## CHAPTER 37

TRANSPORT PATTERNS IN THE CHAO PHYA ESTUARY

by

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### 1 INTRODUCTION

Present day's society asks for ever larger engineering works to be carried out in estuaries. The developing techniques of dredging and construction allow for great interventions in the natural phenomena with often far reaching consequences. The whole intricate system of transports of water, salt and sediments may be drastically changed, affecting the existing quasi-static equilibria between sedimentation and erosion. For the planning of such works a thorough knowledge of the estuarine hydrology is indispensable.

The port of Bangkok, the main gateway for traffic into Thailand, is situated in the estuary of the Chao Phya river (figure 1). Increasing navigation demands improvement of the harbour and its 55 km long approach channel but the interests of agriculture and municipal water supply must also be taken into account.

The Netherlands Engineering Consultants (NEDECO) in combination with the Delft Hydraulics Laboratory have made a four-years study of the estuary covering a field survey and a hydraulic model test. The observations in nature served to obtain insight into the estuarine transport pattern in relation with the boundary conditions given by the regimen of the river and the state of the sea. The small scale tests gave indications of the changes in these phenomena to be expected from alterations of the situation in the estuary and of the discharge characteristics of the river.

The field survey was carried out from 1961 to 1963 with four fully equipped survey vessels to measure current velocities (60,000 times) to take samples of water and sediments, to measure wave heights and for echo-soundings. In a laboratory the samples of water (70,000) and sediments were tested as to silt concentration, salinity and soil-mechanical properties. Together with meteorological, oceanographical and hydrological data from cooperating local authorities a picture was obtained of the phenomena in the estuary and the causes of the siltation in the dredged channel.

The model comprised the 160 km long estuarine stretch of the

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1. Delft Hydraulics Laboratory, The Netherlands.

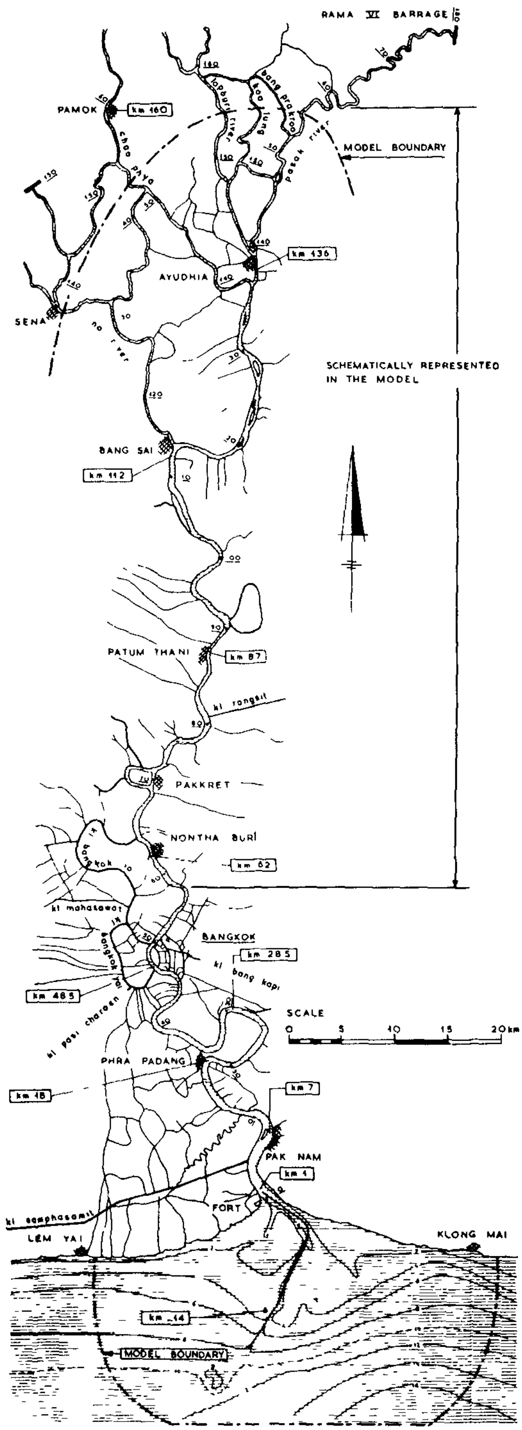


Fig. 1. The estuary and the bar area of the Chao Phya River.

Chao Phya and the adjacent 20 x 40 $km^2$ part of the Gulf of Thailand in which the river has deposited vast mud-flats through which the navigation channel has been dredged. The scale of the horizontal dimensions was 1:500 while the depths were on scale 1:100. The seaward boundary was provided with a tide generator and a supply of salt water which, together with the fresh discharge of the river, gave a good simulation of the hydraulic phenomena in the estuary. Tests with other situations gave indications of the changes in the hydraulic phenomena which, in turn, could be translated into changes of the silting pattern via relationships derived from the data of the field survey.

In this paper some interesting results of the study will be communicated.

## 2 OBSERVATIONS

### 2.1 THE ESTUARY

#### 2.1.1 Topography

The estuary comprises the tidal stretch of the Chao Phya river and the adjacent part of the Gulf of Thailand. The phenomena in this area are the joint result of influences from the river and the sea.

The tidal basin consists of the river and its tributaries up to about 160 km upstream from the river-mouth, and it also includes an intricate network of natural and artificial canals in open connection with the main stream (figure 1). The very stable meandering river continues seaward as a partly dredged artificial channel of 18 km between large shallow mud-flats (figure 2). The gully across the West-Flats often dries at low water but the East channel plays a more important role.

During the past centuries the main channel gradually shifted from west to east leaving growing West-Flats with an accretion of the shore. The East-Flats extended eastward but there the coastline was almost stationary.

