waterloopkundig laboratorium
delft hydraulics laboratory

# The effect of waves on Kaolinite/Sand beds

Report on model investigation

M 2060

August 1985

# The effect of waves on Kaolinite/Sand beds

Report on model investigation

M 2060

August 1985

CONTENTS

CONTENTS (continued)

CONTENTS (continued)

Tables



Figures

Photographs

# 1. Introduction

Each year large quantities of mud are dredged in the area of the harbour of Rotterdam. The dredged materials are dumped at a location (Loswal Noord) in the North Sea not far away from the entrance of the access channel. A part of the dumped material is transported towards the dredging area under the influence of tidal currents and waves. Although the sedimentation of mud in the channels and the harbour basins is a continuous process, indications are that there is a rather large increase of the sedimentation directly after storm periods, especially in the autumn period. Based on this information, the presence of relatively large waves seems to have a dominating influence on the erosion and transport of mud from the dump location to the harbour area.

Review of the literature (Vermaas, 1984) showed that waves are capable of generating a high-concentration layer close to the bed, which is separated from a less dense suspension layer above it by a sharp interface. The high-concentration layer near the bed can be moved easily by tidal currents or wave-induced drift velocities yielding a relatively large transport of sediment material close to the bed. Information of the relevant parameters is extremely scarce.

Therefore, the Delft Hydraulics Laboratory was commissionned by the Directorate Watermanagement and Watermovement of the "Rijkwaterstaat" (letter KZ 250, september 17th 1984) to study the effect of waves on a cohesive sediment bed by carrying out flume experiments in saline (sea-water) conditions.

As a first approach it was decided to use kaolinite material as bed material. The study was aimed at the following phenomena:

1. the presence (or absence) of a high-concentration suspension layer of cohesive material near the bed in relation to the wave conditions,
2. the vertical distribution of the sediment concentrations,
3. the influence of the bed-surface density (bed history) on the generation of a high-concentration suspension layer,
4. the influence of fine sand particles present in the bed material (mixture) on the generation of a high-concentration suspension layer.
5. the horizontal transport of cohesive material due to wave-induced drift velosities.

The study was carried out by Mr L.C. van Rijn, who also composed this report.

# 2. Summary, conclusions and suggestions for further research

## 2.1 Summary

The effect of waves on a sediment bed of cohesive material in sea-water conditions was studied.
Basically, the interaction of waves and a cohesive bed depends on:

- wave conditions,
- bed composition (amounts and type of sediment and organic material),
- bed-surface density (consolidation period)
- salinity and temperature of pore and eroding fluid.

In the present study the afore-mentioned parameters were varied with exception of the salinity ($\simeq$ 31%) and the water temperature ($\simeq$ 10°C). As cohesive material a commercially available kaolinite was used. The chemical, mineralogical and hydraulic properties (such as settling velocity and viscosity) of the kaolinite material are given in Chapter 3. Four experiments (T1, T2, T3, T4) with a pure (consolidated) kaolinite bed were carried out. In two experiments (T5, T6) the bed consisted of a mixture of kaolinite and fine sand (75%-25% and 25%-75%). Finally, an experiment (T7) with a pure sand bed was carried out. The influence of organic material was not studied.

The experiments were performed in a wave flume of the Delft Hydraulics Laboratory. Regular waves (period of 1.5 s and 2.5 s) were generated by a simple wave paddle. The wave heigths were increased in steps. The (deepened) test section had a length of 10 m. Before filling the test section with a layer of kaolinite suspension, partition walls separating the test section from the rest of the flume were installed. The partiton walls were removed after the cohesive bed had consolidated to its final thickness ($\simeq$ 0.05 m). After that the flume was filled slowly with saline water and the wave generator was started. Velocity measurements were carried out by using a Laser Doppler method (preliminary tests with clear water) and an Acoustic Doppler method. Sediment concentrations were measured by using an optical method, a siphon method and a pipet method. A small 5 ml-pipet was also used to collect samples from the (consolidated) kaolinite bed layer. A detailed description of the experimental results is presented in Chapter 5.

The analysis of the experimental results is presented in Chapter 6. Firstly, the concentration distribution of the (consolidated) bed layer is presented and compared with results from the literature. The critical wave conditions for the initiation of motion of a kaolinite bed are given. Suspended sediment concentrations are related to the rms-values of the orbital velocities at the bed, the wave period and the bed-surface concentration. The generation of a high-concentration fluidized sediment suspension layer close to the bed is discussed. Finally, the influence of fine sand particles present in the bed material is reported.

## 2.2 Conclusions

The study has led to the following conclusions:

1. relatively large waves acting on a consolidated bed surface of kaolinite material can fluidize the bed surface and generate a thin fluidized sediment suspension layer with a thickness in the range of 0.01 to 0.02 m and concentrations larger than 100000 mg/l

2. the generation of a fluidized suspension layer seems to have a stabilizing effect by reducing the vertical upward transport of sediment material as a result of the absence of large velocity gradients and hence shear stresses (vortices) at the interface while also the turbulence is damped by the increased density; the equilibrium concentrations above the interface show a rather strong decrease (factor 20 to 50)

3. relatively small waves acting on a bed of kaolinite material can only wash out the top layer of the bed surface resulting in small concentrations which are distributed rather uniformly over the depth; the ratio of the near-bed concentrations and water-surface concentrations is about 2 to 5

4. the kaolinite concentrations at a specific location increase for increasing rms-values of the orbital velocities ($u_{rms}$) following a power-law relationship with an exponent in the range of 3 to 6; the exponent seems to decrease for increasing rms-values (stabilizing effect of fluidized suspension layer); a larger wave period yields smaller concentrations at the same rms-velocties; a larger bed-surface concentration yields smaller concentrations at the same wave conditions.

5. a clear flocculation effect does occur for kaolinite concentrations in the range of 100 to 10000 mg/l resulting in an increase of the median settling velocity with a factor 10; for concentrations larger than 10000 mg/l the settling velocity is reduced by hindered-settling effects.

6. regular waves can generate a wave-induced mass transport close to the bed in the wave direction (velocities in the range of 0.01 to 0.04 m/s were observed).

7. a bed consisting of a large amount (75%) of kaolinite and a small amount (25%) of fine sand ($d_{50}$ = 95 μm) showed a similar erosional behaviour as a pure (100%) kaolinite bed; a fluidized sediment suspension layer was generated close to the bed in which the fine sand particles were buried so that they could not be suspended.

8. a bed surface consisting of a large amount (75%) of fine sand ($d_{50}$ ≃ 95 μm ) and a small amount (25%) of kaolinite showed a strong suppression of the bed-surface ripples compared to those generated in case of a pure (100%) sand bed of the same size ($d_{50}$ ≃ 95 μm ); the sand particles were accumulated at the ripple tops (height ≃ 2 mm) while the kaolinite particles were accumulated in the ripple troughs; the kaolinite concentrations were not larger than about 300 mg/l, even at the largest waves, because only the top layers of the bed surface were washed out; the sand concentrations were much smaller (factor 35) than those generated above a pure (100%) sand bed because of suppression of the bed surface ripples (reduced turbulence level).

## 2.3 Suggestions for further research

It is suggested to carry out:

1. a theoretical study of the interaction of waves with a cohesive sediment bed modelling all relevant parameters such as wave-induced pore pressures, soil stresses, depth-dependent bed densities (see Madsen, 1978 and Yamamoto, 1985); this study should identify the parameters controlling the penetration depth of the wave motion and hence the thickness of the fluidized sediment suspension layer

2. a theoretical study of the vertical concentration distribution modelling the wave-induced mixing, the increased settling velocities for concentrations in the range of 100 to 10000 mg/l (flocculation) and the reduced settling velocities for concentrations larger than 10000 mg/l (hindered settling)

3. an experimental study using natural mud as bed material which may lead to significantly different results depending on the density and the cohesive strength of the consolidated bed surface.

# 3. Chemical, mineralogical and hydraulic properties of kaolinite

## 3.1 Chemical and mineralogical composition

Commercially available kaolinite material was used as sediment material in the present study. The chemical composition, as given by the supplier (BLYTHE, MAASTRICHT, THE NETHERLANDS), is as follows:

| | |
|---|---|
| $SiO_2$ | 49.5% |
| $AL_2O_3$ | 35.4% |
| $H_2O$ | 11.4% |
| $K_2O$ | 1.6% |
| $Na_2O$ | 1.1% |
| $Fe_2O_3$ | 1.0% |

The mineralogical composition, as determined by the laboratory of Soil Mechanics, is as follows:

| | |
|---|---|
| Kaolinite | 80% |
| Illite | 15% |
| Quartz | 4% |
| Smectite | 1% |

## 3.2 Particle size

Particle size analysis was carried out by using a sedimentation method and a laser diffraction method (Malvern, 1984). The sedimentation method is based on the sedimentation of particles in an initially uniform suspension. The settling height is about 0.3 m. The weight of the deposited material is recorded by an under-water balance. Distilled water of 20°C was used as the settling medium. Basiccally, the sedimentation method yields a settling velocity curve, which can be converted to an equivalent quartz particle size curve using the settling velocity formula of Stokes.

The Laser diffraction method uses the principle of Fraunhofer diffraction from the particles. The incident Laser light is diffracted by the particles illuminated to give a stationnary diffraction pattern. A Fourier transform lens focusses the diffraction patherm onto a multi-element photo-electric detector.

Using the measured diffraction pattern, a computer analysis is performed to find the size distribution that gives the closest fitting diffraction pattern. Figure 1 shows the particle size curves based on the above-mentioned analysis methods as well as the particle size curve given by supplier of the kaolinite material. As can be observed, the $d_{50}$ varies in the range of 4 to 6 μm. Particles lager than 50 μm were not detected.

## 3.3 Consolidation

Preliminary to the flume experiments, some consolidation tests were carried out in small cylinder-glasses. The initial heights ($h_o$) of the uniform suspensions were 0.1 and 0.3 m. The initial concentrations were 25, 50, 100, 175, 250 and 500 kg/m$^3$. In all test saline water (salinity = 31°/$_{oo}$, temperature = 10°C) was used. The tests consisted of measuring the height(h) of the kaolinite surface above the bottom of the cylinder as a function of time. The results are presented in Figure 2. The depth-mean concentrations after a consolidation period of 7 days are also reported.
According to Migniot (1968), the consolidation process consists of various phases (see Figure A):

- hindered settling phase (settling of flocs varies linearly with time)
- first settling phase (flocs are bedding down, water being squeezed out)
- second settling phase (water is eliminated by porosity and drainage wells)
- third settling phase (water is eliminated by compression)

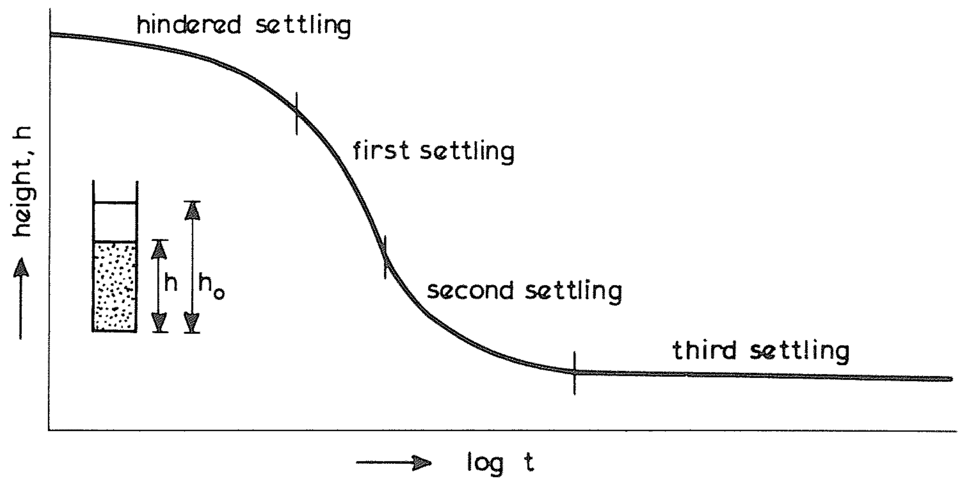



Fig. A Consolidation process

Figure 2 clearly shows the various phases of the consolidation process. In a small layer ($h_o$ = 0.1 m) the consolidation process proceeds relatively fast, because the vertical travel distance for the (expelled) pore water is relatively small. This is clearly visible for most consolidation tests. The mean sediment concentrations (depth-mean values) after 7 days are also reported. The bulk density follows from $\rho_{bulk} = \rho_w + c\ ((\rho_s - \rho\ )/\rho_s)$, where c = concentration, $\rho_w$ = water density, $\rho_s$ = sediment density.

3.4 Settling velocities

An important sediment property of cohesive material is the settling velocity ($w_s$). For particles smaller than about 5 μm the Brownian motion is significant compared with gravitational motion. When the settling particles are cohesive they aggregate on collision forming larger aggregates (flocs) with larger settling velocities. This effect increases for larger concentrations. In the present study special laboratory tests were carried out to examine the influence of the sediment concentration on the settling velocities of kaolinite material. In all these tests saline water was used (salinity = 31°/$_{oo}$, temperature = 10°C). The analysis method consisted of determining the concentrations as a function of time at a fixed height in an initially uniform suspension of about 1 liter. The suspensions were prepared by mixing dry kaolinite material and saline water in a perspex cylinder until a homogeneous suspension was obtained. A simple pipet was used to collect 5 ml-samples of water and sediment at a fixed level of 0.075 m below the surface of the suspension after 5, 10, 20, 30, 60, 120 and 240 minutes (see Fig. B).

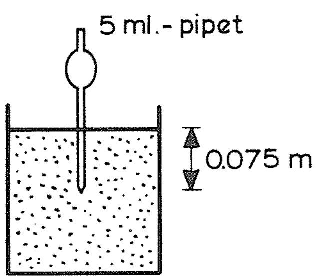



Fig. B Pipet sampling method

The concentration of the samples was determined by using a calibrated turbidity meter (see par 4.3.2). If neceseary, the samples were diluted with clear saline water to fall in the range of the turbidity meter.

Figure 3 shows the settling velocity curves for initial concentrations in the range of 250 to 10000 mg/l. As can be observed, the settling velocities show a large increase for increasing concentrations because of the flocculation effect. The $w_{s,50}$-values are also plotted as a function of concentration (up to 10000 mg/l) in Figure 4. The $w_{s,50}$-values of samples collected during the actual flume tests (see chapter 5) are also shown. These latter values are somewhat larger for concentrations in the range of 100 to 1000 mg/l and somewhat smaller for concentrations in the range 5000 to 10000 mg/l.
Settling velocities for concentrations larger than 10000 mg/l were determined from the subsidence of the kaolinite surface during the initial phase of the consolidation tests (see par. 3.3). These results show a decreasing settling velocity for increasing concentrations (up to 100000 mg/l) which is known as the hindered settling effect. For comparison experimental results reported by Owen (1976) and Nedeco (1965) are also presented. The results of Owen show rather large settling velocities which may be caused by the fact that a relatively long settling tube (length = 2 m) has been used. As a result of the settling of particles over such a large length in still water, there may be an increased flocculation which would not have occurred when a small settling tube was used. Hence, the results of Owen may be representative for the settling process near the turning of the tide (still water). It is questionable if large flocs and hence large settling velocities can exist in the presence of turbulence.
Based on the above-given results, two distinct ranges can be observed.

$$w_s = \alpha\, c^{\beta} \qquad \text{for flocculating suspensions (0 - 10000 mg/l)} \qquad (3.1)$$

$$w_s = w_{s,o}(1-c)^{\gamma} \qquad \text{for hindered-settling suspensions (> 10000 mg/l)} \qquad (3.2)$$

in which:

| | | | |
|---|---|---|---|
| $w_s$ | = | settling velocity | (m/s) |
| $w_{s,o}$ | = | settling velocity of individual particles in clear water | (m/s) |
| $c$ | = | volume concentration | (-) |
| $\alpha$ | = | empirical coefficient | (m/s) |
| $\beta$ | = | empirical coefficient ($\simeq$ 1) | (-) |
| $\gamma$ | = | empirical coefficient ($\simeq$ 4) | (-) |

Hindered settling occurs when there is an upward flow of fluid escaping from between the particles or flocs as they are settling by gravity. A state of fluidization of the bed may occur when the vertical upward fluid flow is so strong that the upward drag forces exerted on the particles or flocs become equal to the downward forces of gravity resulting in a stituation with no net vertical movement of the particles or flocs (static interface between bed and suspension).

## 3.5 Viscosity

The viscosity of a fluid is a measure of its resistance to flow. Newton postulated that the shear stress ($\tau$) within a fluid is proportional to the shear rate (du/dz). The proportionality coefficient is called the dynamic viscosity coefficient ($\mu$). Other fluids are called Non-Newtonian fluids. A kaolinite suspension behaves approximately like a Bingham fluid, which is a subgroup of the Non-Newtonian fluids. The relationship between shear stress and shear rate for this latter type of fluids can be approximated by (see also Fig. C)

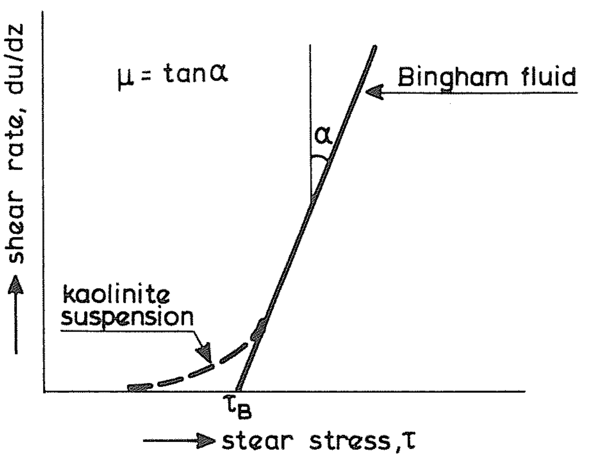



Fig. C Shear stress-shear rate relationship

$$\tau = \tau_B + \mu \frac{du}{dz} \qquad (3.3)$$

in which:

| | | | |
|---|---|---|---|
| $\tau_B$ | = | yield stress | ($N/m^2$) |
| $\mu$ | = | dynamic viscosity coefficient | ($NS/m^2$) |
| u | = | fluid velocity at height z | (m/s) |

Some tests were carried out to determine the dynamic viscosity coefficients of unconsolidated Kaolinite suspensions (large concentrations) using a BROOKFIELD-rotaviscosimeter. This type of viscosimeter is based on the principle of measuring the force required to rotate a spindle in a fluid. The rotaviscosimeter was operated at two speeds (30 and 60 revolutions per minute). Figure 5 shows the μ-coefficient as a function of kaolinite concentration. For comparison a relationship proposed by Engelund and Zhaohui (1984) for kaolinite material in non-saline fluid is shown also. This expression reads as:

$$\mu = 0.001 + 0.206\ c^{1.68} \qquad (3.4)$$

Equation (3.4) yields values which are considerably smaller than the present results. A possible explanation for this discrepancy may be instrumental errors. More research should be carried out to compare various types of viscosimeters.

## 4. Experimental set-up and measuring instruments

### 4.1 Experimental set-up

The experiments were performed in a wave flume (length = 17 m, width = 0.3 m, depth = 0.5 m) of the Delft Hydraulics Laboratory. Figure 6 shows the experimental set-up. Regular waves were generated by a simple wave paddle. At the end of the flume a wave damping structure was installed to reduce wave reflections. At the location of the wave generator and the wave damper a false floor (height = 0.05 m, length = 3.5 m) with a smooth wooden surface was installed. The remaining deeper section of the flume (length = 10 m) was used as the test section where the Kaolinite material was deposited from an initially uniform suspension and tested by the effect of (regular) waves.
Before filling the test section with a layer of kaolinite suspension, partition walls separating the test section from the rest of the flume were installed. The partition walls were removed after the kaolinite bed had consolidated to its final thickness. Then, the flume was filled slowly with saline water (salinity = 31‰, temperature ≃ 10°C).

### 4.2 Measuring instruments

#### 4.2.1 Waves

The wave heights were measured by using a wave height meter based on the principle of conductivity.
Additional information was obtained by visual observation of measuring scales attached to the glass walls of the flume.

#### 4.2.2 Velocities

Time-averaged values and root-mean-square values of the orbital velocities (u, w) were determined using a time-domain analyzer. Instantaneous velocities were measured by:

- laser-doppler method
- acoustic-doppler method

The laser-doppler method (Godefroy, 1978), which can only be operated in clear water, was used in preliminary tests during which the test section was equipped with a flat wooden bottom surface connecting the (permanent) wooden surfaces on both ends of the flume (Fig 6). The results of these measurements are presented in paragraph 5.1.

The acoustic-doppler method which has been used to measure the velocity components in the sediment suspensions, is based on the principle of ultra-sound scattered by the sediment particles (Jansen, 1978). The instrument used in the present study measures the longitudinal velocity component (u) and the vertical component (w) simultaneously. To reduce the instrument-induced velocity disturbances, a new arrangement of the sound source and detectors was designed. This implies a downward-directed sound source. The measuring volume (0.03 x 0.015 x 0.015 m) is located at 0.125 m beneath the vertical (middle) leg of the instrument (Photograph 1). A disadvantage of this arrangement is its sensitivity for sound reflections from the bed surface. Depending on the rigidity of the bed surface, this instrument cannot be used within a distance from the bed of about 0.02 m (soft muddy bed) to 0.05 m (rigid sand bed). The measuring results based on a measuring period of 120s are presented in chapter 5

Preliminary measurements in clear water were carried out to compare the laser-doppler system and the acoustic-doppler system. Both systems were used simultaneously to measure the velocity components in specific points. The measuring period was 60 s. The results are presented in Table 1. Large discrepancies can be observed between the results of the two instruments both in the magnitude as well as in the direction of the velocity components. Assuming the velocities measured by the laser-doppler system to be the most accurate, the results of the acoustical system seem to be:

$\bar{u}$ - velocities : too large for H = 0.014 m and 0.05 m,

$\bar{w}$ -velocities : reasonable,

$u_{rms}$ -velocities : too large for H = 0.014 m, but too small for H = 0.05 m and 0.105 m,

$w_{rms}$ -velocities : too large for H = 0.014 m and reasonable for H = 0.05 m and 0.105 m.

The reason for the observed deviations may be the relatively large measuring volume and the sensitivity for bed-induced sound reflections of the acoustic-doppler system. Since the acoustic system used in this study is a new instrument, more research is necessary to get a better understanding of its accuracy. Because of the relatively bad performance of the acoustic-doppler system, the results of this instrument were not used in the analysis of the concentration-velocity relationships (Chapter 6).

### 4.2.3 Sediment concentrations

Three methods were used to determine the sediment concentrations in the test section of the flume, being a:

- siphon method
- optical method
- pipet method

The siphon method consists of a system of brass intake tubes with an internal diameter of 0.003 m connected to plastic hoses (see Photograph 1). The intake openings were situated normal to the wave direction. The intake velocity can be regulated by varying the height of the outflow opening with respect to the water surface. Using this sampler, nine fluid-sediment samples were taken simultaneously. The samples were collected in plastic bottles (≃ 0.5 liter), which were filled in about 3 minutes. This implies an intake velocity at the sampling location of about 0.4 m/s.

The optical system (opcon, Bosman 1984) which is based on the principle of light extinction by the sediment particles, consists of two vertical legs containing the light source and the light detector (see Photograph 1). The light path length is 0.0296 m. Since the results of the optical sampler are strongly dependent on particle size, a calibration is necessary. Figure 7A shows two calibration curves relating the output signal (volt) to the sediment concentration. Curve I was obtained by measuring the concentrations in a small rotating cylinder (perspex). The cylinder was filled with 2 liters of saline water ($s = 31°/_{oo}$, $Te = 10°C$) in which dry kaolinite of a given weight was put. The fluid-kaolinite mixture was rotated by use of a mechanical propeller. The opcon was put in the rotating suspension and the output signal was read after a period of about 5 minutes.

Curve II is based on a calibration using fluid-kaolinite samples collected by the siphon sampler during the actual flume tests. The samples were transferred to the rotating (calibration) cylinder and the output signal of the opcon was read. After that a small subsample was collected to determine the sediment concentration using the turbidity meter (paragraph 4.3).
As can be observed, there is a rather large discrepancy between curve I and II which may be caused by flocculation effects. Probably, the samples collected during the flume tests consisted of relatively large flocs, which were not broken down in the rotating cylinder.
All opcon-results presented in chapter 5 are based on curve II. The measuring period for the opcon-sampler was 30 seconds.

A 20 ml-pipet was used to collect fluid-kaolinite samples close to the bed during the flume tests (Photograph 3). This sampler consisted of a small suction tube (internal diameter of 0.003 m) connected to a 20 ml-container and equipped with a small piston.
A commercially available 5 ml-pipet was used to collect sediment samples from the consolidated kaolinite bed layer (see Photograph 2). The pipet was attached to a point-gage (accurate to 0.1 mm) to ensure an accurate determination of the sampling depth.

#### 4.2.4 Salinity and temperature

The salinity and temperature was measured with a commercially available instrument (BECKMAN). Comparative measurements showed an inaccuracy of about 5%.

### 4.3 Analysis of sediment samples

To determine the kaolinite concentration of the sediment samples stored in the plastic bottles (0.5 1), small subsamples were withdrawn using a 5 ml-pipet (after shaking the bottle thoroughly). Each subsample was transferred to a small glass tube to be analyzed in a commercially available turbidity meter (HACH, Photograph 4) If necessary, the samples were diluted using clear water of the same salinity to fall in the measuring range (0 - 2000 mg/1) of the turbidity meter. Special calibration tests using the same kaolinite material were carried out yielding a relationship between output signal and kaolinite concentration (Fig. 7B). To determine the overall inaccuracy of the complete analysis method (dilution method and turbidity reading), five suspensions of known concentrations (1000, 5000, 10000 and 20000 mg/l) were prepared and analyzed resulting in a systematic error of about 10%.The measured concentrations were consistently 10% larger than the prepared concentrations. The results presented in Chapter 5 are not corrected for this (small) systematic error.

In some experiments the sediment bed consisted of a kaolinite-sand mixture. The sediment samples collected during these tests were firstly analyzed to determine the kaolinite concentration. After that the samples were poured over a 50 μm-sieve to separate the sand particles. A volumetric method was used to determine the amount of sand particles.

## 4.4 Experimental procedure

The experimental procedure to study the effect of waves on a sediment bed (kaolinite, kaolinite-sand, sand) was as follows (see Fig D):

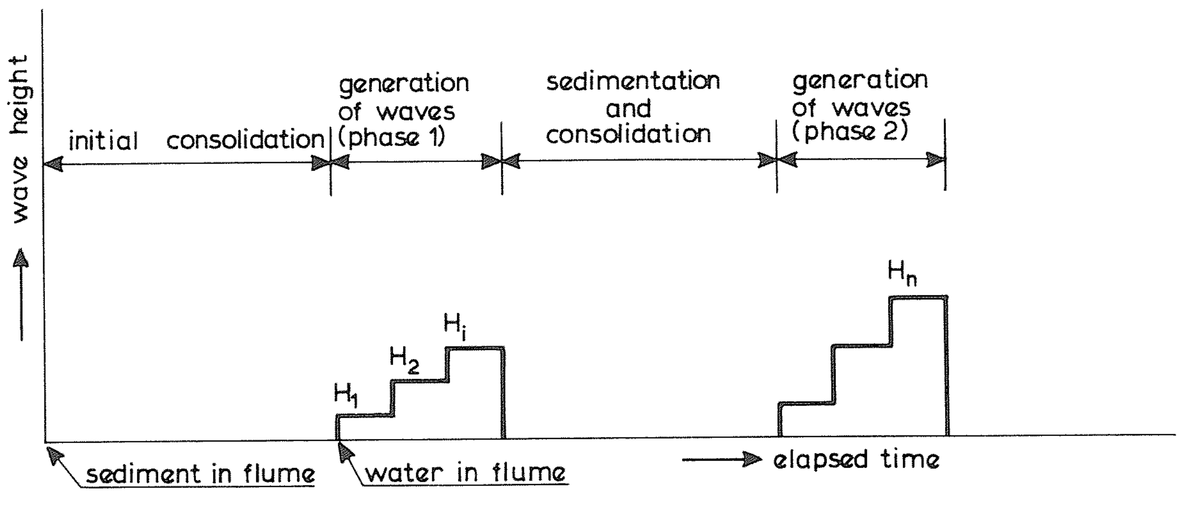



Fig. D Experimental procedure

1. preparation of sediment suspension

   The dry sediment material was poured into a container (≃ 500 l) and mixed with saline water (salinity = 31°/₀₀, temperature ≃ 10°C). To obtain a homogeneous suspension, the fluid-sediment mixture was circulated by a pump system which was also used to fill the test section of the flume.

2. formation of bed layer of sediment

The high concentration suspension was pumped into the test section of the flume. Based on the results of the separate consolidation tests (par. 3.3), the initial layer thickness was chosen in such a way that after consolidation a layer of 0.05 m was obtained to give a smooth transition from the sediment bed to the false wooden floor on both ends of the flume.

3. consolidation of bed layer

The sediment layer was allowed to consolidate for several days. During the consolidation period, bed samples were taken using a 5 ml-pipet (Photograph 2) to determine the vertical distribution of the sediment concentrations at various locations in the test section. At the end of the consolidation period a consolidated bed layer of sediment was obtained with a layer of almost clear (saline) water above the sediment bed. After that the flume was filled slowly with clear water of the same salinity (water depth = 0.25 m).

4. generation of waves (phase 1)

Regular waves were generated by a simple wave paddle. The wave heights were increased in steps until initiation of motion of the sediment material was observed visually. After that the wave height was increased further to generate a low-concentration suspension in the test section. During this period, velocity (acoustical probe) and concentration (optical probe, siphon sampler) measurements were performed. Dye injections were carried out to determine the mass transport velocity of the sediment material close to the bed.

5. deposition of suspended sediment

After stopping the wave generator, the low-concentration suspension was allowed to settle for a period of about 20 hours. At the end of this period several bed samples were taken using the pipet method at three locations in the test section.

6. generation of waves (phase 2)

Waves were generated of increasing heights in steps until initiation of motion of sediment material was observed visually. After that the wave height was increased further to generate a high-concentration suspension in the test section. During this period, velocity (acoustical probe) and concentration (siphon and pipet sampler) measurements were carried out. Fluid-sediment samples were collected to determine the particle fall velocities of the (flocculated) sediment material. Dye injections were carried out to measure the mass transport velocity of the sediment material close to the bed.

At the end of this second period of wave generation the experiment was stopped.

## 5. Description of experimental results

A summary of the experimental conditions is given in Table 4.
A summary of the most important experimental results is given in Table 5.

### 5.1 To-experiment: rigid wooden bottom, wave period = 1.5 and 2.5 s

Preliminary experiments were carried out to examine the longitudinal variation of the wave height and the vertical velocity distributions. The water depth was 0.25 m. The measured wave heights, presented in Table 2, show a gradual decrease because of energy dissipation by wall and bottom fiction. Wave profiles are shown in Figure 8.
Time-averaged and rms-values of the orbital velocities (in longitudinal direction) based on laser-doppler measurements in the centre line of the flume are shown in Table 3 and Fig 9. The measuring period was 60 s. As can be observed, most time-averaged velocities show small positive values (in wave direction). The measured velocity profiles are not in agreement with the theoretical drift velocity profiles for regular uniform waves, as given by Longuet-Higgins (see Fig E).

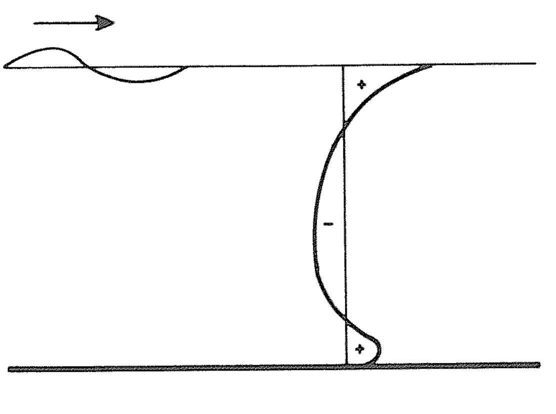



Fig. E Drift velocity profiles

Discrepancies between theoretical and experimental results can be expected because of wave asymmetry and wave energy dissipation effects. However, the presence of a residual flow in the wave direction as indicated by the measuring results, is not realistic. The reason for this is not clear.
As shown in Fig 9, the rms-values of the orbital velocities are nearly constant in vertical direction. Figure 10 shows the rms-value at 0.01 m above the bottom as a function of the wave height. For comparison a theoretical

curve based on linear wave theory is also presented. In case of regular waves it follows that $u_{rms} = \frac{1}{2}\sqrt{2}\ u_{peak}$ ($u_{peak}$ = amplitude of orbital velocity) resulting in:

$$u_{rms\ at\ bottom} = \tfrac{1}{2}\sqrt{2}\ \frac{\pi H}{T}\ \frac{1}{\sinh\,(2\pi h/L)} \tag{5.1}$$

in which:

| | | | |
|---|---|---|---|
| H | = | wave height | (m) |
| L | = | wave length | (m) |
| T | = | wave period | (s) |
| h | = | water depth | (m) |

On the average, the measured rms-values are somwhat larger than those based on linear wave theory. These discrepancies are caused by second order effects (wave asymmetry, wave reflections in the flume) and by limited applicability of the linear wave theory (validity range).

## 5.2 T1-experiment: kaolinite bed, mean bed concentration = 460 kg/m$^3$, wave period = 1.5 s

### 5.2.1 General characteristics

| | | |
|---|---|---|
| initial kaolinite concentration | = | 250 ± 10 kg/m$^3$ |
| initial layer thickness | = | 0.11 ± 0.005 m |
| water depth | = | 0.24 ± 0.01 m |
| salinity | = | 32 ± 1 ‰ |
| water temperature | = | 11 ± 1 °C |

### 5.2.2 Consolidation

| | | |
|---|---|---|
| Total consolidation period | = | 120 hours |
| final layer thickness | = | 0.09 ± 0.005 m |
| final depth-mean concentration | = | 460 ± 20 kg/m$^3$ |

During the consolidation period of the kaolinite bed several samples (using a 5 ml-pipet) were collected at 0.01, 0.025 and 0.045 m below the local kaolinite surface in sections 7, 9 and 11 (see Fig 6). The mean value as well as the smallest and largest value are indicated. The variations are due to spatial variations, sampling errors and analysis errors. The depth-mean concentration is based on the ratio of the initial and the final layer thickness multiplied by the initial sediment concentration. In the final stage of consolidation the near-surface concentration was about 250 $kg/m^3$, the near-bottom concentration was about 550 $kg/m^3$. The surface of the kaolinite bed showed small vertical drains (expulsion of pore water) ending in a small crater (diameter ≃ 10 mm, top height ≃ 2 mm).

### 5.2.3 Generation of waves (phase 1)

T1-1, wave height = 0.008 m, test period = 30 min

In the vicinity of the surface irregularities (craters) weak sediment movement was observed (initiation of motion).

T1-2, wave height = 0.014 m, test period = 30 min

Weak sediment movement was observed at nearly all locations.

T1-3, wave height = 0.024 m, test period = 100 min

General sediment movement was observed. A thin layer (≃ 5 mm) of kaolinite suspension was generated in which clearly visible vortices of kaolinite particles were observed. Figure 12 shows the sediment concentrations at various heights as a function of time. Equilibrium conditions were established after about 100 minutes. The concentrations in the near-bed layer are as large as 400 mg/l. The concentrations near the water surface are as large as 20 mg/l. Figure 13 shows concentration profiles (mean-value and rms-value) at various times. The mean concentrations show a gradual increase from the water surface to the bed. The rms-concentrations are relatively large near the bed (≃ 100 mg/l) but relatively small at higher elevations (≃ 10 mg/l).

T1-4, wave height = 0.04 m, test period = 120 min

In the initial stage a thin layer (≃ 10 mm) of kaolinite suspension with small-scale vortex motions was observed. After 15 minutes the kaolinite surface became instable locally showing small-scale waves (height ≃ 5 mm). In section 12 the top layer of the kaolinite bed was fluidized resulting in a high-concentration suspension layer (thickness ≃ 10 mm, Fig 15). Based on pipet-samples, the concentrations were found to be about 100000 mg/l. The interface of the fluidized layer showed small-scale waves (height ≃ 5 mm). At other locations this fluidized suspension layer was not observed. Figure 14 shows time-concentration curves for section 9.5 m (see Fig 6). Equilibrium conditions were established after 6o minutes. The kaolinite concentrations range from 800 mg/l close to the bed to 200 mg/l near the water surface. Figure 15, 16 and 17 show kaolinite concentration profiles at various locations and times. Figure 17 shows velocity profiles (acoustical method).

T1-5, wave height = 0.06 m, test period = 45 min

At all locations a thin (≃ 10 mm) fluidized suspension layer of high concentrations (≃ 100000 mg/l) was generated. Small-scale waves (height ≃ 5 mm) were observed at the interface of the fluidized layer.
Figure 18 shows concentration (mean-values and rms-values) profiles for section 9. The mean concentrations above the fluidized layer range from 2500 mg/l near the interface to 400 mg/l near the water surface. The rms-values range from 400 mg/l near the interface to 40 mg/l near the water surface. Figure 19 shows concentration and velocity profiles at other locations. At the end of this test period the wave generator was stopped because of intensive erosion of sediment material on both ends of the test section.

