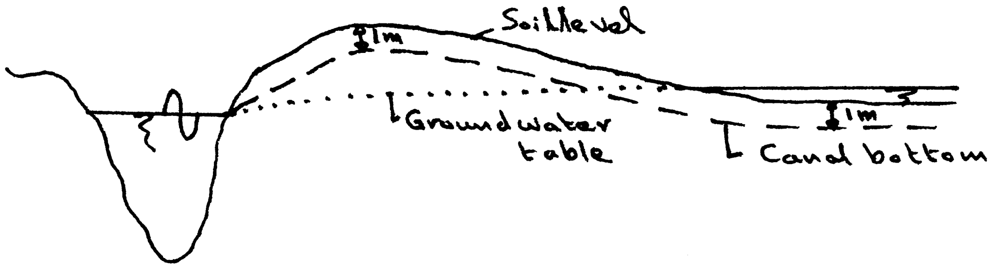


Fig. 6.5 Drainage problem

2 - As a basis for levelling a so-called reference level is used. This can be any chosen level, but it should be the same level for all places within the considered area. Often used is the average waterlevel at the mouth of a river, named mean sea level. The mean water level in other places along the river is not the same as mean sea level, because the water in a river flows and that means there is a slope. See fig. 3.6 and 3.7a. So, calculating the mean level at different locations is not enough. The staff-gauges should be connected by means of levelling. There is unfortunately no other way.

6.3 Measuring of velocities and discharges.

Velocities and discharges have a somewhat lower priority. Normally discharges are only necessary if there are doubts about the availibility of fresh water in the dry season. When we have to make a mathematical model of a river (see chapter 6.4) also discharges are necessary for calibration of the model. When sedimentation or erosion plays a role, velocities become very important. See the lecture notes about sediment.

6.4 Mathematical models.

Any calculation, even a very simple one, is in fact a mathematical model. For simple designs a piece of paper, if necessary with a pocket calculator, is enough. The examples in chapter 6.1 are already rather complicated to do it that way. When a whole unit has to be calculated or a river we need a computer. The examples in chapter 6.1 and in 3.6 were calculated with the program Penpas (Penghitungan Pasang Surut).

This program solves the hydrodynamic equations which describe the motion of fluids in long waves (equation of motion and equation of continuity) numerically.

To make a numerical model of a river system it is necessary to divide the river into different nodes and branches, which is called the schematization. In the nodes the waterlevels are computed and in the branches the discharges and velocities. This schematization forms a reasonable representation of the river geometry like width, depth, storage, etc. At the borders of the model boundary conditions are given, which normally consist of measured waterlevels or discharges (and salinities). To be sure that the model reproduces nature correctly it is necessary to calibrate the model. This means that calculated values along the river are compared with measured values and that parameters like roughness (or diffusion coefficient) are adjusted, because these parameters initially can only be estimated roughly.

As an example of the use of mathematical models, calculations for the Lalang river in South Sumatra are given.

The schematization is given in fig. 6.6, while fig. 6.7 gives some examples of schematized river cross-sections. The results of the calibration of the model are given in fig. 6.8a,c With this model a calculation is made for the influence of improved drainage at the upper Lalang on the waterlevels (and hence the drainage possibilities) in the lower Lalang.

To do so, first a computation with a high wet season discharge was run (estimated with the waterlevel registrations in the Lalang) for the situation without improved drainage. Next a run was made with the same model but with extra discharge in some drainage points. Comparison of the waterlevels in the two cases give the extra rise in waterlevel due to improved drainage (fig. 6.9).

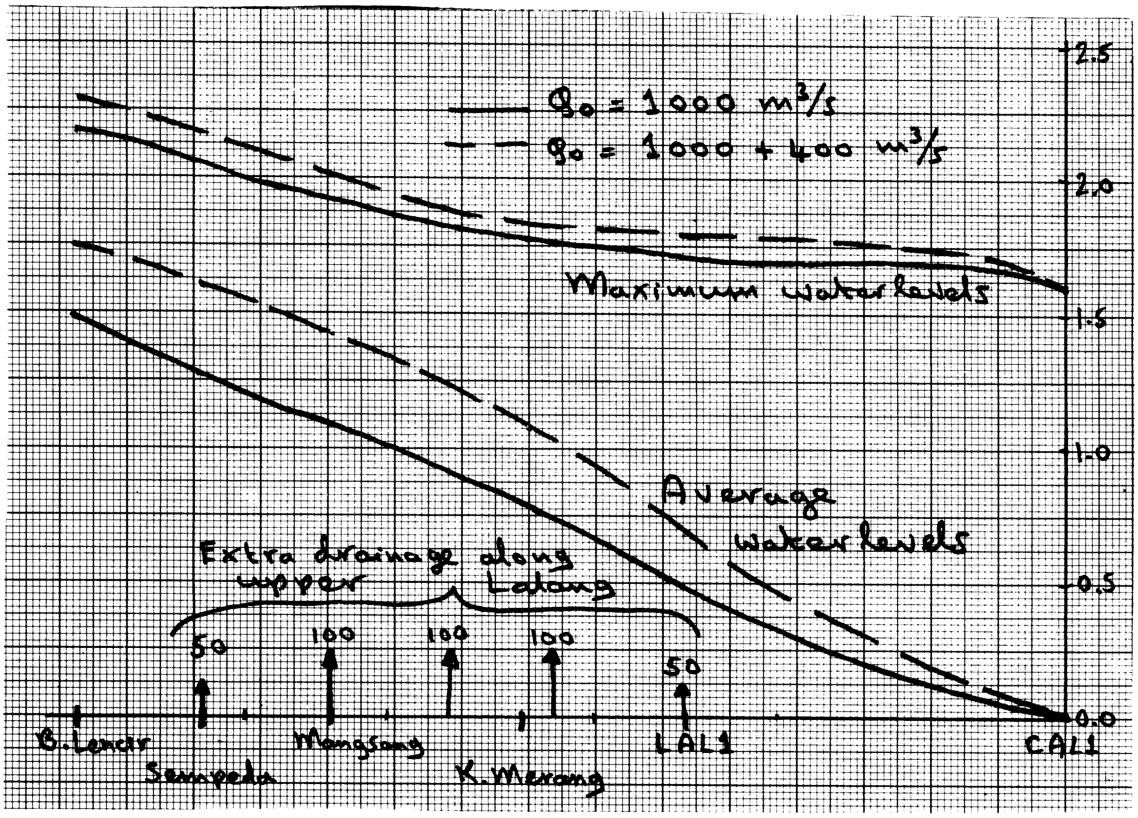
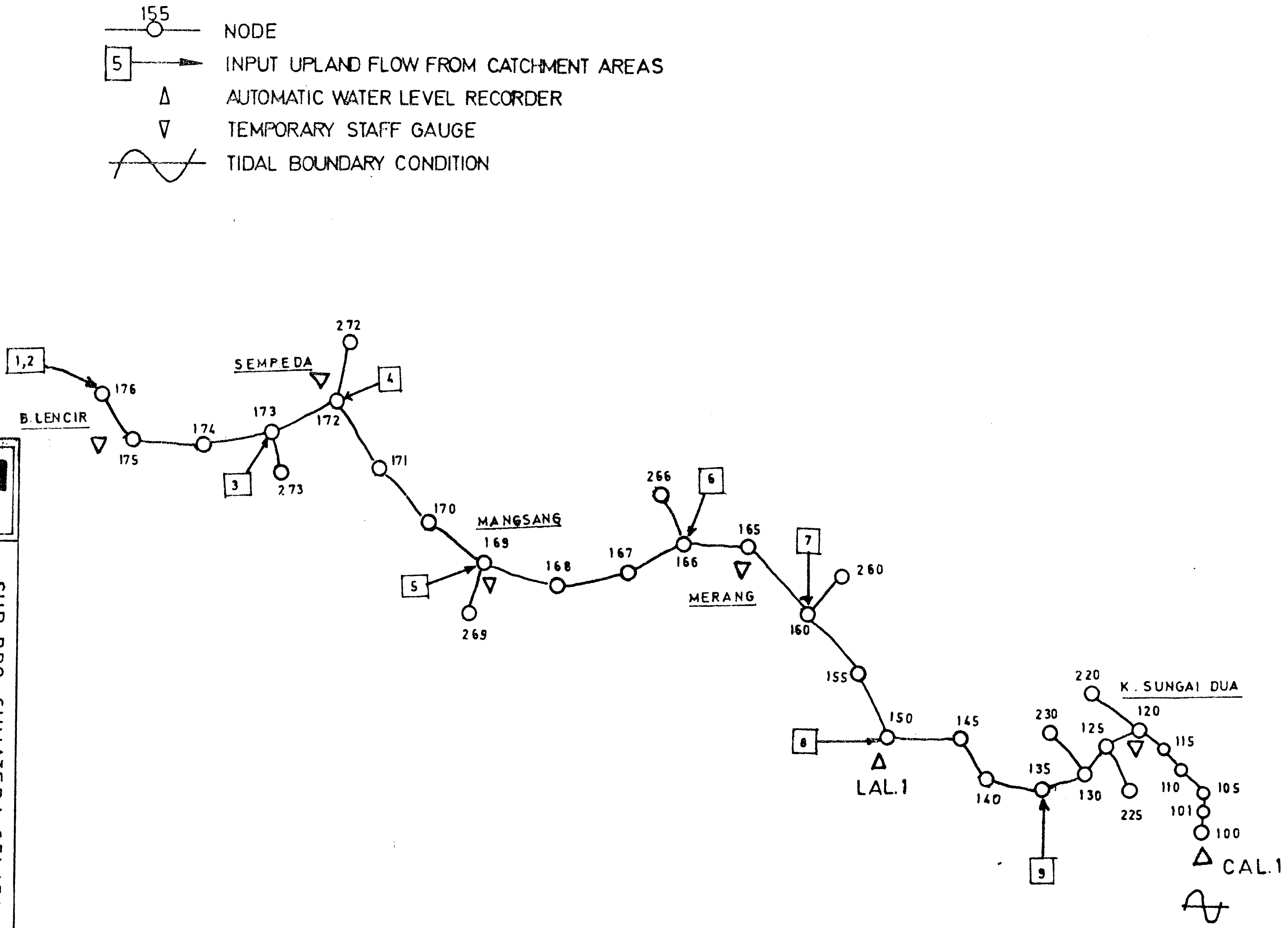