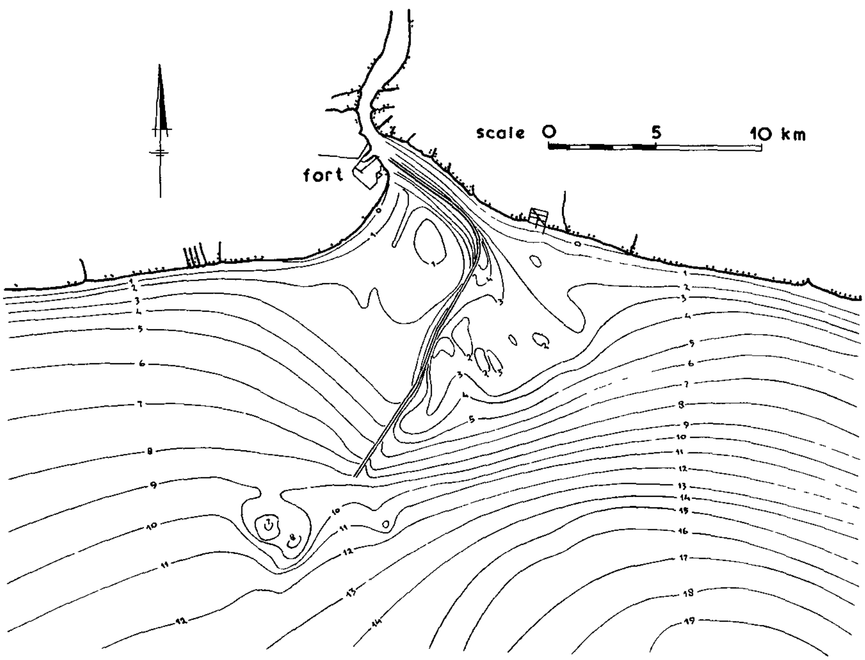


Fig. 2. Topography of the Bangkok Bar.

### 2.1.2 The regimen of the river

The yearly cycle of the river flow shows a dry period between January and July with discharges of 25 to 250 $m^3$/sec and with the minimum in May. The spate period from July to December shows a maximum discharge of about 4,000 $m^3$/sec at the end of October or in the first half of November.

The silt concentration in the river-water is maximal, and exceeds 500 p.p.m, at the onset of the spate period. During August September and October the greater part of the annual silt supply of $4.7 \times 10^6$ tons comes down. Then in the second half of the wet season the water is relatively clean (less than 100 p.p.m.). The dry season contributes about $0.2 \times 10^6$ tons to the yearly silt load of the Chao Phya.

During the maximum spate a "bubble" of silty fresh water can be observed extending more than 20 km from the river-mouth into the Gulf of Thailand.

Huge reservoirs are being built in the northern tributaries of the Chao Phya to generate electricity and to provide more water for irrigation. These works will increase the minimum discharge of the river to about 250 $m^3$/sec and cut off the peak of the discharge hydrograph during the wet season.

### 2.1.3 Conditions at sea

The tide in the northern part of the Gulf of Thailand varies between diurnal and semi-diurnal with a range of 1.5 to 3 m around an average of 2.1 m. This tidal wave travels across the Bar area and into the Chao Phya river.

At an average temperature of about 30° C the density of the sea-water is about 1,021 kg/$m^3$ which is 25 kg/$m^3$ more than the specific mass of the river-water.

Waves of considerable height can only be generated by winds from between south-east and south-west prevailing from March to September including the South-west Monsoon blowing from May to September. Its counterpart lasts from November to February. The height of the waves in this shallow (15 m) sea rarely exceed 1.25 to 1.5 m.

## 2.2 GENERAL TRANSPORT PATTERNS

### 2.2.1 Flows

The discharge of the Chao Phya river causes a net seaward flow, on which the tide superimposes a horizontal oscillation with an amplitude of 10 to 15 km.

During the dry season the lower 160 km of the river form a 65 $km^2$ tidal basin with a prism of about 100 million $m^3$. The upper limit is pushed down to km 70 in the wet season and then the tide hardly turns at the mouth.

Inertia and hydraulic friction cause a phase lag such that the slack waters occur 1.5 to 2 hours after high-water and low-water. Consequently the average water level during flood is about 1 m higher than during ebb. This asymmetry causes a surplus flood flow over the shallow parts of the Flats and (together with the river discharge) a net ebbward water transport through the main Channel and sometimes through the East Channel.

The south-west monsoon wind (June, July, August) strengthens flood flows across the West-Flats while it causes a west to east drift current along the coast.

### 2.2.2 Salinity and density effects

The system of flows is still more complicated because the more heavy sea water penetrates into the estuary along the bottom; mainly through the channels. The lighter fresh water flows seaward on top of the salt water and gradually mixes with it. In a state of a equilibrium there is no net transport (averaged over a tidal cycle) of salt through a cross-section of the estuary.

The intrusion of the salt water is counteracted by the friction and mixing at the interface with the seaward flow of river water. The length of intrusion almost solely depends on the discharge of the river. The whole pattern of the density distribution oscillates with the tidal motion. This "shaking" also intensifies the process of mixing between fresh and saline water.

A system of stratified flows exists when the river discharge exceeds 1,000 $m^3$/sec. The typical salt wedge oscillates along the bottom near the river-mouth and in the northern half of the Channel. During the dry season with a river flow less than 100 $m^3$/sec the pattern is of the mixed type with weak density gradients upto 70 km into the river. Then the average intrusion (x, km) of the salinity (s) is closely related to the discharge of the river (Q, $m^3$/sec) and the salinity ($s_o$) at the mouth of the river

$$\frac{s}{s_o} = e^{-18.10^{-6}\,Q\,x^2}$$

If from the observed velocities at the surface and at the bottom the tidal influences are averaged out a typical circulation of inward bottom flow and seaward surface flow is obtained in the brackish part of the estuary (figure 3). Even during the dry season its existance could be proved. This means that always a convergence of resultant bottom flows occurs at the limit of the salt intrusion.