## 5.3 T2-experiment: kaolinite bed, mean bed concentration = 460 kg/m$^3$, wave period = 2.5 s

### 5.3.1 General characteristies

| | | |
|---|---|---|
| initial kaolinite concentration | = | 250 ± 10 kg/m$^3$ |
| initial layer thickness | = | 0.11 ± 0.005 m |
| water depth | = | 0.24 ± 0.01 m |
| salinity | = | 31 ± 1 ‰ |
| water temperature | = | 10 ± 1 °C |

### 5.3.2 Consolidation

| | | |
|---|---|---|
| Total consolidation period | = | 96 hours |
| final layer thickness | = | 0.059 ± 0.003 m |
| final depth-mean concentration | = | 460 ± 20 kg/m3 |

Figure 20 shows the kaolinite concentrations in the consolidated bed layer. In the final stage of consolidation the near-surface concentration was about 360 $kg/m^3$, the near-bottom concentration was about 600 $kg/m^3$. The surface of the bed showed small vertical drains ending in a small crater (diameter ≃ 10 mm, height ≃ 2 mm)

### 5.3.3 Generation of waves (phase 1)

T2-1, wave height = 0.014 m, test period = 30 min

Weak sediment movement was observed in the vicinity of the bed surface irregularities (initiation of motion).

T2-2, wave height = 0.03 m, test period = 240 min

General sediment movement was observed. Initially a thin (≃ 5 mm) layer of kaolinite suspension was generated in which small vortices did occur. The sediment concentrations in this layer were approximately 200 to 300 mg/l. After 60 minutes the interface of the suspension layer had reached the water surface. Figure 21 shows time-concentration curves. Equilibrium conditions were established after 180 min with concentrations varying from 1000 mg/l (near the bed) to 150 mg/l (near the water surface).

Figure 22 shows concentration profiles (mean-values and rms-values) at various times. As can be observed, there is a near-bed layer of relative large mean concentrations (500 to 1000 mg/l). The rms-concentrations in this layer are about 100 to 200 mg/l, which is approx 20% of the mean values. At higher levels the rms-values are only 5 to 10% of the mean concentrations indicating much smaller fluctuations.

Figure 23 shows velocity profiles (acoustical method).

### 5.3.4 Sedimentation and consolidation

After stopping the wave generator, the kaolinite suspension was allowed to settle for 16 hours. At the end of this period the fluid in the flume was relatively clear and small irregularities (height ≃ 2 mm) became visible at the surface of the bed.

### 5.3.5 Generation of waver (phase 2)

T2-3, wave height = 0.05 m, test period = 120 min

Locally, the bed surface showed small-scale waves (height ≃ 5 mm). However, a clearly visible fluidized suspension layer of high concentrations was not observed during this test period .

Figure 24 shows time-concentration curves. Equilibrium conditions were established after 60 min with concentrations varying from about 2000 mg/l (near the bed) to 700 mg/l near the water surface.

Figure 25 shows concentration profiles (mean-values and rms-values) at various times. Close to the bed the rms-values are as large as 400 mg/l, which is about 20% of the mean concentrations. At higher levels the rms-values are only 5% to 10% of the mean concentrations indicating relatively small concentration fluctuations.

During this test period the siphon sampler was used to withdraw fluid-kaolinite samples at 0.02 m and 0.17 m above the bed surface. These samples were stored in 1 liter-bottles to determine the particle-fall velocity curves using the pipet-method (see par. 4.3). Before the start of the analysis the samples were stirred gently to obtain a homogeneous suspension. The results, presented in Figure 26, show an equivalent Stokes diameter (median value) of about 14 μm at 0.02 m above the bed (concentration = 2400 mg/l) and about 6 μm at 0.17 m above the bed (concentration = 800 mg/l). As expected, a relativley large particle size does occur in regions with relatively high concentrations because of the flocculation effect.

Figure 26 also shows velocity profiles (acoustical method).

T2-4, wave height = 0.075 m, test period = 30 min

At the start of this test period the mean thickness of the kaolinite bed was about 0.058 m. Because of intensive erosion this value reduced to 0.046 m after 15 minutes. The siphon sampler was used to collect fluid-kaolinite samples. The concentration profiles are shown in Figure 27. Extremely large concentrations can be observed ranging from 60000 mg/l (close to the bed) to 7500 mg/l (near the water surface). A clear fluidized suspension layer of high concentrations (> 100000 mg/l) was not observed.

Figure 27 also shows measured velocity profiles (acoustical method).

## 5.4 T3-experiment: kaolinite bed, mean bed concentration = 640 kg/m$^3$, wave period = 2.5 s

### 5.4.1 General characteristics

| | | | |
|---|---|---|---|
| initial kaolinite concentration | = | 500 ± 25 | kg/m$^3$ |
| initial layer thickness | = | 0.063 ± 0.003 | m |
| water depth | = | 0.25 ± 0.01 | m |
| salinity | = | 31 ± 1 | ‰ |
| water temperature | = | 10 ± 1 | °C |

### 5.4.2 Consolidation

| | | | |
|---|---|---|---|
| total consolidation period | = | 115 | hours |
| final layer thickness | = | 0.049 ± 0.005 | m |
| final depth-mean concentration | = | 640 ± 50 | kg/m$^3$ |

Figure 28 shows the kaolinite concentrations of the consolidated bed layer. After a consolidation period of 115 hours the near-surface concentration was about 400 kg/m$^3$, the near-bottom concentration was about 700 kg/m$^3$. The surface of the kaolinite bed showed small vertical drains ending in small craters (diameter ≃ 5 mm, height ≃ 1 mm).

### 5.4.3 Generation of waves (phase 1)

T3-1, wave height = 0.02 m, test period = 30 min

Weak sediment movement was observed near the bed-surface irregularities. A thin (≃ 3 mm) suspension layer with concentrations of about 100 mg/l was generated locally.

T3-2, wave height = 0.03 m, test period = 30 min

General sediment movement was observed at all locations. A thin (≃ 10 mm) suspension layer with concentrations of about 200 mg/l was generated. Small fluid-sediment vortices were clearly visible in this layer.

T3-3, wave height = 0.048 m, test period = 180 min

The thickness of the (dilute) kaolinite suspension gradually increased. After 60 minutes the interface had reached the water surface.
Figure 29 shows time-concentration curves. Equilibrium conditions were established after approximately 120 minutes with concentrations ranging from 2000 mg/l (near the bed) to 500 mg/l (near the water surface).
Figure 30 shows concentration profiles (mean-values and rms-values) at various times. A thin (≃ 0.01 m)layer of reltively large concentrations (1000 to 3500 mg/l) can be observed. The rms-values in this layer range from 200 to 700 mg/l, which is about 20% of the mean concentrations. During this test period samples were collected to determine the particle fall velocities (pipet method). The results, presented in Figure 31, show an equivalent Stokes diameter (median value) of about 9 µm near the bed (concentration = 1500 mg/l) and of about 5 µm near the water surface (concentration = 435 mg/l).
Figure 31 also shows velocity profiles (acoustical method).

T3-4, wave height = 0.072 m, test period = 60 min

Locally, intensive erosion did occur resulting in scour holes with a depth of about 0.01 to 0.03 m. At these locations violent vortex motions were generated (Photograph 7 and 8). At other locations (section 11, Photograph 5) the top layer of the bed surface was fluidized resulting in a thin (≃ 10 - 20 mm) moving suspension layer with concentrations in the range of 100000 to 300000 mg/l (based on pipet-samples).
Figure 32 shows measured concentrations for section 9.6 (see Fig 6). At this location a high-concentration suspension layer with concentrations in the range of 10000 to 60000 mg/l was generated. A fluidized suspension layer (concentrations > 100000 mg/l) did not occur in sedion 9.6 (Photograph 6).
Equilibrium conditions were established after about 60 minutes.
Figure 33 shows measured velocity profiles (acoustical method)

### 5.4.4 Sedimentation and consolidation

After stopping the wave generator, the suspension was allowed to settle and consolidate for 19 hours. After this period the fluid in the flume was relatively clear. Locally, scour holes were visible. At other locations the bed surface was rather flat. The pipet-sampler was used to collect bed samples in section 7, 9 and 11. The sediment concentrations (presented in Figure 28) at

0.025 m below the bed surface are rather large (800-900 kg/m$^3$). The reason for this large value is not clear.

### 5.4.5 Generation of waves (phase 2)

T3-5, wave height = 0.02 m, test period = 30 min

Weak sediment movement was observed. Small-scale ripples (height ≃ 1 mm, length ≃ 10 mm) were generated by the peak-velocities but disappeared at the zero-crossing of the orbital velocity.

T3-6, wave height = 0.072 m, test period = 60 min

During this test period similar phenomena were observed as for the T3-4 test period. The measured concentrations are shown in Figure 32.
Samples were collected to determine the particle fall velocities. The results, presented in Figure 33, show an equivalent Stokes diameter (median value) of about 10 µm near the bed (concentration = 8500 mg/l) and of about 6 µm near the water surface (concentration = 1000 mg/l).

## 5.5 T4-experiment: kaolinite bed, mean bed concentration = 640 kg/m$^3$, wave period = 1.5 s

### 5.5.1 General characteristics

| | | | |
|---|---|---|---|
| initial kaolinite concentration | = | 500 ± 25 | kg/m$^3$ |
| initial layer thickness | = | 0.061 ± 0.003 | m |
| water depth | = | 0.25 ± 0.01 | m |
| salinity | = | 31 ± 1 | ‰ |
| water temperature | = | 9 ± 1 | °C |

### 5.5.2 Consolidation

| | | | |
|---|---|---|---|
| total consolidation period | = | 144 | hours |
| final layer thickness | = | 0.048 ± 0.005 | m |
| final depth-mean concentration | = | 640 ± 50 | kg/m$^3$ |

Figure 34 shows the kaolinite concentrations of the consolidated bed layer. After a consolidation period of 102 hours the near-surface concentration was about 400 kg/m3, the near-bottom concentration was about 800 kg/m3. The surface of the kaolinite bed showed vertical drains ending in small craters.

### 5.5.3 Generation of waves (phase 1)

T4-1, wave height = 0.014 m, test period = 30 min

Weak sediment movement was observed. Locally, a thin (≈ 2 mm) layer of kaolinite suspension was generated.

T4-2, wave height = 0.022 m, test period = 60 min

General sediment movement was observed at all locations. A thin (≈ 10 mm) layer of kaolinite suspension was generated in which concentrations of about 100 mg/l were measured. Vortex motions were also observed.

T4-3, wave height = 0.03 m, test period = 60 min

The thickness of the kaolinite suspension layer increased gradually to about 0.05 m. At the end of this test period a vague interface was visible at 0.05 m above the bed.
Figure 35 shows time-concentration curves. The mean concentrations range from about 500 mg/l near the bed to about 50 mg/l near the interface of the suspension layer.
Figure 36 shows concentration profiles (mean-values and rms-values) at various times. The rms-values are about 20% of the mean concentrations. Dye injections close to the bed showed the presence of an average mass-transport velocity in the wave direction of about 5 mm/s.

T4-4, wave height = 0.047 m, test period = 240 min

In the initial stage of this test period the kaolinite concentrations were reduced because the suspension layer was diluted by (orbital) mixing with clear water from higher levels (see Figure 37). After 30 minutes this process was stopped and the concentrations near the bed showed a rapid increase. Probably, some time is needed to reduce the cohesive strength of the bed surface bed by wave action. Equilibrium conditions were established after about 180 min with concentrations ranging from about 2500 mg/l near the bed to about 500 mg/l near the water surface.
Figure 38 shows concentration profiles (mean-values and rms-values) at various times. Near the bed the rms-values are about 20% of the mean concentrations; at higher levels the rms-values are about 5 to 10% of the mean-values.
Suspension samples were collected using the siphon sampler to determine the

particle fall velocities. The results, presented in Figure 39, show an equivalent Stokes diameter (median value) of about 6 μm. The largest value does occur near the bed surface where the largest concentrations can be observed. These results donot indicate a significant flocculation effect.
Figure 39 shows measured velocity profiles (acoustical method). Dye injections close to the bed showed the presence of an average mass-transport velocity in the wave direction of about 10 mm/s.

### 5.5.4 Sedimentation and consolidation

After stopping the wave generator, the kaolinite suspension was allowed to settle and consolidate for 43 hours. After this period the fluid in the flume was relatively clear. Locally, small scour holes with a depth of 0.02 m were visible. At other locations the bed surface was flat. The pipet-sampler was used to collect bed samples in section 7, 9 and 11 (see Fig 6). The vertical concentration distribution, presented in Figure 34, shows values in the range 350 to 750 $kg/m^3$.

### 5.5.5 Generation of waves (phase 2)

T4-5, wave height = 0.014 m, test period = 30 min

Weak sediment movement was observed near the bed-surface irregularities. No movement was observed at locations with a flat surface.

T4-6, wave height = 0.022 m, test period = 30 min

General sediment movement was observed at all locations. A thin (≃ 10 mm) layer of kaolinite suspension was generated (concentrations of about 100 mg/l). Locally, small-scale ripples were generated at high orbital velocities.

T4-7, wave height = 0.07 m, test period = 150 min

In the initial stage of this period a fluidized suspension layer with a thickness of about 10 mm was generated. The concentrations in this layer were larger than 100000 mg/l. At the end of the test period the thickness of the fluidized layer was about 25 mm. During this period the thickness of the consolidated bed decreased from 48 mm (t = 0 min) to about 25 mm (t = 150 min). This is shown schematically in Figure 40. The concentrations above the

fluidized suspension layer are in the range of 20000 mg/l near the bed to about 4000 mg/l near the water surface (after 150 min).
Figure 41 shows particle fall velocities and velocity profiles. The equivalent Stokes diameter (median value) is about 11 μm at both levels.
Dye injections close to the bed showed the presence of an average mass-transport velocity in the wave direction of about 20 mm/s. Because of the net mass-transport in the wave direction, the high-concentration suspension layer became relatively thick at the end of the flume, while at the beginning of the test section the layer thickness was reduced to approximately zero.

## 5.6 T5-experiment: kaolinite-sand bed, mean bed concentration = 790 kg/m$^3$, wave period = 1.5 s

### 5.6.1 General characteristics

| | | | |
|---|---|---|---|
| initial kaolinite concentration | | = | 480 ± 25 kg/m$^3$ |
| initial sand concentration | | = | 120 ± 5 kg/m$^3$ |
| initial layer thickness | | = | 0.063 ± 0.003 m |
| sand size | $d_{50}$ | = | 95 μm |
| | $d_{10}$ | = | 75 μm |
| | $d_{90}$ | = | 125 μm |
| water depth | | = | 0.25 ± 0.01 m |
| salinity | | = | 31 ± 1 ‰ |
| water temperature | | = | 7 ± 1 °C |

The kaolinite (75%) and sand (25%) materials were mixed to obtain a homogeneous slurry which was pumped into the test section.

### 5.6.2 Consolidation

| | | |
|---|---|---|
| total consolidation period | = | 119 hours |
| final layer thickness | = | 0.048 ± 0.005 m |
| final depth-mean concentration | = | 790 ± 50 kg/m$^3$ |

Figure 42 shows kaolinite and sand concentrations of the consolidated bed layer. After a consolidation period of 96 hours the kaolinite and sand concentrations near the surface were about 400 and 60 kg/m$^3$; the kaolinite and sand concentrations near the bottom are about 700 kg/m3 and 130 kg/m3.

### 5.6.3 Generation of waves (phase 1)

T5-1, wave height = 0.014 m, test period = 30 min

Weak sediment (kaolinite) movement was observed locally. A thin (≃ 2 mm) layer of kaolinite suspension was generated.

T5-2, wave height = 0.022 m, test period = 30 min

General sediment (kaolinite) movement was observed at all locations. A thin (≃ 10 mm) layer of kaolinite suspension was generated (concentrations ≃ 300 mg/l).

T5-3, wave height = 0.03 m, test period = 90 min

The thickness of the kaolinite suspension increased to about 0.05 m. At the end of the test period a vague interface was visible at 0.05 m above the bed surface. Figure 43 shows time-concentration curves. The mean concentrations range from 700 mg/l near the bed to about 100 mg/l at a level of 0.05 m above the bed surface. Figure 44 shows concentration profiles (mean-values and rms-values) at various times. Near the bed the rms-values are about 20% of the mean concentrations.

T5-4, wave height = 0.048 m, test period = 210 min

Equilibirum conditions were established after 120 minutes with kaolinite concentrations ranging from 1500 mg/l near the bed to 300 mg/l near the water surface (Fig 45). Locally, isolated spots of accumulated sand particles were visible with a diameter of about 5 mm and a height of about 1 mm (see Photograp 9). Small-scale vortex motions were generated near these spots. Suspended sand particles were not detected (siphon samples).

Figure 46 shows concentration profiles (mean-values and rms-values) at successive times. Near the bed the rms-values are about 20% of the mean concentrations. At higher levels the rms-values are not larger than 10% of the mean concentrations.

Figure 47 shows particle fall velocities and velocity profiles. The equivalent Stokes diameter (median value) is about 5 μm at 0.02 m above the bed (concentration = 310 mg/l) and a similar value at 0.17 m above the bed.

### 5.6.4 Sedimentation and consolidation

After stopping the wave generator, the kaolinite suspension was allowed to settle and consolidate for 18 hours. At the end of this period the bed surface showed small local irregularities (height ≃ 1 mm). At other locations the bed surface was flat. The pipet sampler was used to collect bed sampler in section 7, 9 and 11. The vertical distribution of the sand and kaolinite concentrations are shown in Figure 42. The sand concentrations range from 60 to 240 kg/m$^3$; the kaolinite concentrations range from 400 to 900 kg/m$^3$. Compared with the results after a consolidation period of 96 hours, the sediment concentrations at 0.015 and 0.025 m below the bed surface show a considerable increase.

### 5.6.5 Generation of waves (phase 2)

T5-5 wave height = 0.014 m, test period = 30 min

Weak sediment (kaolinite) movement was observed near the bed-surface irregularities. No movement was observed at locations with a flat surface.

T5-6, wave height = 0.022 m, test period = 30 min

General sediment (kaolinite) movement was observed near the bed-surface irregularities.

T5-7, wave height = 0.07 m, test period = 180 min

In the initial stage of this period (after 15 min) a fluidized suspension layer with a thickness of about 10 mm and concentrations larger than 100000 mg/l (pipet samples) was generated. The interface showed the presence of small-scale waves (height ≃ 3 mm). Locally, intensive erosion of bed material did occcur resulting in scour holes with a depth of 20 mm which were filled almost directly with high-concentration fluid-kaolinite material (concentrations ≃ 100000 mg/l). Locally, the suspension layer showed strong wave action (Photographs 11 and 12).
Equilibrium conditions were established after 120 hours (Fig 48). At the end of the test period the thickness of the fluidized suspension layer was about 25 mm with concentrations ranging from 100000 to 500000 mg/l (see Figure 49 and Photograph 10). Sand particles (concentration ≃ 70000 mg/l) were only

detected at a level of 20 mm below the interface of the fluidized layer. The kaolinite concentrations above the fluidized layer are in the range from about 10000 mg/l near the bed to about 2500 mg/l near the water surface. Suspended sand particles were not detected above the interface of the fluidized layer. Figure 50 shows particle fall velocities (section 9.6) and velocity profiles (section 10). The equivalent Stokes diameter (median value) is about 8 µm at 0.17 m above the bed (concentration = 3150 mg/l) and about 10 µm at 0.12 m above the bed (concentration = 5550 mg/l).

## 5.7 T6-experiment: sand-kaolinite bed, mean bed concentration = 1650 kg/m$^3$, wave period = 1.5 s

### 5.7.1 General characteristics

| | | | |
|---|---|---|---|
| initial kaolinite concentration | | = | 400 ± 25 kg/m$^3$ |
| initial sand concentration | | = | 1250 ± 50 kg/m$^3$ |
| initial layer thickness | | = | 0.055 ± 0.005 m |
| sand size | $d_{50}$ | = | 95 µm |
| | $d_{10}$ | = | 75 µm |
| | $d_{90}$ | = | 125 µm |
| water depth | | = | 0.25 ± 0.01 m |
| salinity | | = | 31 ± 1 °/$_{oo}$ |
| water temperature | | = | 7 ± 1 °C |

The dry sand (75%) and kaolinite (25%) materials were mixed thoroughly; a small amount of saline water was added to fill the pores of the mixture and the mixing process was repeated until a homogeneous mixture was obtained. After that the mixture was transferred (buckets) to the test section of the flume. A scraper attached to a carriadge on top of the flume walls was used to level the sand- kaolinite bed. Although the major part of the mixture consisted of sand (75%), it looked and feeled like a clayey slurry (hand samples). Because of the large specific surface area of the kaolinite material, all sand particles can be covered by a film of kaolinite particles giving a clayey-locking mixture.

### 5.7.2 Consolidation

| | | |
|---|---|---|
| total consolidation period | = | 120 hours |
| final layer thickness | = | 0.053 ± 0.005 m |
| final depth-mean concentration | = | 1650 ± 100 $kg/m^3$ |

During the consolidation period the average layer thickness was reduced from 0.055 m to 0.053 m. Bed surface samples were collected to determine the sand and kaolinite concentrations, which were close to the initial values as given above. At the end of the consolidation period the bed surface showed small crater-shaped irregularities (diameter ≃ 10 mm, height ≃ 2 mm) being the relicts of the bed-levelling process. The top layer of the bed surface consisted of a thin (< 1 mm) film of kaolinite material.

### 5.7.3 Generation of waves (phase 1)

T6-1, wave height = 0.014 m, test period = 30 min

Weak movement of the kaolinite material was observed near the bed-surface irregularities.

T6-2, wave height = 0.022 m, test period = 30 min

General movement of the kaolinite material was observed. A thin (≃ 5 mm) suspension layer was generated with concentrations of about 50 to 100 mg/l.

T6-3, wave height = 0.03 m, test period = 75 min

The thickness of the kaolinite suspension layer increased to the water surface. Figure 51 shows time-concentration curves. The mean concentrations range from 100 mg/l close to the bed surface to about 50 mg/l at a level of 0.05 m above the bed surface. The kaolinite concentrations remained almost constant during the test period. Figure 52 shows concentration and velocity profiles. The concentration distribution is almost uniform in vertical direction. Suspended sand particles were not detected.

T6-4 wave height = 0.05 m, test period = 90 min

Locally, isolated spots (diameter ≃ 5 mm, height ≃ 1 mm) of accumulated sand particles were generated. The sand particles moved forwards and backwards in the rolling mode of transport. Suspended sand particles were not observed visually and not detected in the siphon samples. Figure 53 shows time-concentration curves for the kaolinite particles. The concentrations which are almost constant in time, range from about 100 mg/l close to the bed to about 50 mg/l near the water surface. Figure 54 shows concentration and velocity profiles. The concentration distribution is almost uniform in vertical direction.

T6-5, wave height = 0.07 m, test period = 90 min

The diameter of the sand spots was increased to about 10 mm. The distance between the spots was reduced to 0.05 m. The sand particles only moved by rolling. Figure 55 shows time-concentration curves for the kaolinite particles. The concentrations range from 130 mg/l near the bed surface to 110 mg/l near the water surface. Figure 56 shows concentration and velocity profiles.

T6-6 wave height = 0.10 m, test period = 60 min

Small-scale sand ripples (height ≃ 2 mm, length ≃ 25 mm, distance ≃ 50 mm) were generated on top of the homogeneous sand-kaolinite bed (see Photograp 1). Sand particles were suspended to a level of about 0.1 m above the bed surface based on the analysis of siphon samples. Figure 57 shows time-concentration-curves for the kaolinite particles. Figure 58 shows concentration (sand and kaolinite) profiles and velocity profiles. The kaolinite concentrations show an almost uniform distribution (≃ 300 mg/l). The sand concentrations range from about 100 mg/l close to the bed surface to about 10 mg/l at a level of 0.15 m above the bed surface.

## 5.8 T7-experiment: sand bed, mean bed concentration = 1600 kg/m$^3$, wave period = 1.5s

### 5.8.1 General characteristics

| | | | |
|---|---|---|---|
| layer thickness | | = 0.05 ± 0.003 | m |
| water depth | | = 0.25 ± 0.01 | m |
| water temperature | | = 7 ± 1 | °C |
| salinity | | = 31 ± 1 | ‰ |
| sand size | $d_{50}$ | = 95 | μm |
| | $d_{10}$ | = 75 | μm |
| | $d_{90}$ | = 125 | μm |

A layer of sand particles was transferred (by buckets) to the test section of the flume and levelled (scraper) resulting in a flat bed surface.

5.8.2 Generation of waves (phase 1)

T7-1, wave height = 0.03 m, test period = 30 min

Weak movement of the sand particles was observed at all locations (flat bed surface).

T7-2 wave height = 0.05 m, test period = 60 min

After 10 minutes small-scale ripples with a length of 0.05m and a height of 0.01 m were generated. Figure 59 shows sand concentration and velocity profiles. The mean sand concentrations range from 2000 mg/l close to the bed to about 1 mg/l near the water surface.

T7-3, wave height = 0.07 m, test period = 60 min

The ripple length increased to 0.06 m; while the ripple height remained the same (≈ 0.01 m). Figure 60 shows sand concentration and velocity profiles. The sand concentrations range from 3500 mg/l near the bed to 5 mg/l near the water surface.

T7-4, wave height = 0.10 m, test period = 60 min

The ripple height increased to 0.015 m, while the ripple length remained at 0.06 m. Figure 61 shows sand concentration and velocity profiles. The sand concentrations range from 11000 mg/l near the bed surface to about 15 mg/l near the water surface.

# 6. Analysis of experimental results

## 6.1 Summary of experimental results

Consolidated beds of various sediment materials (pure kaolinite, kaolinite-sand mixtures, pure sand) were subjected to (regular) wave action. The wave heights were increased in steps.
Initiation of motion of a pure kaolinite bed was observed at very small rms-values of the orbital velocities at the bed (0.02 to 0.05 m/s). The oscillating character of the wave motion seems to have a rather dominating influence because experiments with a current alone (no waves) showed no motion of consolidated kaolinite material upto velocities of 0.4 m/s.
By increasing the wave height a thin suspension layer was generated close to the bed surface. Small vortices were clearly visible in this layer. Because of the mixing action of these vortices the interface of the suspension moved (slowly) upwards. Equilibrium conditions with relatively large concentrations near the bed (≃ 500 mg/l) and relatively small concentrations near the water surface (≃ 100 mg/l) were established after about 2 hours. The erosion seems to stop as successive layers of particles or flocs are eroded and more deeper layers with a higher density and hence a higher erosion resistance become exposed. By a further increase of the wave height the erosion resistance of these deeper layers can be overcome resulting in larger concentrations. Depending on the wave height, the wave period and the bed surface concentration, the top layers of the bed surface can even be fluidized resulting in a high-concentration (> 100000 mg/l) suspension layer near the bed. The thickness of this layer was about 0.01 m in the present experiments. Above the high-concentration layer a less dense suspension layer (5000 to 10000 mg/l) was present. Dye injections close to the bed showed the presence of wave-induced mass transport in the wave direction. The mass-transport velocities were in the range of 0.01 to 0.03 m/s, depending on the wave height.
Continuous erosion did occur at the largest wave heights when the applied bed-shear stresses exceeded the critical shear stresses of the bed material in the lower layers.
The effect of the sequence of wave height increases on the kaolinite cocentrations is shown schematically in Figure F.

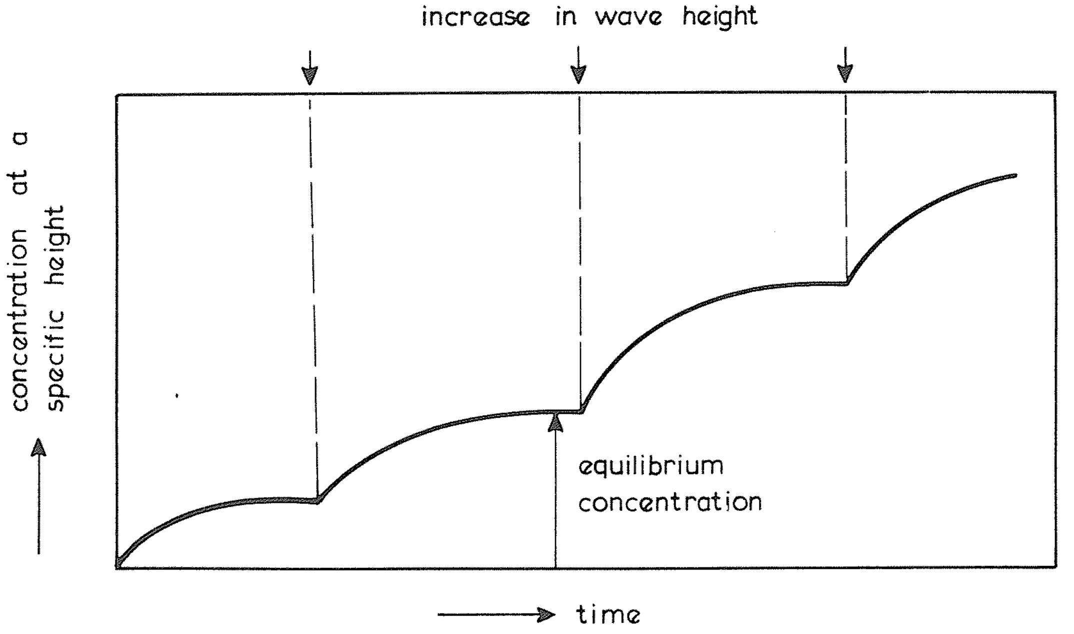



Fig. F Kaolinite concentrations at various wave heights

An experiment with waves over a consolidated bed consisting of kaolinite material (75%) and a small amount of fine sand particles (25%) showed similar results as for a pure kaolinite bed. Suspended sand concentrations were not observed.

Completely different results were obtained in an experiment with a bed consisting of fine sand (75%) and a small amount of kaolinite (25%). Even at the largest waves the kaolinite concentrations were very small (≃ 300 mg/l). The vertical concentration distribution was almost uniform. The sand concentrations were also very small compared with those generated for a pure sand bed.

## 6.2 Sediment concentrations of bed layer

Based on the results shown in Figs 11, 20, 28, 34 and 42, a typical concentration profile with low but finite concentrations near the bed surface and high concentrations near the bottom can be observed. The results are summarized in Fig 62. The depth-mean concentration is based on the ratio of the initial and final bed-layer thickness multiplied by the initial sediment concentration. For comparison some results of Dixit (1982) for kaolinite material in non-saline conditions are shown. Dixit used a freezing method to collect a vertical sample of the bed. Results of Thorn and Parsons (1980) for natural muds are also plotted. They used a settling column of 10 m to study the consolidation process. The final bed thicknesses were in the range 0.25 to 0.4 m. The results of the present experiments are in reasonable agreement with those of Dixit with exception of the near-surface region. In that region the present results are more in agreement with the sediment concentrations of natural muds. Based on the measurements of Dixit and Thorn and Parsons who analyzed samples close to the bed surface, the sediment concentrations near the bed surface are in the range of 0.2 to 0.7 times the depth-mean concentration. Thorn and Parsons assume that a cohesive bed will show an increasing resistance to erosion at deeper layers because of the increasing sediment concentrations.

### 6.3 Initiation of motion

Initation of motion was determined by increasing the wave height in steps until weak movement of the bed surface particles or flocs was observed. Critical wave heights were measured and converted to orbital velocities at the bed (rms-values, Table 3). Figure 63A (see also Table 6) shows the rms-values of the critical orbital velocities at the bed as a function of the bed surface concentration. This latter parameter is assumed to be equal to 0.5 times the depth-mean concentration ($c_s = 0.5\ \bar{c}_{bed}$, see Fig 62). Figure 63B shows the critical conditions for initation of motion in terms of a dimensionless acceleration parameters ($u_{rms}/g\ T$). This parameter seems to be more appropriate because it expresses the oscillating character of the wave motion. No information of critical wave conditions for a kaolinite bed could be found in the literature.
Review of the literature showed much information of the critical conditions for initiation of motion in an unidirectional current without waves. Critical current velocities were in the range of 0.5 to 1 m/s for cohesive beds. In the present study one experiment with a current alone (no waves) was carried out. The maximum current velocity was about 0.4 m/s, but no movement of the bed surface particles was observed ($c_s \simeq 300$ kg/m$^3$).

Creutzberg and Postma (1979) studied the presence of silt in the bed of the North Sea in relation to the local current and orbital velocities. Critical velocities of natural silt were measured in a circular flume neglecting the wave influence. Relatively high critical velocities were measured for consolidated beds. These values were compared with the local current velocities superimposed by orbital velocities. The present results however indicate that the surface of a cohesive bed is set in motion at relatively small velocities in the presence of waves. Based on Figure 63, the critical wave height for a kaolinite bed in natural conditions has been computed. Assuming a bed-surface concentration of 200 $kg/m^3$, a wave period of 7 s, a water depth of 10 m, the critical rms-value of the orbital velocity at the bed is about 0.1 m/s which corresponds to a critical wave height of 0.25m.

## 6.4 Erosion of bed surface

### 6.4.1 Kaolinite bed surface

Each experiment consisted of a sequence of increasing wave heights. At each wave height equilibrium conditions were established after a few hours (see Fig F). Figures 64 and 65 show the equilibrium concentrations at 0.005, 0.03, 0.1 and 0.2 m above the consolidated bed as a function of the rms-values of the orbital velocites ($u_{rms}$) at the bed and the wave period (T). The rms-values were those measured with the laser-doppler method (see par. 4.2.2 and 5.1).
The plotted concentrations are also reported in Table 5. As can be observed, there is a power-law relationship between the concentrations and the rms-velocities with an exponent in the range of 3 to 6. The exponent seems to decrease for increasing rms-velocities when a fluidized suspension layer (concentrations > 100000 mg/l) is generated close to the bed (T1, T3 and T4). In the absence of such a layer (T2) the exponent is nearly constant (Fig 63). Apparently, the generation of a fluidized suspension layer reduces the vertical upward transport of sediment material. The reason for this may be the absence of large velocity gradients and hence shear stresses at the interface of the fluidized suspension layer. Vortex generation was not observed at this location. Influence of the wave period can be observed by comparing the results for T = 1.5 s and T = 2.5 s. The concentrations are somewhat smaller for a larger wave period at the same rms-velocity. Another remarkable effect is the absence of a fluidized suspension layer (concentrations > 100000 mg/l) for a mean bed density of 460 $kg/m^3$ and T = 2.5 s (Fig 64 and Table 5). Influence of the bed density can be observed by comparing the results of Figs 64 and 65, yielding smaller concentrations for a larger bed density. This can be explained by assuming that a larger bed density is related to a larger ero-

sion resistance as suggested by Thorn and Parsons (1980) and Mehta and Partheniades (1982).

The present results have been used to determine a criterion for the onset of the fluidization process. This process is assumed to be initiated by wave-induced oscillations at the bed surface resulting in vertical pressure gradients and hence vertical in and outflow of pore water. Because of an increase of the water pressure in the pores the effective soil stress may be reduced substantially yielding a fluidized state of the top layers of the bed. As a result of this fluidization process there is a vertical rise of the bed surface due to expansion of the fluidized mass. The penetration depth of the vertical motions seems to increase for increasing wave heights and to decrease for increasing bed densities as shown by Lhermitte (1960). Since the fluidization process is largely controlled by wave-induced oscillations near the bed, a dimensionless acceleration parameter ($u_{rms,\ bed}$ /g T) is introduced to represent the onset of fluidization, as shown in Figure 66A. The onset of fluidization is also related to a pressure-gradient parameter suggested by Lhermitte (1960), which reads as follows (see Fig 66B):

$$\left(\frac{dp}{dx}\right)_{max} = \frac{H\ k}{\cosh(kh)} \qquad (6.1)$$

in which:

H = wave height (m)

k = wave number (= $2\pi/L$ ) ($m^{-1}$)

h = water depth (m)

L = wave length (m)

Based on the results presented in Figure 66, the onset of fluidization for a kaolinite bed in natural conditions has been computed. Assuming h = 10 m, T = 7 s, L = 60 m, the fluidization of a kaolinite bed (surface concentration ≃ 200 $kg/m^3$) is initiated for a wave height of about 1.5 m (Fig 66 A) or a wave height of about 1 m (Fig 66 B).

The observed layer thickness of the fluidized sediment suspension is also related to the acceleration parameter and the pressure-gradient parameter of Lhermitte, as shown in Figure 67. The influence of the bed-surface concentration is not quite clear. The results seem to indicate a somewhat larger layer thickness for a larger bed surface concentration. Review of the literature shows very little information of fluidized suspension layers. Kendrick and Clifford (1981) carried out experiments in a wave flume using natural mud from Belawan, Indonesia. At a wave height of 0.15 m and a wave period of 2 s in (saline) water with a depth of 0.55 m they observed a turbid layer close to the bed with a thickness of about 0.05 m and concentrations in the range of 10000 to 30000 mg/l. A less dense layer with concentrations of about 2000 mg/l was present above the turbid layer. These results are qualitatively in agreement with the results of the present study. The generation of a fluidized suspension layer close to the bed was not reported explicitly by Kendrick and Clifford. Mehta and Partheniades (1982) and Dixit (1982) carried out experiments in a rotating annular flume and a flow recirculating flume using a kaolinite bed. Waves were not present. Distilled as well as saline water was used. Maximum current velocities of about 0.5 m/s were generated resulting in concentrations upto 15000 mg/l. A fluidized sediment suspension near the bed was not observed. Vertical concentration gradients were not reported. Thus, current-related mixing seems to generate almost uniform concentration profiles.