Fig. 6.9 Effect of drainage improvement on waterlevels at Lalang river



SUB. PRO. SUMATERA SELATAN

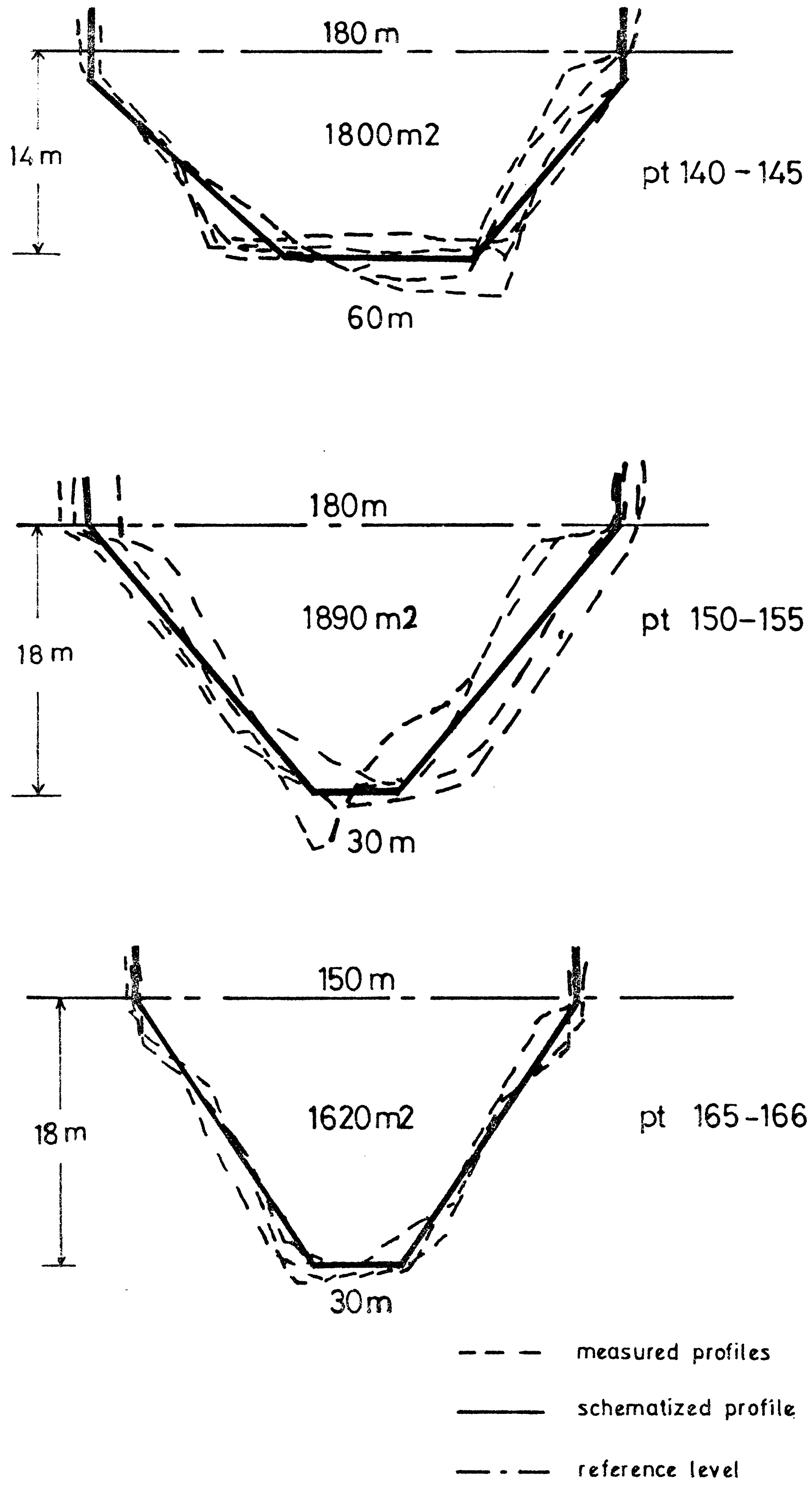
P4S HYDROMETRIC AND HYDRAULICS PROJECT

SCHEMATIZATION LALANG RIVER
FOR MATHEMATICAL MODEL

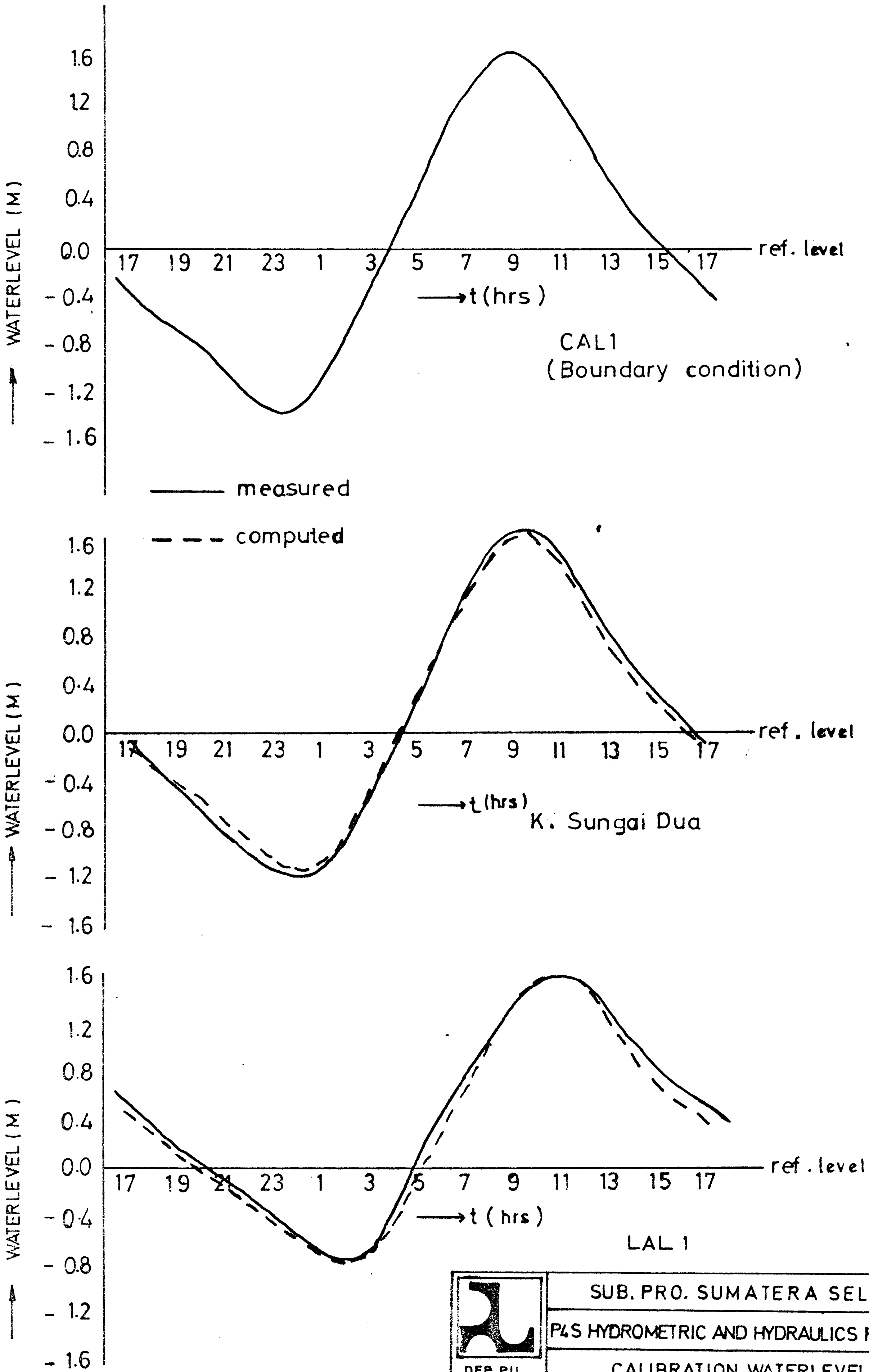
DEP. PUTL
P4S/DPMA
BTA-60

DATE

FIG. ~~26~~ 6.6



DEP. PU P4S/DPMA BTA-60	SUB. PRO. SUMATERA SELATAN
	P4S HYDROMETRIC AND HYDRAULICS PROJECT
	EXAMPLES OF SCHEMATIZED BRANCHES
	DATE · FIG 276.7