At the bottom in the brackish area the flood flows are strengthened by the density effects while the ebb currents are weakened. This phenomenon is very prominent in the northern part of the Channel during the wet season. The river discharge then cuases a very strong erosive ebb current along the bottom upstream of the salt wedge. Farther downstream this flow is separated from the bottom by the slowly retreating saline water which in this way protects the bottom against erosion.

Resultant bottom currents are seaward in the fresh part of the river and in the almost homogeneously saline part of the

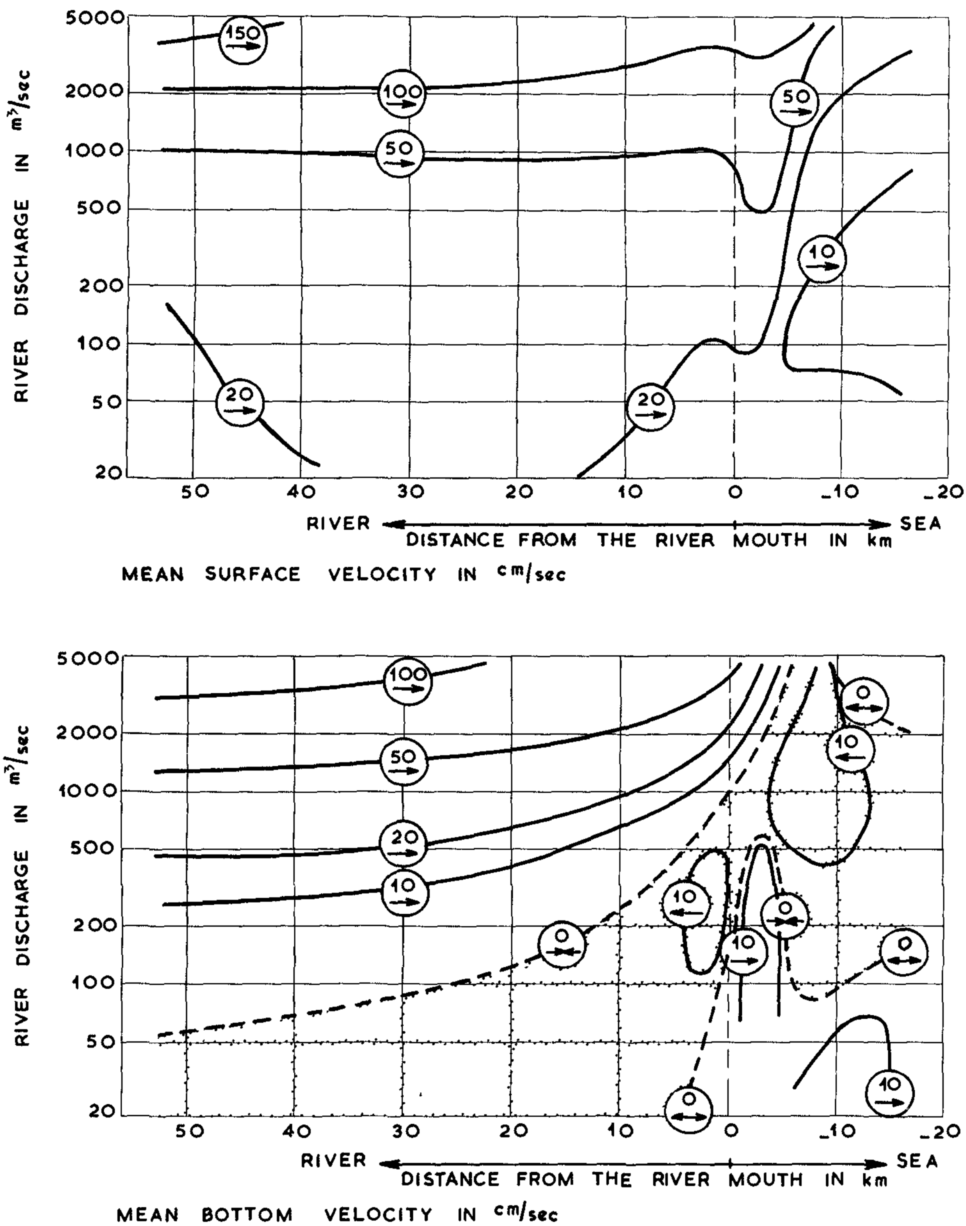


Fig. 3. Mean (resultant) velocities at the surface and at the bottom plotted against the river discharge and the location in the River and the channel.

Channel during the dry seasons when the mechanisms described in the preceding paragraph are prevailing.

Surface flows are always resultantly seaward except on the shallow flats during the dry season.

The whole pattern gradually varies with the annual cycle of the river discharge. The transient phenomena occurring in this varying system appear to be of great significance in the displacement of sediments.

2.2.3 Transports of sediments

In general the annual riverine supply of about 5 million tons of silt travels through the estuary and finally contributes to the accretion of the coast and the Bar area. The sediments are mainly carried by the water.

In detail the process is much more complicated because of the occurrence of great internal displacements. Often the net transport appears as the difference of huge quantities carried to and fro by ebb and flood. The resultant displacement is often caused by second order factors such as asymmetry of the tide, asymmetry of the topography, density effects and drift currents. The process interacts with the bottom via erosion and sedimentation. The latter is greatly influenced by the flocculation of silt in saline water. In some cases the sediments move in the form of fluid mud.