Using the results presented in Figure 67, the thickness of a fluidized-sediment suspension layer in natural conditions with a kaolinite bed has been computed. Assuming $h = 10$ m, $H = 3$ m, $T = 7$ s and a bed-surface concentration of 200 kg/m$^3$, the layer thickness will be about 0.02 m (Fig 67A) or about 0.05 m (Fig 67B). Since the characteristic parameters controlling the fluidization process are not (yet) known, it is not surprizing that the parameters applied in Figure 67 lead to significantly different results for the layer thickness. In a previous study (Vermaas, 1984) the layer thickness of the fluidized sediment suspension was assumed to be related to the turbulent boundary layer thickness near the bed. Normally, such a layer only develops above a rigid bed surface. In the present experiments the consolidated bed surface remained rigid upto a wave height of about 0.03 to 0.04 m. Using the relationships proposed by Jonsson (1966), the turbulent boundary layer thickness will be about 2 mm for these conditions, which is considerably smaller than the observed suspension layer thickness of 5 to 10 mm with concentrations upto 500 mg/l. After the onset of the fluidization process, a rigid bed surface is no longer present. Actually, the top layer of the bed surface is set into motion and the boundary layer is located in this moving bed surface.

Therefore, it is more logic to relate the thickness of the fluidized sediment layer to the penetration depth of the wave motion into the bed surface. As stated before, the parameters which controll the fluidization process are not yet known. Therefore, it is recommended to carry out more research to get a better understanding of the wave-bed interaction. Recently, some attempts were made to investigate the wave-induced pressures and shear stresses in a sediment bed (Madsen, 1978 and Yamamoto, 1985). Although such a study may not lead to results which are directly applicable to natural conditions, it can identify the characteristic parameters of the wave-bed interaction.

Information of the vertical concentration distributions as observed in the present experiments is given in Figure 69A. The concentration at z = 0.03 m above the consolidated bed is used as reference concentration. For relatively small waves the vertical concentration distribution is rather uniform. The ratio between the near-bed concentration and the water-surface concentration is about 2 to 5. For relatively large waves the vertical concentration distribution seems to depend on the generation of a fluidized suspension layer close to the bed. As noted before, such a layer seems to reduce the vertical upward transport of sediment material because of the absence of large velocity gradients (and hence shear stresses) at the interface. When a fluidized suspension layer is generated close to the bed, there is a relatively sharp interface with large concentration gradients near the bed. Above this high-concentration layer a less dense layer is present. The concentration ratio between these two layers is in the range of 20 to 50 (Fig 69). When there is no fluidized suspension layer in the presence of relatively large waves, the vertical concentration distribution seems to be more uniform. The ratio between the near-bed concentration and water surface concentration was less than 10 in the T2-experiment (Table 5).

Finally, flocculation and hindered-settling effects are discussed. Fluid-sediment samples were collected during the wave experiments. The pipet method was used to determine the settling velocity curves of these samples (see par. 3.4) The median settling velocities ($w_{s,50}$) are plotted in Figure 4, showing a clear flocculation effect for concentrations in the range 200 to 10000 mg/l. The results are in agreement with the settling velocities measured in a special laboratory set-up (black dots). Hindered settling effects did occur for concentrations larger than about 10000 mg/l.

### 6.4.2 Kaolinite (75%) - sand (25%) bed surface

A (well-mixed) consolidated bed of kaolinite (75%) and sand (25%) particles was subjected to a series of waves of increasing heights (in steps). The basic characteristics of the tests are presented in par 5.6. Comparison of the measured kaolinite concentrations of the T4-and T5-experiment (Table 5) show similar results (variations within a factor 2 are not supposed to be significant). A typical phenomenon before the onset of the fluidization process was the formation of (isolated) spots of accumulated sand particles (diameter ≃ 5 mm, height ≃ 1 mm). During the fluidization of the bed surface, the sand particles disappeared by sinking in the fluidized kaolinite layer. Analysis of samples collected in this latter layer showed the absence of sand particles in the top layer (≃ 0.01 m), as shown in Figure 49. Typical concentration profiles are shown in Figures 44 and 49. Summarizing, it is concluded that a relatively small amount (25%) of sand particles does not have a significant effect on the erosion of the kaolinite material.

### 6.4.3 Sand (75%) - kaolinite (25%) bed surface

A well-mixed bed of sand (75%) and kaolinite (25%) particles was subjected to a series of waves of increasing heights (in steps). Because of the relatively large specific area of the kaolinite particles, the sand particles were covered by a film of kaolinite particles giving a clayey-looking mixture. The kaolinite concentrations, shown in Figure 68, remained very small because only the top layer of the bed was washed out. Even, at a relatively large wave height of 0.10 m (water depth = 0.25 m) the kaolinite concentrations were not larger than about 300 mg/l. For comparison the results of the T5-experiment (75% kaolinite) are also plotted, showing much larger concentrations (factor 10 to 100). The concentration profiles (Figs 52, 54, 56, 58) were almost uniform because the concentrations were too low to cause significant flocculation. After washing out the top layer, isolated spots of sand particles were generated, which changed into small-scale ripples at increasing wave heights. In the final stage these ripples consisted of sand particles at the ripple tops and of kaolinite particles in the ripple-troughs. (see Photo 1). The maximum ripple height was only 2 mm, which is very small compared with the ripple height of about 10 mm generated in T7-experiment where a pure sand bed was used. As a result of the strong suppression of the ripple height by the kaolinite particles acting as a binding agent, the formation of high-energy containing vortices which can suspend sand particles, was hindered. Only at the largest wave height of 0.1 m relatively small sand concentrations were measured.

Compared with the values measured in the T7-experiment for the same wave height (= 0.1 m), the sand concentration were reduced from 7000 mg/l to 200 mg/l close to the bed (factor 35), as shown in Fig 69.

Summarizing, it is concluded that a small amount of cohesive particles causes a large reduction of the sand concentrations and transport, mainly because of the suppression of the ripple heights by the cohesive material acting as a binding agent.

### 6.4.4 Mass transport velocities

During the T4-experiment dye injections were made close to the bed surface (Table 5). Mass-transport velocities were determined from the movement of the dye centre (in the wave direction), which moved somewhat slower than the dye front. Theoretical mass-transport velocities close to the bed for waves in water of uniform depth are given by Longuet-Higgins (1953):

The maximum mass-transport velocity close to the bed is:

$$\bar{u}_{mass} \simeq 1.4 \frac{k}{\omega} (\hat{u}_{bed})^2 \simeq 2.8 \frac{k}{\omega} (u_{rms,\ bed})^2 \qquad (6.2)$$

in which:

| | | | |
|---|---|---|---|
| $\hat{u}_{bed}$ | = | peak value of orbital velocity at the bed | (m/s) |
| k | = | $2\pi/L$ | ($m^{-1}$) |
| $\omega$ | = | $2\pi/T$ | ($s^{-1}$) |
| L | = | wave length | (m) |
| T | = | wave period | (s) |

Predicted and observed values are given in the following table.

| wave height (m) | rms-velocity (m/s) | near-bed mass transport velocity (m/s) | |
|---|---|---|---|
| | | predicted | observed |
| 0.030 | 0.075 | 0.01 | 0.005 |
| 0.047 | 0.11 | 0.02 | 0.01 |
| 0.070 | 0.15 | 0.04 | 0.02 |

The predicted values are systematically too large (factor 2). Better agreement would have been obtained when the mass transport velocities of the dye front were measured.

## References


BOSMAN, J., 1984
Design and Specifications of Opcon
Delft Hydraulics Laboratory, R716-VI, Delft, The Netherlands

CREUTZBERG, F. and POSTMA, H., 1979
An Experimental Approach to the Distribution of Mud
in the Southern North Sea
Netherlands Journal of Sea Research, Vol. 13

DIXIT, J.G. 1982
Resuspension Potential of Deposited Kaolinite Beds
Coastal and Oceanographic Eng. Dep, Univ. of Florida, USA

ENGELUND, F. and ZHAOHUI, W., 1984
Instability of Hyperconcentrated Flow
Journal of Hydraulic Engineering, Vol 110, No 3

GODEFROY, H.W.H.E., 1978
Application of the Laser Doppler Velocity Method
Imeko Conference on Flow Measurements of Fluids, Groningen, The Netherlands

JANSEN, R.M.J., 1978
In-situ Measurement of Sediment Transport by means of Ultrasound Scattering
Delft Hydraulics Laboratory, Publication 203, Delft, The Netherlands.

JONSSON, I.G., 1966
Wave Boundary Layers and Friction Factors
Proc. 10th Coastal Congress, Tokyo, Japan

KENDRICK, M.P. and CLIFFORD, J.E., 1981
Hydraulic Studies of the Port of Belawan, Indonesia
Proc. Seatec III, Singapore

LHERMITTE, P., 1960
Mouvements des Materieux de fonds sons l'action de la houle
Proc. 7th Coastal Eng. Conf., Vol. I, The Hague, The Netherlands

LONGUET-HIGGENS, M.S.
Mass Transport in Water Waves
Phil. Trans. Royal Soc., Vol 245 A, No 903, London

MADSEN, O.S., 1978
Wave-Induced Pore Pressures and Effective Stresses in a Porous Bed
Geotechnique 28, No 4

MALVERN INSTRUMENTS, 1984
Particle Sizer Handbook

MEHTA, A.J. and PARTHENIADES, E., 1982
Resuspension of Deposited Cohesive Sediment Beds
Proc. 18th Coastal Eng. Conf., Cape Town, South Africa

MIGNIOT, C., 1968
Etude des Propriétés Physiques de différents Sédiments très fins et de leur compotement sous des action hydrodynamique
La Houille Blanche, Vol 23, No 7

NEDECO, 1965
Siltation Bangkok Port Channel
The Hague, The Nederlands

OWEN, M.W., 1976
Determination of the Settling Velocities of Cohesive Muds
Hydraulics Research Station, Report No. IT 161, Wallingford, England

THORN, M.F.C. and PARSONS, J.G. 1980
Erosion of Cohesive Sediments in Estuaries
Third Int. Symp. on Dredging Technology, Bordeaux, France

VERMAAS, H., 1984
The Effect of Waves on a Mud Bed (in dutch)
Delft Hydraulics Laboratory, S 579, Delft, The Netherlands

YAMAMOTO, T., 1985
Wave Damping by Soil Motion
Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 11, No 1

wave height = 0.014 m wave period = 1.5 s section = 9.6 m

| height above bed (m) | $\bar{u}$ (m/s) | | $\bar{w}$ (m/s) | | $u_{rms}$ (m/s) | | $w_{rms}$ (m/s) | |
|---|---|---|---|---|---|---|---|---|
| | acous | laser | acous | laser | acous | laser | acous | laser |
| 0.05 | 0.024 | 0.0041 | 0.0035 | 0.0023 | 0.061 | 0.043 | 0.021 | 0.0071 |
| 0.075 | 0.034 | 0.0021 | 0.0043 | 0.0026 | 0.059 | 0.037 | 0.021 | 0.0057 |
| 0.10 | 0.034 | 0.0017 | 0.0058 | 0.0019 | 0.045 | 0.040 | 0.020 | 0.0085 |

wave height = 0.05 m wave period = 1.5 s section = 9.6 m

| height above bed (m) | $\bar{u}$ (m/s) | | $\bar{w}$ (m/s) | | $u_{rms}$ (m/s) | | $w_{rms}$ (m/s) | |
|---|---|---|---|---|---|---|---|---|
| | acous | laser | acous | laser | acous | laser | acous | laser |
| 0.05 | -0.017 | 0.0014 | 0.012 | 0.0013 | 0.123 | 0.141 | 0.027 | 0.013 |
| 0.075 | 0.015 | 0.0015 | 0.009 | -0.0015 | 0.095 | 0.142 | 0.027 | 0.020 |
| 0.10 | -0.013 | 0.0040 | 0.0046 | -0.0016 | 0.116 | 0.143 | 0.024 | 0.026 |

wave height = 0.105 m wave period = 1.5 s section = 9.6 m

| height above bed (m) | $\bar{u}$ (m/s) | | $\bar{w}$ (m/s) | | $u_{rms}$ (m/s) | | $w_{rms}$ (m/s) | |
|---|---|---|---|---|---|---|---|---|
| | acous | laser | acous | laser | acous | laser | acous | laser |
| 0.05 | -0.004 | 0.028 | -0.0016 | -0.0021 | 0.139 | 0.263 | 0.031 | 0.024 |
| 0.075 | -0.004 | 0.026 | -0.0014 | -0.0031 | 0.160 | 0.266 | 0.031 | 0.040 |
| 0.10 | -0.014 | 0.027 | 0.0018 | -0.0050 | 0.192 | 0.268 | 0.031 | 0.053 |

$\bar{u}$ = mean longitudinal velocity (pos. in wave direction)

$\bar{w}$ = mean vertical velocity (pos. in upward direction)

$u_{rms}$ = root-mean square longitudinal velocity

$w_{rms}$ = root-mean square vertical velocity

laser = Laser-doppler method

acous = Acoustic-doppler method

Table 1, Velocity data

| section | Mean wave height (m) | | |
|---|---|---|---|
| | 0.033 | 0.055 | 0.105 |
| 4 | 0.036 | 0.058 | 0.111 |
| 5 | 0.035 | 0.058 | 0.111 |
| 6 | 0.035 | 0.058 | 0.112 |
| 7 | 0.034 | 0.059 | 0.115 |
| 8 | 0.034 | 0.059 | 0.115 |
| 9 | 0.034 | 0.058 | 0.113 |
| 10 | 0.033 | 0.055 | 0.105 |
| 11 | 0.031 | 0.051 | 0.093 |
| 12 | 0.029 | 0.050 | 0.091 |
| 13 | 0.029 | 0.051 | 0.090 |
| 14 | 0.028 | 0.051 | 0.098 |

wave period = 1.5 s

water depth = 0.25 m

water temperature ≃ 11 °C

Table 2, Wave height data

| No | sediment | mean bed concen tration ($kg/m^3$) | waves Height (m) | waves period (s) | Fluidi zed kao linite layer (m) | Equilibrium Kaolinite concentrations (mg/l) at height z above consolidated bed 0.005 (m) | 0.01 (m) | 0.03 (m) | 0.05 (m) | 0.10 (m) | 0.20 (m) | Equilibrium sand concen trations at height z 0.01 (m) | 0.05 (m) | 0.10 (m) | 0.20 (m) | Stokes dia meter (µm ) at height z 0.02 (m) | 0.17 (m) | mass trans port velocity (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T1-3 | kaolinite | 460 | 0.024 | 1.5 | n.p. | 500 | 150 | 75 | 50 | 40 | 25 | | | | | - | - | - |
| 4 | | | 0.040 | 1.5 | 0.01 | 100000 | - | 750 | 650 | 550 | 450 | | | | | - | - | - |
| 5 | | | 0.060 | 1.5 | 0.01 | 100000 | - | 2600 | 2000 | 1500 | 650 | | | | | - | - | - |
| T2-2 | kaolinite | 460 | 0.03 | 2.5 | n.p. | 1000 | 500 | 250 | 200 | 170 | 150 | | | | | - | - | - |
| 3 | | | 0.05 | 2.5 | n.p. | 5000 | 2000 | 1800 | 1500 | 1000 | 700 | | | | | 14 | 6 | - |
| 4 | | | 0.075 | 2.5 | n.p. | 60000 | 40000 | 20000 | 1800 | 15000 | 7500 | | | | | - | - | - |
| T3-3 | kaolinite | 640 | 0.048 | 2.5 | n.p. | 5000 | 3500 | 1000 | 800 | 600 | 400 | | | | | 9 | 5 | - |
| 4 | | | 0.072 | 2.5 | 0.01 | 100000 | 30000 | 6000 | 5000 | 3000 | 1900 | | | | | 10 | 6 | - |
| T4-3 | kaolinite | 640 | 0.03 | 1.5 | n.p. | 220 | 180 | 80 | 50 | 40 | 30 | | | | | - | - | 0.005 |
| 4 | | | 0.047 | 1.5 | n.p. | 2500 | 2000 | 1500 | 1300 | 1000 | 500 | | | | | 6 | 5 | 0.01 |
| 8 | | | 0.07 | 1.5 | 0.01-0.025 | 300000 | 100000 | 20000 | 7000 | 6000 | 4000 | | | | | 11 | 11 | 0.02 |
| T5-3 | kaolinite (75%) | | | | | | | | | | | | | | | | | |
| | sand (25%) | 790 | 0.03 | 1.5 | n.p. | 600 | 300 | 150 | 130 | 120 | 100 | 0 | 0 | 0 | 0 | - | - | - |
| 4 | | | 0.048 | 1.5 | n.p. | 1500 | 800 | 700 | 500 | 350 | 250 | 0 | 0 | 0 | 0 | 6 | 5 | - |
| 7 | | | 0.07 | 1.5 | 0.01-0.25 | 400000 | 200000 | 15000 | 6000 | 5000 | 3000 | 50000 | 0 | 0 | 0 | 10 | 8 | - |
| T6-3 | sand (75%) | | | | | | | | | | | | | | | | | |
| | kaolinite (25%) | 1700 | 0.03 | 1.5 | n.p. | 100 | 80 | 60 | 50 | 50 | 50 | 0 | 0 | 0 | 0 | - | - | - |
| 4 | | | 0.05 | 1.5 | n.p. | 100 | 80 | 70 | 60 | 60 | 60 | 0 | 0 | 0 | 0 | - | - | - |
| 5 | | | 0.07 | 1.5 | n.p. | 130 | 120 | 110 | 110 | 110 | 110 | 0 | 0 | 0 | 0 | - | - | - |
| 6 | | | 0.10 | 1.5 | n.p. | 330 | 310 | 300 | 300 | 300 | 280 | 200 | 20 | 10 | 3 | - | - | - |
| T7-2 | sand | 1600 | 0.05 | 1.5 | | | | | | | | 2000 | 100 | 10 | 1 | | | |
| 3 | | | 0.07 | 1.5 | | | | | | | | 3000 | 150 | 20 | 5 | | | |
| 4 | | | 0.10 | 1.5 | | | | | | | | 7000 | 250 | 40 | 15 | | | |

– not measured

n.p. not present

Table 3, Mean-velocities and rms-velocities for various wave conditions (Laser-doppler method).

| No | sediment | mean-bed concentration ($kg/m^3$) | | Layer thickness (m) | | Total consolidation period | Salinity | water temperature | water depth | waves (phase 1) | | | sedimentation period | waves (phase 2) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | initial | final | initial | final | (hours) | (‰) | (°C) | (m) | height (m) | period (s) | test period (min) | (hours) | height (m) | period (s) | test period (min) |
| T1-1 | kaolinite | 250 | 460 | 0.11 | 0.059 | 120 | 32 | 11 | 0.24 | 0.008 | 1.5 | 30 | | | | |
| 2 | | | | | | | | | | 0.014 | 1.5 | 30 | | | | |
| 3 | | | | | | | | | | 0.024 | 1.5 | 100 | | | | |
| 4 | | | | | | | | | | 0.040 | 1.5 | 120 | | | | |
| 5 | | | | | | | | | | 0.060 | 1.5 | 45 | | | | |
| T2-1 | kaolinite | 250 | 460 | 0.11 | 0.059 | 96 | 31 | 10 | 0.24 | 0.014 | 2.5 | 30 | | | | |
| 2 | | | | | | | | | | 0.030 | 2.5 | 240 | | | | |
| 3 | | | | | | | | | | | | | 16 | 0.050 | 2.5 | 120 |
| 4 | | | | | | | | | | | | | | 0.075 | 2.5 | 30 |
| T3-1 | kaolinite | 500 | 640 | 0.063 | 0.049 | 115 | 31 | 10 | 0.25 | 0.020 | 2.5 | 30 | | | | |
| 2 | | | | | | | | | | 0.030 | 2.5 | 30 | | | | |
| 3 | | | | | | | | | | 0.048 | 2.5 | 180 | | | | |
| 4 | | | | | | | | | | 0.072 | 2.5 | 60 | | | | |
| 5 | | | | | | | | | | | | | 19 | 0.020 | 2.5 | 30 |
| | | | | | | | | | | | | | | 0.072 | 2.5 | 60 |
| T4-1 | kaolinite | 500 | 640 | 0.061 | 0.048 | 144 | 31 | 9 | 0.25 | 0.014 | 1.5 | 30 | | | | |
| 2 | | | | | | | | | | 0.022 | 1.5 | 60 | | | | |
| 3 | | | | | | | | | | 0.030 | 1.5 | 60 | | | | |
| 4 | | | | | | | | | | 0.047 | 1.5 | 240 | | | | |
| 5 | | | | | | | | | | | | | 43 | 0.014 | 1.5 | 30 |
| 6 | | | | | | | | | | | | | | 0.022 | 1.5 | 30 |
| 7 | | | | | | | | | | | | | | 0.070 | 1.5 | 150 |
| T5-1 | kaolinite (75%) sand (25%) | 600 | 790 | 0.063 | 0.048 | 119 | 31 | 7 | 0.25 | 0.014 | 1.5 | 30 | | | | |
| 2 | | | | | | | | | | 0.022 | 1.5 | 30 | | | | |
| 3 | | | | | | | | | | 0.030 | 1.5 | 90 | | | | |
| 4 | | | | | | | | | | 0.048 | 1.5 | 210 | | | | |
| 5 | | | | | | | | | | | | | 18 | 0.014 | 1.5 | 30 |
| 6 | | | | | | | | | | | | | | 0.022 | 1.5 | 30 |
| 7 | | | | | | | | | | | | | | 0.070 | 1.5 | 180 |
| T6-1 | sand (75%) kaolinite (25%) | 1650 | 1700 | 0.055 | 0.053 | 120 | 31 | 7 | 0.25 | 0.014 | 1.5 | 30 | | | | |
| 2 | | | | | | | | | | 0.022 | 1.5 | 30 | | | | |
| 3 | | | | | | | | | | 0.030 | 1.5 | 75 | | | | |
| 4 | | | | | | | | | | 0.050 | 1.5 | 90 | | | | |
| 5 | | | | | | | | | | 0.070 | 1.5 | 90 | | | | |
| 6 | | | | | | | | | | 0.10 | 1.5 | 60 | | | | |
| T7-1 | sand | 1600 | 1600 | 0.05 | 0.05 | 0 | 31 | 7 | 0.25 | 0.03 | 1.5 | 30 | | | | |
| 2 | | | | | | | | | | 0.05 | 1.5 | 60 | | | | |
| 3 | | | | | | | | | | 0.07 | 1.5 | 60 | | | | |
| 4 | | | | | | | | | | 0.10 | 1.5 | 60 | | | | |

Table 4. Experimental conditions

| section | waves | | $\bar{u}$ -velocity (m/s) | | | | | $u_{rms}$ -velocity (m/s) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | period | height | z = 0.01 | 0.02 | 0.05 | 0.10 | 0.20 | z = 0.01 | 0.02 | 0.05 | 0.10 | 0.20 |
| (m) | (s) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) | (m) |
| 9.6 | 1.5 | 0.014 | 0.009 | 0.001 | 0.004 | 0.002 | - | 0.036 | 0.037 | 0.043 | 0.04 | - |
| 9.6 | 1.5 | 0.020 | 0.001 | 0.001 | - | - | - | 0.057 | 0.057 | - | - | - |
| 9.6 | 1.5 | 0.030 | 0.001 | 0.002 | 0.007 | 0.003 | - | 0.054 | 0.088 | 0.089 | 0.087 | - |
| 9.6 | 1.5 | 0.050 | - | - | 0.001 | 0.004 | - | - | - | 0.140 | 0.143 | - |
| 9.6 | 1.5 | 0.072 | - | - | 0.01 | 0.006 | - | - | - | 0.175 | 0.216 | - |
| 9.6 | 1.5 | 0.105 | - | - | 0.028 | 0.027 | - | - | - | 0.263 | 0.268 | - |
| 9.6 | 2.5 | 0.014 | -0.026 | 0.028 | - | - | - | 0.037 | 0.046 | - | - | - |
| 9.6 | 2.5 | 0.020 | -0.023 | -0.013 | - | - | - | 0.038 | 0.070 | - | - | - |
| 9.6 | 2.5 | 0.030 | -0.010 | -0.007 | - | - | - | 0.056 | 0.095 | - | - | - |
| 9.0 | 1.5 | 0.057 | -0.001 | 0.002 | 0.003 | 0.007 | 0.017 | 0.107 | 0.112 | 0.114 | 0.150 | 0.129 |
| 10.0 | 1.5 | 0.053 | 0.002 | 0.002 | 0.003 | -0.004 | 0.018 | 0.122 | 0.121 | 0.121 | 0.127 | 0.144 |
| 11.0 | 1.5 | 0.047 | 0.005 | 0.004 | 0.005 | 0.008 | 0.015 | 0.129 | 0.133 | 0.129 | 0.133 | 0.156 |
| 9.0 | 1.5 | 0.087 | -0.007 | -0.006 | -0.001 | 0.011 | 0.041 | 0.147 | 0.157 | 0.150 | 0.161 | 0.174 |
| 10.0 | 1.5 | 0.078 | 0.005 | 0.002 | 0.012 | 0.021 | 0.031 | 0.170 | 0.161 | 0.168 | 0.173 | 0.219 |
| 11.0 | 1.5 | 0.076 | 0.001 | -0.003 | 0.006 | 0.014 | 0.038 | 0.191 | 0.179 | 0.177 | 0.184 | 0.216 |
| 9.0 | 1.5 | 0.115 | -0.003 | 0.001 | 0.004 | 0.018 | 0.077 | 0.193 | 0.203 | 0.200 | 0.217 | 0.247 |
| 10.0 | 1.5 | 0.108 | 0.001 | 0.003 | 0.012 | 0.027 | 0.069 | 0.206 | 0.201 | 0.197 | 0.209 | 0.233 |
| 11.0 | 1.5 | 0.103 | 0.002 | 0.006 | 0.013 | 0.026 | 0.066 | 0.221 | 0.221 | 0.221 | 0.227 | 0.276 |

$\bar{u}$ = mean longitudinal velocity

$u_{rms}$ = root-mean-square longitudinal velocity

measuring period = 60 s

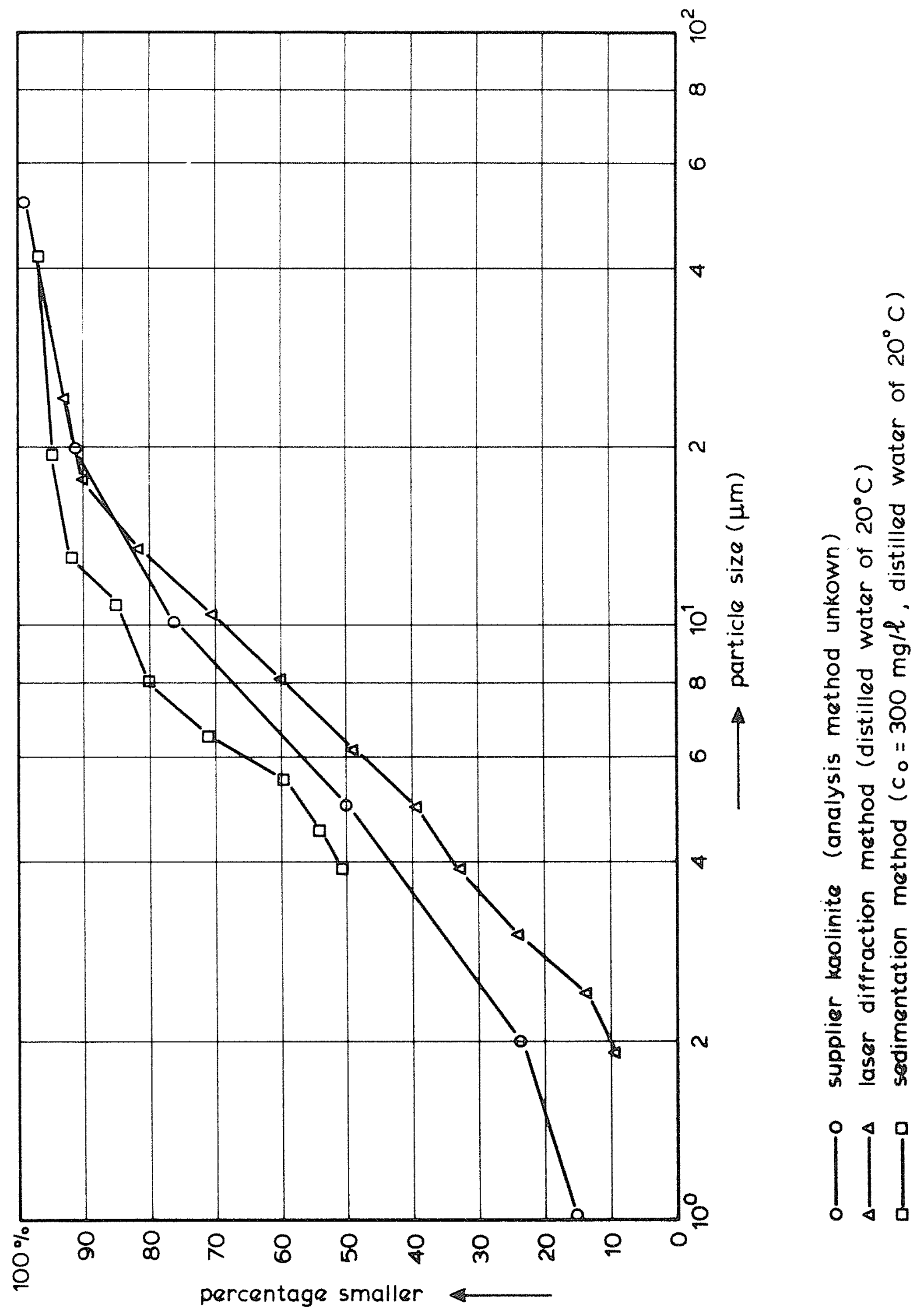
water depth = 0.25 m

water temperature ≈ 11 °C

Table 5, Experimental results

| no | sediment | bed surface concentration (kg/m$^3$) | wave characteristics for weak movement of bed surface material | | | |
|---|---|---|---|---|---|---|
| | | | height H (m) | period T (s) | $u_{rms}$ (m/s) | $\frac{u_{rms}}{gT}$ (m/s$^2$) |
| T1 | kaolinite | 230 | 0.008 | 1.5 | 0.022 | 0.0015 |
| T2 | kaolinite | 230 | 0.014 | 2.5 | 0.035 | 0.0014 |
| T3 | kaolinite | 320 | 0.02 | 2.5 | 0.05 | 0.002 |
| T4 | kaolinite | 320 | 0.014 | 1.5 | 0.038 | 0.0025 |
| T5 | kaolinite (75%)<br>sand (25%) | 320 | 0.014 | 1.5 | 0.038 | 0.0025 |
| T6 | sand (75%)<br>kaolinite (25%) | | 0.014 | 1.5 | 0.038 | 0.0025 |
| T7 | sand | 1600 | 0.03 | 1.5 | 0.075 | 0.0051 |