SUB. PRO. SUMATERA SELATAN

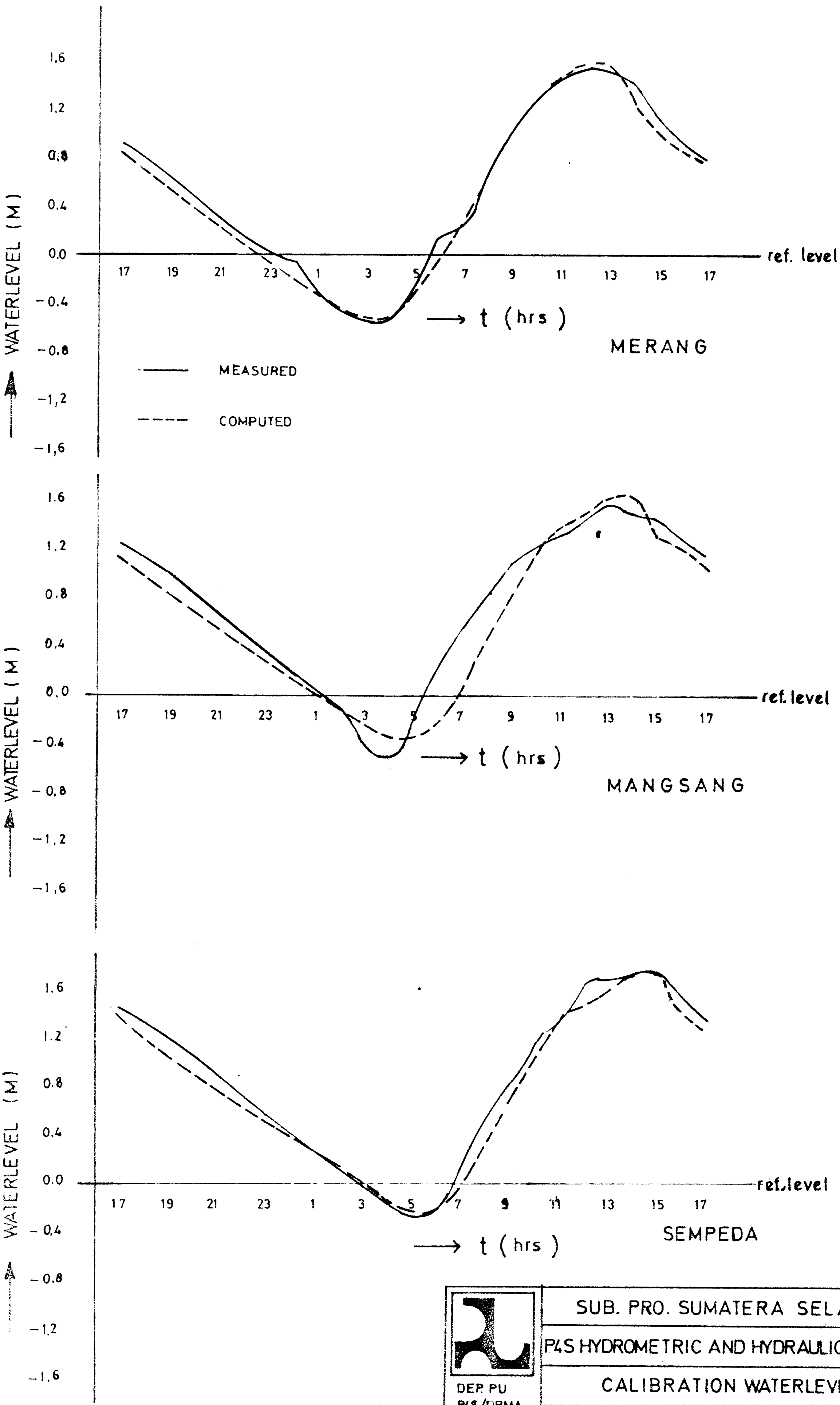
P4S HYDROMETRIC AND HYDRAULICS PROJECT

CALIBRATION WATERLEVELS

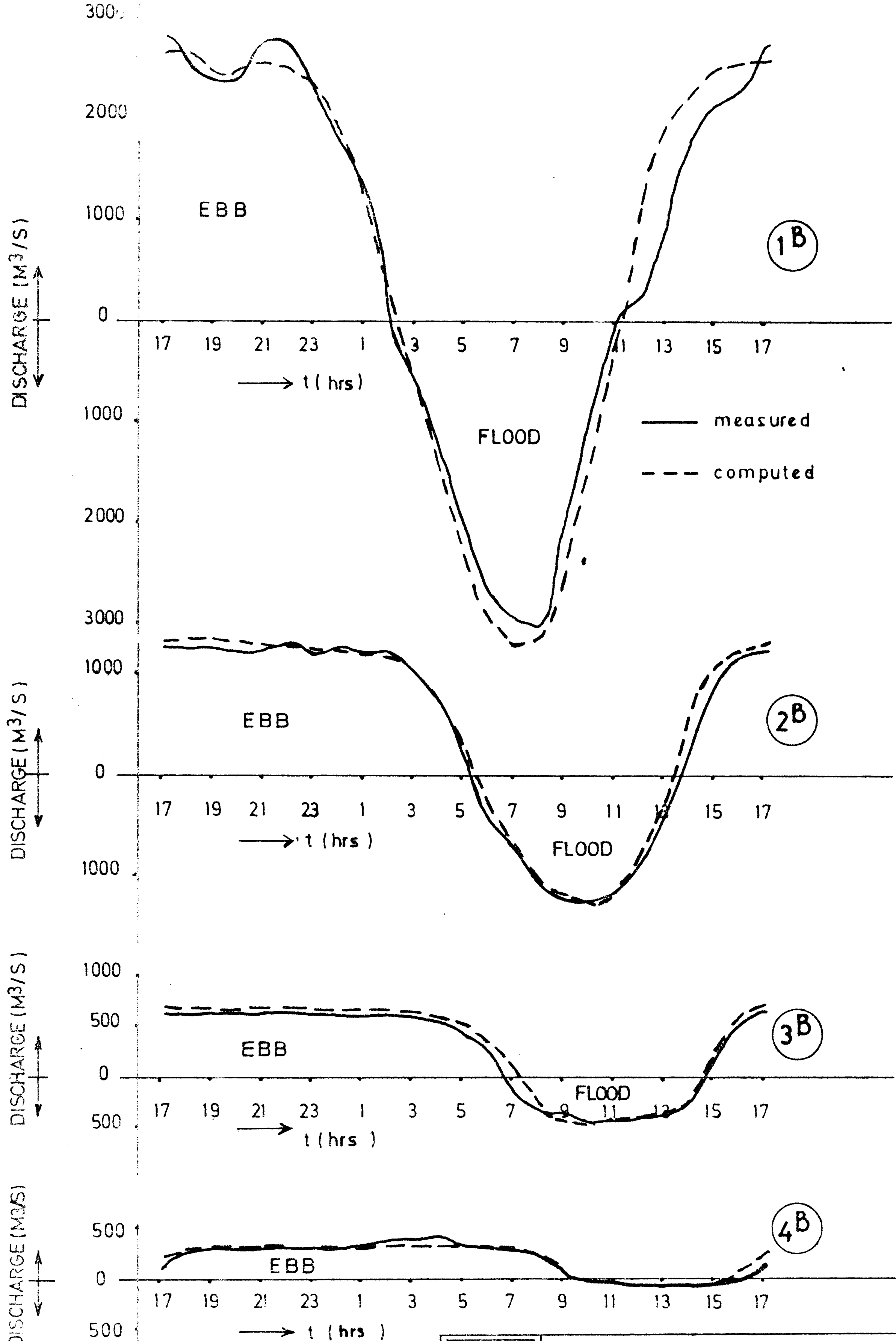
DEP. PU
P4S DPMA
BTA-60

DATE 23/24 - 1 - 1978

FIG ~~2.8~~ 6.8a



DEP. PU P4S/DPMA BTA-60	SUB. PRO. SUMATERA SELATAN
	P4S HYDROMETRIC AND HYDRAULICS PROJECT
	CALIBRATION WATERLEVELS
	DATE 23/24 - 1 - 1978 — FIG. ~~28~~ 6.8b



DEP. PU P4S/DPMA BTA-60	SUB. PRO. SUMATERA SELATAN
	P4S HYDROMETRIC AND HYDRAULICS PROJECT
	CALIBRATION DISCHARGES
	DATE 23/24 - 1 - 1978 — FIG ~~3~~26.8c

6.5 Influence of extra storage on tidal flow.

To conclude these notes we will have a look into the effect of making units along the rivers or more in general the effect of enlargement of the water storage in tidal areas. This is only meant as an introduction to the courses about salinity and sediments.

Without giving formulae we can say that an increase in storage area will also increase the tidal flow through the canal or construction that connects the area with the tide outside. So, the velocity in a canal with a "kolam" will be higher than without it. And also the ebb and flood discharges (velocities) through a river mouth will increase when a lot of units are connected with the river. As an illustration the velocity at the end of a canal with and without "kolam" is given in fig. 6.10.

Possible consequences for erosion and salt intrusion will be discussed in the courses on those subjects.