The most convenient start of a description of the yearly cycle of sediment transports is the end of the wet season, when the river has just deposited its load outside the mouth and its lower stretch is cleaned by the strong ebb currents.

During the subsequent dry season the fresh deposits are greatly reshuffled by the flows. About 2.5 million tons of sediments move northward over the West-Flats being eroded by waves and transported by a resultant flood flow. A part of this material settles in the northern part of the Channel and 1 million tons are carried into the river by the density current along the bottom; 0.5 million tons is transported further upstream than Bangkok at 50 km from the mouth.

The East-Channel shows a seaward transport of about 1 million tons and half that amount moves down the main Channel (figure 4).

At the beginning of the new wet season in the middle of July the saline water is pushed out of the river and with it the 1 million tons of silt that intruded during the dry season plus 0.2 million tons of silt supplied by the river during that period. Then in a few months from July to October the river brings down 4.5 million tons of new silt.

In the fresh water the silt forms an almost stable suspension but entering saline water it starts a rapid flocculation (see 2.3.1). Great quantities of silt settle down in the brackish area. Near the bottom it enters into to inward density flow which carries it back towards the tip of the salt wedge.

In this way the greater part of the rapid supply of silt is

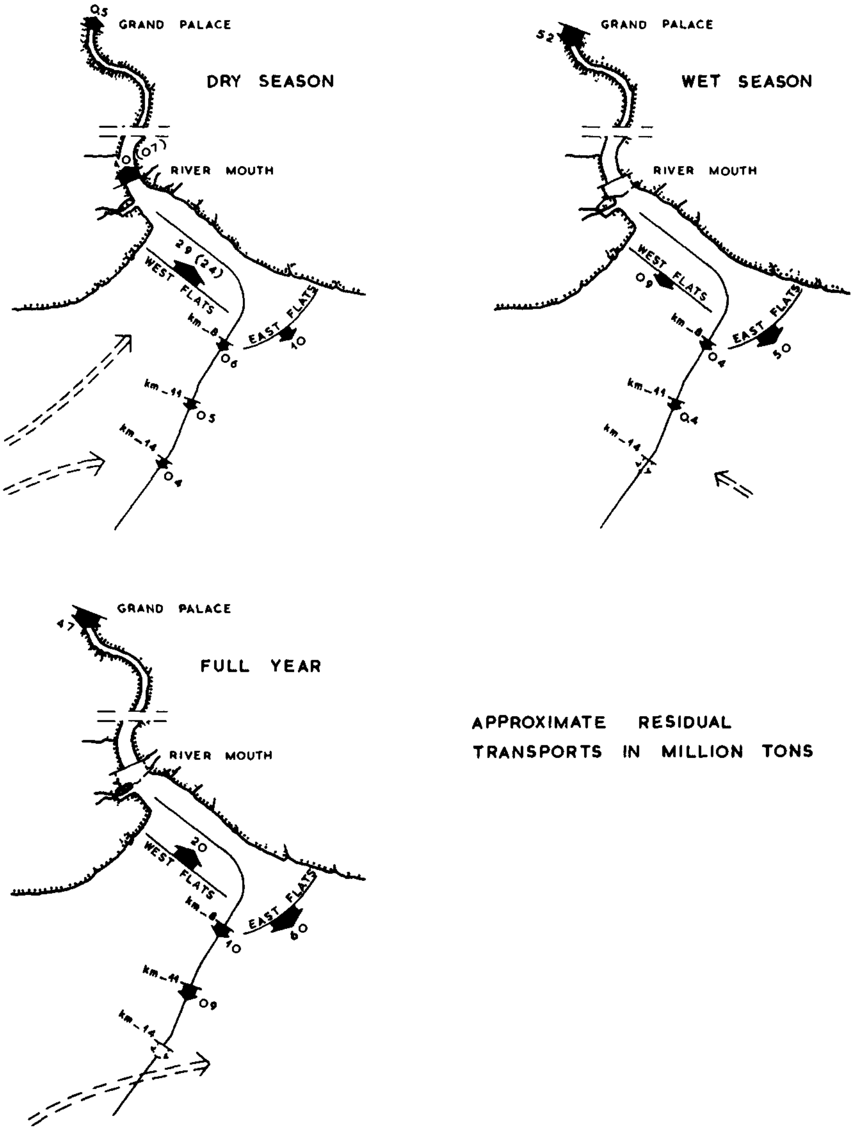


Fig. 4. Review of the seasonal and yearly residual silt transports in the estuary.

catched in the salt wedge (see 2.3.5) and temporarily stored in the northern part of the Bar area where it causes great deposits partly in the form of soft silt (see 2.3.2).

In the meantime but at a slower rate silt is transported away: 0.9 million tons to the West-Flats, 5 million tons across the East-Flats and 0.4 million tons through the main channel. These transports continue throughout the second half of the wet season when the supply by the river gradually ceases and thus the stored sediments are removed by the natural forces. The temporary silting, however, requires dredging to maintain enough depth for navigation.

Dredging is an important factor in the pattern of transports. About 5 million $m^3$ or 2 million tons of silt are removed annually. More than half of it is dredged in the southern part of the Channel where it is supplied, partly through the Channel from the north and even more by the surrounding shallows where it is churned up by the waves. In the deep Channel waves and currents are to weak to remove these deposits.

## 2.3 SPECIAL ASPECTS

### 2.3.1 Flocculation

In very fine sediments, consisting of typical clay minerals, the particles have the shape of flat plates or needles of which the greater dimensions are a few microns or less. Because of the large specific surface, the structure of the chrystals and the interaction with the surrounding water with dissolved salts the interparticle forces can become great with respect to the weight of the particles. These effects largely depend on the salinity of the water.