Table 6, Wave data for initiation of motion

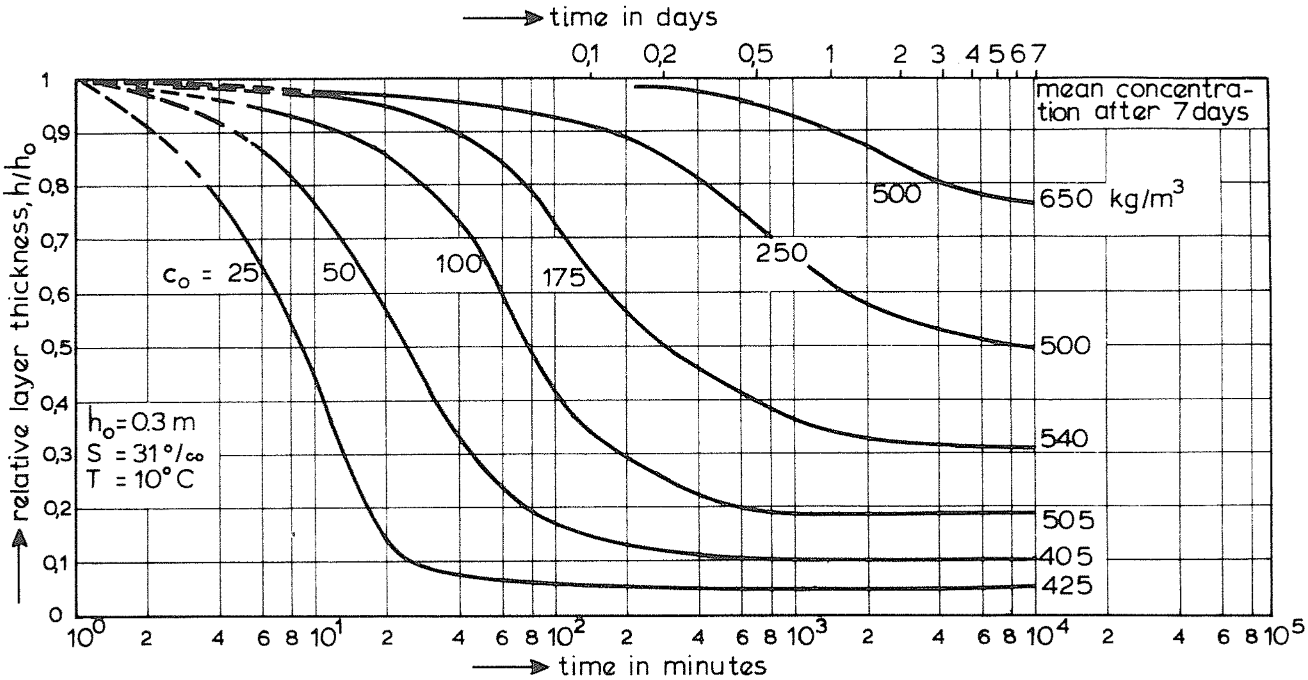


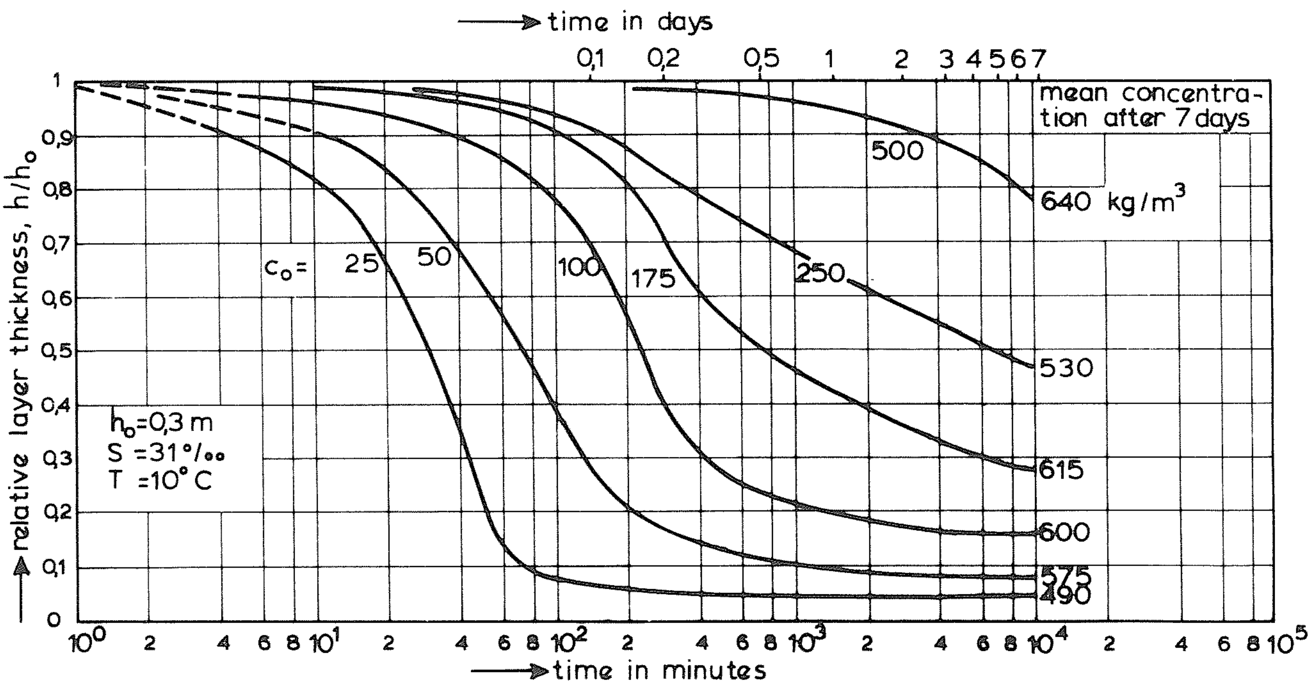

PARTICLE SIZE OF KAOLINITE

DELFT HYDRAULICS LABORATORY

M 2060

FIG. 1



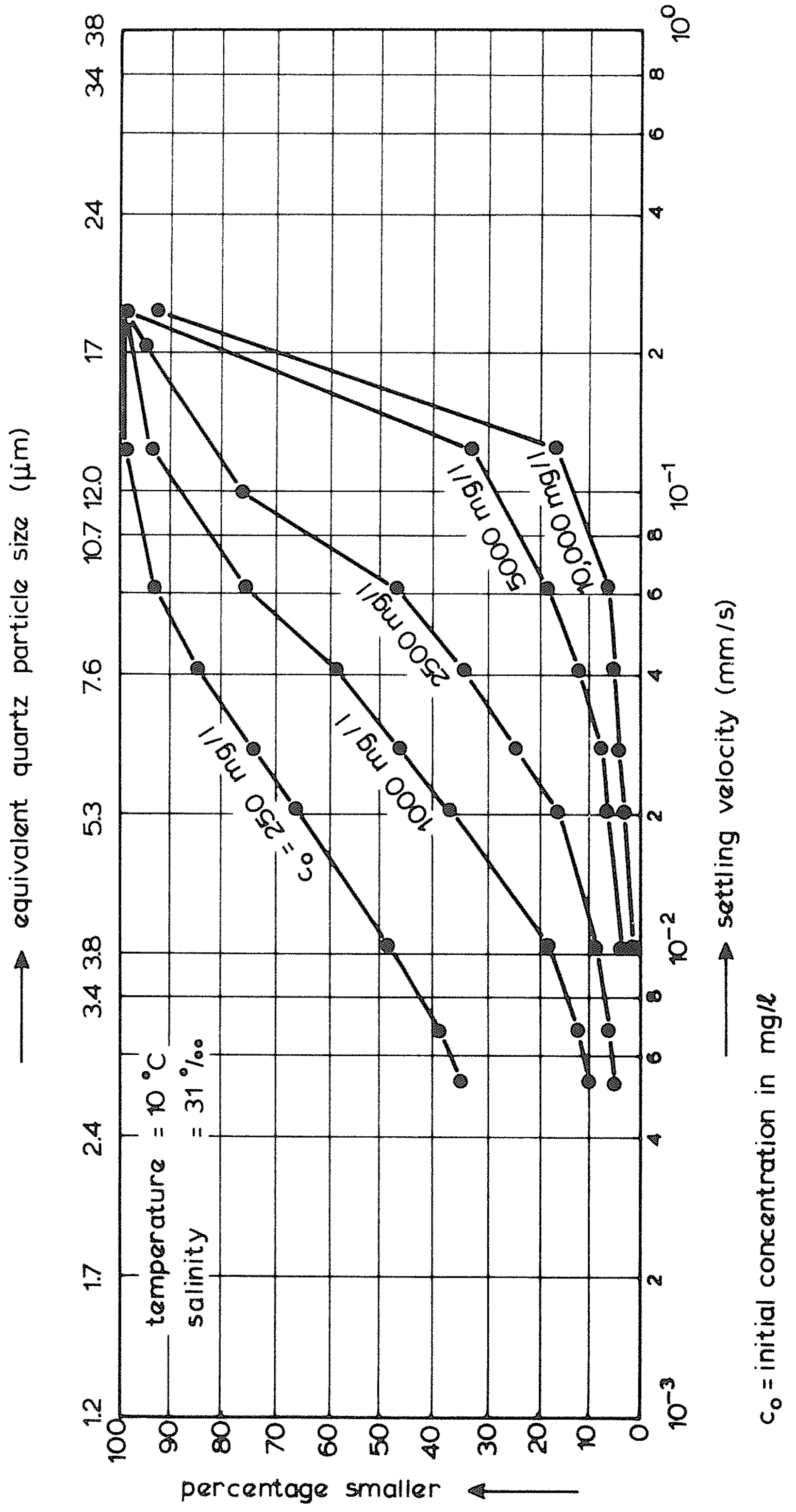




$c_o$= initial concentration in kg/$m^3$

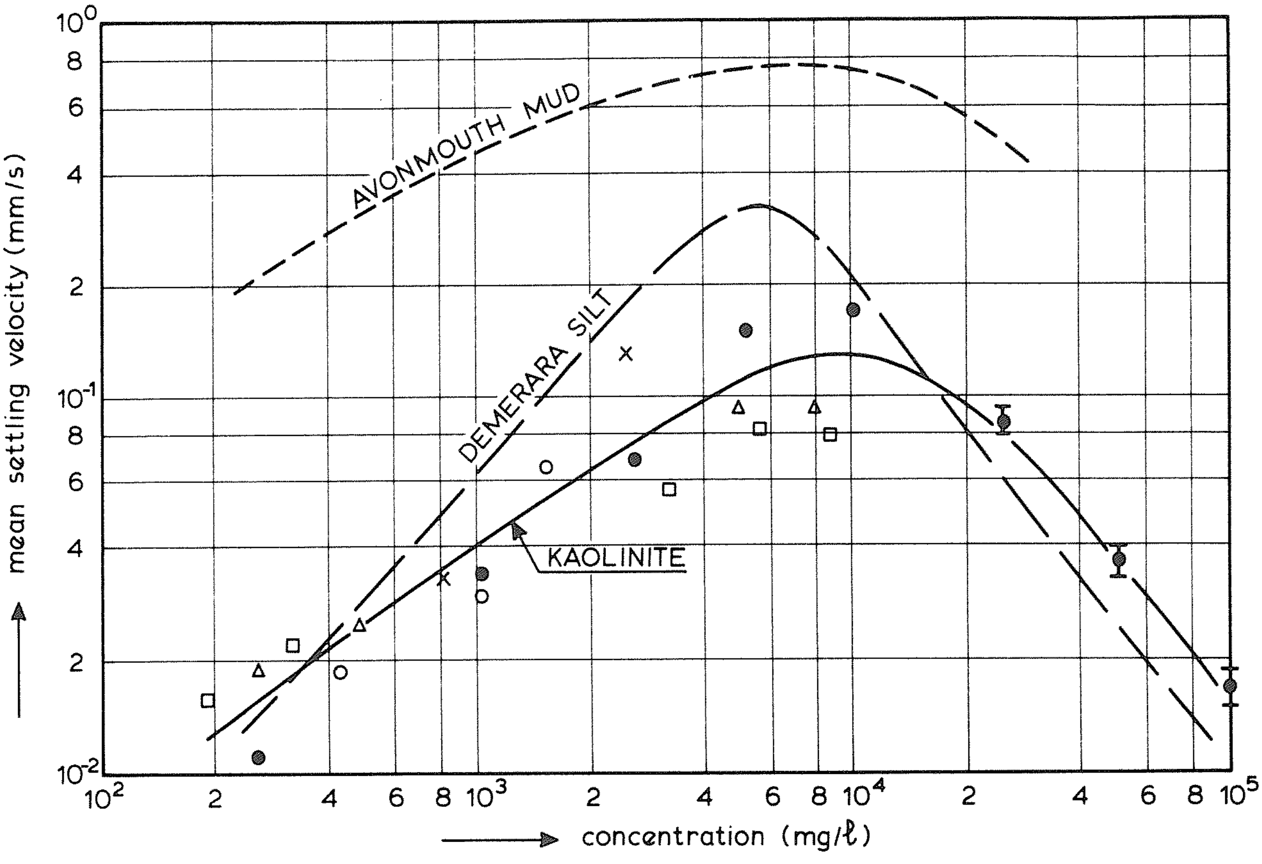
CONSOLIDATION CURVES OF KAOLINITE

DELFT HYDRAULICS LABORATORY

M 2060 FIG. 2




| SETTLING VELOCITY CURVES OF KAOLINITE | | |
|---|---|---|
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 3 |



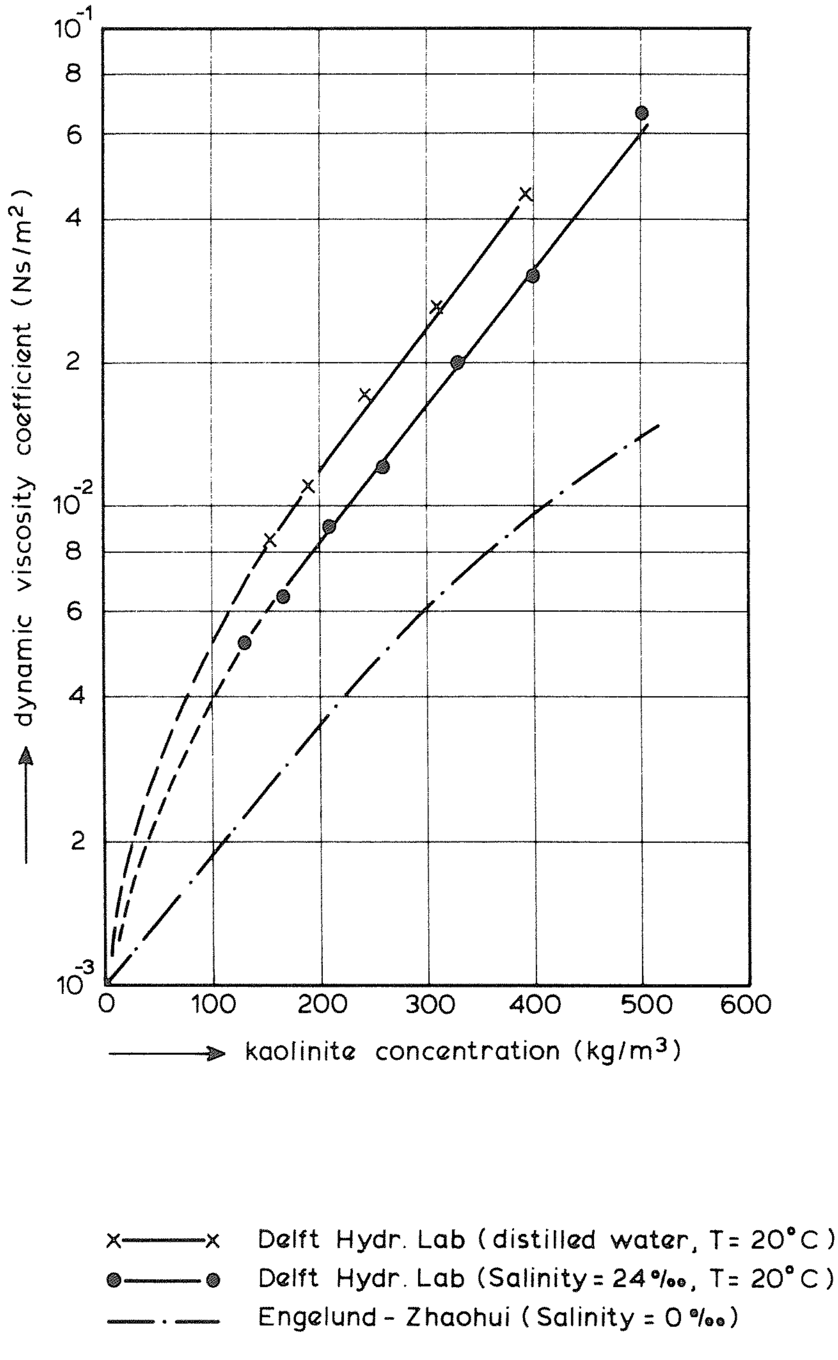

KAOLINITE (s = 31 ‰, T = 10°C)

- ● laboratory samples
- × T2, ○ T3, △ T4, □ T5 — flume samples
- consolidation tests

– – – – AVONMOUTH MUD s = 32 g/ℓ, T = 20°C (OWEN, 1970)

— — DEMERARA SILT (NEDECO, 1965)

| | | |
|---|---|---|
| SETTLING VELOCITY AS A FUNCTION OF CONCENTRATION | | |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG 4 |

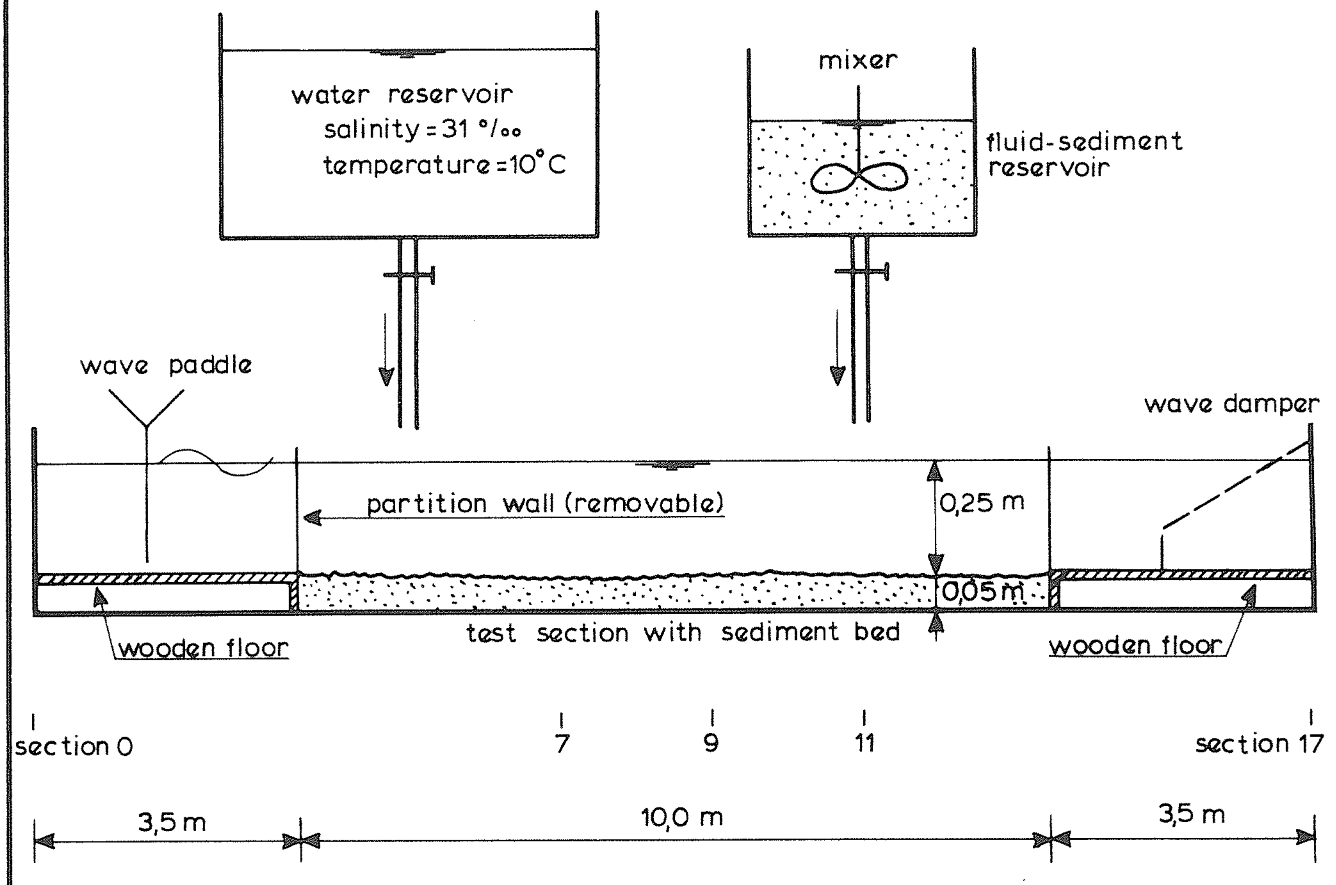



VISCOSITY OF KAOLINITE AS A FUNCTION OF CONCENTRATION

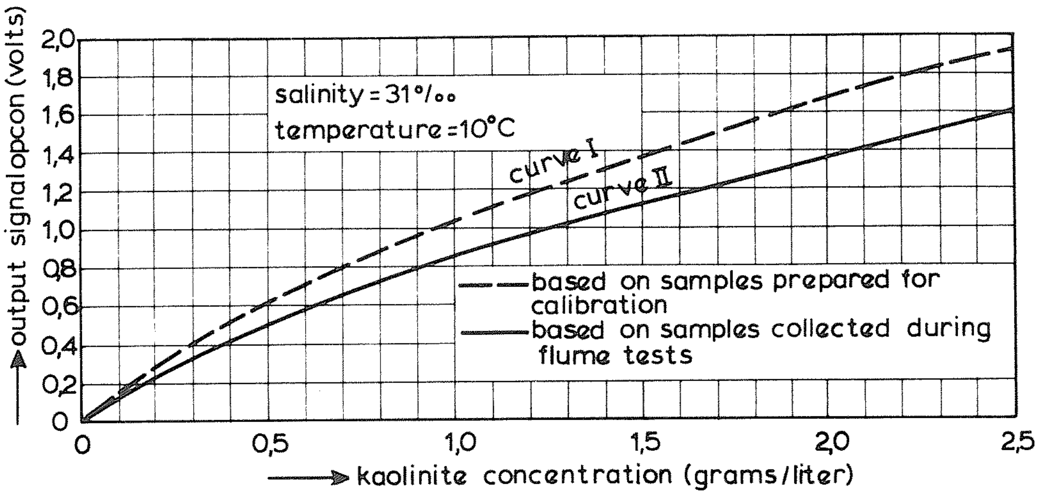
DELFT HYDRAULICS LABORATORY

M 2060

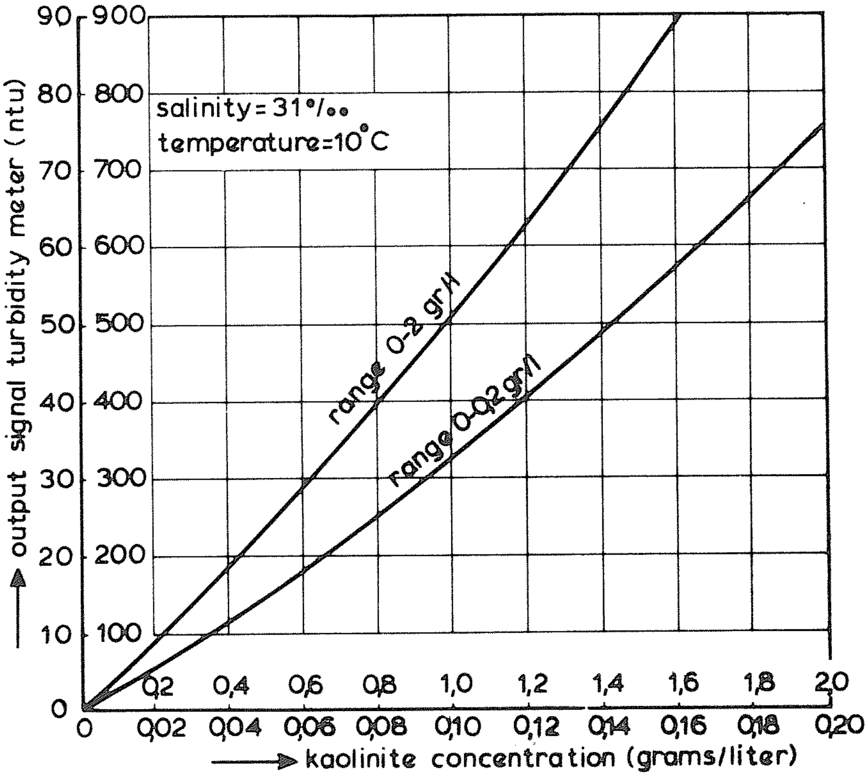
FIG. 5




| | | |
|---|---|---|
| EXPERIMENTAL SET-UP | | |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 6 |



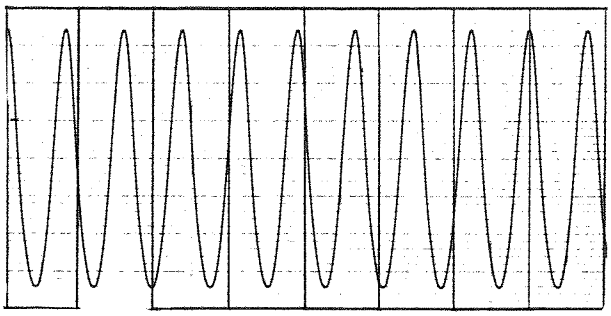

a. calibration curves opcon



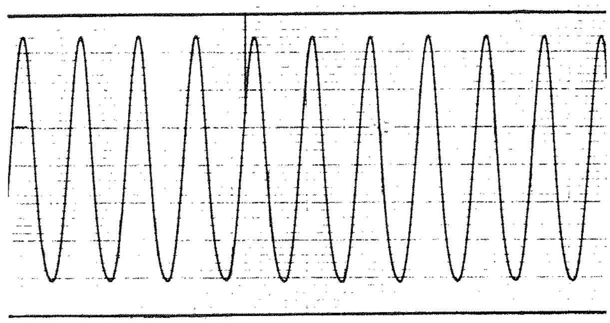

b. calibration curves turbidity meter

CALIBRATION CURVES OPTICAL CONCENTRATION METERS

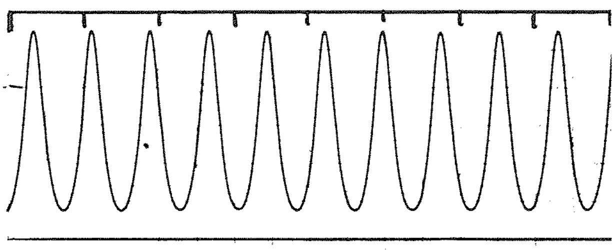
DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 7



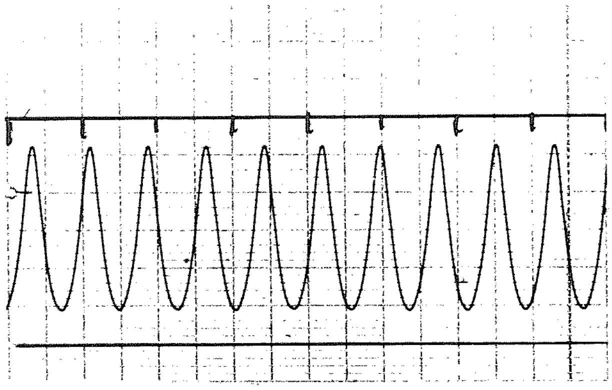
section 8 wave height = 0,034 m
wave period = 1,5 s



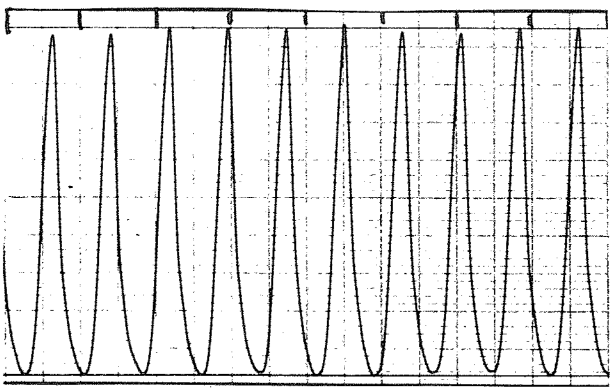
section 10 wave height = 0,033 m
wave period = 1,5 s



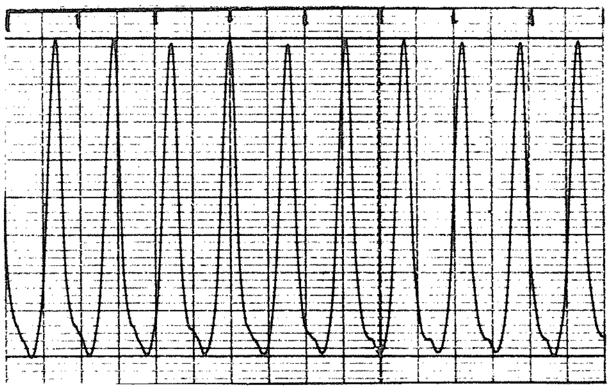
section 8 wave height = 0,059 m
wave period = 1,5 s



section 10 wave height = 0,055 m
wave period = 1,5 s



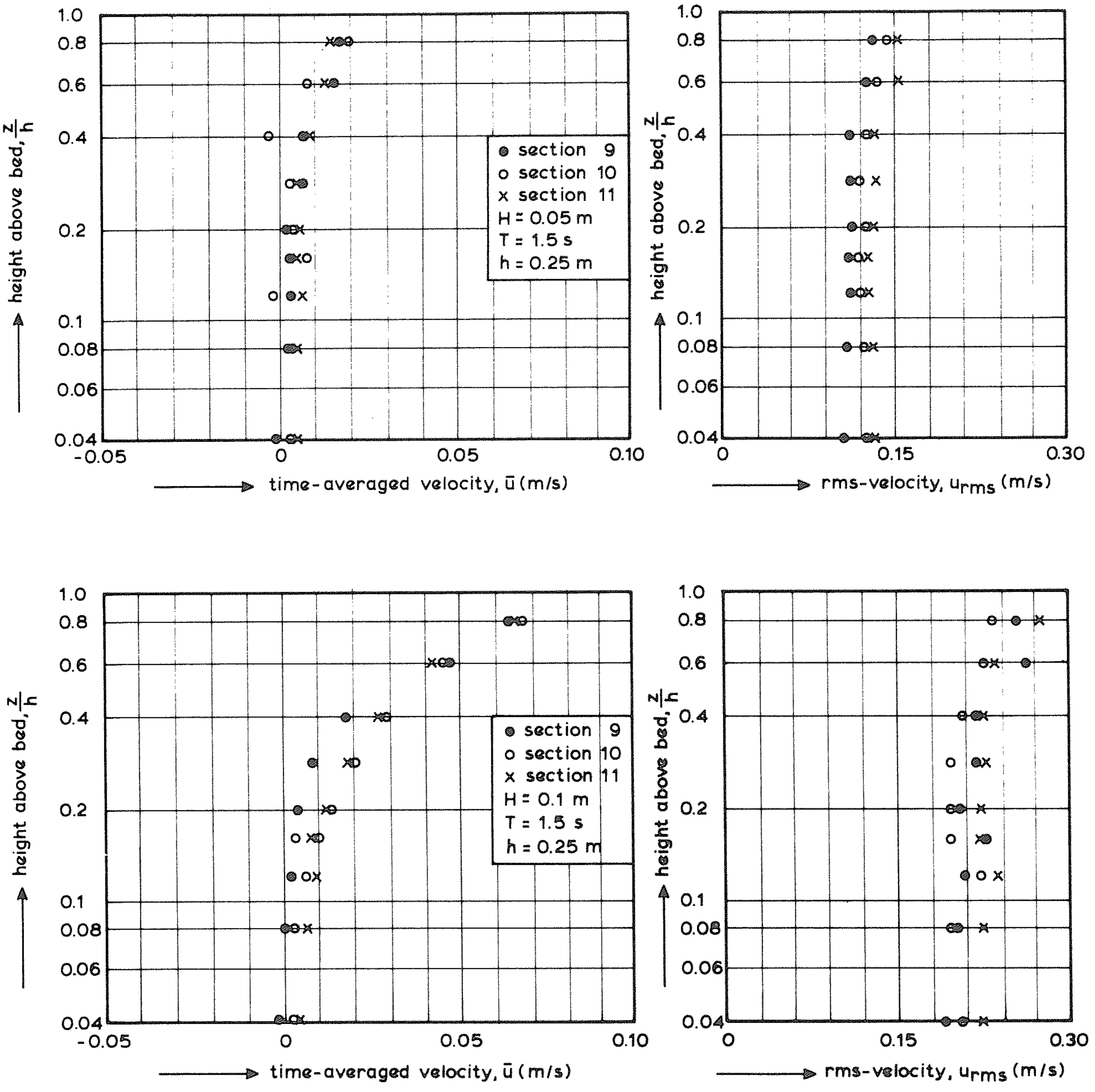
section 8 wave height = 0,115 m
wave period = 1,5 s



section 10 wave height = 0,105 m
wave period = 1,5 s

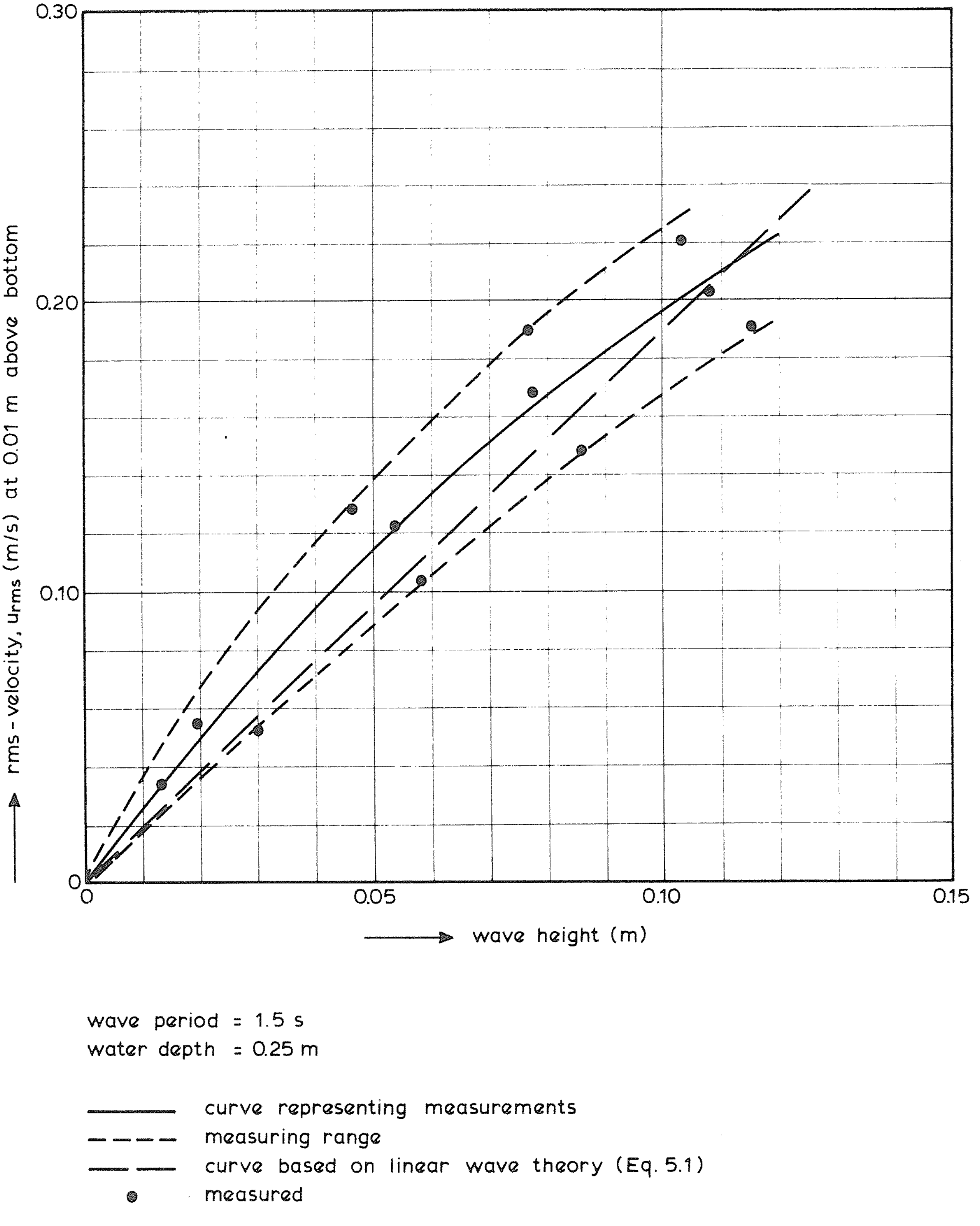
WAVE PROFILES

DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 8



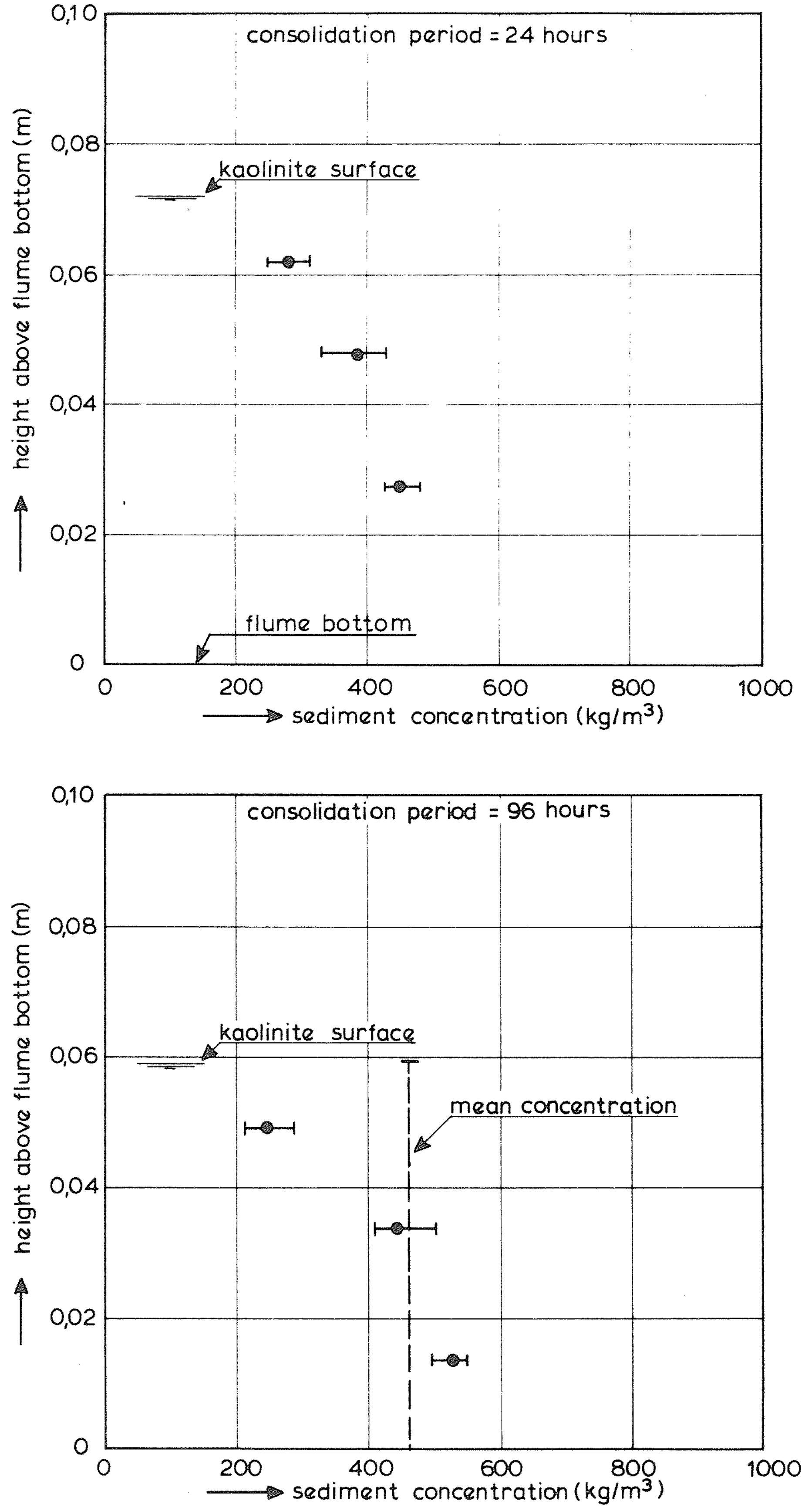

TIME-AVERAGED AND RMS-VELOCITIES
(LASER DOPPLER)

DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 9

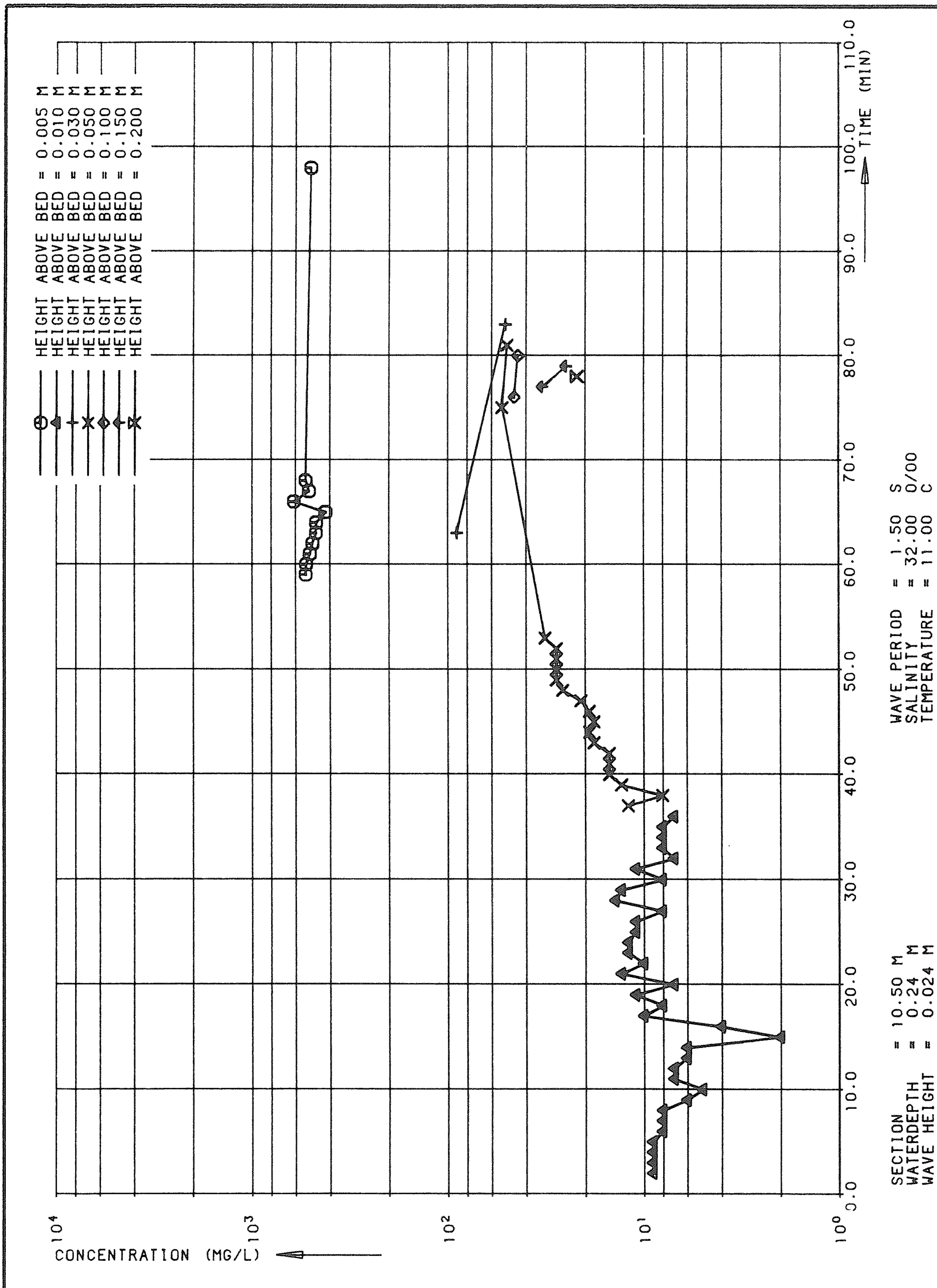



RMS-VELOCITY AS A FUNCTION OF WAVE HEIGHT

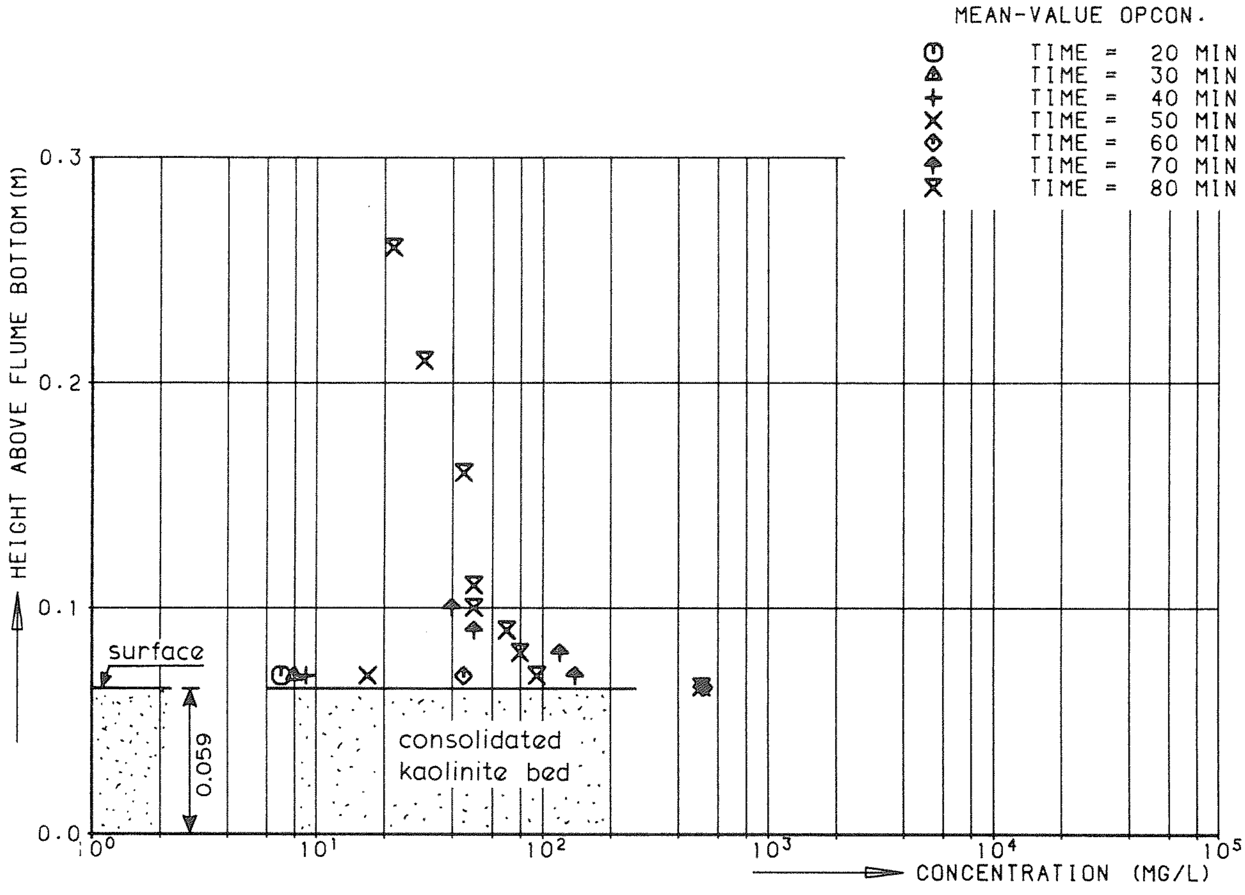
DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 10