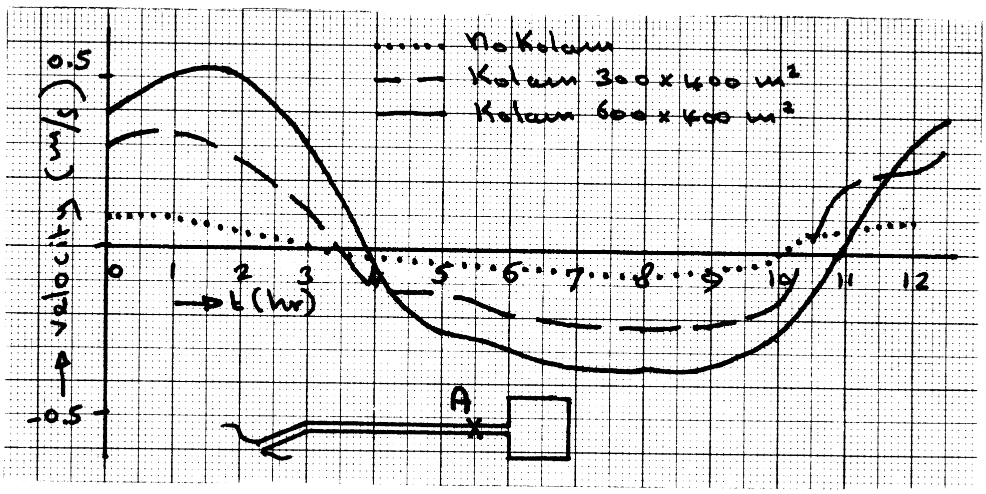
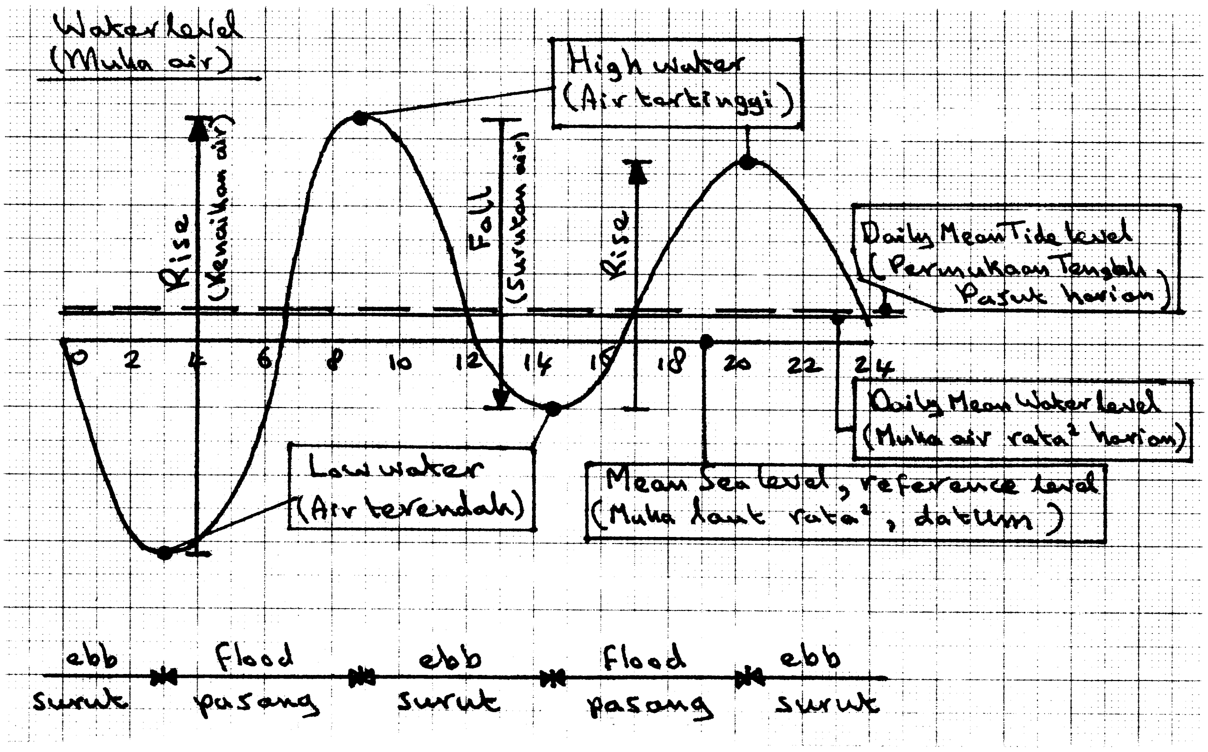
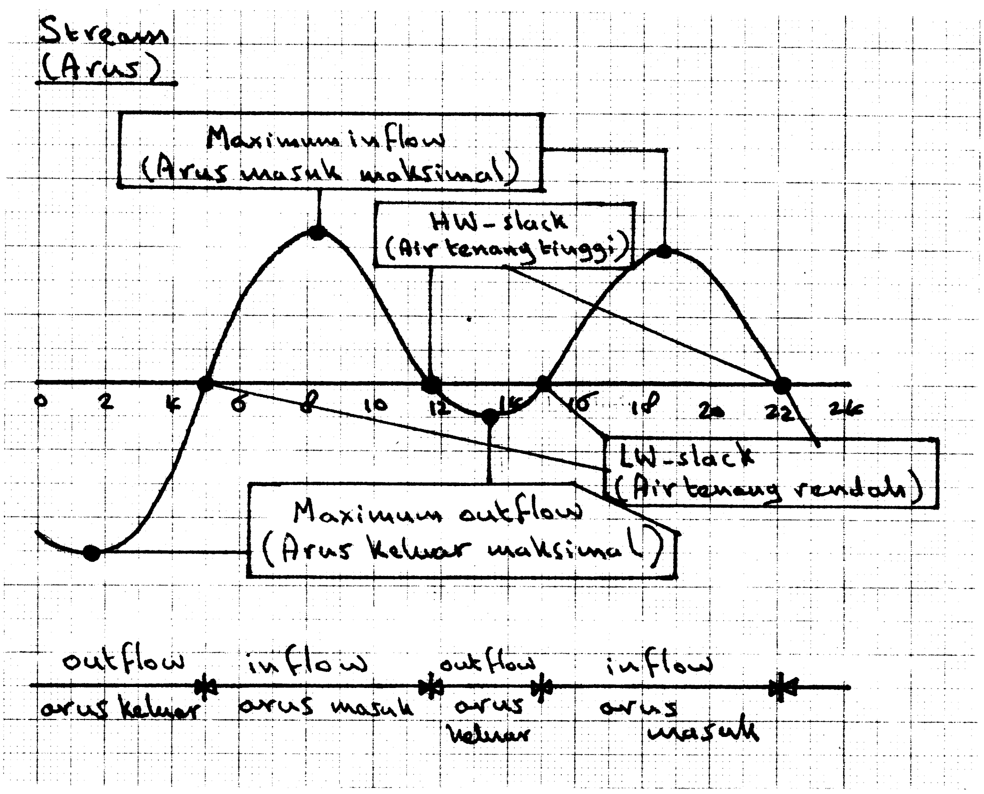
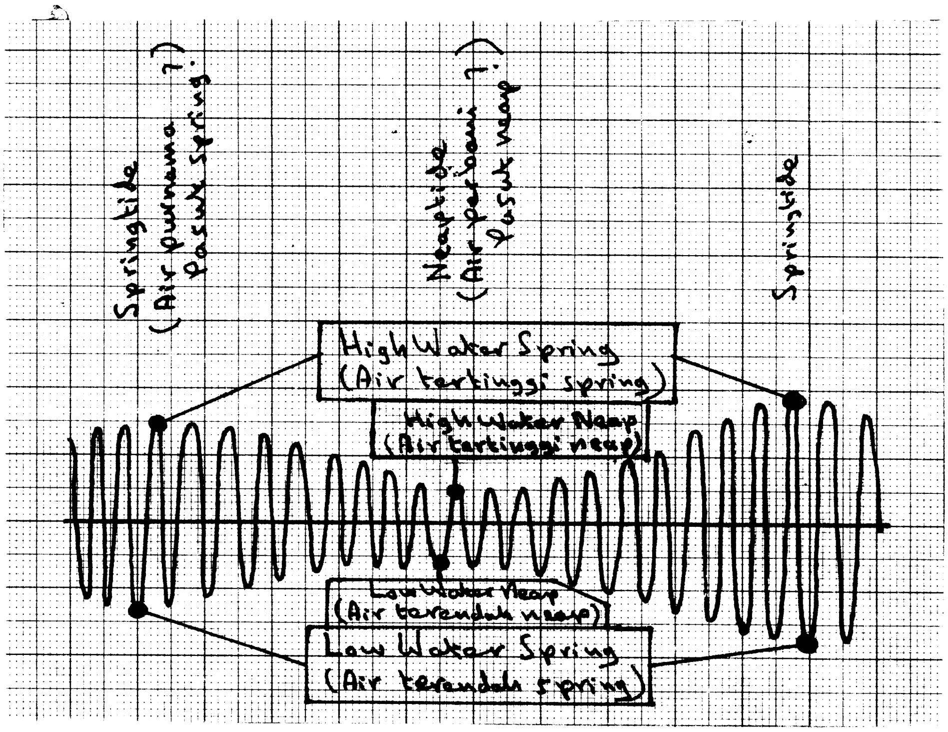


Fig. 6.10 Velocity in pt. A, influence of storage area.

Annex I Definitions







Mean Water Level (MWL)	Average waterlevel within a certain period in any place $\left(\int_0^T h/T\right)$
Mean Tide Level (MTL)	Average of HW and LW within a certain period in any place. $\left(\sum_{i=1}^{n} (HW+LW)/n\right)$
Mean Sea Level (MSL)	Average waterlevel at sea or rivermouth within a long period (several years) $\left(\int_0^T h/T\right)$
Mean Low (High) Water (MLW, MHW)	Average of all Low (High) waterlevels within a long period.
Mean Low (High) Water Spring (MLWS, MHWS)	Average of all Low (High) Water Springs within a long period.
Mean Low (High) Water Neap (MLWN, MHWN)	Average of all Low (High) Water Neaps within a long period.
Mean Range	MHW + MLW
Mean Spring Range	MHWS + MLWS
Mean Neap Range	MHWN + MLWN
Amplitude	Half Range
LW(HW)-slack	Slack after LW(HW)

Annex II

Available books for further study.