In the fresh water of the Chao Phya with 100 to 250 p.p.m. of dissolved electrolytes repulsive forces are relatively great so that particles repel each other thus forming a rather stable suspension especially in turbulent water.

At higher salinities the magnitude of the repulsive forces decreases and suspensions become very unstable at a salt content of about 3,000 p.p.m. which is 10% of that of sea water. A further increase of the salinity does not affect the interparticle forces any more.

Under these circumstances colliding particles stick together and form flocs. Relative motions and collisions of particles can be caused by Brownian motions, a velocity gradient (especially in turbulent flow) and difference in settling velocity of which the latter two are of greater importance in an estuary. The number of collisions increases with the concentration of particles and the effectiveness depends on the stability of the suspension. On the other hand large flocs are damaged by collisions and because of hydrodynamic forces so that they can only attain a limited size.

Flocculation greatly increases the sedimentation velocity of the silt. Figure 5 shows results of settling tests with natural

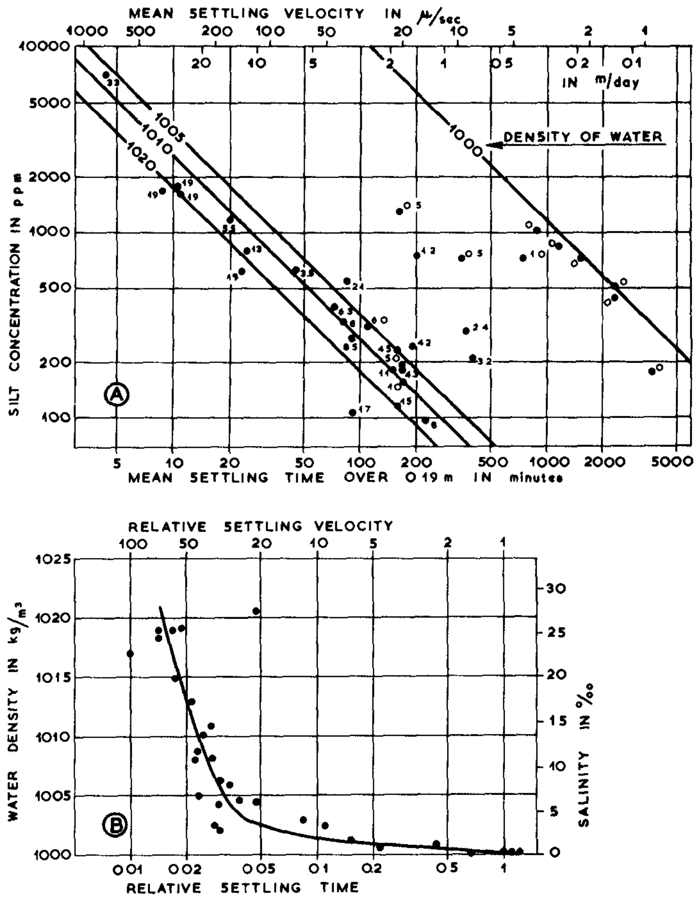


**Fig. 5. Observed settling velocities in undisturbed samples from the Chao Phya estuary.**

suspensions, taken from the estuary, of different salinity and silt concentration. It appears that in saline water the fall velocity exceeds 50 times its value in fresh water but also the influence of concentration stands out clearly.

In the estuary flocculation occurs where silty fresh water mixes with sea water which is in the river during the dry season and in the Bar Area during the wet season.

A great amount of water is included in the flocs thus virtually increasing the amount of sediment upto 5 to 10-fold the volume of the primary particles. Sedimentation leads to voluminous deposits of mud with a very high water content and a low specific weight.

### 2.3.2 Soft silt

Soft silt is a fluid suspension of silt in water with a density between 1,100 and 1,250 kg/$m^3$ (concentration 100,000 to 300,000 p.p.m.) and with a viscosity between 0.1 and 5 kg/m sec (water 0.001). It occurs at places and times of heavy silting of flocculated sediments from a dense suspension in relatively quiet water; which is in the northern part of the Channel during the first half of the wet season and in the southern part of the Channel from September to November and during April and May. The maximum accumulation attained 0.8 to 1.2 million $m^3$ in the wet season and 0.5 to 0.7 million $m^3$ in the dry season.

On echograms of cross-sections of the Channel it appears as a partially reflecting horizontal interface at a distance of 0.5 to 2.5 m above the hard bottom. In longitudinal sections it may show a gentle slope (0.1 to 1 m/km) from which, in combination with transport measurements, the existence of flow in the soft silt has been inferred causing transports of even 50,000 tons of silt at certain days through the cross-section at the mouth of the river. These motions disturb the consolidation and thixotropic stiffning of the suspension.

The soft silt is so soft that ships can sail through it. In other places (British Guiana) a negative keel clearance is quite normal but in the narrow Bangkok seaway the danger of poor manoeuvrability of a ship would be too great.

The consolidation of soft silt is very slow; laboratory tests showed that layers of 0.5 to 2.5 m thickness remain fluid over periods of several weeks, even in a settling tube. The increase of the density starts at the bottom. If the density becomes more than about 1,250 kg/$m^3$ the matter gradually attains the stiffness of the normal mud of which the bottom of the Channel consists.

Resuspension of soft silt occurs when the boundary between the dense viscous suspension and the flowing water overhead becomes unstable which is at a velocity of 0.2 to 1 m/sec depending on the concentration of sediments in the soft silt.