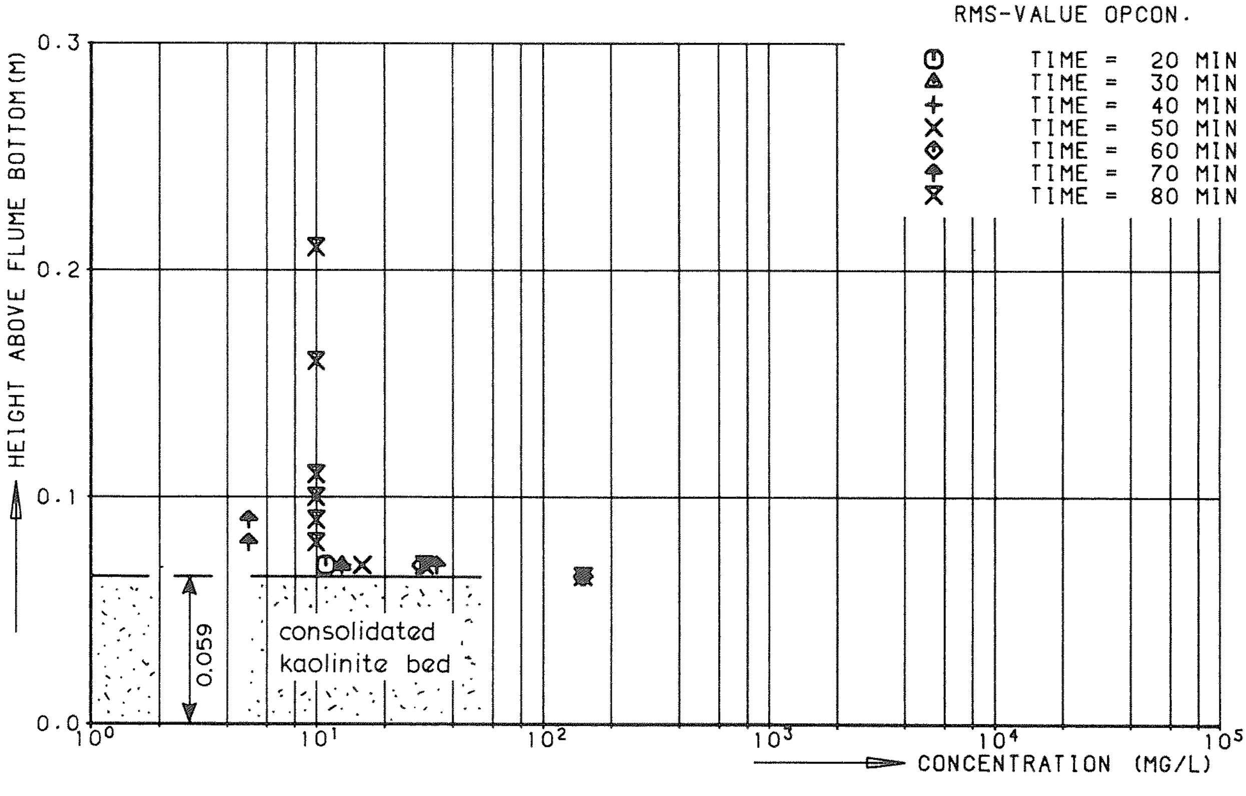



| | | |
|---|---|---|
| SEDIMENT CONCENTRATIONS IN BED LAYER | | T 1 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 11 |




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T1-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 12 |

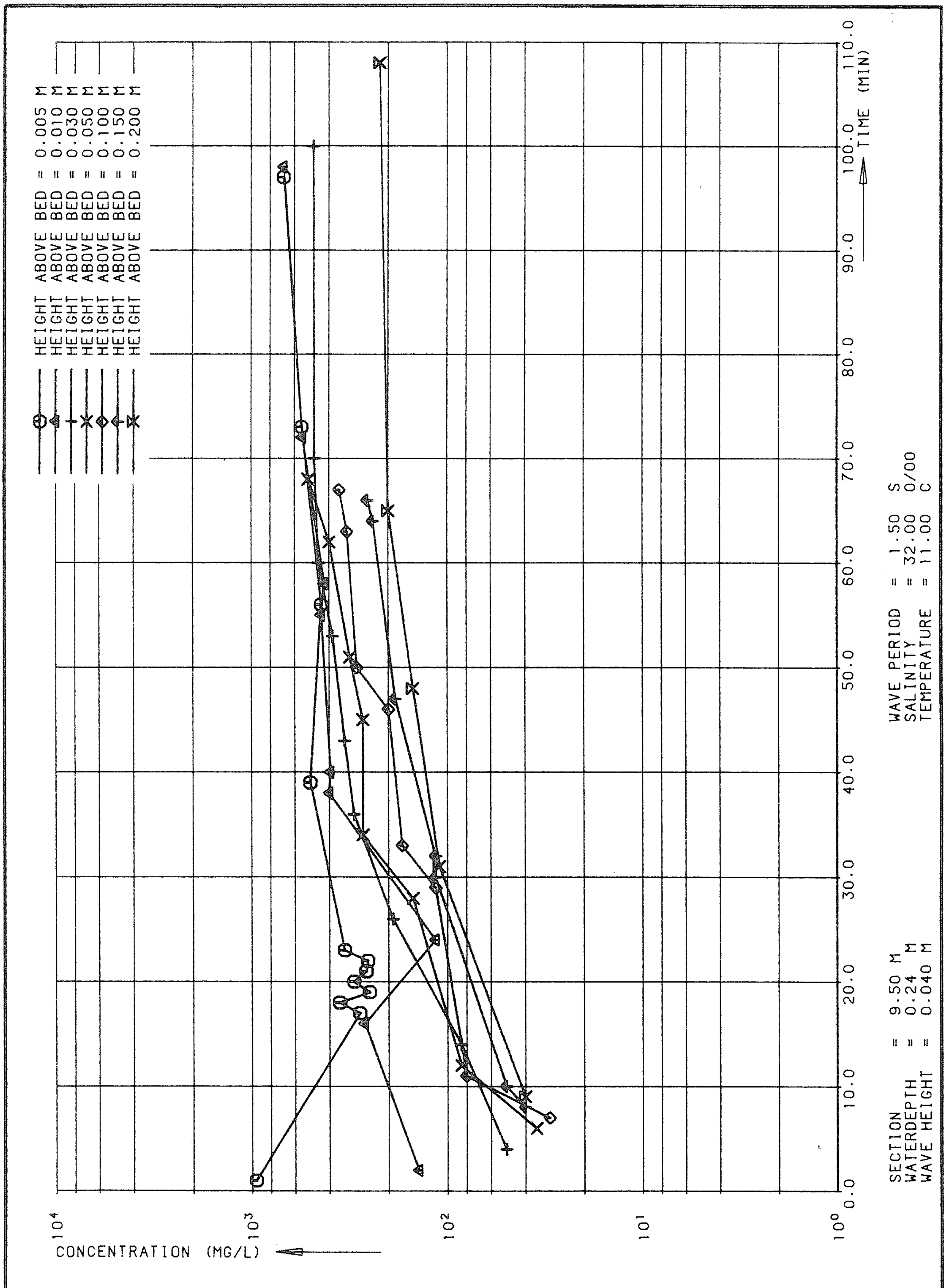


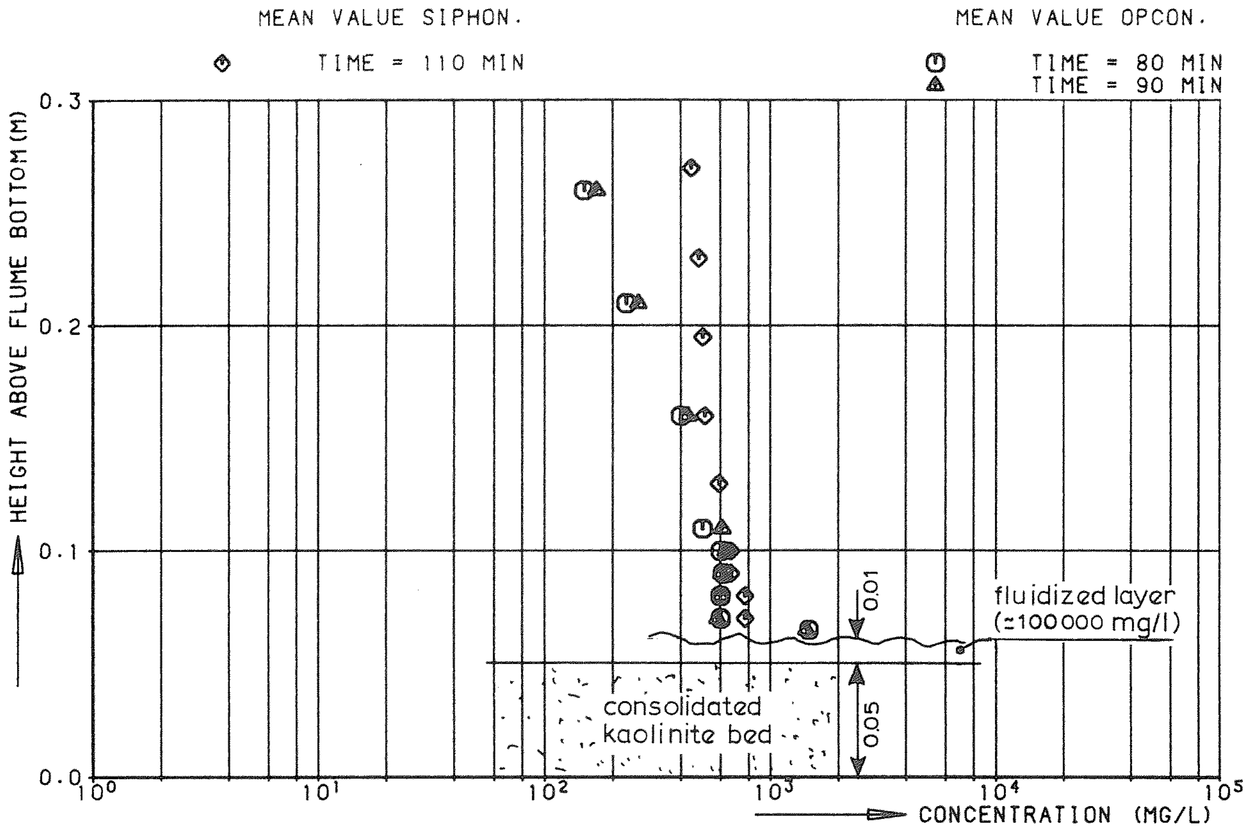

SECTION = 10.50 M
WATERDEPTH = 0.24 M
WAVE HEIGHT = 0.024 M

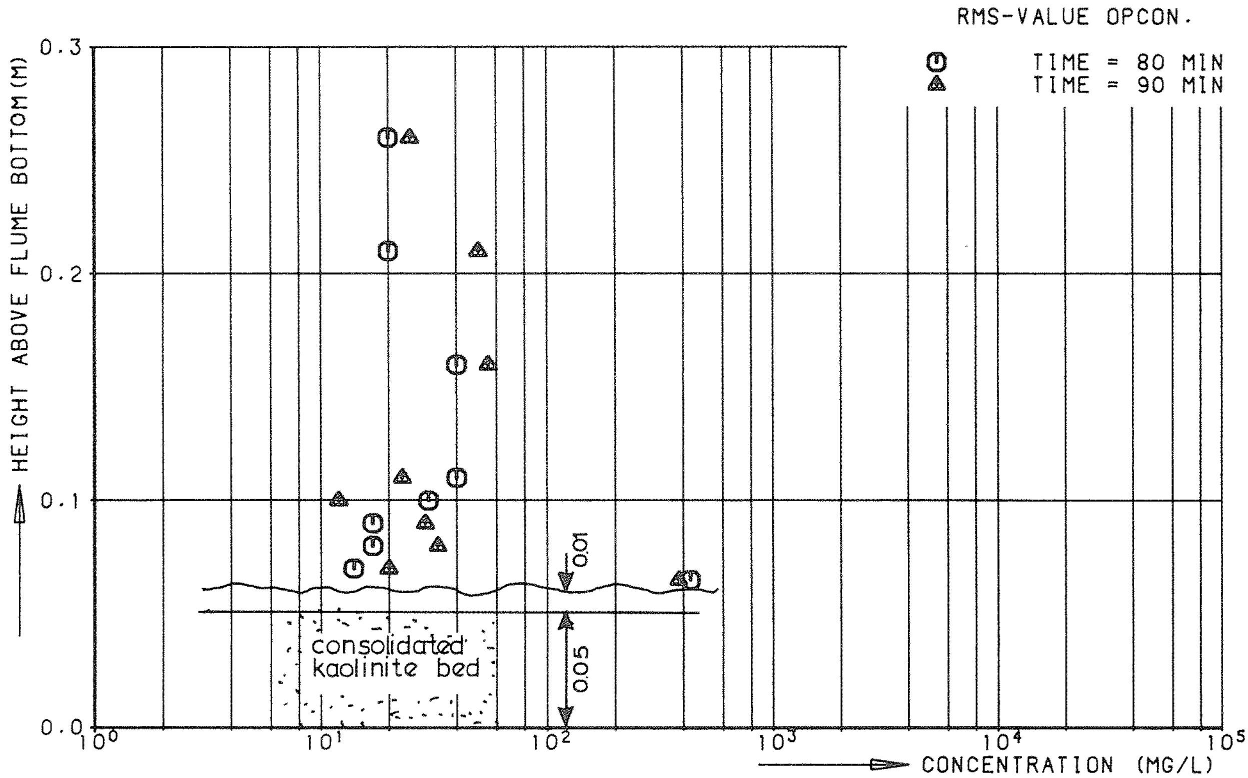
WAVE PERIOD = 1.50 S
SALINITY = 32.00 0/00
TEMPERATURE = 11.00 C

| | | |
|---|---|---|
| CONCENTRATION PROFILES (OPCON) | | T1-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 13 |




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T1-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 14 |




| | | | | | |
|---|---|---|---|---|---|
| SECTION | = 12.00 | M | WAVE PERIOD | = 1.50 | S |
| WATERDEPTH | = 0.25 | M | SALINITY | = 32.00 | 0/00 |
| WAVE HEIGHT | = 0.04 | M | TEMPERATURE | = 11.00 | C |

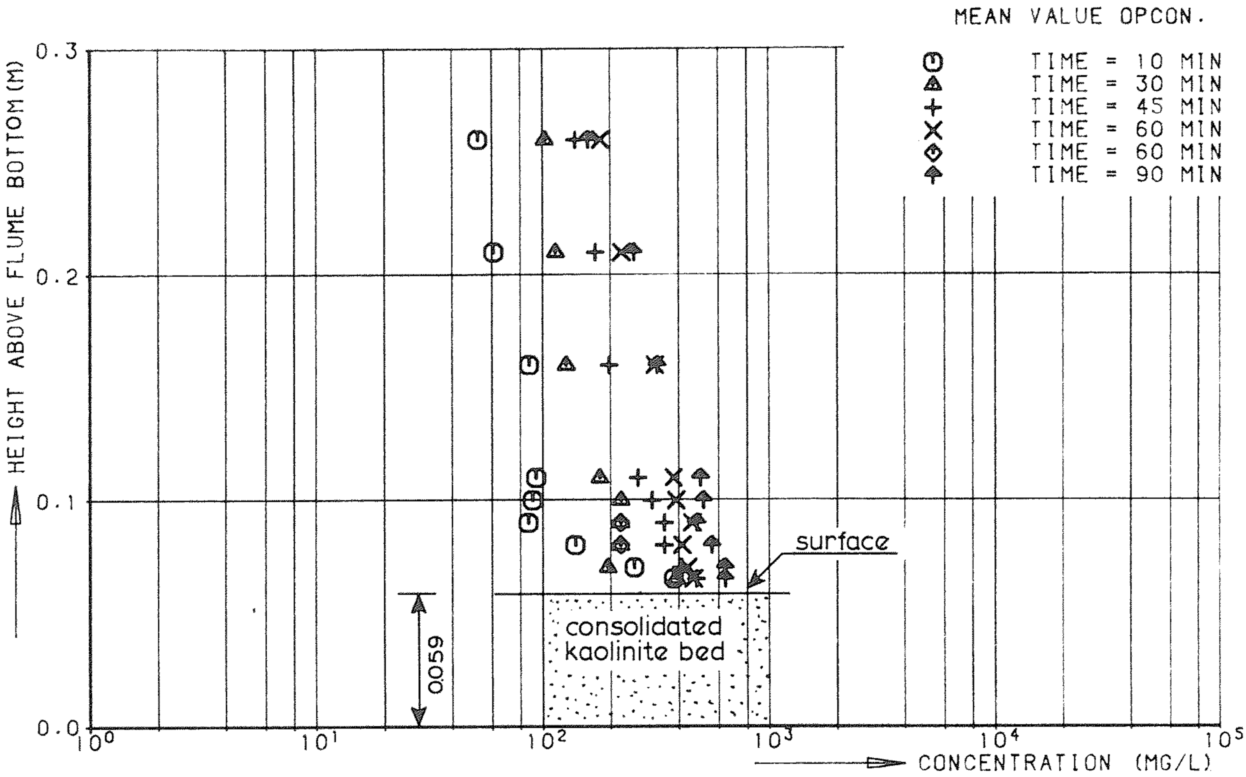
CONCENTRATION PROFILES (OPCON)
CONCENTRATION PROFILES (SIPHON)

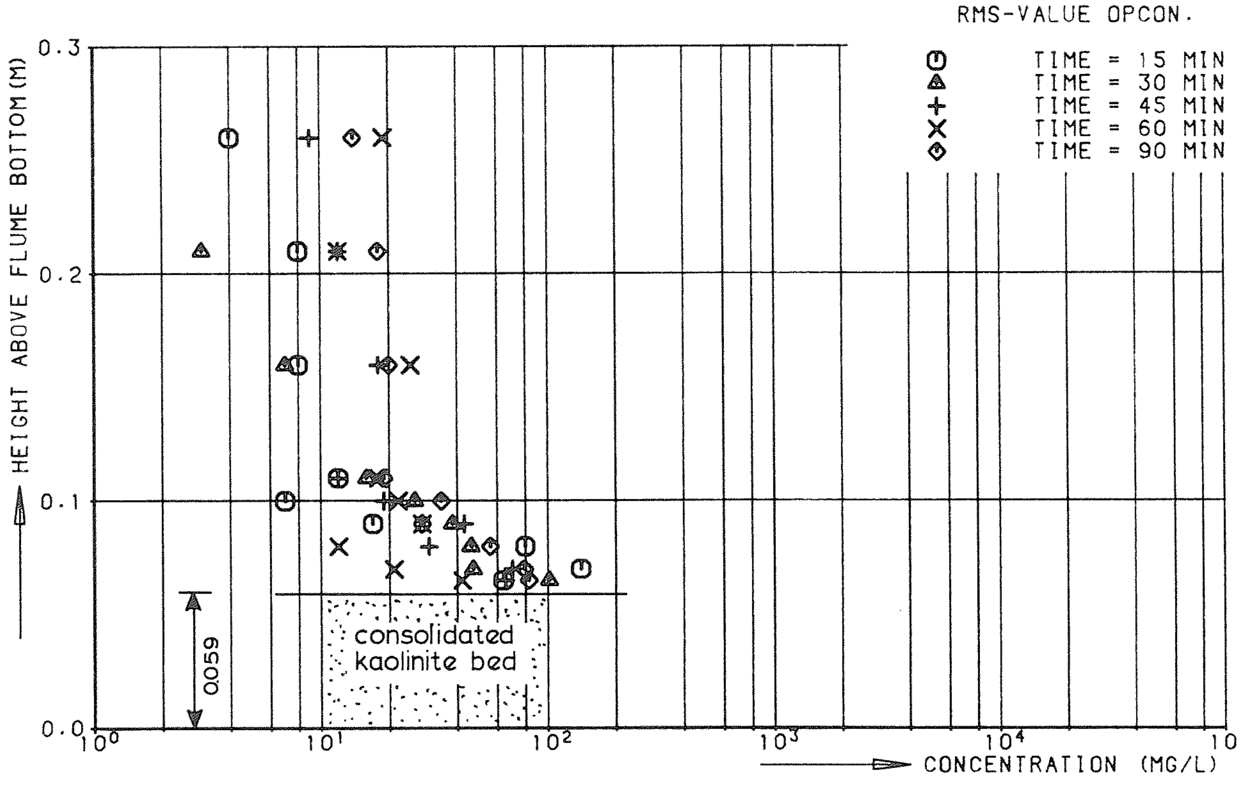
T 1-4

DELFT HYDRAULICS LABORATORY

M 2060

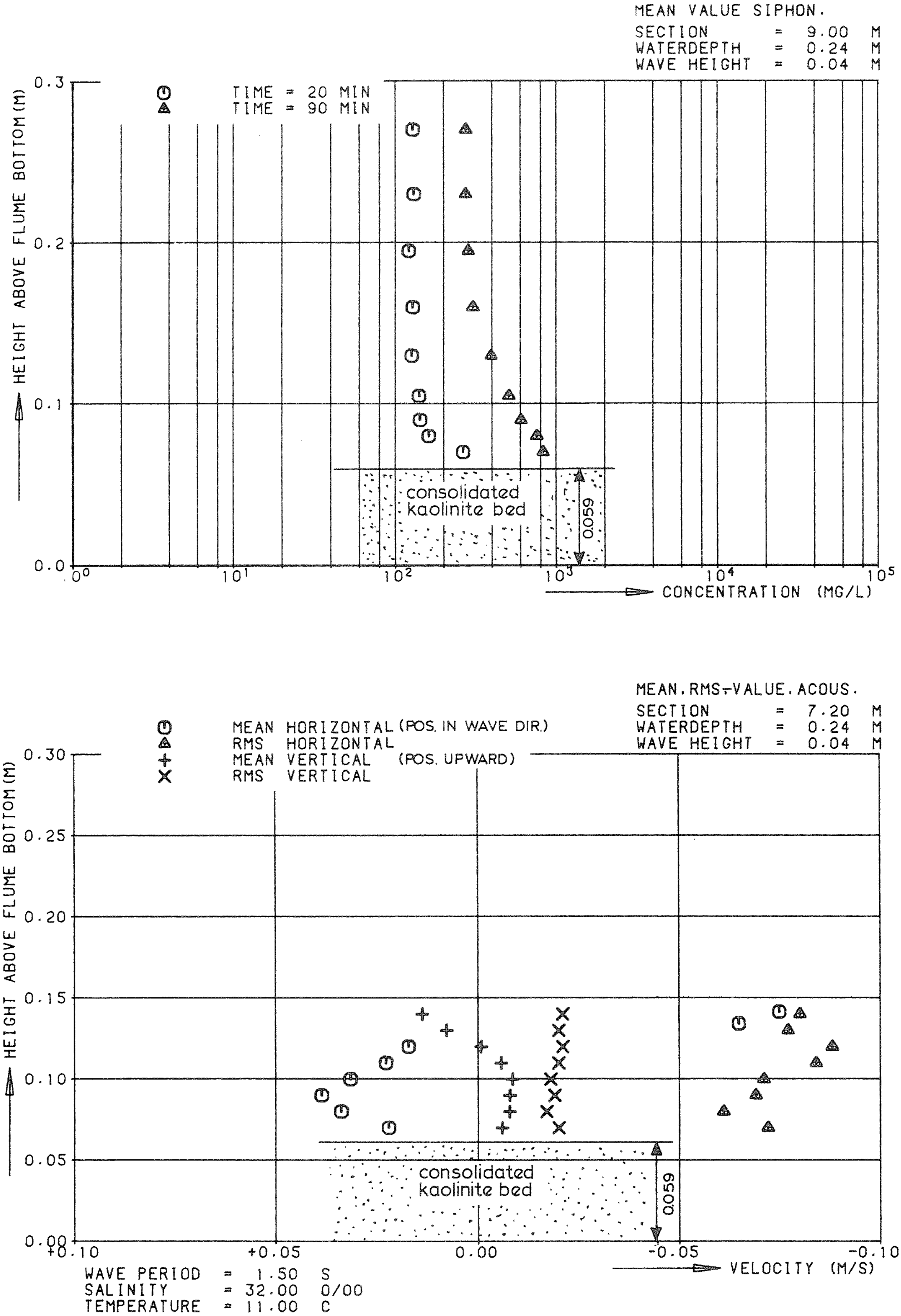
FIG. 15



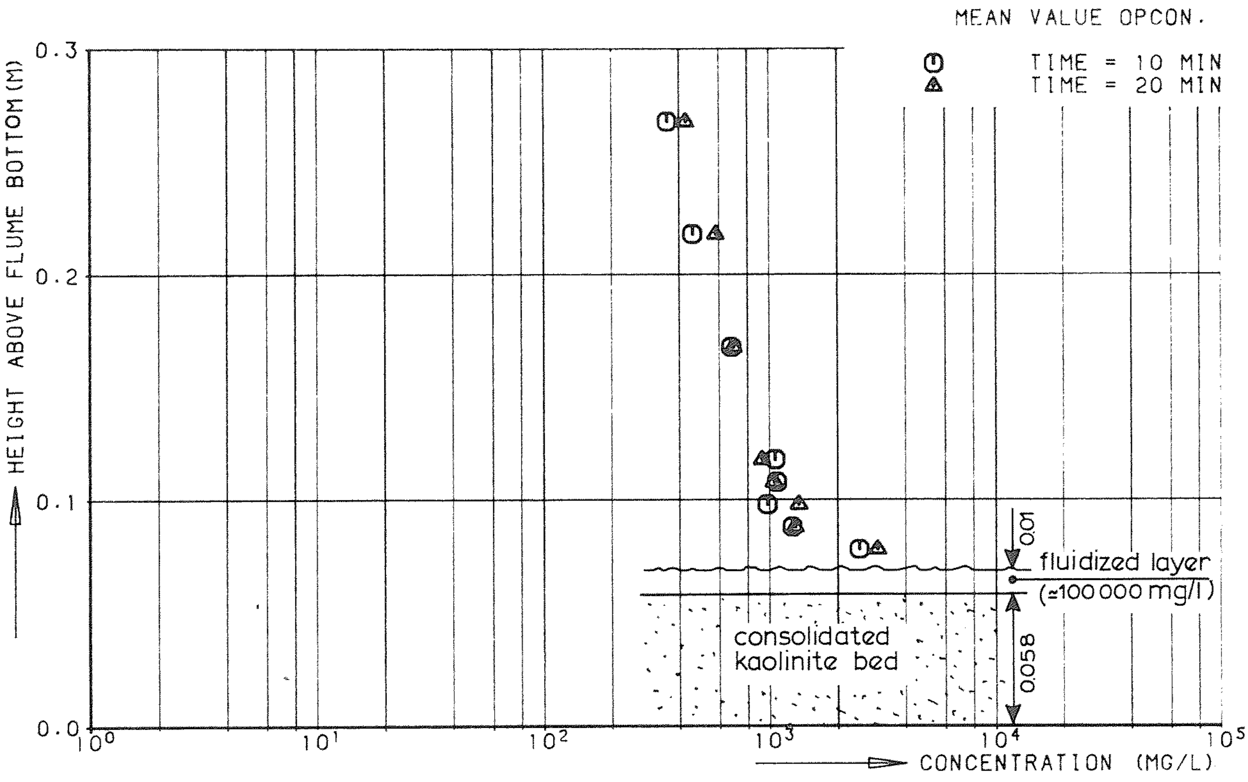



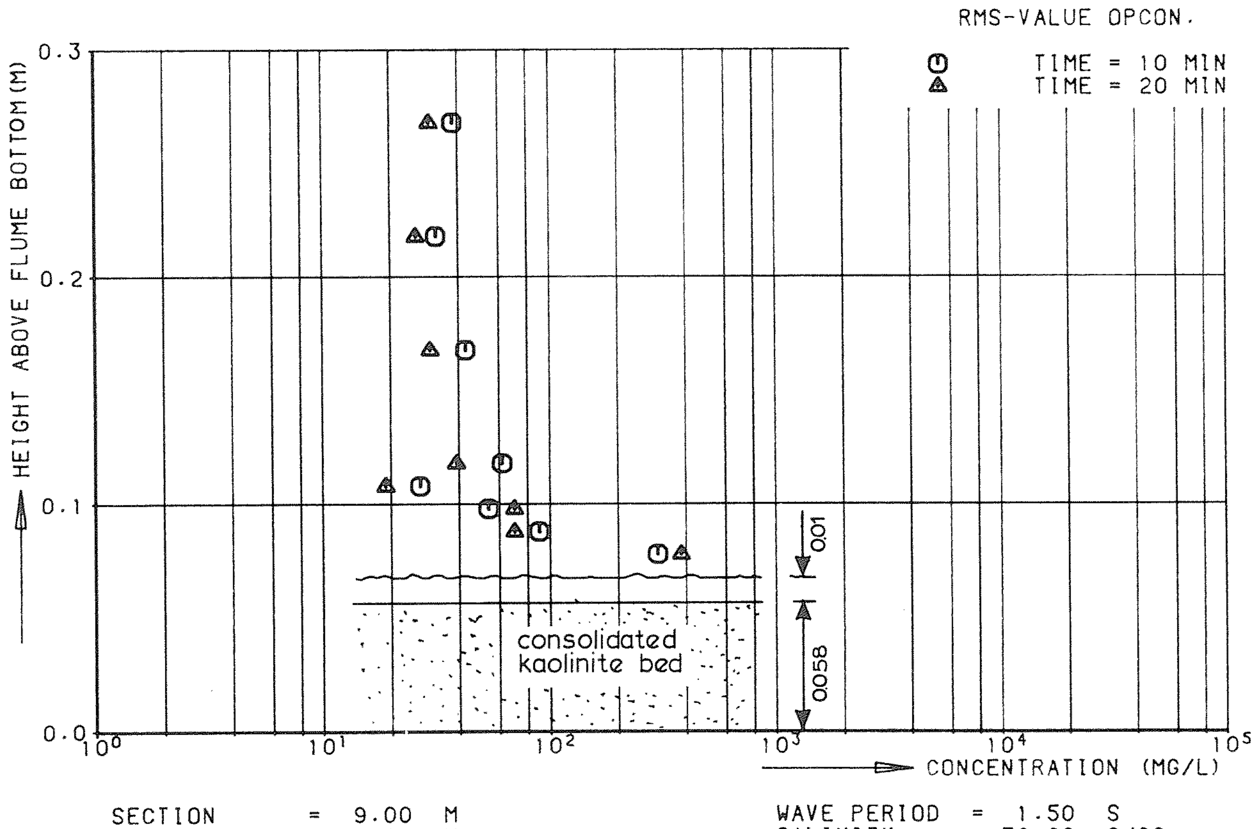

| | | | |
|---|---|---|---|
| SECTION | = 9.50 M | WAVE PERIOD | = 1.50 S |
| WATERDEPTH | = 0.24 M | SALINITY | = 32.00 0/00 |
| WAVE HEIGHT | = 0.04 M | TEMPERATURE | = 11.00 C |

| | | |
|---|---|---|
| CONCENTRATION PROFILES (OPCON) | | T 1-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 16 |




| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON)<br>VELOCITY PROFILES (ACOUS ) | | T 1-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 17 |