(See also: List of available books, etc. in library BTA-60)

Writer/editor	Title	Subject of chapter	Library number
British Admiralty	Manual of tides	2, 3, 4.4, 5.1	B1.1
Dronkers	Tidal computations in rivers and coastal waters	2, 3, 4.4, 5.4, 6.5	B3.2
Ippen	Estuary and coastline hydrodynamics	2, 3, 5.1, 5.2	A1.2
Henderson	Open channel flow	5.4	A1.3
Hsu a.o.	Irrigation and drainage in tidal regions	6.1	F.27
British Admiralty	Manual of hydrographic surveying	6.1, 6.3	A2.1a, b
Gersie	Hydrometry in tidal areas	6.1, 6.2, 6.3	A2.11
Defant	The tides of the East Indian archipelago	4.1	B2.14
Ievyevich	Unsteady flow in open channels	6.4	B3.1a, b, c
TNO	Hydraulic research for water management	6.4	A3.2

ANNEX III Kamus kecil

attraction force	gaya tarik gravitasi
amplify	kuatkan
apogee	jarak bulan-bumi terbesar
beats	layangan
celerity	kecepatan rambatan
celestial bodies	bintang², benda² angkasa
crest	puncak
damping	peredaman
distortion	pengobahan bentuk
equator	khatul'istiwa
equilibrium	kesetimbangan
forced oscillations	getaran oleh gaya dari luar
free oscillations	getaran bebas
friction	gesekan
lunar	dari bulan
natural period	periode alami
perigee	jarak bulan-bumi terkecil
perpendicular	tegak lurus
point of gravity	titik berat
pole	kutub
pressure	tekanan
principal	utama
progressive wave	gelombang maju
reflection	pantulan
slope	kemiringan
solar	dari mata hari
standing wave	gelombang tegak
steep	curam

Annex IV

Dari: Sears/Zemansky, Fisika untuk Universitas, Jakarta 1962

5-5 Hukum Newton tentang gravitasi djagad. Dalam peladjaran tentang Mekanika, ber-kali2 kita djumpai gaja2 sebagai akibat tarikan gravitasi antara bumi dengan benda2 dipermukaannja. Gaja2 ini disebut berat dari benda itu. Sekarang akan kita bahas peristiwa gravitasi ini dengan agak lebih mendalam.

Hukum gravitasi djagad ditemukan oleh Sir Isaac Newton dan pertama kali diumumkannja pada tahun 1686. Hukum itu bunjinja :

Setiap partikel materi dalam alam semesta menarik partikel2 materi lainnja dengan gaja jang berbanding lurus dengan hasilkali massa partikel2 itu dan berbanding terbalik dengan kwadrat djarak antaranja.

$$F \propto \frac{mm'}{r^2}$$

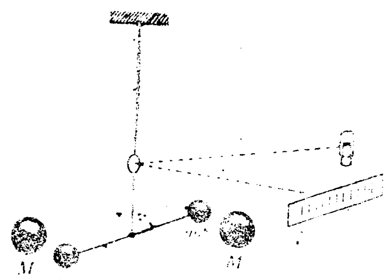
Perbandingan diatas dapat dirubah mendjadi sebuah persamaan dengan mengalikannja dengan konstante G jang disebut konstante gravitasi.

$$F = G\frac{mm'}{r^2} \qquad (5\text{-}5)$$

Dikisahkan bahwa Newton menjimpulkan hukum ini berdasarkan duga-dugaannja ketika melihat buah apel jang djatuh dari pohonnja kebumi. Tetapi, perhitungan2nja jang mula2 diumumkannja sebagai pembuktian hukum tersebut, adalah mengenai gerak bulan mengelilingi bumi.

Harga numerik konstante G itu tergantung dari satuan2 jang digunakan untuk gaja, massa dan djarak. Besarnja dapat ditentukan setjara eksperimen dengan mengukur gaja tarik gravitasi antara dua benda jang massanja m dan m' sudah diketahui pada djarak antaranja jang diketahui pula. Pada benda2 jang berukuran sedang gaja ini ketjil sekali, tetapi dapat djuga diukur dengan alat jang ditjiptakan Rev. John Michel, meskipun Sir Henry Cavendish laku jang pertama kalinja memakai untuk tudjuan tersebut dalam tahun 1798. Coulomb-pun djuga mempergunakan alat sematjam ini untuk menjelidiki gaja tarik dan gaja tolak listrik dan magnit.

Neratja Cavendish itu terdiri dari dua bola ketjil bermassa m (Gmb. 5-2), umumnja dibuat dari emas atau platina jang dipasangkan pada pangkal dan udjung sebuah batang horisontal dan ringan. Batang ini digantungkan pada tengah2nja dengan benang halus jang vertikal, misalnja benang dari kwarts. Sebuah tjermin ketjil jang dilekatkan pada benang tadi memantulkan berkas tjahaja kesebuah mistar. Tjara memakai timbangan ini seperti berikut. Dua bola besar bermassa m', biasanja dari timah hitam, diletakkan seperti dalam gambar. Gaja2 tarik gravitasi antara bola2 besar dan bola ketjil menimbulkan sebuah koppel jang menjebabkan benang dan tjermin terpuntir lewat sudut ketjil. Gerak puntiran ini menggerakkan berkas tjahaja tadi sepandjang mistar.



Gmb. 5-2. Azas neratja Cavendish.

Gerak berkas tjahaja itu dapat dibuat tjukup besar, kalau dipakai benang jang halus sekali, sehingga gaja2 gravitasi tersebut dapat diukur dengan tjukup teliti. Diukur dengan tjara ini, konstante gravitasi ternjata sama dengan

$$G = 6{,}670 \times 10^{-8} \text{ dyne. cm}^2/\text{gm}^2$$
$$= 6{,}670 \times 10^{-11} \text{ newton. m}^2/\text{kg}^2.$$

TJONTOH: Hitunglah gaja tarik gravitasi antara bola besar dan bola ketjil sebuah neratja Cavendish, bila $m = 1$ gm, $m' = 500$ gm, $r = 5$ cm. (Dua bola jang saling tarik-menarik massanja masing2 se-olah2 terkumpul dipusat masing2)

$$F = \frac{(6{,}67 \times 10^{-8} \text{ dyne.cm}^2/\text{gm}^2) \times (1 \text{ gm}) \times (500 \text{ gm})}{(5 \text{ cm})^2} = 1{,}33 \times 10^{-6} \text{ dyne},$$

atau kira2 seperdjuta dyne !

6-3 Gaja sentripetal. Karena persamaan untuk pertjepatan partikel jang bergerak dalam lingkaran sudah kita ketahui, sekarang dapatlah kita gunakan hukum kedua Newton untuk menghitung gaja resultan jang bekerdja padanja. Besarnja pertjepatan itu sama dengan v^2/R dan arahnja kepusat, sebab itu besarnja gaja resultan pada benda bermassa m ialah

$$\Sigma F = m \frac{v^2}{R} \tag{6-9}$$

Arah gaja resultan djuga kepusat. Gaja ini dinamakan gaja sentripetal. (Sebenarnja kurang tepat, sungguhpun sudah lazim, untuk menjamakan gaja ini dengan kata sifat „sentripetal", se-olah² ada perbedaan sifat antara gaja sentripetal dengan gaja² lainnja; tidaklah demikian halnja. Seperti gaja² lainnja, gaja sentripetal itupun merupakan gaja tolak dan gaja tarik jang dikerdjakan oleh tongkat dan tali, atau sebagai akibat gaja gravitasi atau sebab² lainnja. Istilah „sentripetal" menundjuk pada efek gaja, artinja, menimbulkan perubahan dalam hal arah ketjepatan benda jang dipengaruhinja dan bukan perubahan dalam hal besar ketjepatan itu).

Seseorang jang me-mutar²kan dalam lingkaran seutas tali jang pada udjungnja diikatkan sebuah barang, akan merasakan, bahwa memang perlu mengerdjakan gaja sentripetal jang menudju kepusat itu. Bila tali itu putus, arah ketjepatan tidak ber-ubah² lagi (ketjuali kalau ada gaja² lain bekerdja) dan benda itu lalu melajang sepandjang sebuah garis singgung pada lingkaran

TJONTOH 2. Gaja sentripetal jang menjebabkan bulan tetap dilintasannja, ialah gaja tarik gravitasi jang dikerdjakan oleh bumi terhadap bulan. Tundjukkanlah, bahwa massa bumi dapat dihitung, apabila diketahui konstante gravitasi G, djari² lintasan bulan R dan waktu edar bulan T.

Misalkan m_E ialah massa bumi dan m_M massa bulan. Djadi

$$\Sigma F = m \frac{v^2}{R},$$

$$G \frac{m_E m_M}{R^2} \text{ (1)} = m_M \frac{(2\pi R/T)^2}{R} \text{ (2)}$$

dan sebab itu

$$m_E = \frac{4\pi^2 R^3}{GT^2}.$$

ini relasi antara gerakan bulan dan dunia. (1) = F_a = $F_{sentripetal}$

(2) = F_c = $F_{sentrifugal}$

Lihat bab 2.1

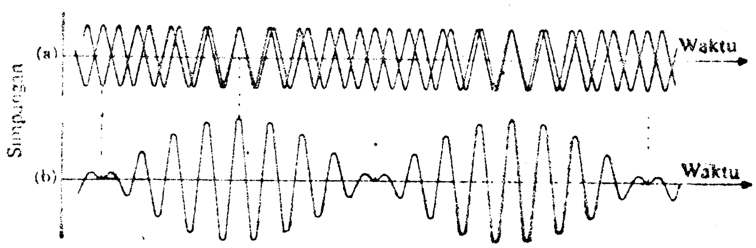
23-6 Lajangan (beats). Sebagai tjontoh interferensi telah kita singgung gelombang stationer dalam kolom udara. Interferensi itu timbul bila dua deretan gelombang jang sama amplitudo dan frekwensinja merambat lewat daerah jang sama dengan arah berlawanan. Sekarang kita bahas interferensi djenis lain, jaitu jang timbul bila dua deretan gelombang jang amplitudonja sama, tetapi frekwensinja sedikit berbeda, merambat daerah jang sama. Ini dapat terdjadi bila dua garpu nada jang frekwensinja berbeda sedikit, sekali dibunjikan atau djika dua kawat piano jang sedikit „tidak stem" kena satu pemukul.