### 2.3.3 Flows and silt transports

In general flowing water transports sediments by carrying it in suspension or by dragging it along the bottom. In the Chao Phya Estuary most of the fine silt moves as a suspension. Consequently the motions of silt show some similarity with the flows of fresh and saline water but there are some significant differences:

- the gravity of the sediment particles
- disappearance from the flow by deposition at the bottom
- return into the flow by erosion.

Especially the interaction with the inhomogeneous bottom causes that relationships between flows and silt transports differ with place and time.

An interesting example of these phenomena is shown in figure 6 which depicts the results of fourteen hours of observations in

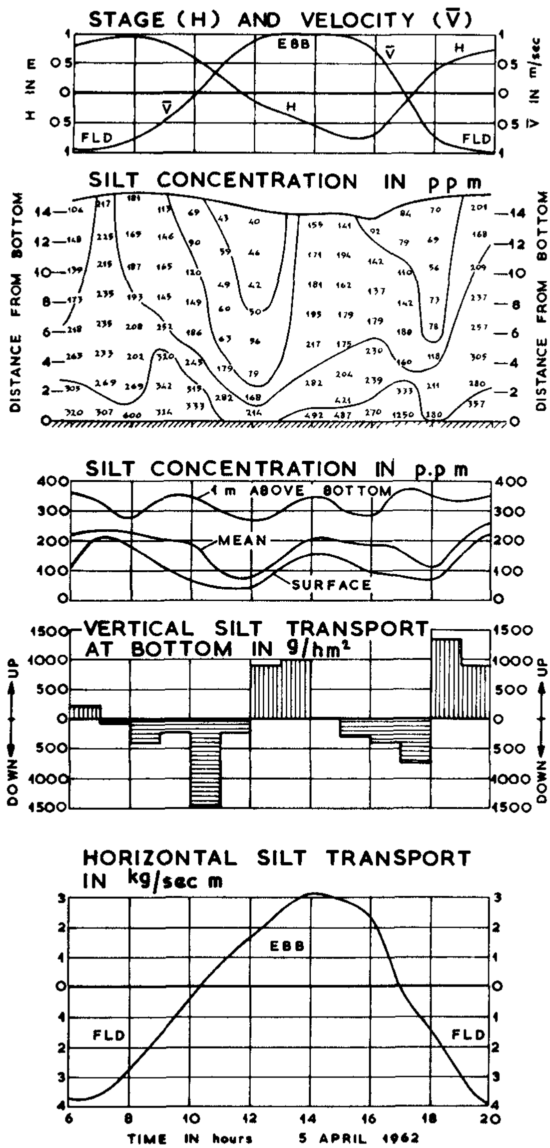


Fig. 6. Analysis of a transport measurement at km +51 in the river.

the river within the city of Bangkok. The complex variability of the waterlevel, the current velocity, the silt concentration, the vertical silt transport and the horizontal silt transport is given for one vertical during a tidal cycle. Even in this relatively simple case the relationships between flow and silt load are complex.

The horizontal transports mainly consist of sediments carried to and fro by the oscillating tidal currents. A resultant displacement is caused by a net flow of the water or by a difference in the silt loads during ebb and flood. The first mechanism applies to the river during the periods of high discharge. A correlation between the transports and the tide may be expected in the mainly tidal areas outside the river mouth throughout the year and in the river during the dry season.

After some trials an usable relationship was found between the total sediment transports during a cross-section during periods of ebb and flood, and the relevant falls (difference in the level of a H.W. and the subsequent L.W.) and rise (difference in level of a L.W. and the subsequent H.W.) of the tide. Figure 7 shows some of the obtained graphs which depend on the location ar the season. In addition to these relationships the influence of the wind (via drift currents and waves) could be established for the transports across the West-Flats and through the river-mouth during the dry season.

These relationships, which were obtained from observations during a certain season, were used to estimate the sediment transports during days at which no measurements were carried out. By this method of interpolation a picture was obtained of the total transport patterns in the seasons.

### 2.3.4 Erosion and deposition

The occurrence of erosion and deposition mainly depends on the velocity of the flow, the silt-load of the water and the composition of the bottom.

From a number of measurements the variations of the silt load of the flow have been computed as is shown in figure 6. In all these cases the composition of the bottom was homogeneous over a long distance so that it might be assumed that the increases and decreases of the load were due to erosion and deposition. Figure 8 shows how the vertical transport to and from the bottom is related to the velocity of the flow and the concentration of silt in the water at one location in two seasons.

In general clear water is more erosive than silty water and contrary deposition occurs at higher velocities from water with a greater silt load. The vertical transports are much smaller in the brackish milieu (March) than during the wet season (July) which must mainly be attributed to the greater sedimentation velocity of the flocculated silt.