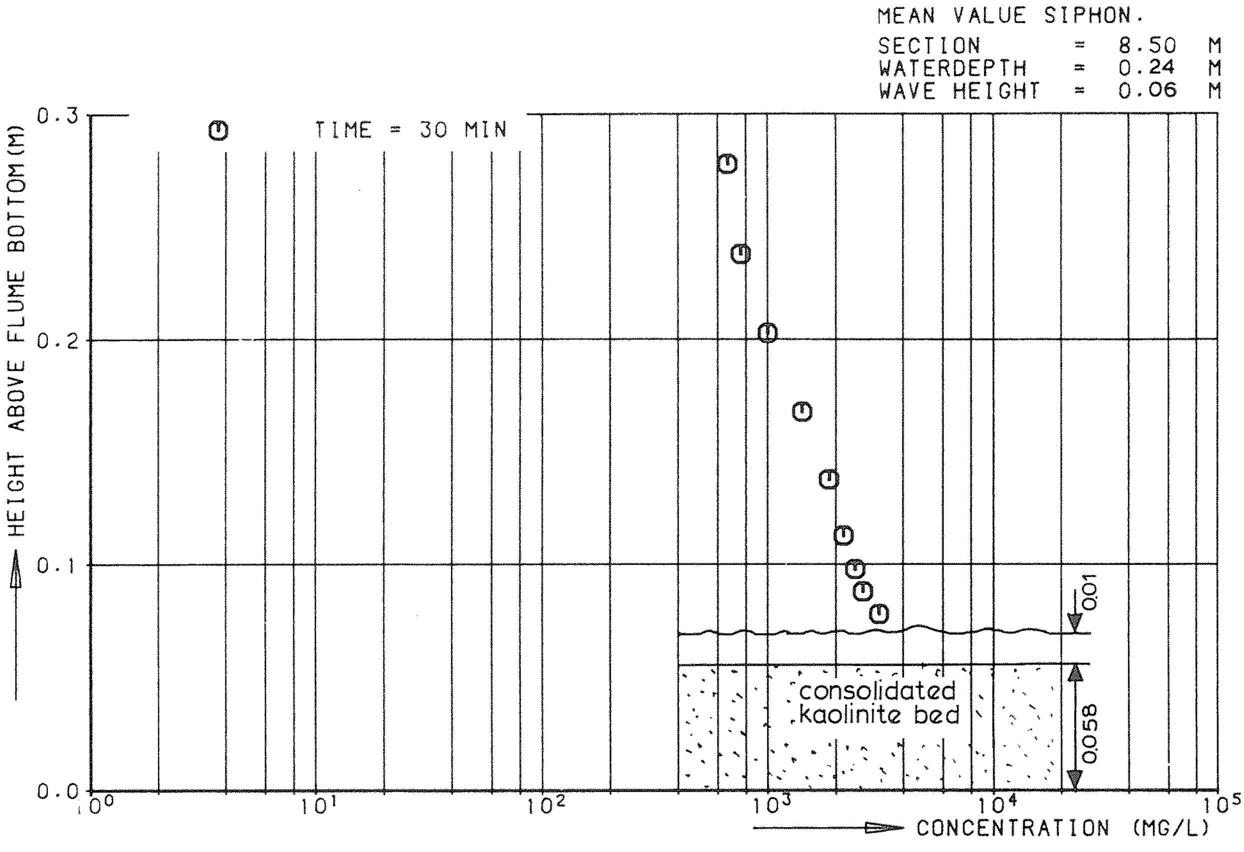


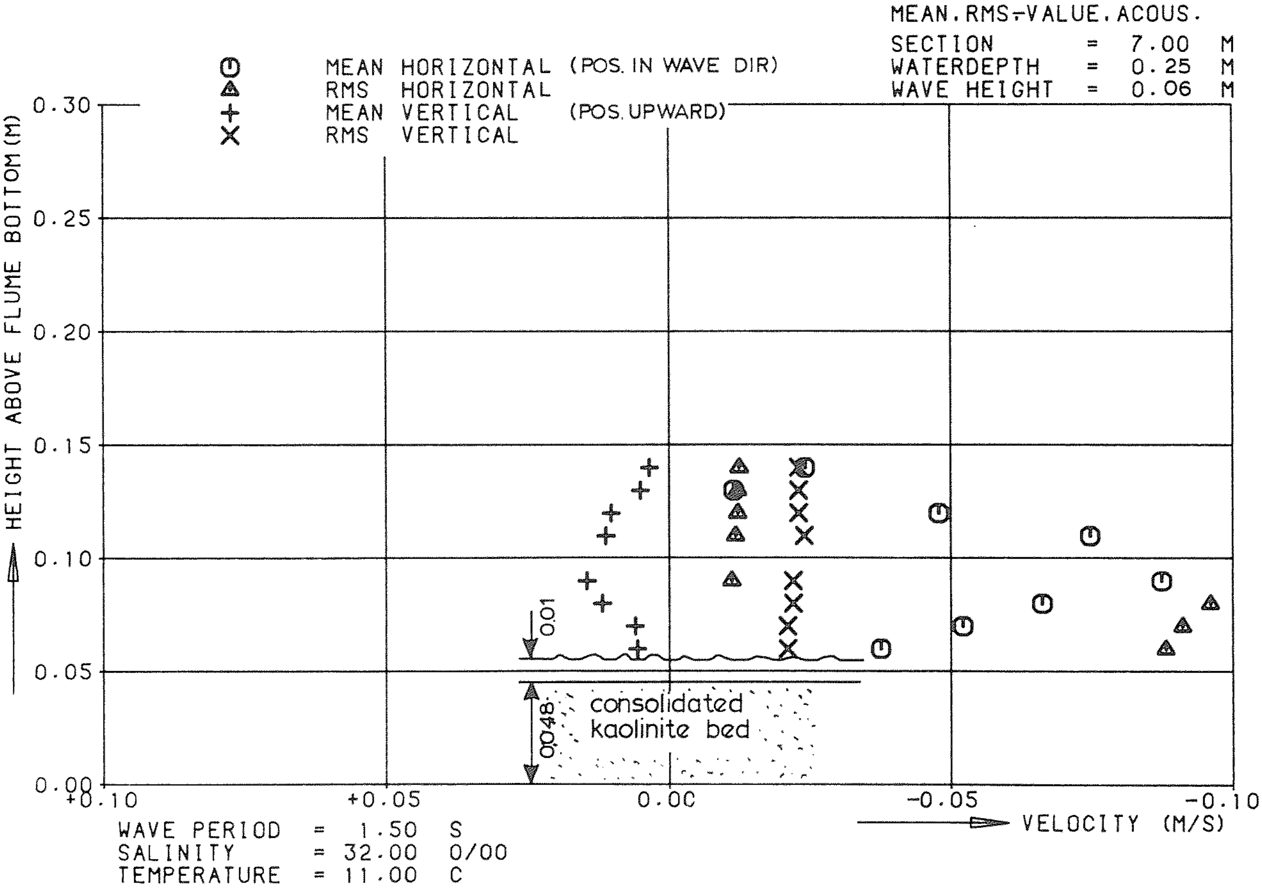




SECTION = 9.00 M
WATERDEPTH = 0.24 M
WAVE HEIGHT = 0.06 M

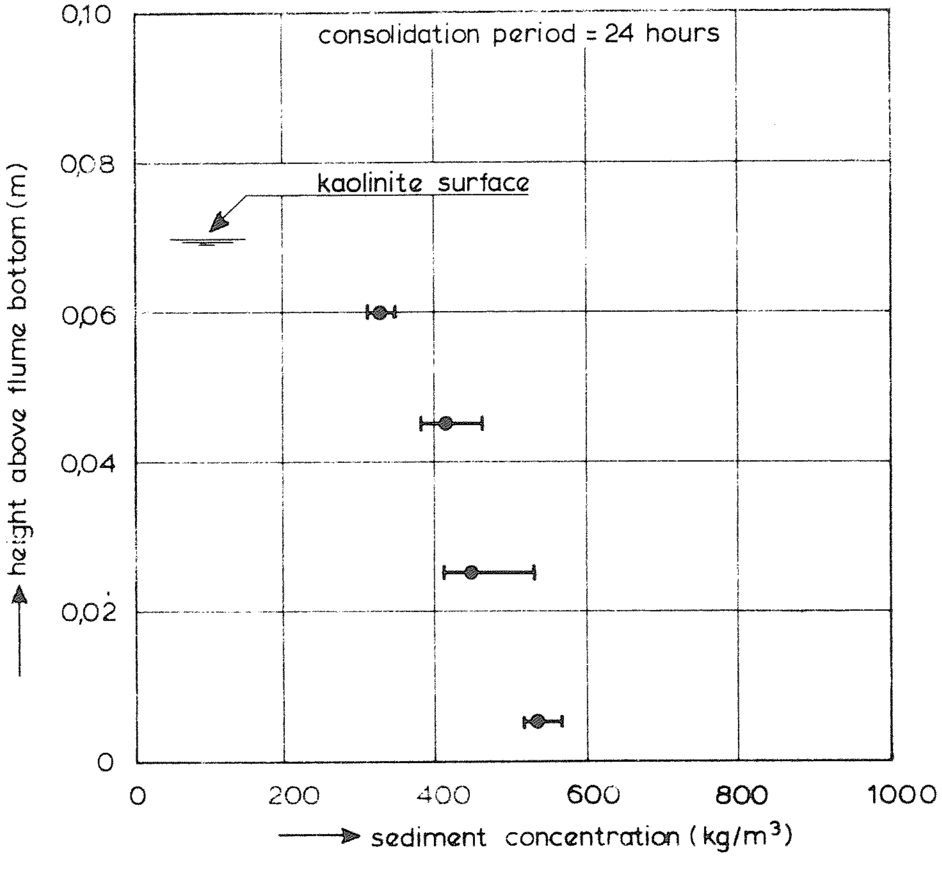
WAVE PERIOD = 1.50 S
SALINITY = 32.00 0/00
TEMPERATURE = 11.00 C

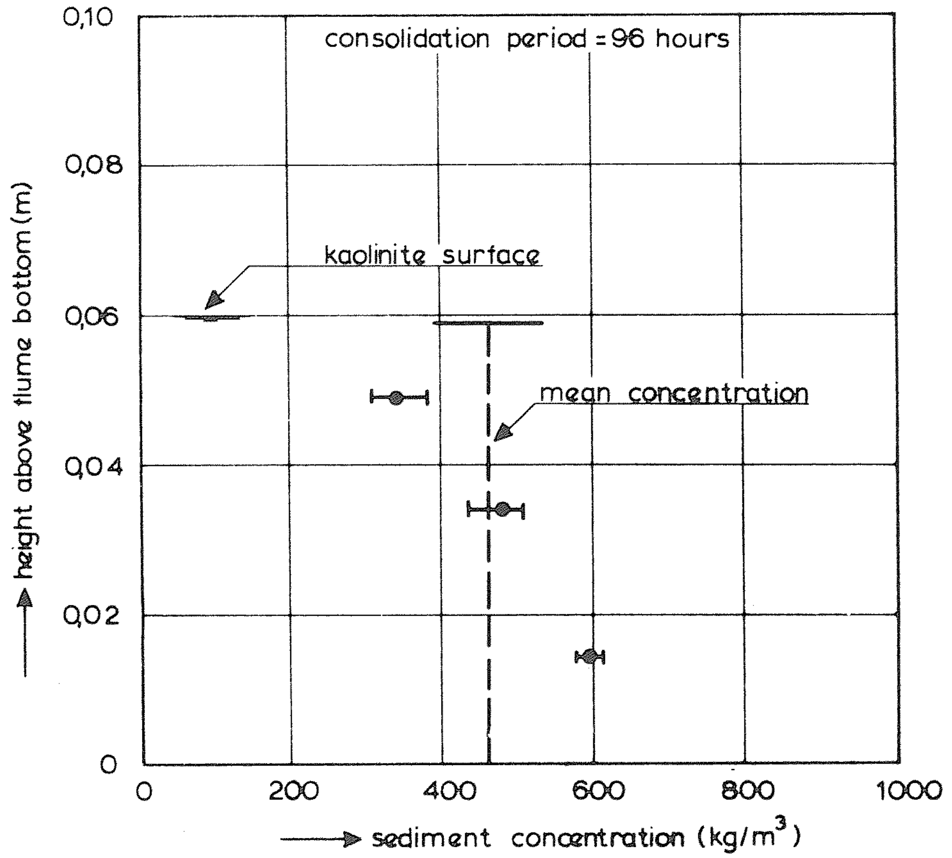
| | | |
|---|---|---|
| CONCENTRATION PROFILES (OPCON) | | T1-5 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 18 |



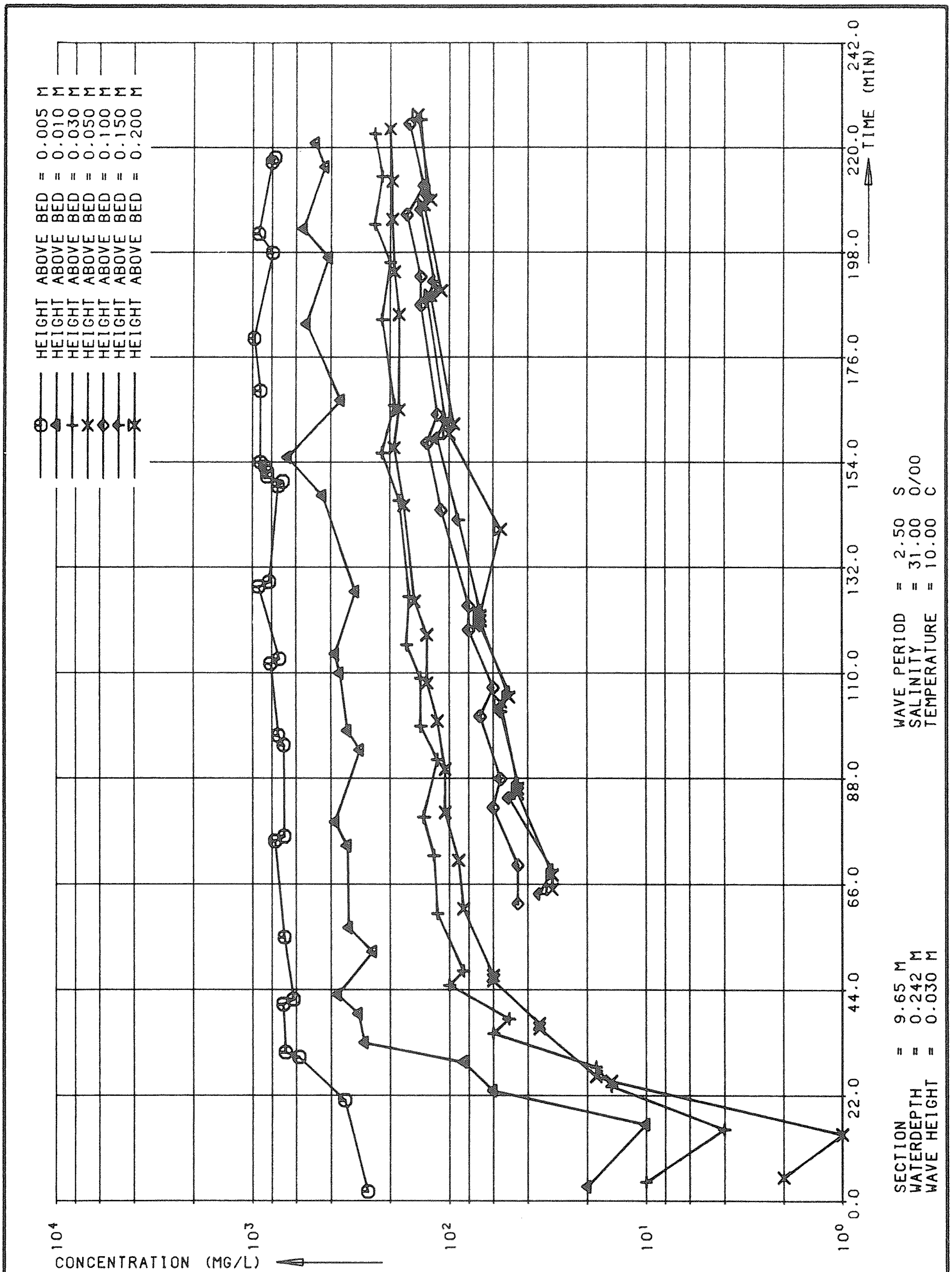




| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON)<br>VELOCITY PROFILES (ACOUS ) | | T1-5 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 19 |

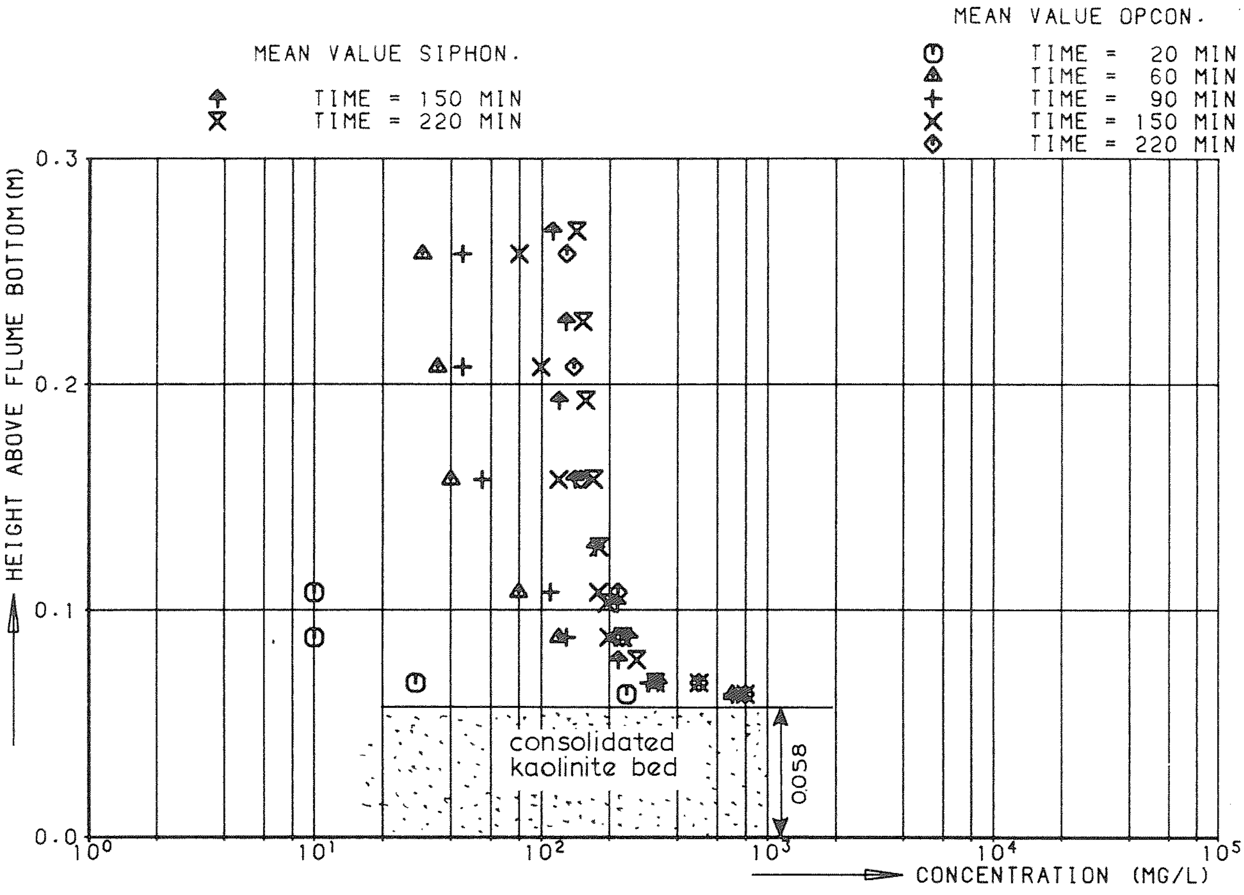


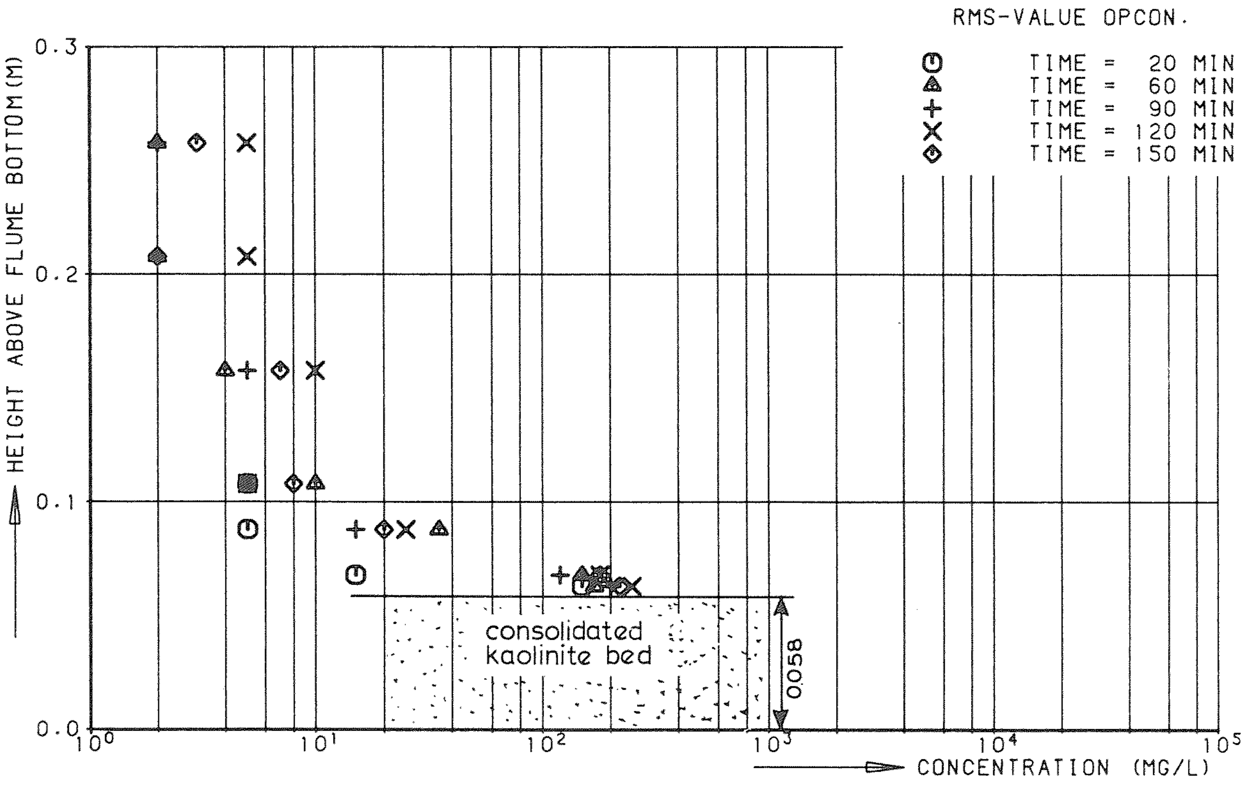




| | | |
|---|---|---|
| SEDIMENT CONCENTRATIONS IN BED LAYER | | T 2 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 20 |




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T 2-2 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 21 |




| | | |
|---|---|---|
| SECTION | = | 9.65 M |
| WATERDEPTH | = | 0.242 M |
| WAVE HEIGHT | = | 0.03 M |

| | | |
|---|---|---|
| WAVE PERIOD | = | 2.50 S |
| SALINITY | = | 31.00 0/00 |
| TEMPERATURE | = | 10.00 C |

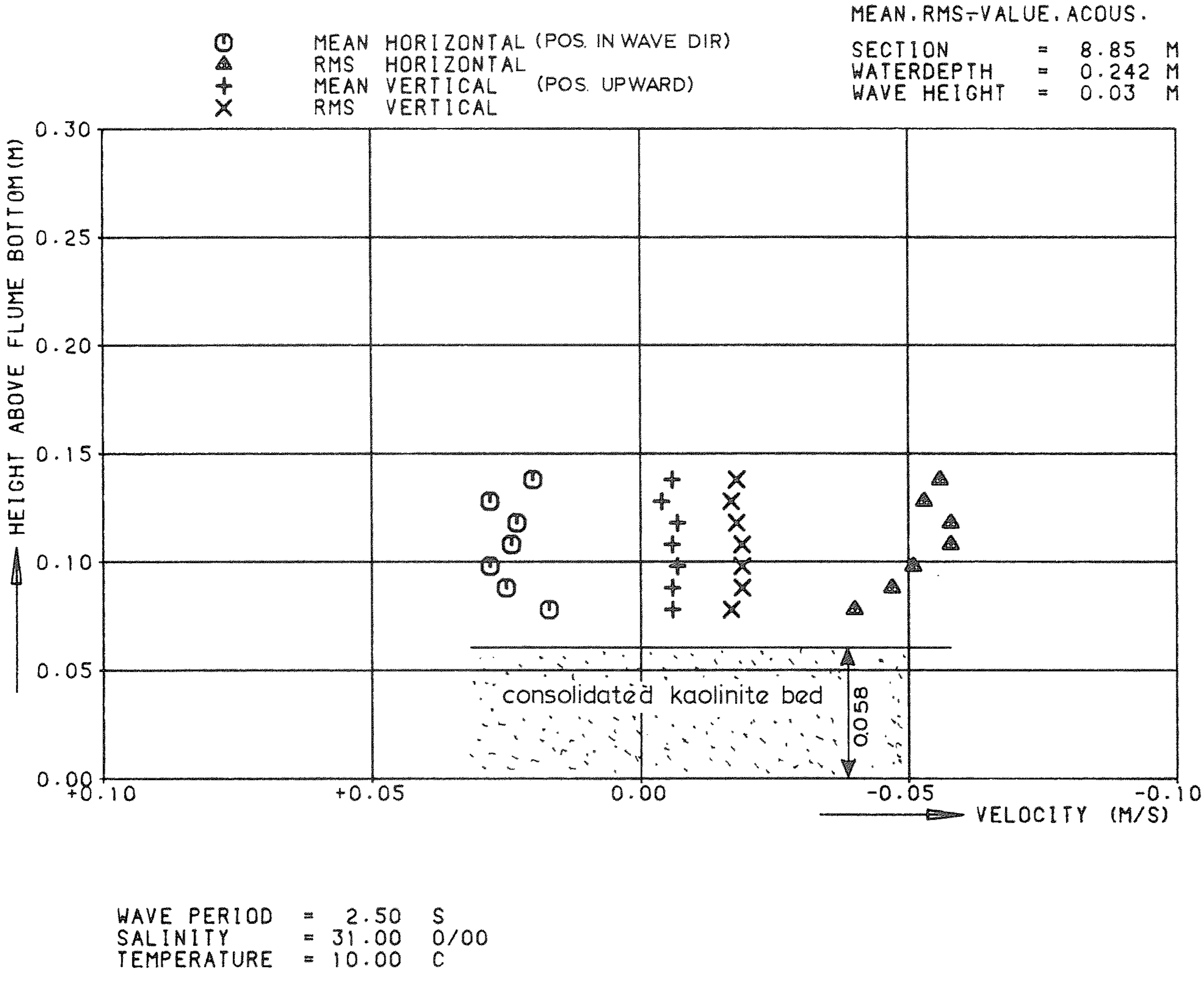
CONCENTRATION PROFILES (OPCON)
CONCENTRATION PROFILES (SIPHON)

T 2-2

DELFT HYDRAULICS LABORATORY

M 2060

FIG. 22



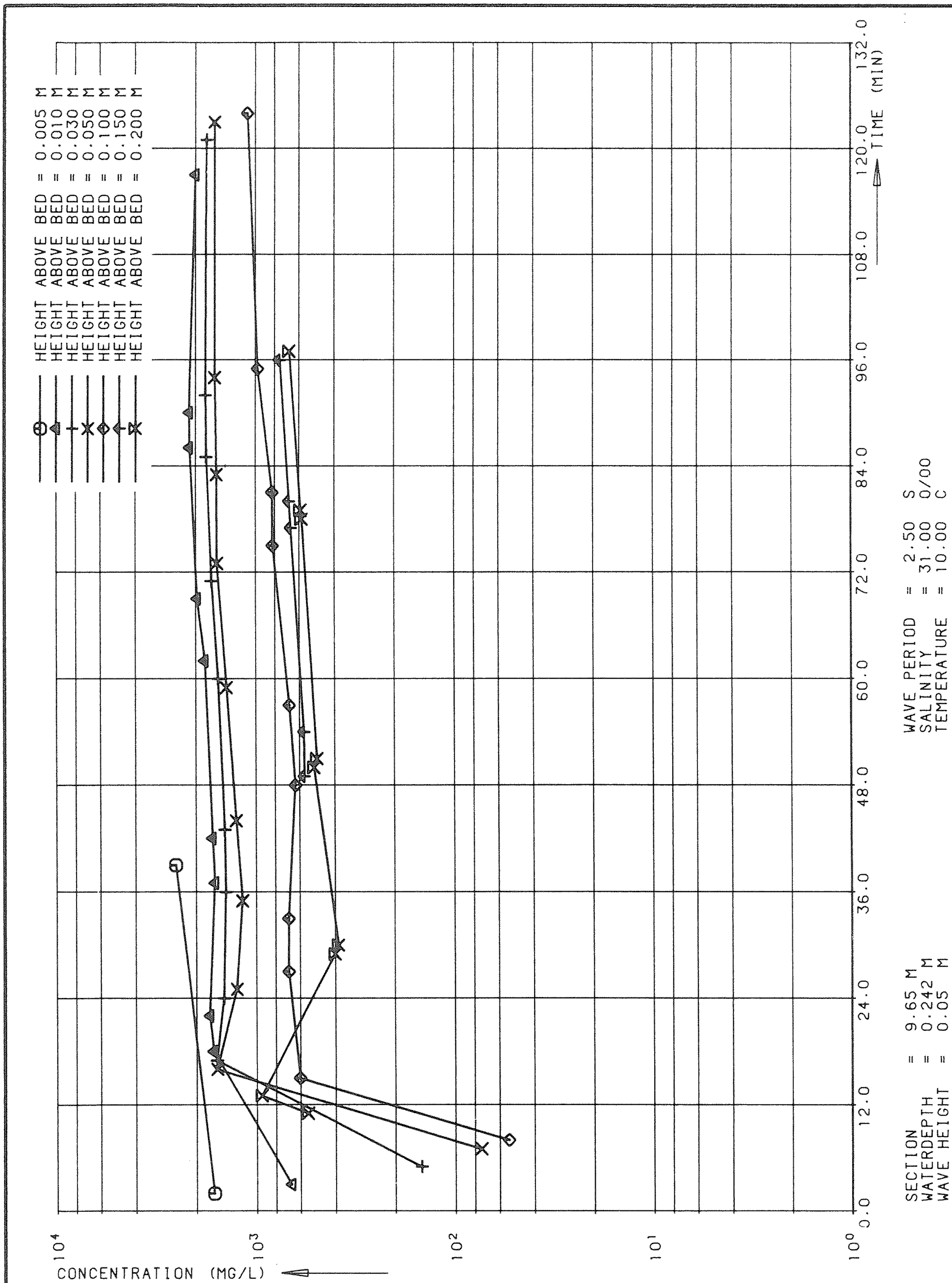

VELOCITY PROFILES (ACOUS)

T 2-2

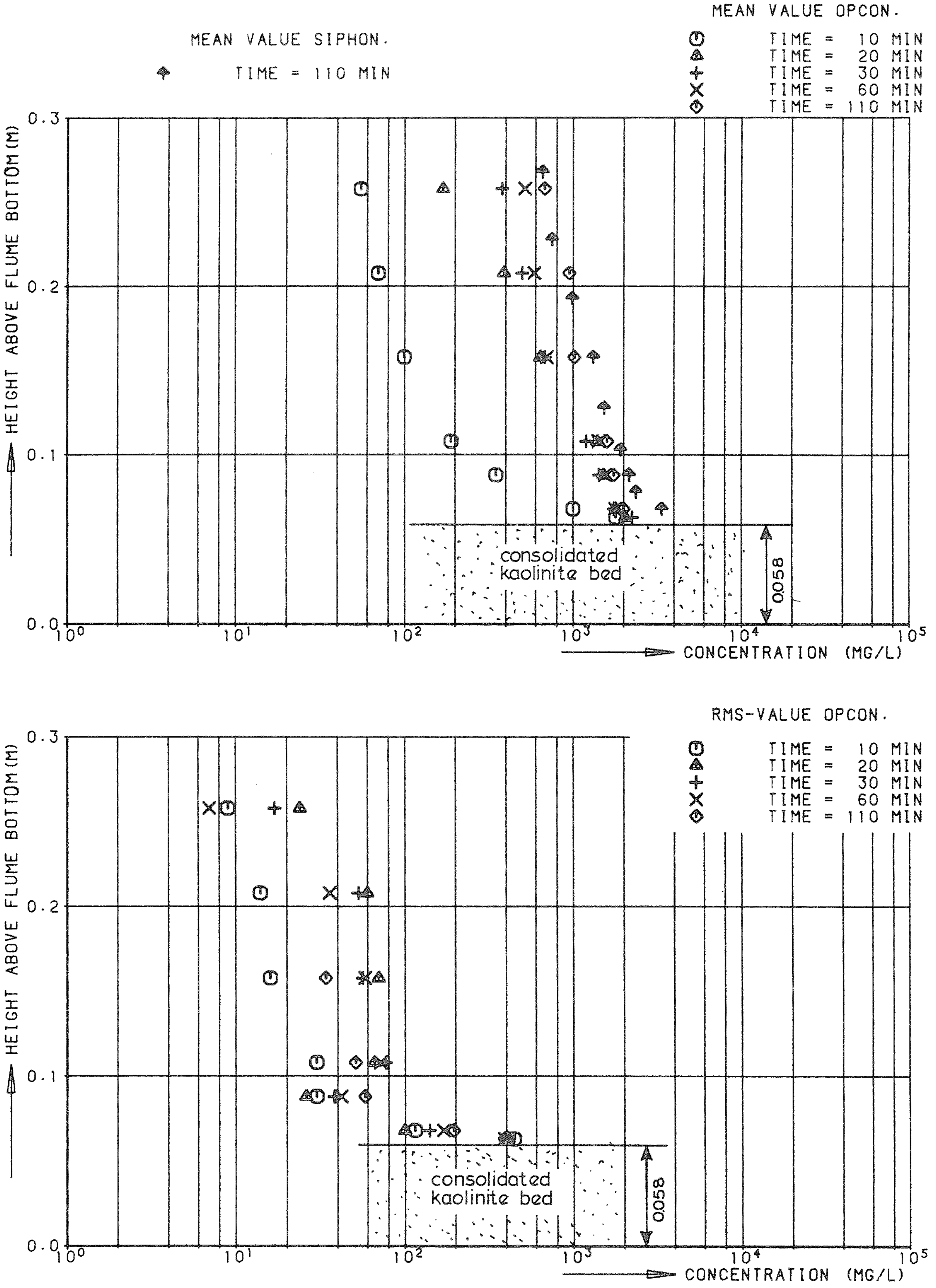
DELFT HYDRAULICS LABORATORY

M 2060

FIG. 23




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T 2-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 24 |



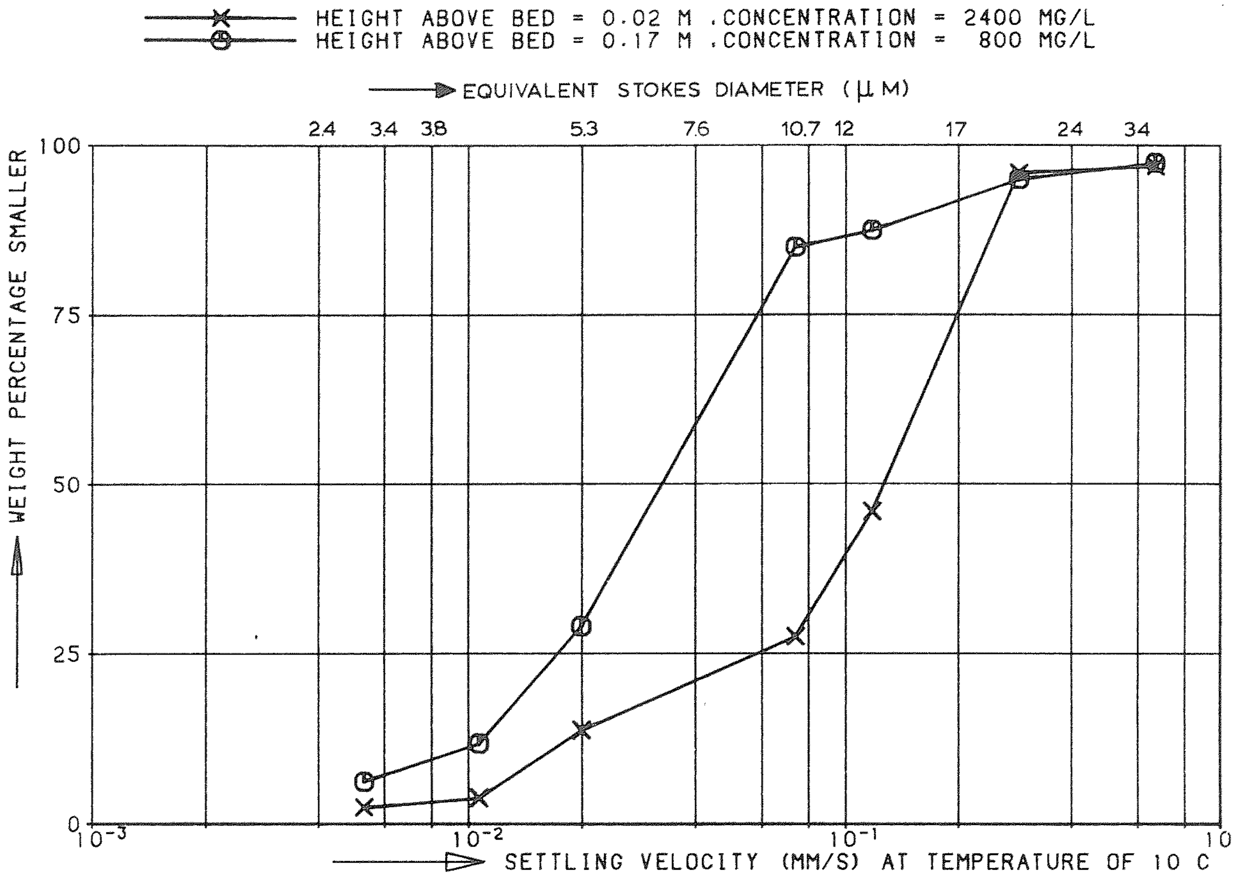

SECTION = 9.60 M
WATERDEPTH = 0.242 M
WAVE HEIGHT = 0.05 M

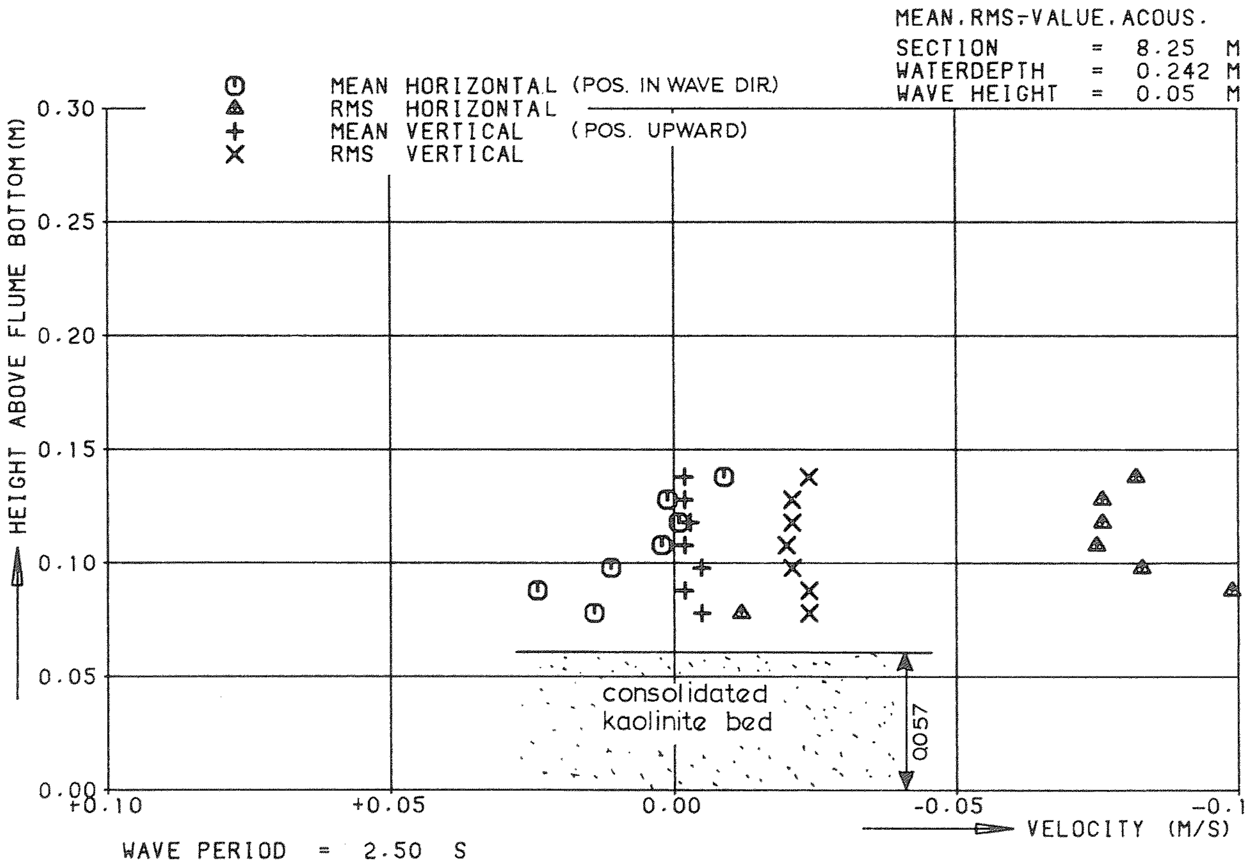
WAVE PERIOD = 2.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