Marilah kita tindjau suatu titik dalam ruang jang dilalui gelombang² itu pada waktu bersamaan. Gerak² melintang jang ditimbulkan oleh masing² gelombang digambarkan sebagai fungsi waktu pada grafik (a) dalam Gmb. 23-7. Djika pandjang total sumbu waktu menjatakan waktu satu detik, maka grafik² menggambarkan frekwensi² 16 get/det dan 18 get/det. Untuk memperoleh resultante getaran, kita gunakan azas superposisi, jaitu grafik (b). Disini kelihatan bahwa amplitudo berubah dengan waktu. Perubahan² amplitudo ini menimbulkan perubahan keras bunji, disebut *lajangan*. Dua helai dawai dapat distem hingga mempunjai frekwensi jang sama dengan menambah gaja tegangan pada salah satunja, seraja keduanja sama² dibunjikan sampai lajangan lenjap.

Timbulnja lajangan dapat diterangkan setjara matematik seperti berikut: Gerak² melintang jang disebabkan oleh dua gelombang jang sama² lewat satu titik dalam ruang ialah:

$$y_1 = A \cos 2\pi f_1 t, \qquad y_2 = A \cos 2\pi f_2 t$$

(amplitudonja dianggap sama)



Gmb. 23-7. Lajangan itu berupa ajunan amplitudo jang ditimbulkan oleh dua gelombang bunji jang frekwensinja berbeda sedikit.

Berdasarkan azas superposisi resultante gerak melintang itu ialah:

$$y = y_1 + y_2 = A\,[\cos 2\pi f_1 t + \cos 2\pi f_2 t]$$

dan, karena

$$\cos a + \cos b = 2 \cos \frac{a+b}{2} \cos \frac{a-b}{2},$$

maka

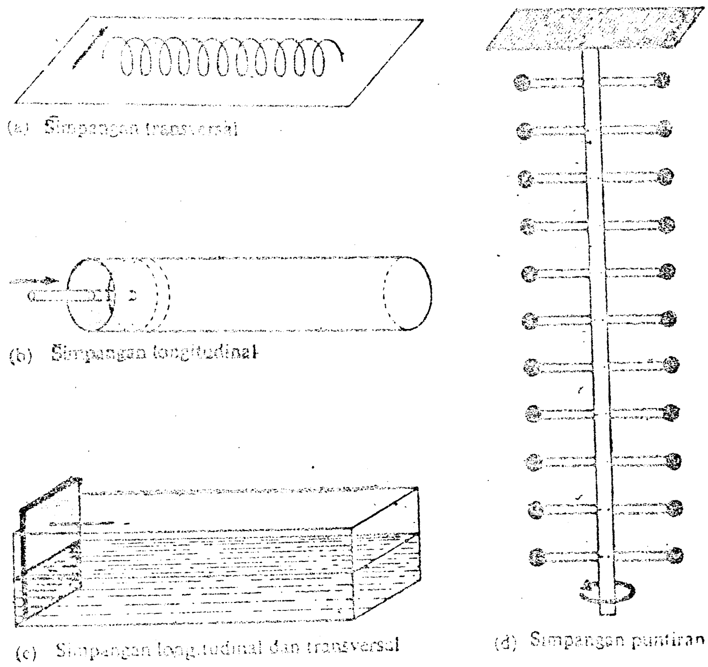
$$y = \left[2A \cos 2\pi \left(\frac{f_1 - f_2}{2} \right) t \right] \cos 2\pi \frac{f_1 + f_2}{2} t.$$

Getaran jang timbul lalu dapat dipandang sebagai getaran dengan frekwensi $(f_1 + f_2)/2$, atau frekwensi rata² kedua nada, dan dengan amplitudo menurut rumus diantara tanda kurung besar. Djadi amplitudonja ber-ubah² dengan waktu pada frekwensi $(f_1 - f_2)/2$. Djika f_1 hampir sama dengan f_2, maka nilai suku ini ketjil dan fluktuasi amplitudo amat lambat. Djika amplitudo besar, bunji akan keras, dan sebaliknja. Lajangan, atau amplitudo maksimum, akan timbul bila $\cos 2\pi \frac{f_1 - f_2}{2} t$ sama dengan 1 atau — 1. Karena tiap² harga ini timbul sekali sadja dalam satu getaran, maka djumlah lajangan per detik ialah dua kali frekwensi $(f_1 - f_2)/2$, atau *djumlah lajangan per detik sama dengan selisih frekwensi²*.

Ini sama dengan formula 2.1 (Bab 2.2) Periksa sendiri. $(f = 1/T)$

21-1 Rambatan gangguan dalam suatu medium. Dimisalkan suatu medium terdiri dari sedjumlah besar partikel² jang satu sama lainnja saling dihubungkan oleh bahan *elastik.* Bila salah satu udjung medium itu diganggu atau digerakkan setjara apa sadja, maka gerak ini tidak akan sekaligus kentara disemua bagian medium itu. Gerak awal akan menimbulkan gaja elastik pada bagian bahan jang terdapat dengan gerak awal itu, lalu pada bagian terdekat selandjutnja dan begitulah seterusnja. Dengan perkataan lain: *gerak itu akan merambat sepandjang medium dengan ketjepatan tertentu.*

Dalam gambar 21-1 (a), medium itu ialah sebuah pegas, atau boleh pula kawat jang ditegangkan. Bila udjung kirinja digerakkan sedikit dalam arah tegaklurus pandjangnja, maka gerak melintang ini akan timbul ber-turut² pada setiap gelung dan terdjadilah rambatan denjut melintang sepandjang pegas tersebut.



Gmb. 21-1. Rambatan gangguan.

Dalam Gmb. 21-1 (b) medium adalah tjairan atau gas didalam tabung. Udjung tabung sebelah kanan mati, sedangkan udjung sebelah kiri ditutup dengan piston jang dapat digerakkan. Bila piston digerakkan sedikit kekanan, maka merambatlah denjut memandjang lewat medium dalam tabung tadi.

Dalam Gmb. 21-1 (c) medium ialah tjairan didalam bak pandjang. Gerak mendatar dari sekeping kaju pada udjung sebelah kiri akan menimbulkan perpindahan pada tjairan, jaitu perpindahan memandjang dan perpindahan sedikit melintang. Gangguan ini akan merambat sepandjang medium.

Dalam Gmb. 21-1(d) medium ialah sedjumlah „dumbell" jang dipasangkan pada sepotong badja pandjang. Kalau dumbell jang paling bawah diputar sedikit timbullah gerak jang dinamakan *gerak puntir* jang akan mendjalar arah keatas medium dengan ketjepatan tertentu.

Dibawah ini akan ditundjukkan bahwa tjepatnja denjutan jang ditimbulkan oleh suatu gerak jang ketjil tergantung hanja dari sifat² fisis tertentu *dari medium sendiri* dan bukan dari tjepat gerak awal.

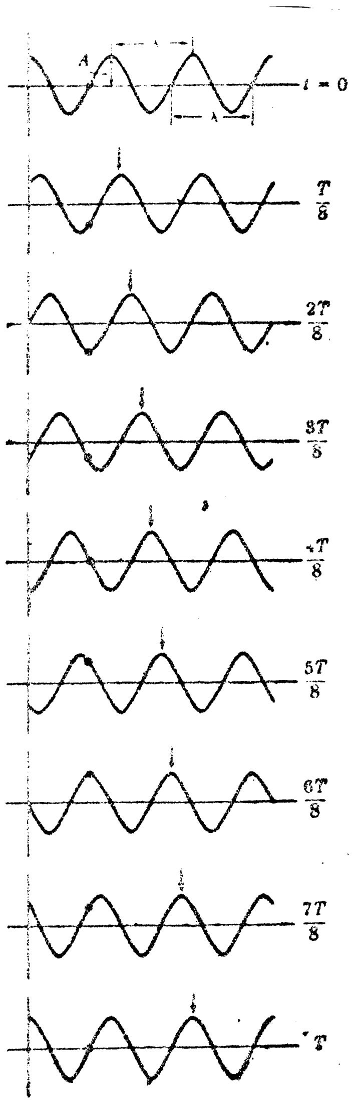
21-4 Gerak gelombang. Jang baru sadja kita bitjarakan ialah hanja gangguan paling sederhana jang dapat diberikan pada sutu medium, jaitu perpindahan transversal atau perpindahan longitudinal jang tunggal.

Sekarang misalkan salah satu udjung suatu medium digetarkan setjara berkala. Djadi y (baik melintang maupun memandjang) ber-rubah^2 dengan waktu menurut persamaan untuk SHM

$$y = A \cos 2\pi f t.$$

Dalam waktu setengah getaran merambatlah simpangan kesatu djurusan dalam medium dan selama setengah getaran lebihnja berlangsung simpangan kedjurusan jang berlawanan. Deretan gerak getaran tak putus jang timbul dan mendjalar dengan ketjepatan jang tergantung dari sifat^2 mediumnja. Deretan gerak getaran ini disebut *gelombang*.