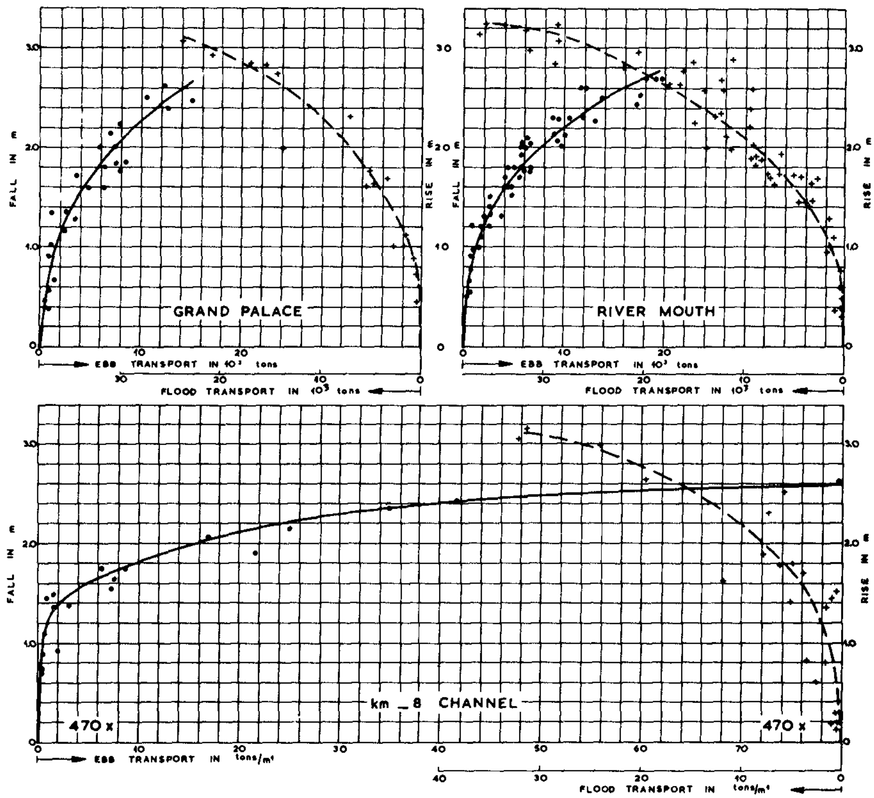


Fig. 7. Rises vs. flood-transports and falls vs. ebb-transports from the measurements in the dry season at Grand Palace, at the river-mouth and in the channel at km -8.

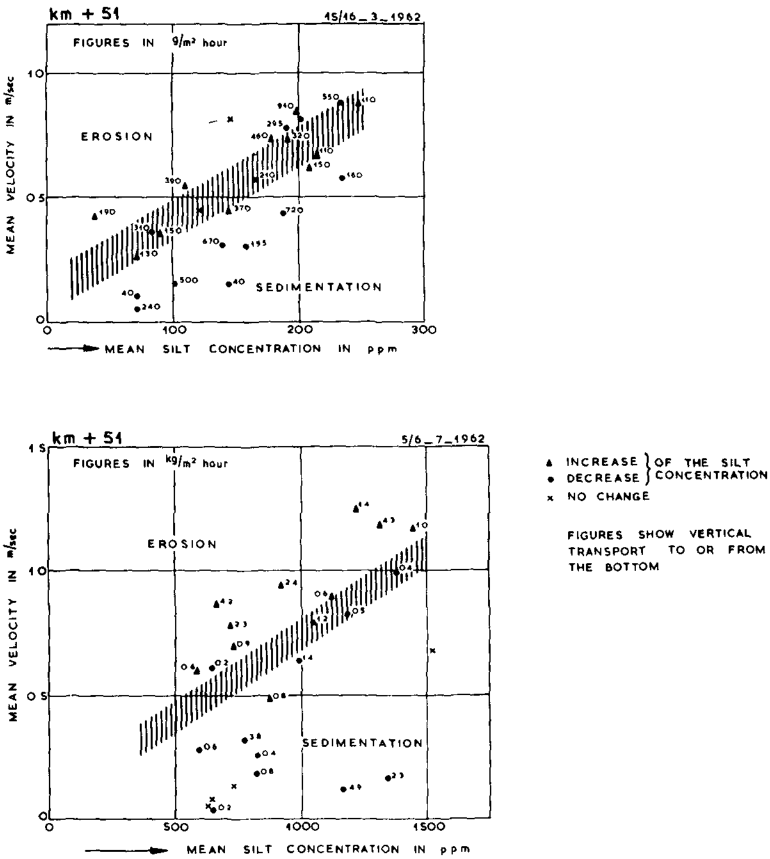


**Fig. 8. Sedimentation and erosion in relation with flow velocity and silt concentration.**

## 2.3.5 Transient phenomena

The transitional area between the fresh river-water and the saline sea-water is of great significance in all estuarine transports. Its character and its location mainly depend upon the discharge of water and silt from the river and the more short periodic tides at sea.

Special attention must be given to the resultant inward bottom flow in the area of brackish water which converges with the seawardly moving fresh water. This pattern greatly influences the distribution of mobile sediments which lay on the bottom and move in suspension mainly near the bottom.

In this area of converging bottom flows a certain amount of sediments is accumulated which is more or less inherent to this part of the estuary. It includes quantities of erodible mud and soft silt on the bottom.

It is, however, not always the same silt but there is a continuous supply by the river and from the sea while sediments are lost through transports by the resultant seaward flow in the upper layers of the estuary. After some time a situation of equilibrium might be expected but the variations in the supply of fresh water and silt do not allow for it. In the course of a yearly cycle periods of accumulation and loss alternate. Moreover the point of convergence gradually shifts with variations of the river discharge.

Accumulation occurs during the dry season when about 1 million tons of sediments intrude into the river and are stored together with a supply of 0.2 million tons by the Chao Phya. Half of this total quantity can be found in the vicinity of Bangkok, upstream of 50 km from the river mouth at the end of the dry season.

Then, between July and the middle of October, about 4,5 million tons of sediment are supplied by the river. The quantity of accumulated silt increases to about 2 million tons and the whole mass gradually shifts to the mouth of the river and the northern part of the Bar Area. Great deposits of soft silt appear in these parts of the channel and dredging helps the natural seaward transport mechanisms.

During the second half of the wet season the sediment supply of the river is small but the water discharge remains high. Most of the accumulated material is carried away; mainly to the East-Flats. About half December the soft silt disappears. With the decrease of the river discharge the cycle starts again.

Apart from this local accumulation of great quantities of sediment also the aspect of the transports involved in the migration of the point of convergence and the inherent mass of sediment deserve our attention. In this way a mere variation of the river discharge without changes of the sediment supply can set in motion great masses of sediment. If a harbour basin is situated in the area concerned great silting may occur within a short period.