CONCENTRATION PROFILES (OPCON)
CONCENTRATION PROFILES (SIPHON)

T2-3

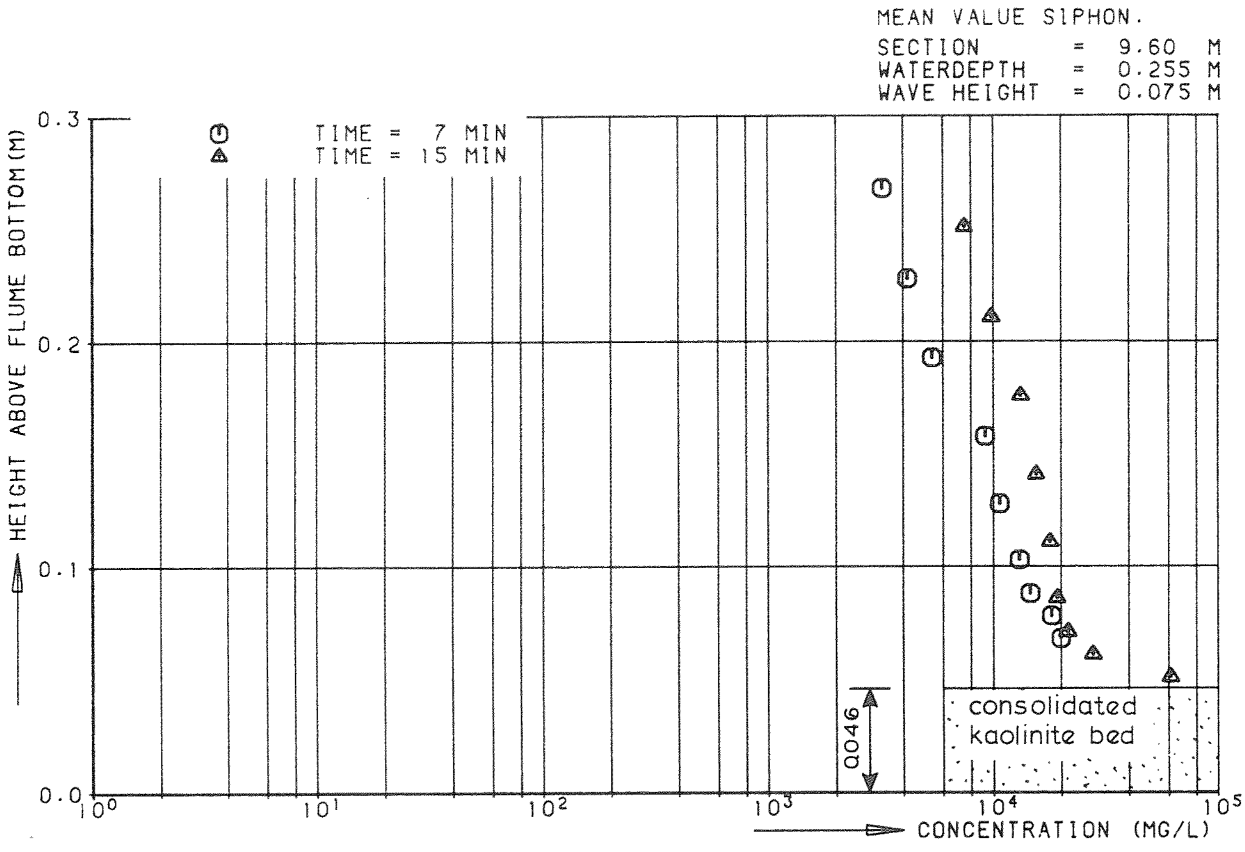
DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 25

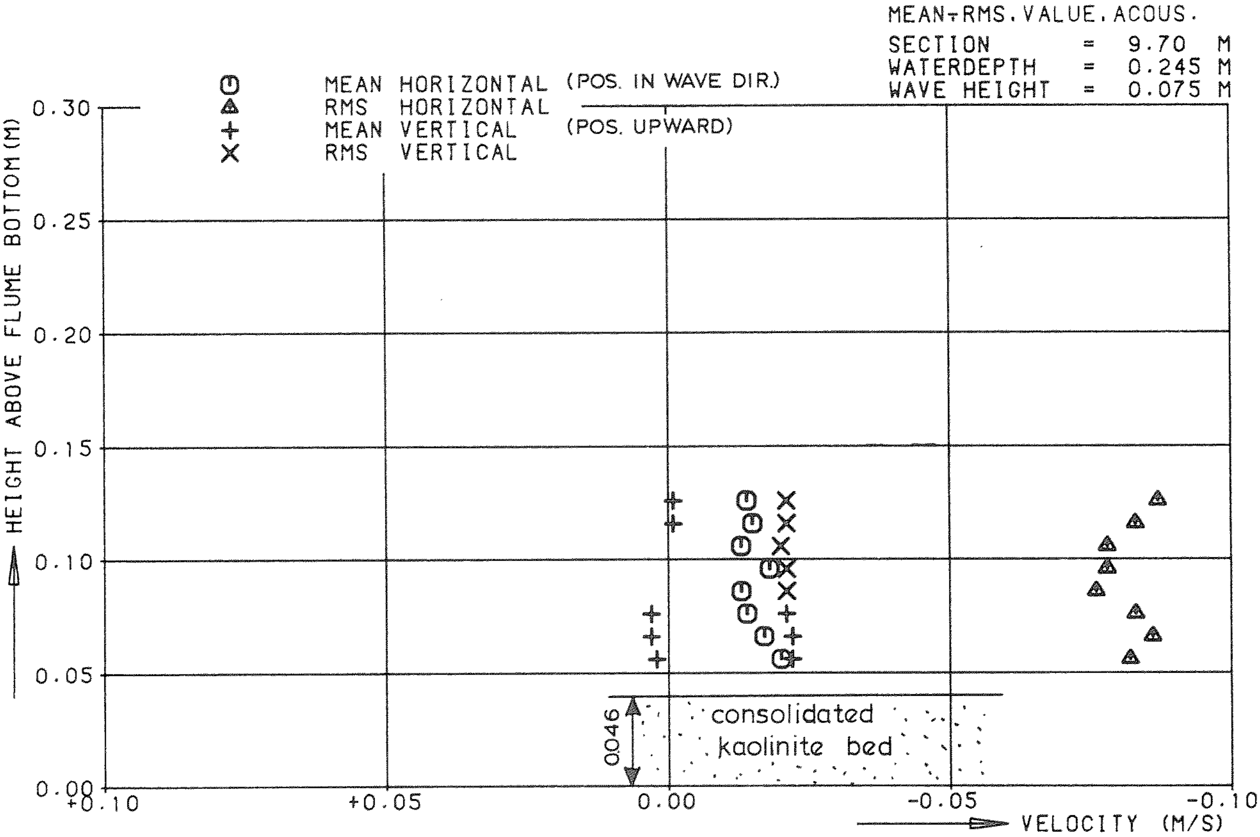



WAVE PERIOD = 2.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

| | | |
|---|---|---|
| SETTLING VELOCITY CURVE<br>VELOCITY PROFILES (ACOUS) | | T2-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 26 |




WAVE PERIOD = 2.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

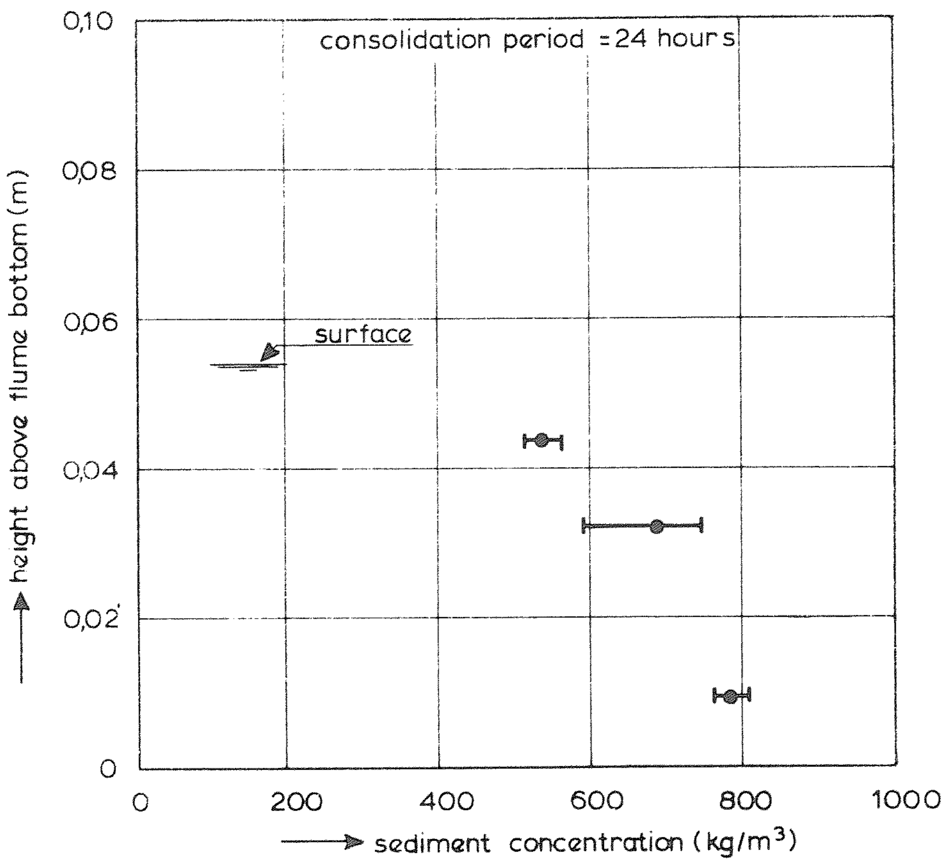
CONCENTRATION PROFILES (SIPHON)
VELOCITY PROFILES (ACOUS)

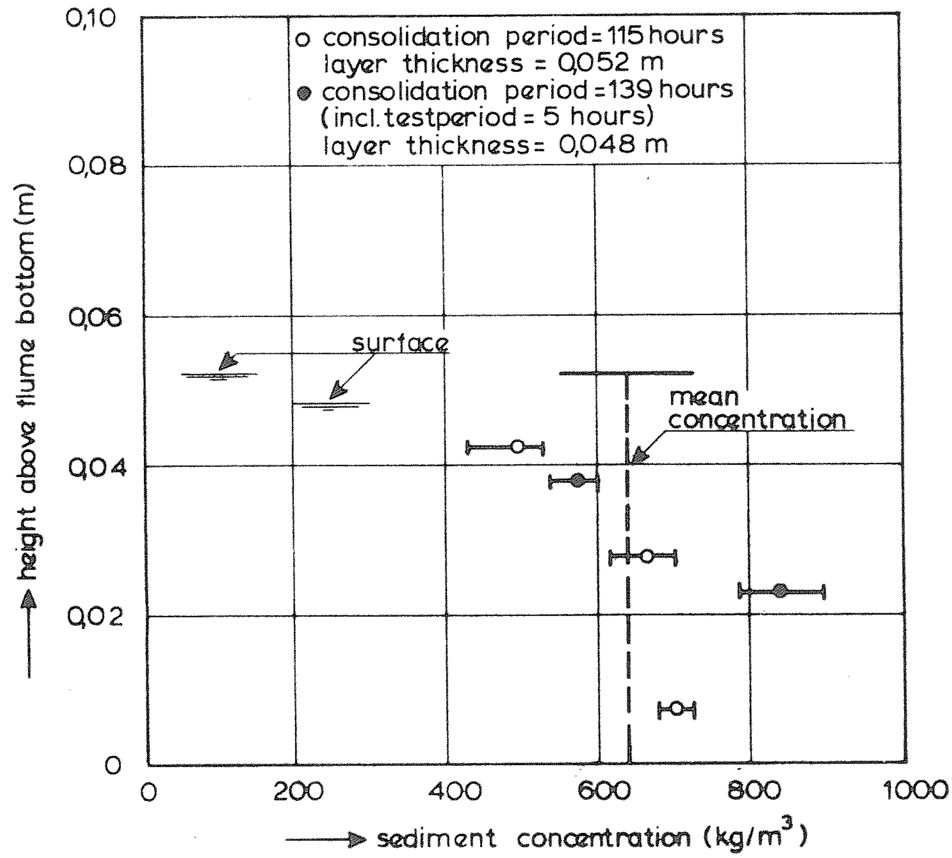
T2-4

DELFT HYDRAULICS LABORATORY

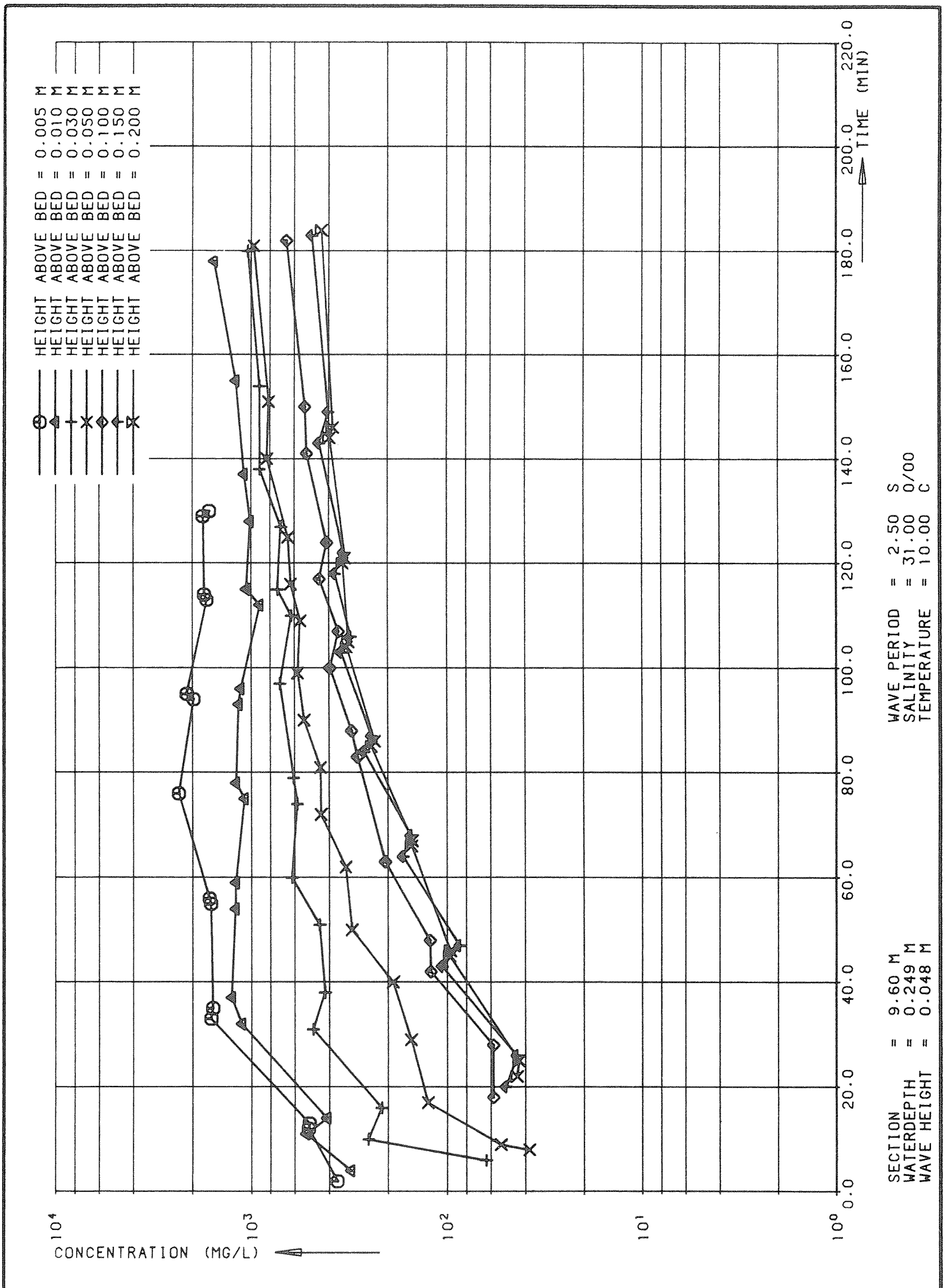
M 2060

FIG. 27




| SEDIMENT CONCENTRATIONS IN BED LAYER | | T 3 |
|---|---|---|
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 28 |



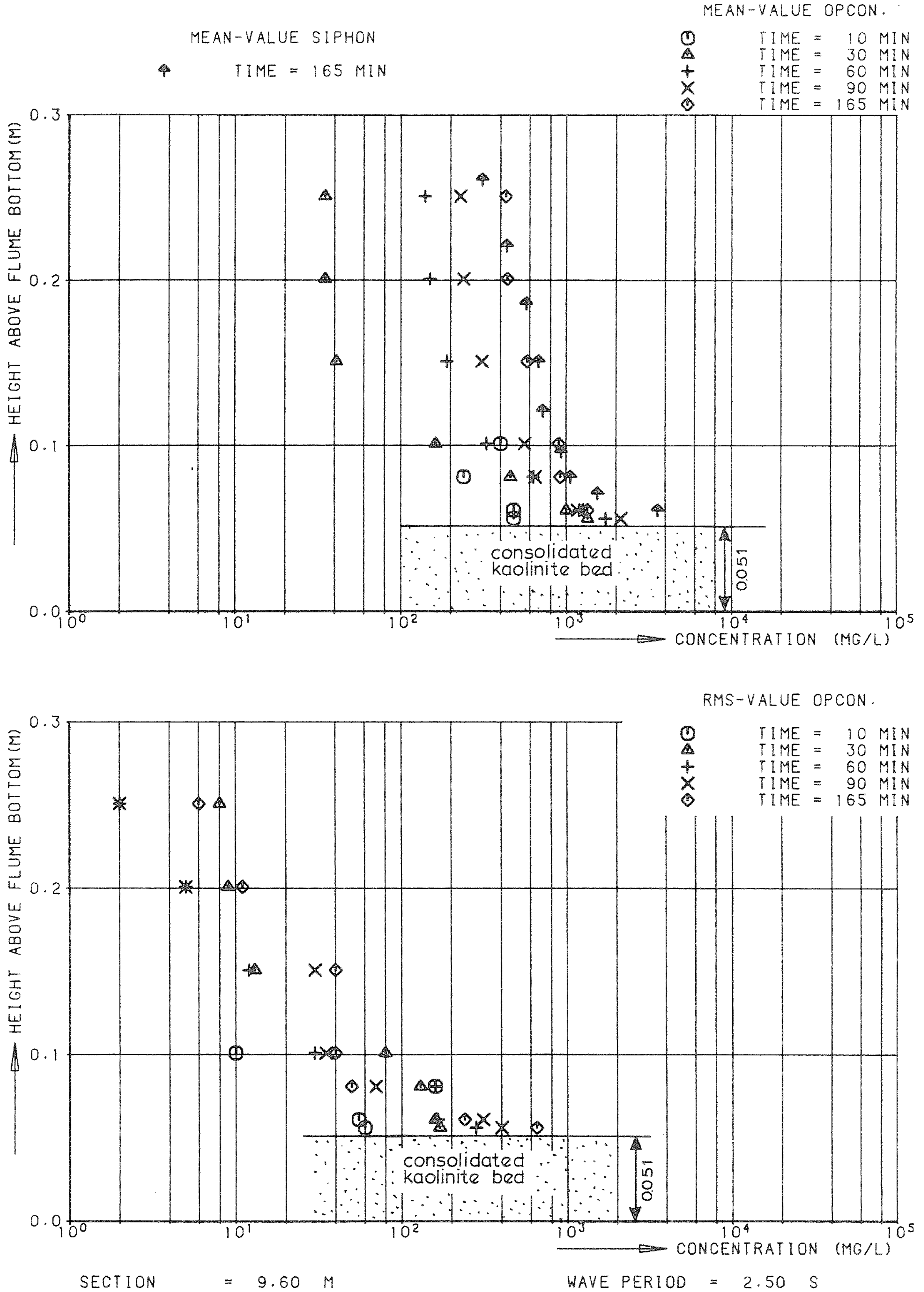

TIME-CONCENTRATION CURVES (OPCON)

T 3-3

DELFT HYDRAULICS LABORATORY

M 2060

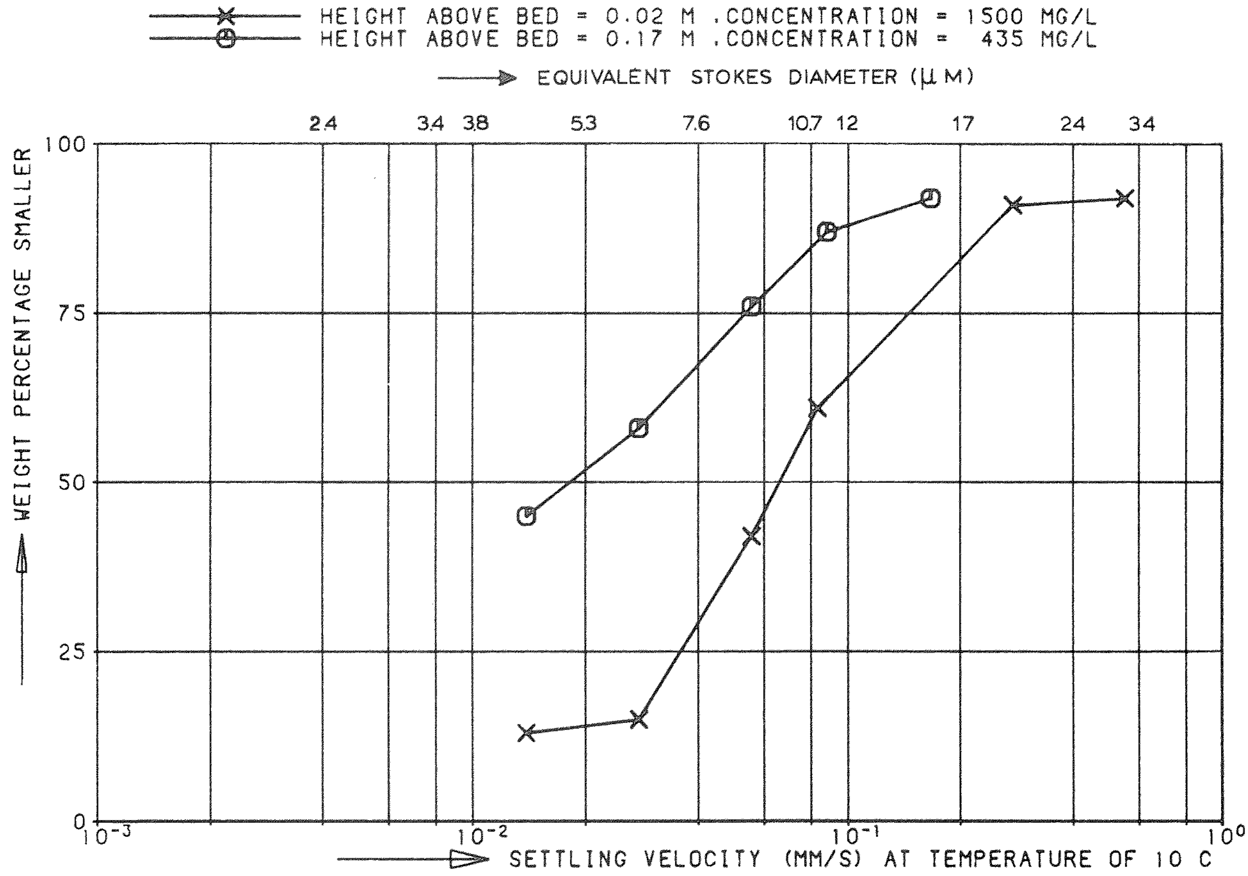
FIG. 29

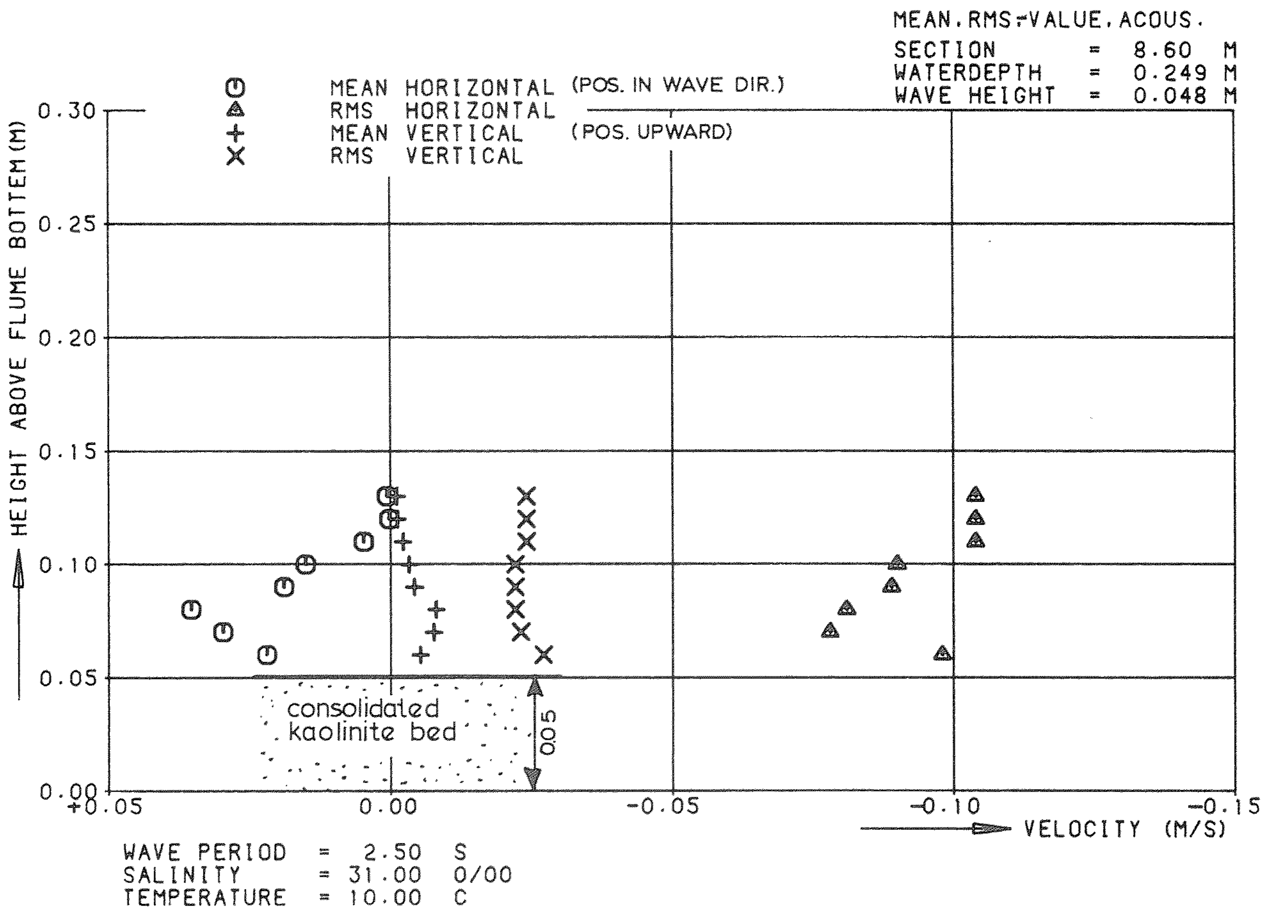



SECTION = 9.60 M
WATERDEPTH = 0.249 M
WAVE HEIGHT = 0.048 M

WAVE PERIOD = 2.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

| | |
|---|---|
| CONCENTRATION PROFILES (OPCON)<br>CONCENTRATION PROFILES (SIPHON) | T 3-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 — FIG. 30 |



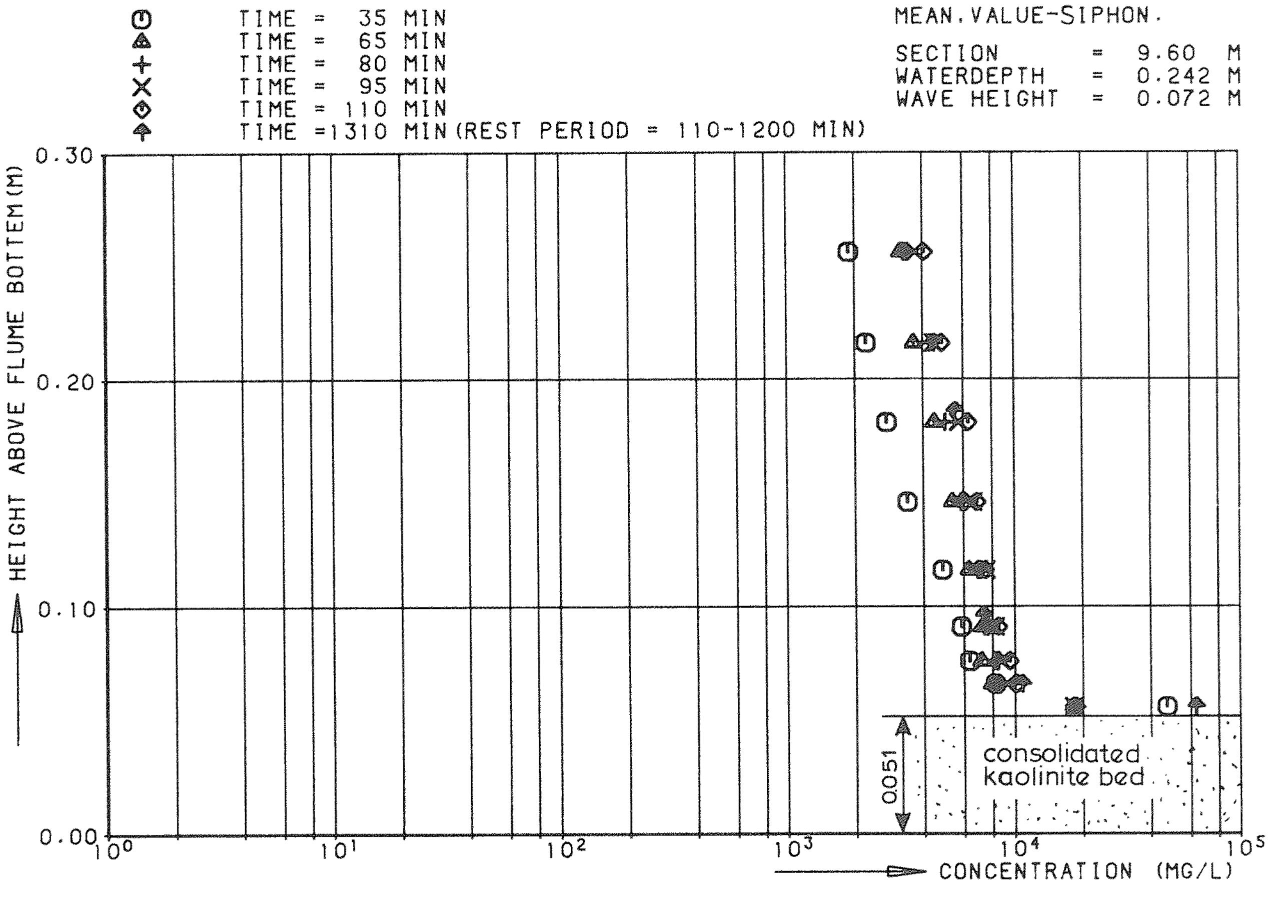

SETTLING VELOCITY CURVE
VELOCITY PROFILES(ACOUS)