Untuk djelasnja, misalkan salah satu udjung dawai jang terentang digetarkan setjara berkala dalam arah transversal dengan gerak getaran selaras (SHM): amplitudo A, frekwensi f dan periodenja $T = 1/f$. Dawai itu kita anggap sangat pandjang sehingga efek^2 pada udjung lainnja boleh kita abaikan sadja. Maka merambatlah tak putus^2 gelombang sinusoida sepandjang dawai tadi. Pada Gmb 21-4 diperlihatkan bentuk dari bagian dawai dekat udjung jang bergetar dengan selang waktu $^1/_8$ periodenja. Dawai itu dimisalkan sudah tjukup lama bergetar, sehingga, mulai dari djarak tak tertentukan dari udjung jang digetarkan, mendjadi berbentuk sinusoida. Dari gambar tersebut dapatlah dilihat, bahwa bentuk gelombang itu terus madju kekanan, seperti ditundjukkan oleh anak panah pendek jang menundjuk kesuatu puntjak gelombang tertentu, sedangkan setiap titik pada dawai (lihat noktah hitam) ber osilasi terhadap titik kesetimbangannja dengan gerak getaran selaras. Penting sekali untuk diketahui perbedaan antara gerak *bentuk gelombang*, jang bergerak dengan ketjepatan konstan u sepandjang dawai, dan gerak satu titik pada dawai, jang berupa gerak melintang serta getaran selaras.



Gmb. 21-4. Gelombang transversal berbentuk sinus merambat kekanan, dilukiskan pada tiap^2 selang sebesar 1/8 kala.

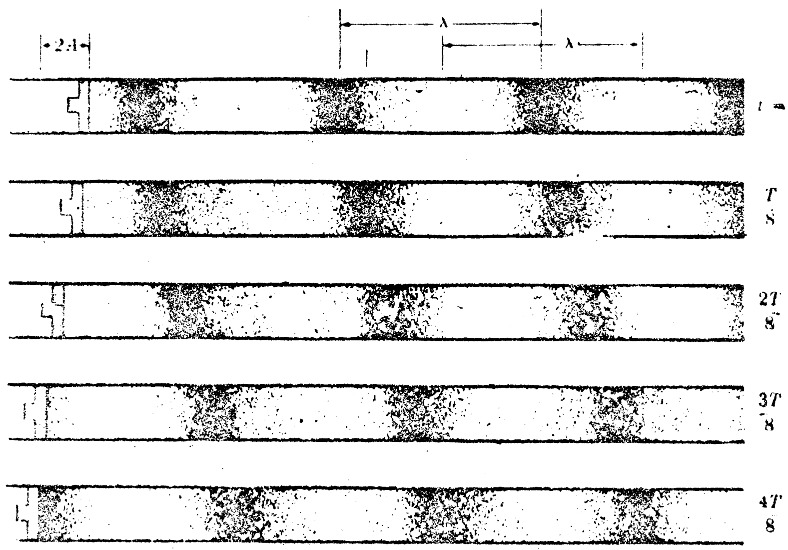
Djarak antara dua titik maksima berturutan (atau antara dua titik berturutan jang sama fasenja), disebut *pandjang gelombang* dan ditandai dengan λ. Oleh karena bentuk gelombang tadi, jang mendjalar dengan ketjepatan konstan, madju sedjauh satu pandjang gelombang selang waktu satu periode maka $u = \lambda/T$ atau

$$\boxed{u = f\lambda} \qquad (21\text{-}4)$$

Artinja, *ketjepatan rambatan sama dengan hasilkali frekwensi dengan pandjang gelombang.*

Bandingkan dengan formula 3.2 (Bab 3.3)

Untuk memahami mekanik gelombang longitudinal, perhatikanlah Gmb. 21-5, jang melukiskan sebuah tabung pandjang berisi zat-air dan berpiston diudjung sebelah kirinja. Bintik² menggambarkan partikel² zat-alir. Misalkan piston kita gerakkan dengan getaran selaras sedjadjar dengan arah pandjang tabung. Dalam sebagian waktu dari setiap osilasi timbullah suatu daerah jang tekanannja lebih tinggi dari pada tekanan dalam kesetimbangan. Daerah

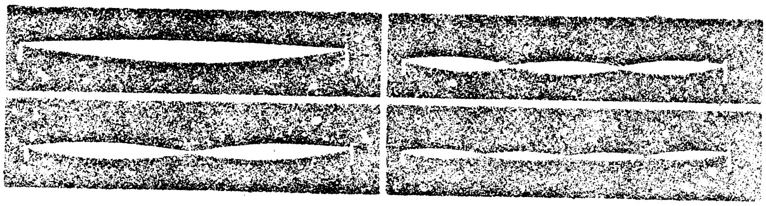


Gmb. 21-5. Gelombang longitudinal sinusoidal merambat kekanan, diperlihatkan pada tiap² selang sebesar 1/8 kala.

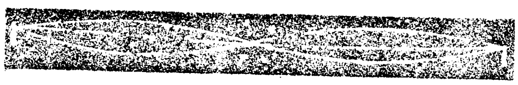
demikian disebut *perapatan*, dalam gambar ialah bagian jang titik²nja sangat rapat. Sesudah terdjadi perapatan ini, timbul suatu daerah jang tekanannja lebih rendah dari tekanan waktu dalam keadaan setimbang, disebut perenggangan dan dilukiskan dengan titik² jang djarang. Perapatan dan perenggangan bergerak kekanan dengan ketjepatan konstan u, seperti jang ditundjukkan oleh letak² anak panah. Gerak satu partikel adalah gerak getaran selaras, sedjadjar dengan arah rambatan, seperti ditundjukkan oleh titik hitam besar.

Pandjang gelombangnja ialah djarak antara dua perapatan ber-turut² atau dua perenggangan ber-turut². Disini persamaan dasar $u = f\lambda$ berlaku pula, seperti halnja dengan semua matjam gelombang.

22-2 Gelombang² stationer pada tali. Bila sederetan gelombang terus-menerus sampai pada udjung tetap seutas tali, gelombang² pantulan jang terus-menerus se-olah² mulai pada udjung tersebut dan merambat kearah jang berlawanan. Asalkan sadja batas elastik dari tali itu tidak dilampaui dan perpindahan tjukup ketjilnja, perpindahan sebenarnja dari setiap titik tali itu ialah djumlah aldjabar dari perpindahan masing² gelombang, suatu kedjadian jang disebut *azas superposisi.* Azas ini sangat pentingnja pada semua djenis gerak gelombang, dan berlaku bukan hanja untuk gelombang² dalam tali, tetapi djuga untuk gelombang² bunji dalam udara, gelombang² tjahaja, bahkan untuk gelombang² apapun. Untuk efek jang ditimbulkan bila dua (atau lebih) deretan gelombang² pada waktu bersamaan merambat lewat suatu daerah jang tertentu, dipakai istilah *interferensi.*



Gmb. 22-5(a) Gelombang tegak dalam dawai jang terentang. (time exposure)

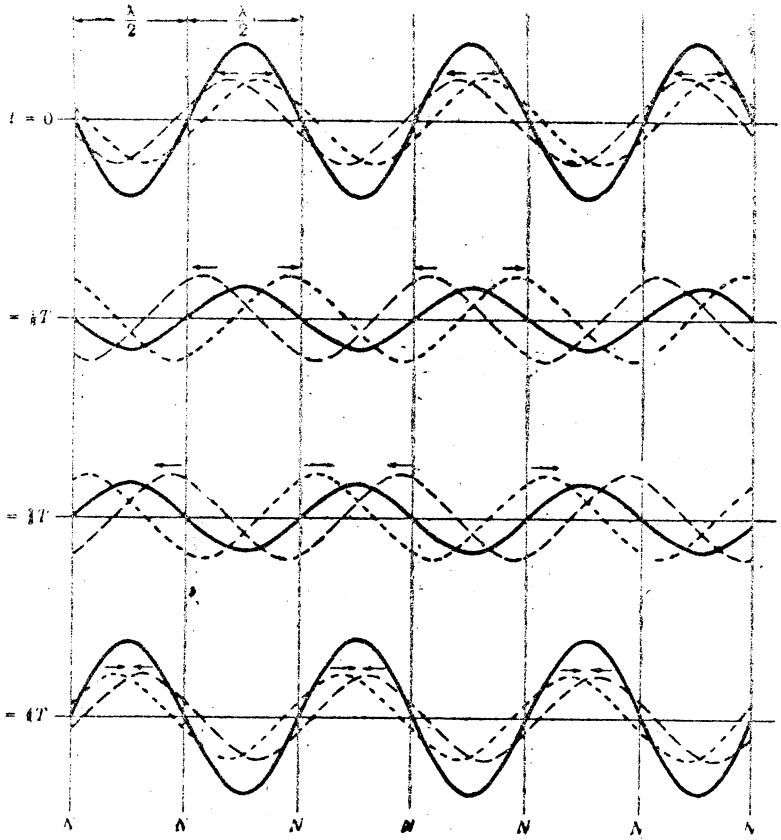


Gmb. 22-5(b) Foto multiflas suatu gelombang tegak, dengan simpul² di-tengah²nja dan pada kedua udjungnja.