Especially during the wet season similar processes occur on a small scale near the tip of the salt wedge as a consequence of the oscillating tidal flows. During flood salt water, suspended silt and soft silt move inward. During ebb the salt water is pushed back by the relatively clean fresh water which also erodes the soft silt that came in with the flood. The eroded material and the new silt from the river are transported seaward in the top layers of the water to settle down and partly to be carried back by the inward bottom flow. The quantity of sediment circulated in this way has been estimated at upto 50,000 tons per day.

## 3 THE MODEL-INVESTIGATION

The horizontal dimensions of the estuary were in the model reproduced on scale 1:500 and the depths were on 1:100. With these scales and this distortion a good reproduction was expected of the flows and the distribution of the salt in the estuary. The technique of model investigations has not yet been developed so far that silting and scouring of silt proper can be simulated in a model. These phenomena had to be derived from the hydraulic information from the model in combination with knowledge from the field study.

The seaward boundary of the model (figure 9) was provided with a supply of salt water to maintain a constant salinity and an electronically governed tide generator which could reproduce any tidal variation of the sea-level. The model was built of concrete with the appropriate roughness of its bottom. The river part of the estuary was made geometrically conformal upto the limit of salt intrusion (60 km from the mouth) but the remaining part of the tidal basin was compacted in the form of a labyrinth which only served to simulate the tidal phenomena in combination with a variable discharge of fresh water.

The model-investigation started with a period of calibration and adjustment by reproducing some characteristic patterns of flows and salinity as observed during the field-investigation. Thereafter the following situations were tested:

1. the existing situation,
2. the existing alignment of the channel but with a dam across the West-Flats to block the dry season supply of sediments,
3. two different realignments of the channel across the East-Flats to fit the channel in the pattern of ebb-currents,
4. a realignment of the lower stretch (5 km) of the channel for the same reasons, and
5. channels with an increased depth (8.5 m to 10 m) and width (100 m to 150 m).

All these situations were subjected to the same standard boundary conditions viz.: river discharges of 50, 250, 1,000 and 4,000 $m^3$/sec in 4 combinations with three characteristic types of tide. In all cases the same measurements were made . Comparison of the results gave indications of the effects of modifications of the situation and of a change of the regimen of the river.

With these results of the tests the feasability of the proposed improvements of the situation could be judged, mainly with respect to the estimated amount of maintenance dredging.

The total study finally resulted in recommendations on the depth, width and alignment of the Channel taking regard with navigation and maintenance dredging, on the relocation of the dumping area for the dredged material and on dredging techniques in the port as well as in the access-channel.

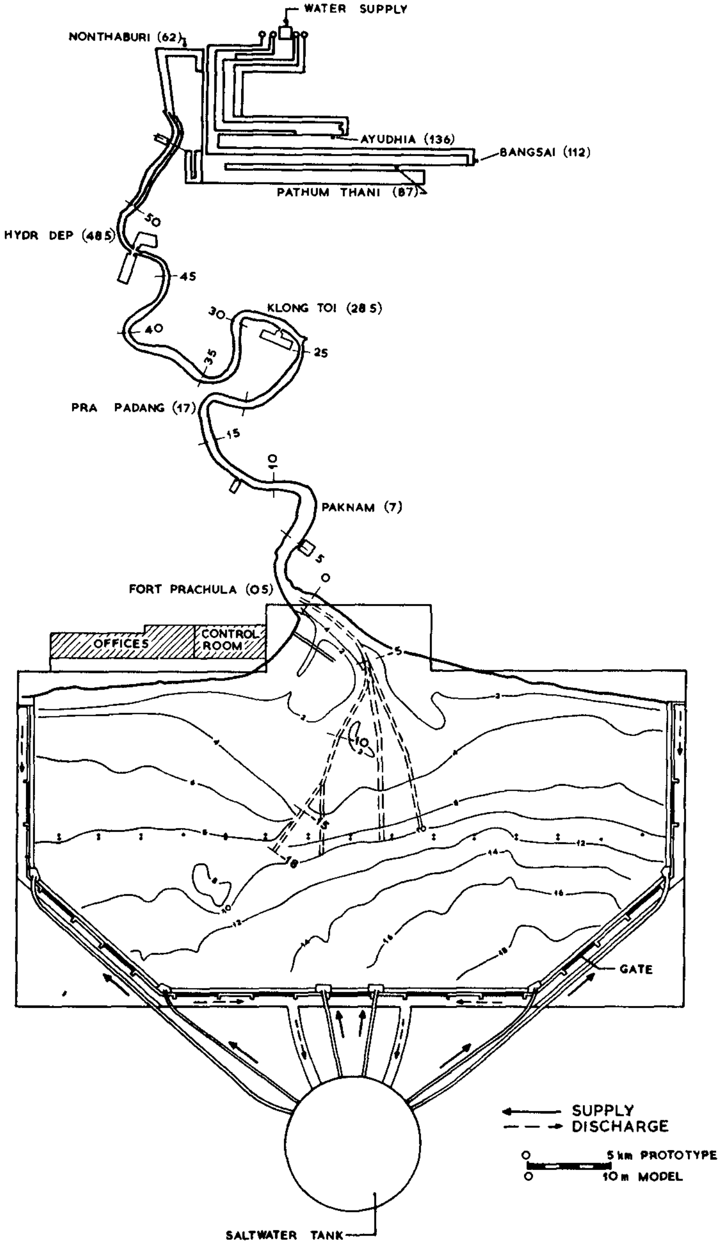


Fig. 9. The model and auxiliary installations.