Dalam keadaan ini, dari bentuk tali tidak kentara bahwa ada dua gelombang jang bergerak dalam arah jang saling berlawanan. Djika frekwensinja tjukup besar sehingga mata tidak dapat mengikuti gerak, tali tampaknja ter-bagi² mendjadi seperti pada foto „time exposure" pada Gmb. 22-5(a). Foto multiflash tali tersebut pada Gmb. 22-5(b) melukiskan beberapa bentuknja sesa'at². Pada setiap sa'at (ketjuali ketika tali terentang lurus) bentuknja ialah seperti kurva sinusoida, tetapi berlainan dengan gelombang merambat jang amplitudonja selalu konstan, disini bentuk gelombang itu tidak berobah posisinja (setjara longitudinal) sedangkan amplitudonja ber-rubah². Beberapa titik tertentu, disebut simpul, senantiasa tetap tidak bergerak. Tepat di-tengah² antara titik² ini, jaitu pada perut (loop) atau anti simpul (antinodes), besar perubahan² amplitudonja maximum. Getaran keseluruhnja disebut gelombang *stationer.*

Untuk memahami perihal pembentukan gelombang stationer, perhatikanlah grafik bentuk gelombang pada empat sa'at jang berbeda 1/8 periode, seperti pada Gmb. 22-6. Kurva ter-putus² pendek melukiskan gelombang jang merambat kekanan; kurva ter-putus² pandjang melukiskan gelombang jang merambat kekiri jang sama ketjepatan, pandjang gelombang dan amplitudenja. Kurva jang tebal melukiskan bentuk resultante gelombang jang diperoleh dengan menggunakan azas superposisi, jaitu dengan mendjumlahkan perpindahan². Di titik² pada tali jang diberi tanda N, resultante perpindahan selalu sama dengan nol. Inilah simpul²nja. Di tengah² antara simpul², getaran² mempunjai amplitudo jang terbesar. Dari gambar itu djelaslah bahwa

$$\left\{\begin{matrix}\text{djarak dari simpul kesimpul} \\ \text{atau} \\ \text{djarak dari perut keperut}\end{matrix}\right\} = \frac{\lambda}{2}$$



Gmb. 22-6. Terbentuknja gelombang tegak

Persamaan untuk gelombang stationer dapat diperoleh dengan mendjumlahkan perpindahan dua gelombang jang amplitudonja, periodenja dan pandjang gelombangnja sama, tetapi arah rambatnja berlawanan. Djadi djika

$$y_1 = A \cos 2\pi \left(\frac{t}{T} - \frac{x}{\lambda}\right) \quad \text{(arah } x \text{ positif)},$$

$$y - A \cos 2\pi \left(\frac{t}{T} + \frac{x}{\lambda}\right) \quad \text{(arah } x \text{ negatif)}.$$

maka

$$y_1 + y_2 = A\left[\cos 2\pi \left(\frac{t}{T} - \frac{x}{\lambda}\right) + \cos 2\pi \left(\frac{t}{T} + \frac{x}{\lambda}\right)\right].$$

Dengan menggunakan persamaan² ini untuk cosinus djumlah dan selisih dua sudut, lalu menggabungkan suku², achirnja didapat

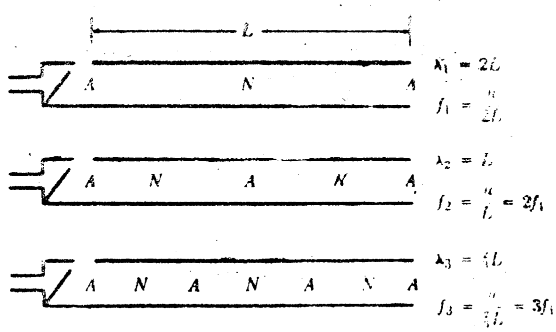
$$y_1 + y_2[2A \cos 2\pi ft] \cos \frac{2\pi x}{\lambda} \qquad (22\text{-}1)$$

Djadi bentuk tali pada setiap sa'at ialah kurva cosinus jang amplitudonja ber-ubah² (rumus dalam tanda kurung siku) dengan waktu.

22-8 Getaran pipa organa. Bila salah satu udjung sebuah pipa terbuka dan arus udara dihembuskan kepinggirnja, maka timbullah getaran[2] dan pipa itu beresonansi pada frekwensi[2] dasarnja. Seperti halnja dengan dawai jang dipetik, frekwensi dasar serta nada atasnja timbul bersamaan. Dalam

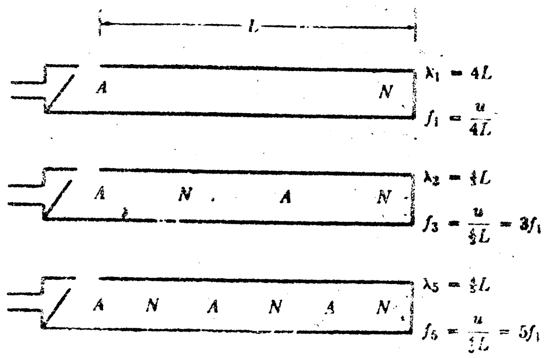
hal pipa jang terbuka, frekwensi dasar f_1 bersesuaian dengan sebuah perut pada tiap[2] udjung dan sebuah simpul ditengahnja, seperti dilukiskan pada bagian atas Gmb. 22-11. Diagram[2] dibawahnja pada Gmb. 22-11 melukiskan dua buah nada[2] atas jang seperti terlihat adalah harmonik kedua dan ketiga. *Pada pipa terbuka frekwensi dasar ialah u/2L dan semua harmonik ada.*

Sifat[2] pipa jang tertutup diperlihatkan oleh diagram[2] Gmb. 22-12. Frekwensi dasarnja ialah $u/4L$, djadi seperdua dari frekwensi dasar pipa terbuka jang sama pandjangnja. Dalam bahasa musik, pitch pipa tertutup lebih rendah satu oktaf dari pitch pipa terbuka jang sama pandjangnja. Dari diagram[2] lainnja pada Gmb. 22-12 dapat dilihat, bahwa harmonik kedua, ke-empat dan seterusnja tidak ada. Djadi, *frekwensi dasar pipa tertutup ialah u/4L dan harmonik jang ada hanja harmonik angka gandjil.*



Gmb. 22-11.

Tjara bergetar pipa organa terbuka.



Gmb. 22-12.

Tjara bergetar pipa organa tertutup.

Bandingkan dengan bab 3.9.

Awas! Di ilmu bunyi perut (A) adalah tempat dengan gerakan horisontal maximal. Dan simpul (N) adalah tempat dengan tekanan maksimal.

Di hidrodinamika terbalik.

22–5 **Resonansi.** Pada umumnja, kalau terhadap suatu benda jang dapat bergetar bekerdja sederet impuls berkala jang ber-frekwensi sama dengan salah satu frekwensi wadjar getaran benda itu, maka timbullah pada benda tersebut getaran dengan amplitudo jang relatif besar. Fenomena ini dinamakan resonansi, dan dikatakan benda itu *beresonansi* dengan impuls jang bekerdja padanja.

Tjontoh jang umum dari resonansi mekanik ialah kalau kita mendorong sebuah ajunan. Ajunan ialah pendulum jang mempunjai frekwensi wadjar tunggal jang tergantung dari pandjangnja. Djika pada ajunan tadi setjara berkala dikerdjakan dorongan² jang frekwensinja sama dengan frekwensi ajunan, gerak ajunan itu dapat dibuat besar sekali. Djika frekwensi dorongan² itu tidak sama dengan frekwensi wadjar ajunan, atau djika dorongan² itu diberikan setjara tidak berkala, maka ajunan itu boleh dikatakan tidak akan bergetar sama sekali.

Dawai jang direntangkan (dan lain² sistim jang akan dibitjarakan nanti dalam bab ini) mempunjai frekwensi² wadjar jang banjak djumlahnja; djadi berlainan dengan ajunan mathematik jang hanja mempunjai satu frekwensi wadjar. Andaikan ialah satu udjung dawai tetap, sedangkan udjungnja jang lain digerak-gerakkan dalam arah transversal. Amplitudo pada udjung jang digerakkan ini ditentukan oleh mekanik penggeraknja. Pada dawai timbullah gelombang² stationer, berapapun djuga frekwensi *f*. Djika frekwensi tidak sama dengan salah satu frekwensi wadjar dawai, amplitudo diperut akan ketjil sekali. Akan tetapi djika frekwensi sama dengan *salah satu* dari frekwensi² wadjar, maka dawai dalam keadaan resonansi dan amplitudo perutnja djauh lebih besar dari amplitudo udjung jang di-gerak²kan. Dengan kata² lain, walaupun udjung jang digerak-gerakkan itu bukan simpul, namun udjung ini lebih dekat ke-simpul dari pada ke-perut kalau dawai dalam keadaan resonansi. Dalam Gmb. 22-5(a), udjung kanan dawai tetap dan udjung kirinja digetarkan dengan amplitudo ketjil kearah vertikal. Gelombang² stationer jang amplitudo-nja relatif besar timbul, bila frekwensi osilasi udjung dawai jang kiri sama dengan frekwensi dasar atau sama dengan frekwensi salah satu dari nada² atas jang tiga pertama.

Djembatan, atau dalam hal ini setiap struktur, dapat bergetar dengan frekwensi² wadjar jang tertentu. Kalau frekwensi langkah teratur sepasukan tentara sama dengan salah satu frekwensi wadjar djembatan jang dilaluinja, maka timbul suatu getaran dengan amplitudo besar jang mungkin membahajakan. Sebab itulah barisan harus berdjalan dengan langkah tidak teratur bila melintasi djembatan.

Menjetel radio adalah satu tjontoh resonansi listrik. Dengan memutar sebuah knop, frekwensi wadjar arus bolak-balik dalam Circuit penerima disamakan dengan frekwensi gelombang jang disiarkan oleh stasiun radio jang hendak kita dengar. Resonansi optik dapat pula timbul antara atom² gas bertekanan rendah dengan gelombang² tjahaja jang berasal dari lampu jang berisi atom² jang sama. Djadi tjahaja lampu natrium menjebabkan atom² natrium dalam bola lampu dari gelas bersinar dengan tjahaja natrium kuning jang chas.

Fenomena resonansi dapat terlihat pada gelombang longitudinal jang ditimbulkan diudara oleh pelat bergetar atau garpu nada (tuning fork). Djika dua buah garpu nada jang serupa diletakkan agak berdjauhan, lalu salah satu dibunjikan, maka garpu jang satu lagi akan masih kedengaran berbunji, walaupun bunji jang pertama se-konjong² diredam. Kalau pada salah satu garpu ditempelkan lilin atau tanah liat sedikit, maka frekwensi garpu ini akan berubah, dan perubahan ini tjukup untuk menghilangkan resonansi.