T 3-3

DELFT HYDRAULICS LABORATORY

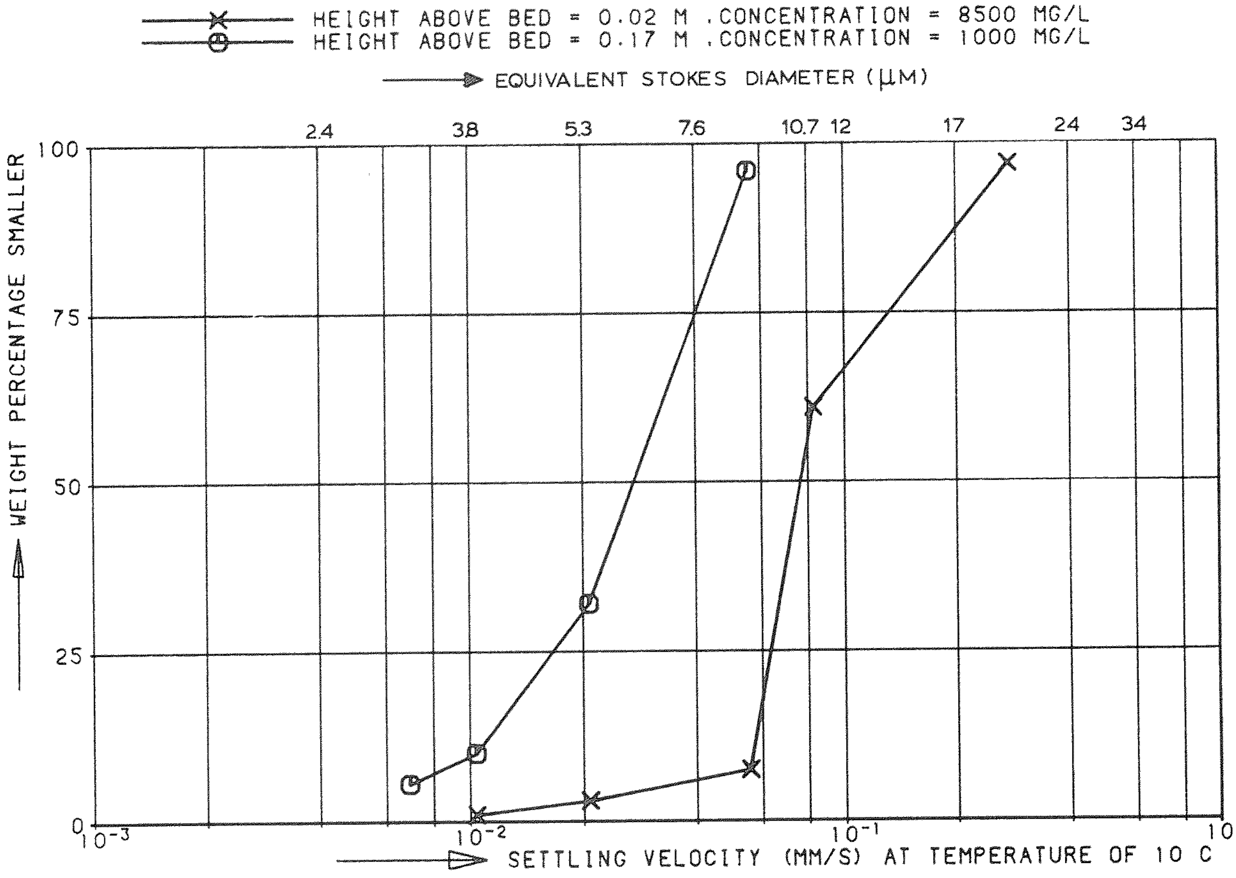
M 2060

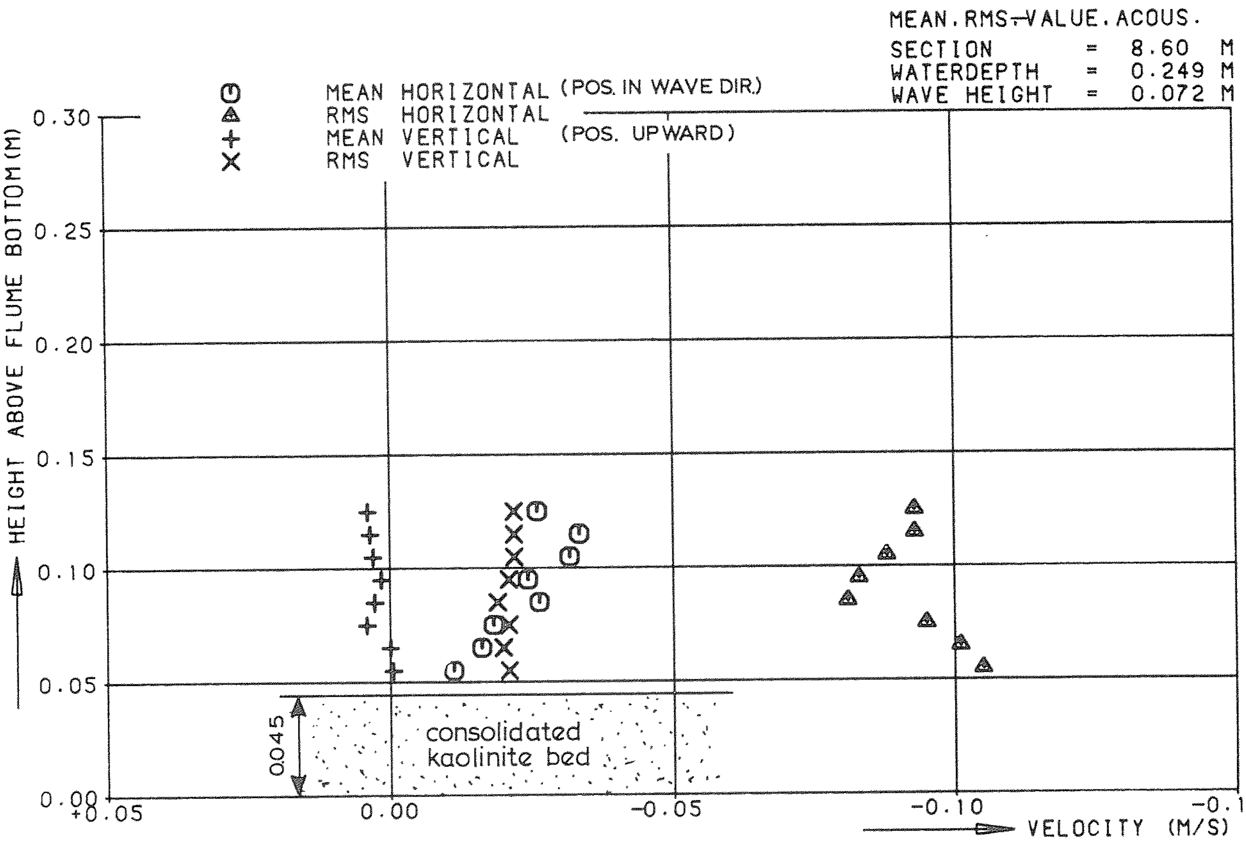
FIG. 31




WAVE PERIOD = 2.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

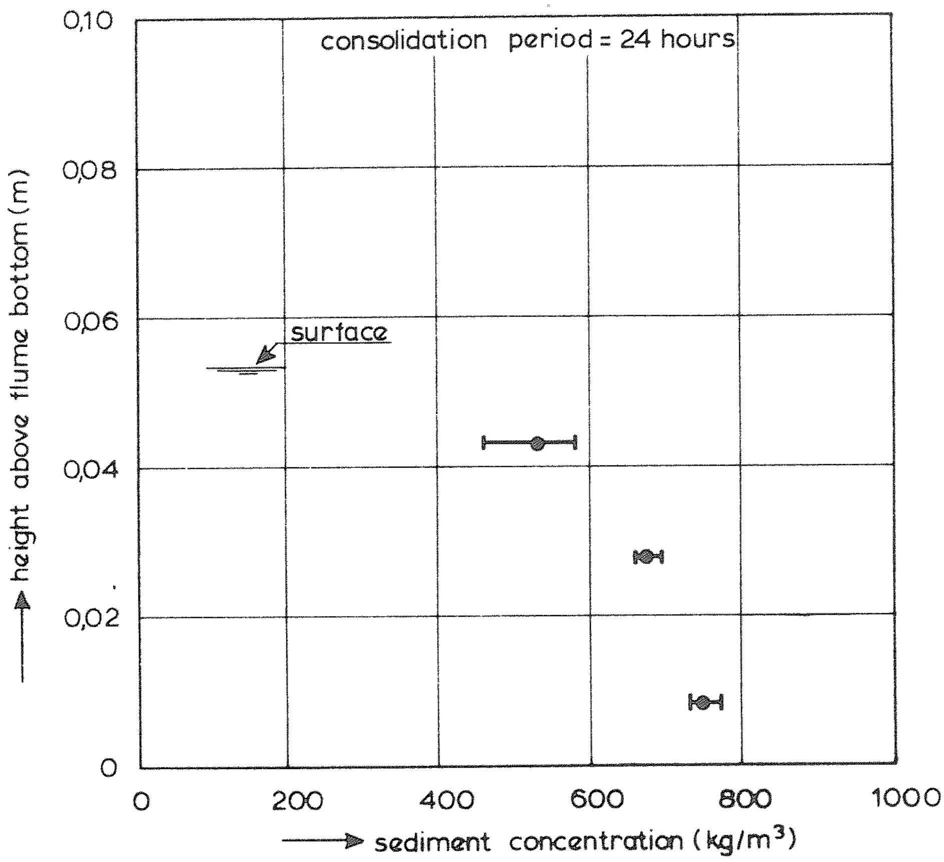
| | | |
|---|---|---|
| CONCENTRATION PROFILES(SIPHON) | | T3-4/6 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 32 |

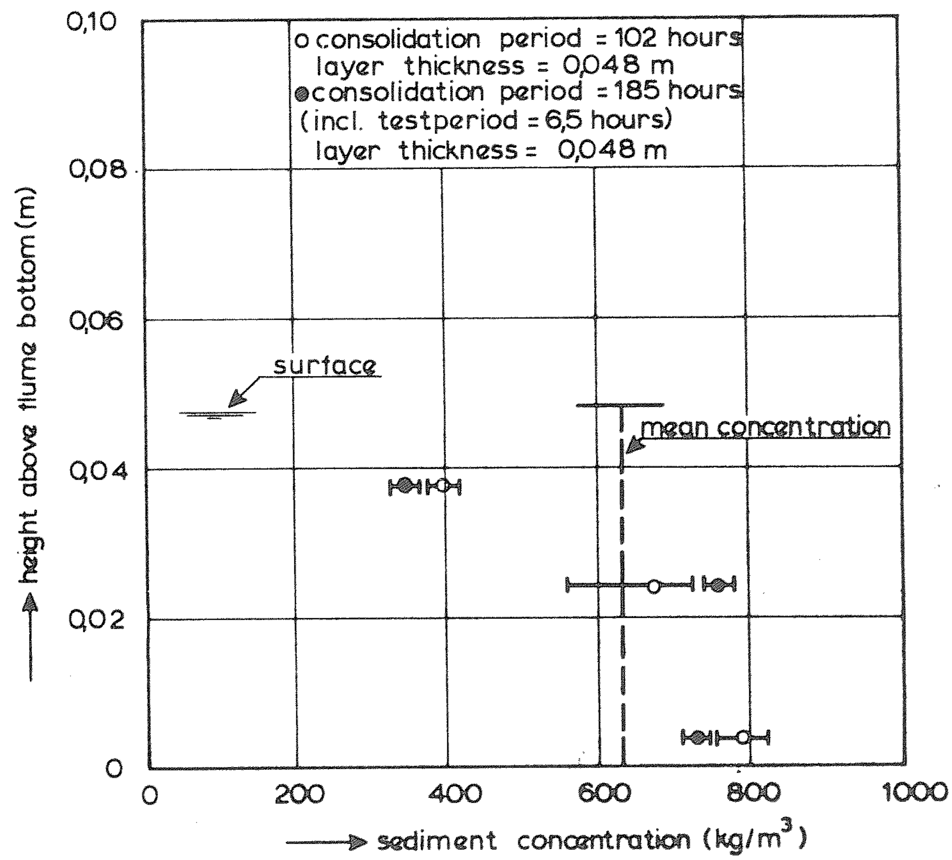


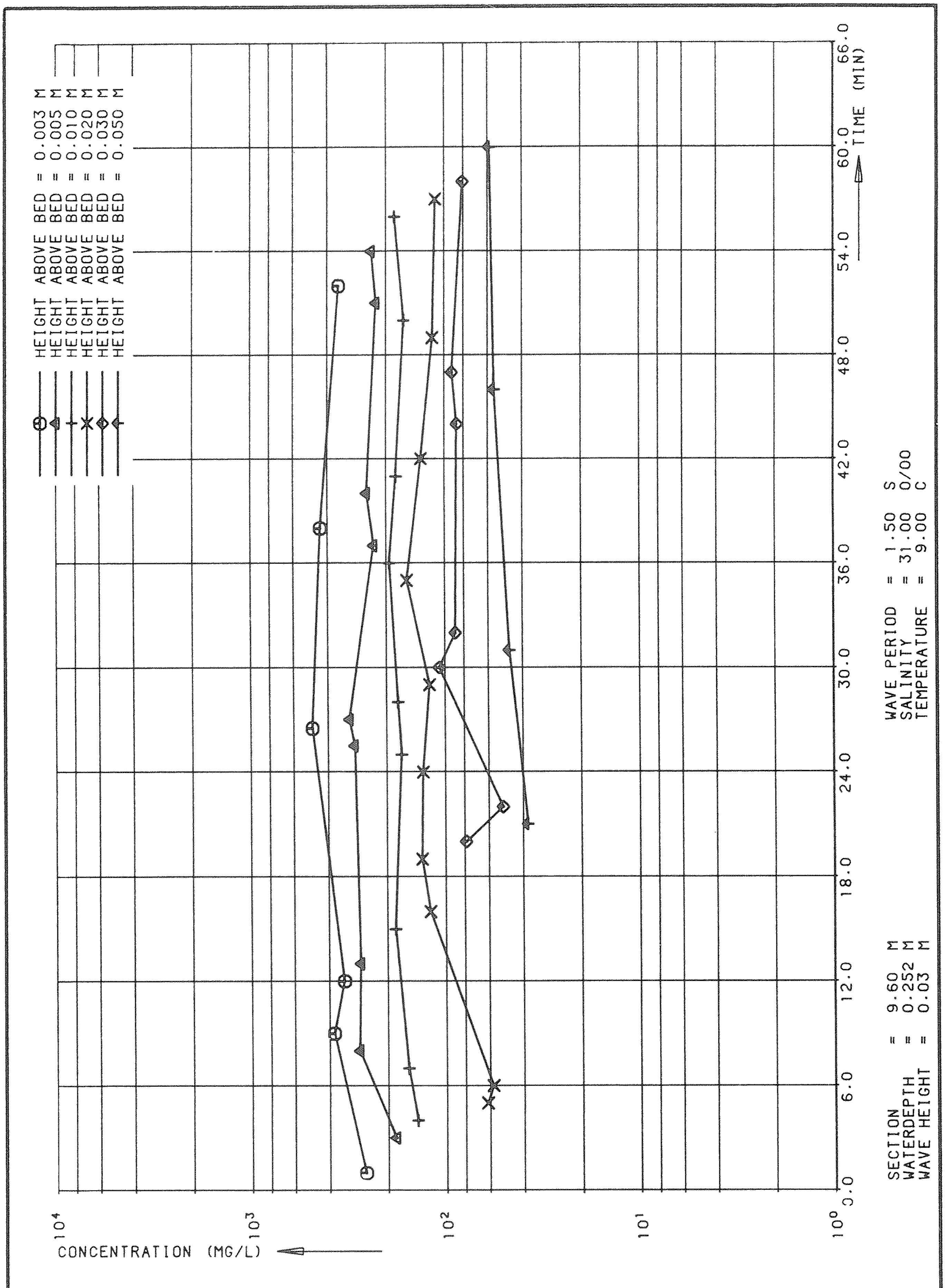

WAVE PERIOD = 2.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

| | | |
|---|---|---|
| SETTLING VELOCITY CURVE<br>VELOCITY PROFILES (ACOUS) | | T3-4/6 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 33 |

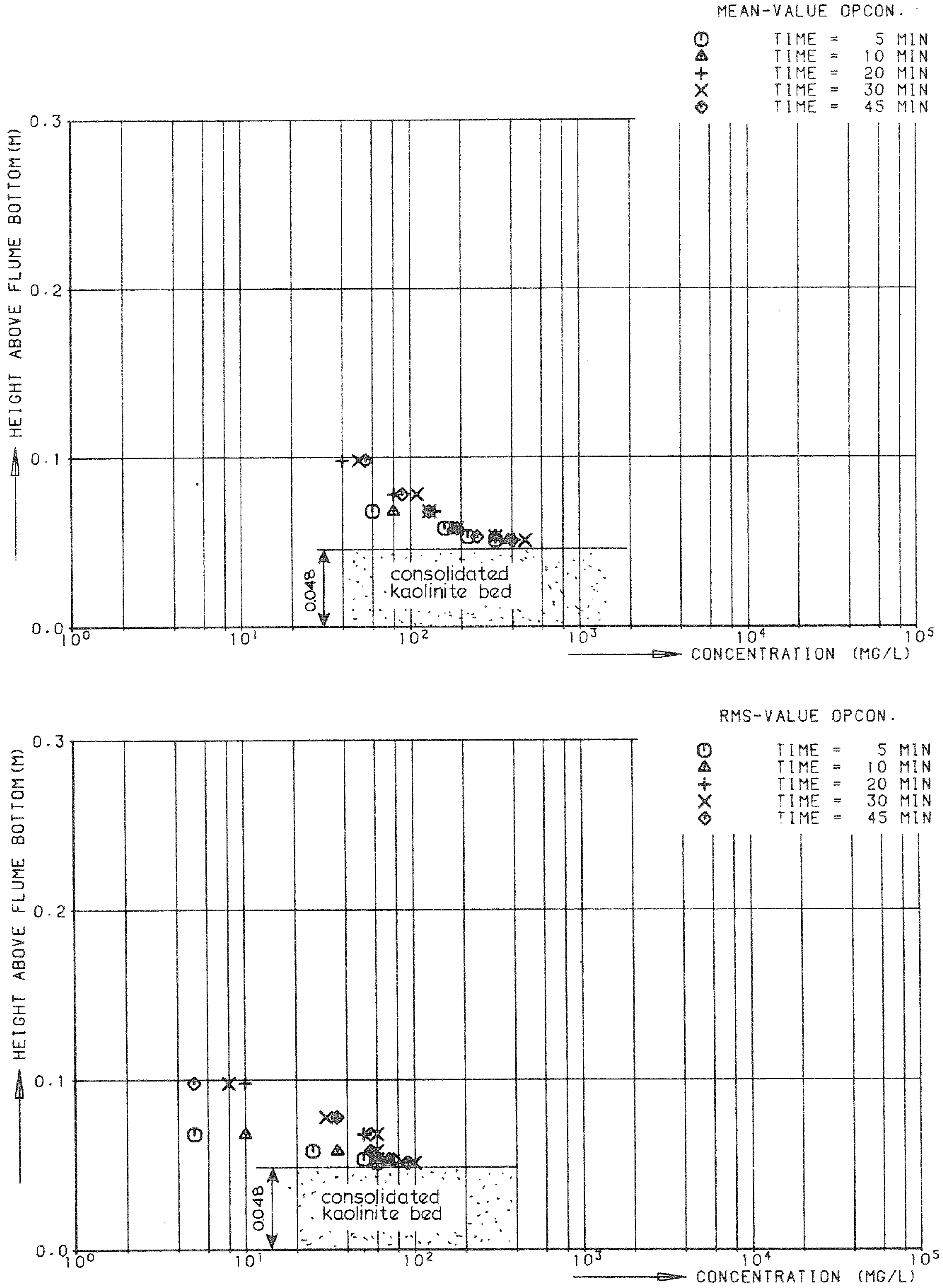



| | | |
|---|---|---|
| SEDIMENT CONCENTRATIONS IN BED LAYER | | T 4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 34 |



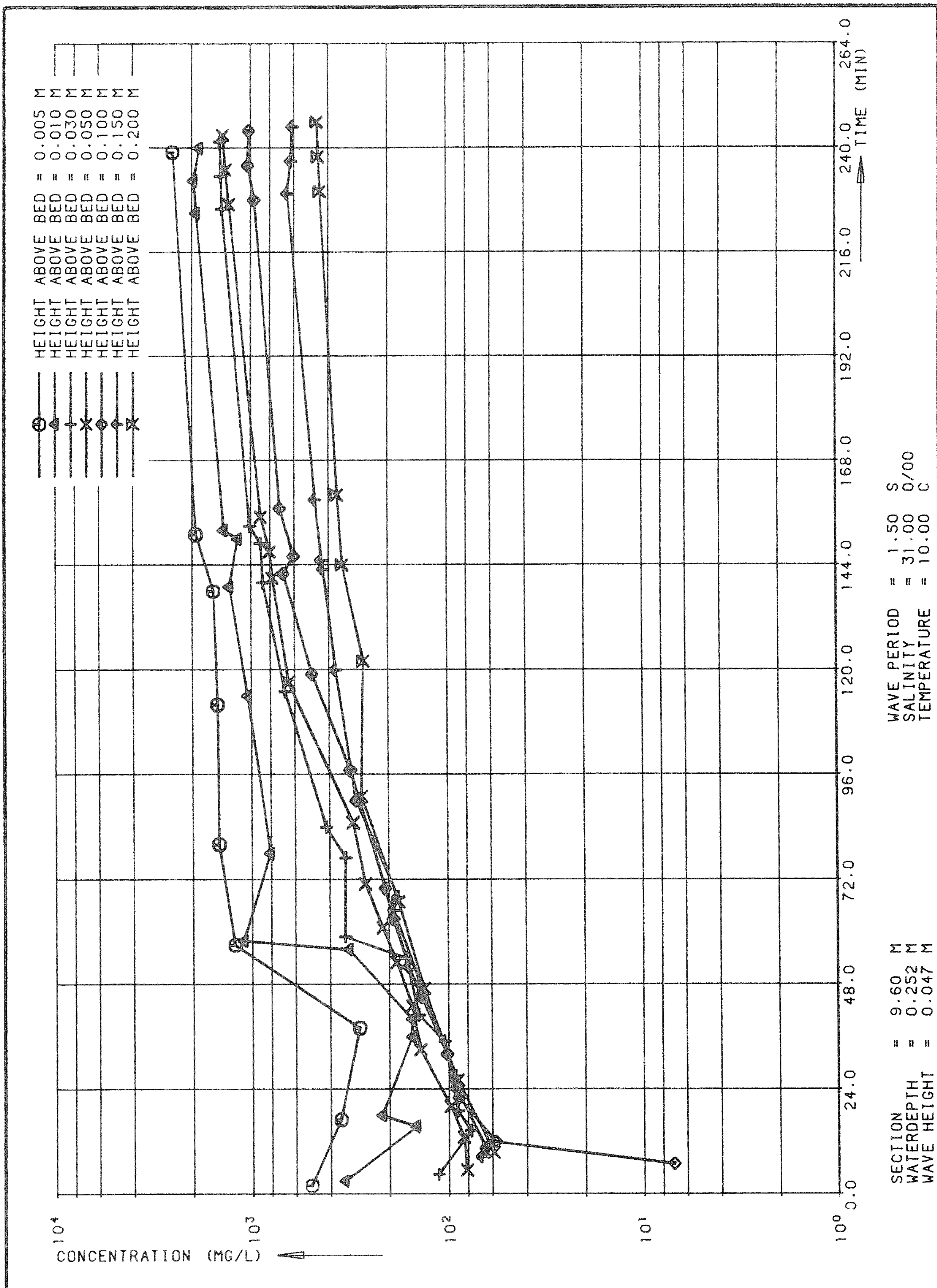

| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T 4-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG.35 |



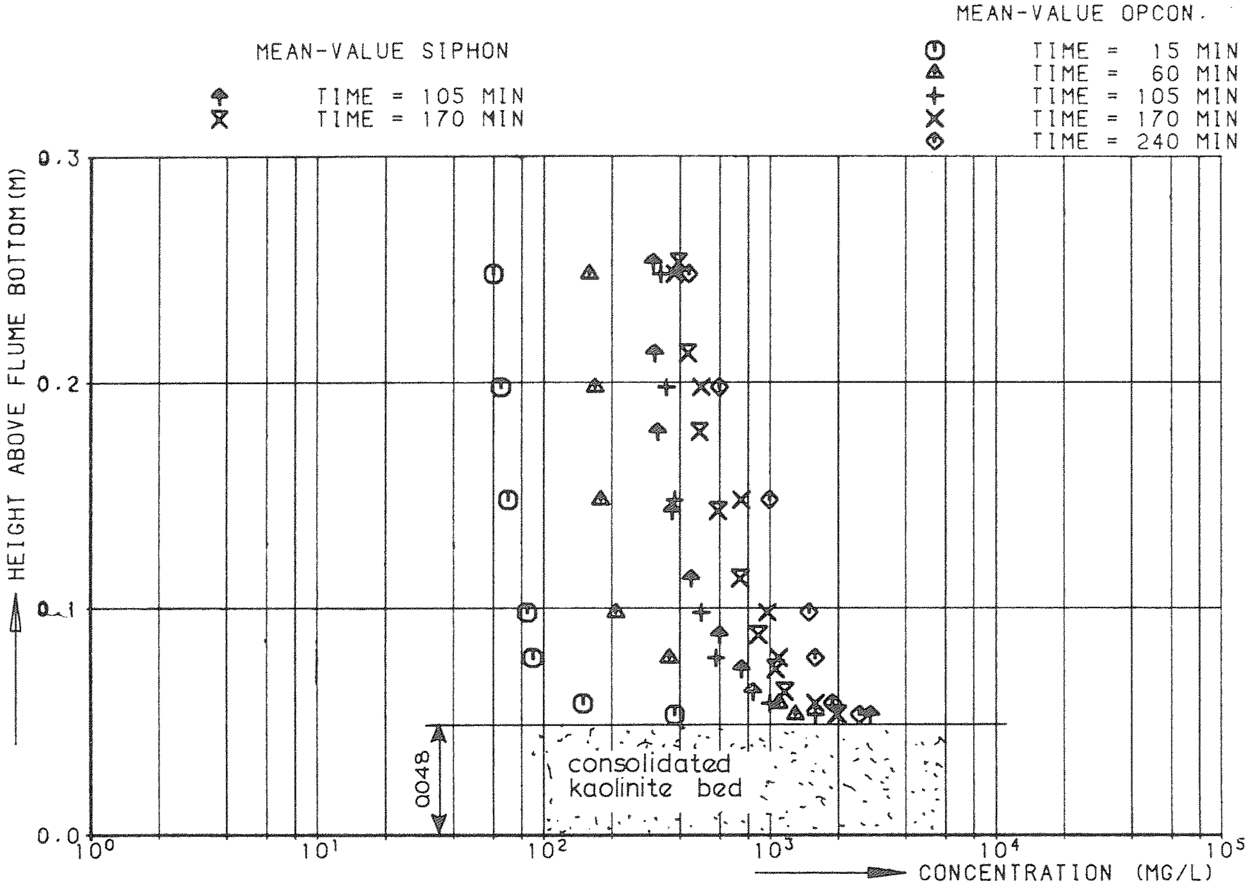

SECTION = 9.60 M
WATERDEPTH = 0.252 M
WAVE HEIGHT = 0.03 M

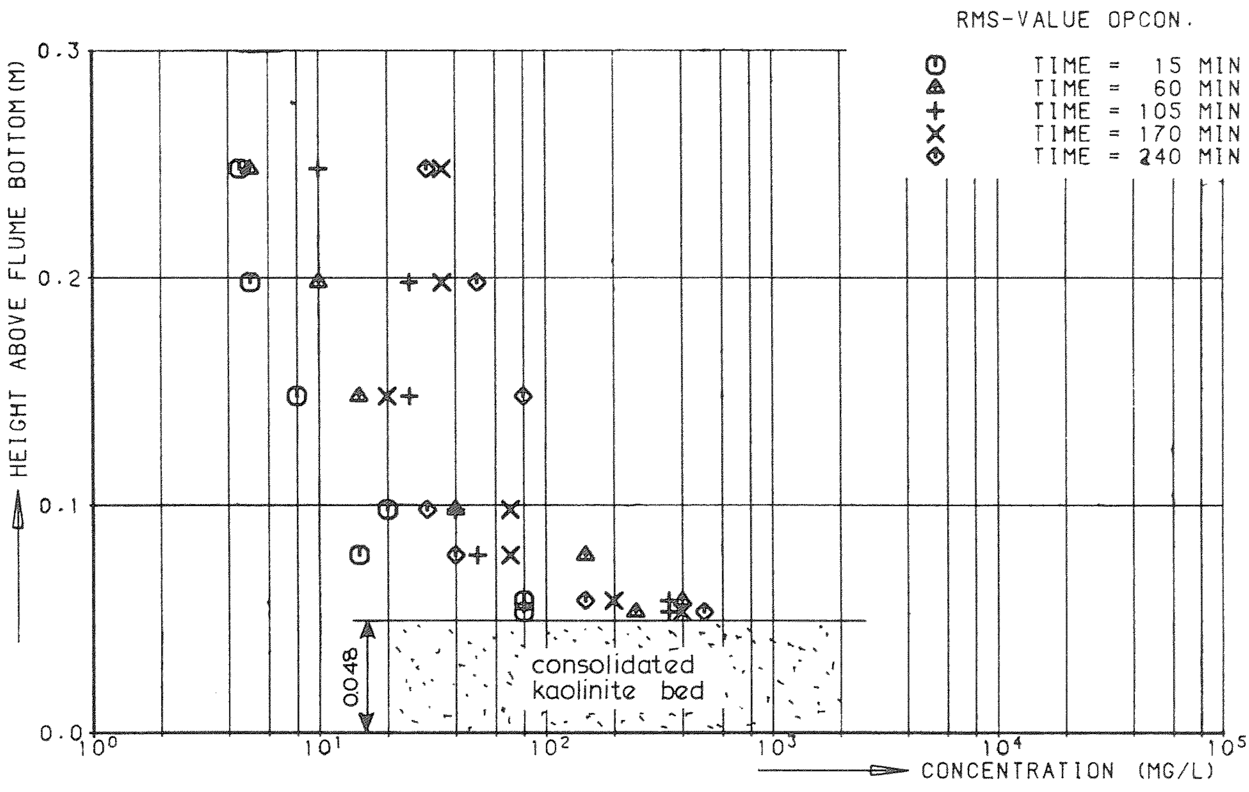
WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 9.00 C

| | | |
|---|---|---|
| CONCENTRATION PROFILES (OPCON) | T4-4 | T 4-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 36 |




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T4-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 37 |




SECTION = 9.60 M
WATERDEPTH = 0.252 M
WAVE HEIGHT = 0.047 M

WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

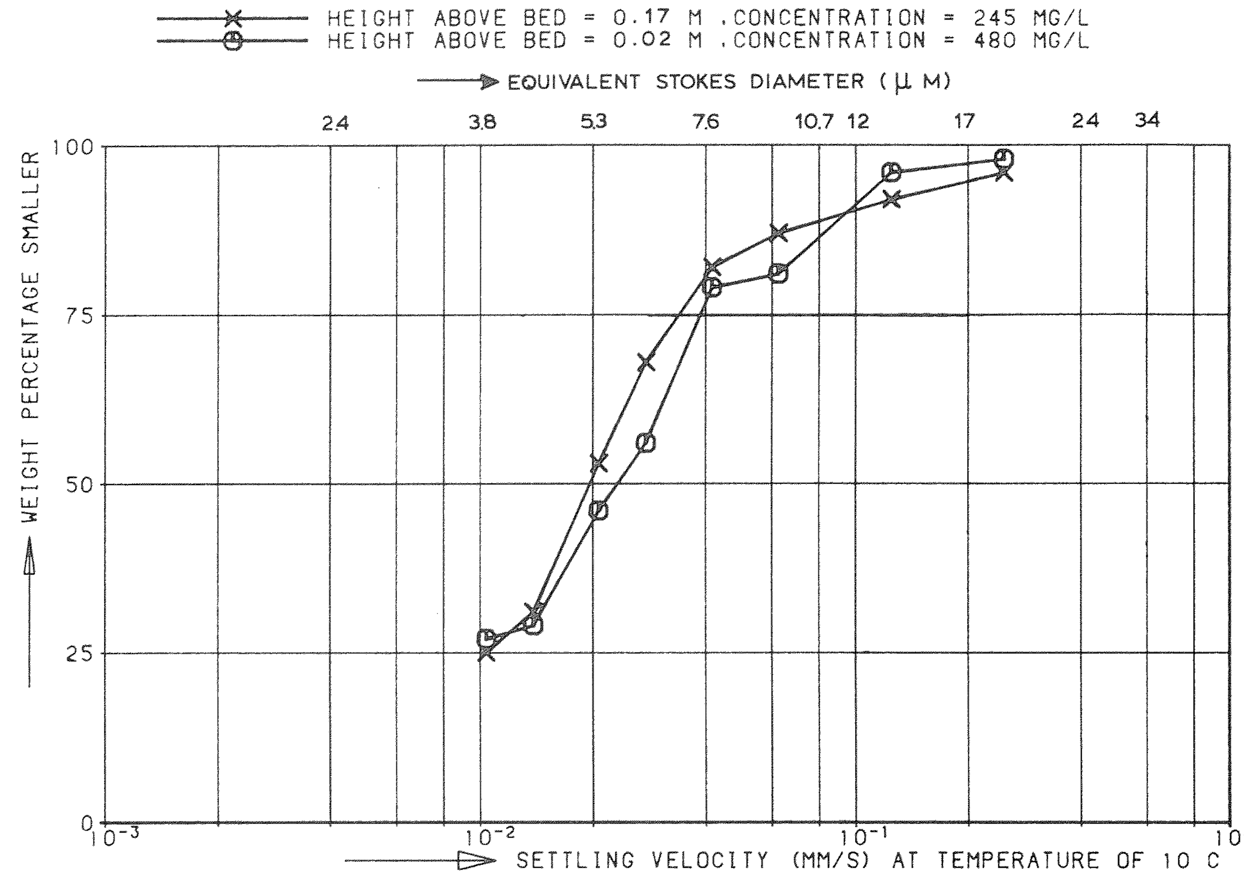
CONCENTRATION PROFILES (OPCON)
CONCENTRATION PROFILES (SIPHON)

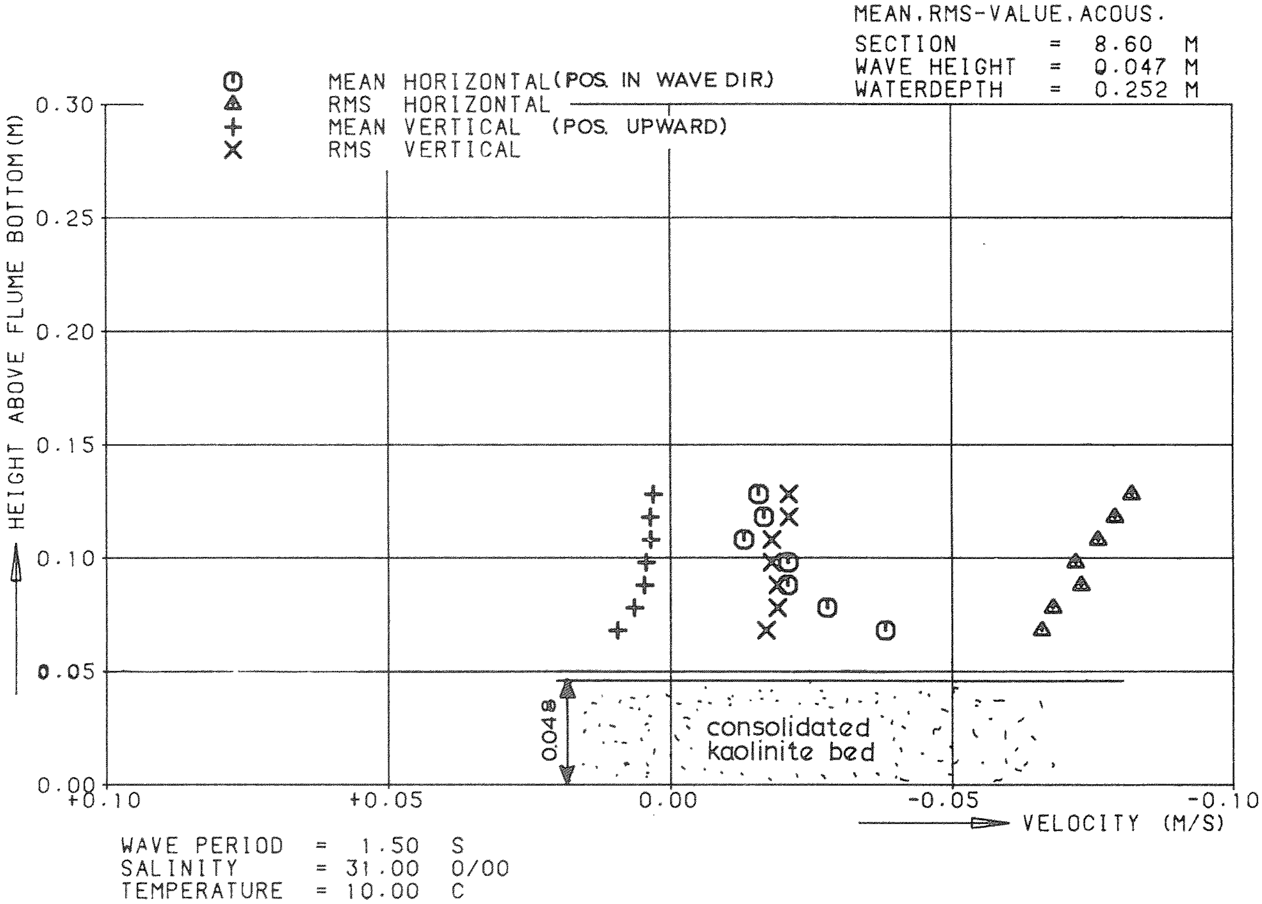
T4-4

DELFT HYDRAULICS LABORATORY

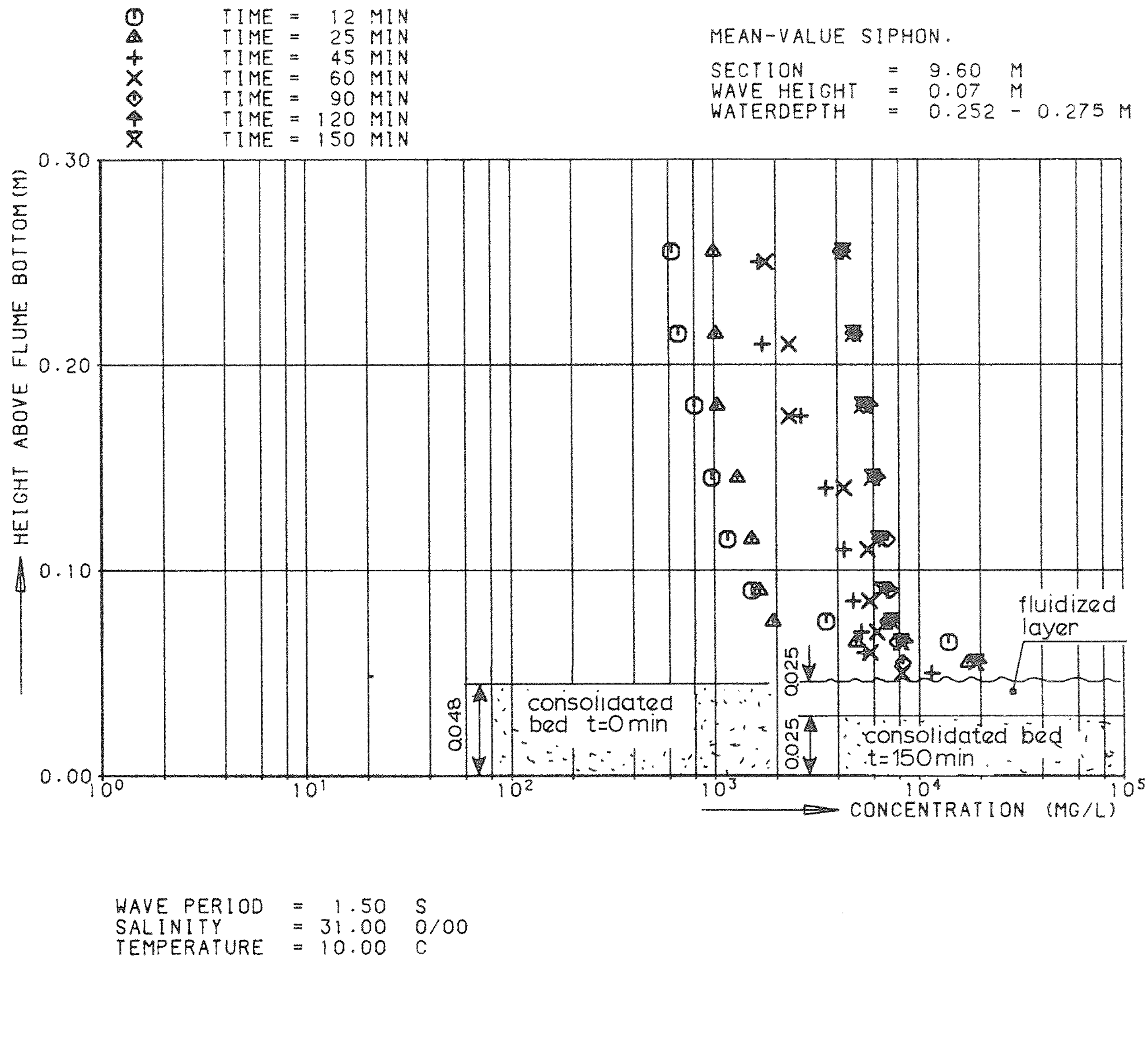
M 2060

FIG. 38




| | |
|---|---|
| SETTLING VELOCITY CURVE<br>VELOCITY PROFILES (ACOUS) | T4-5 / T 4-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 / FIG. 39 |



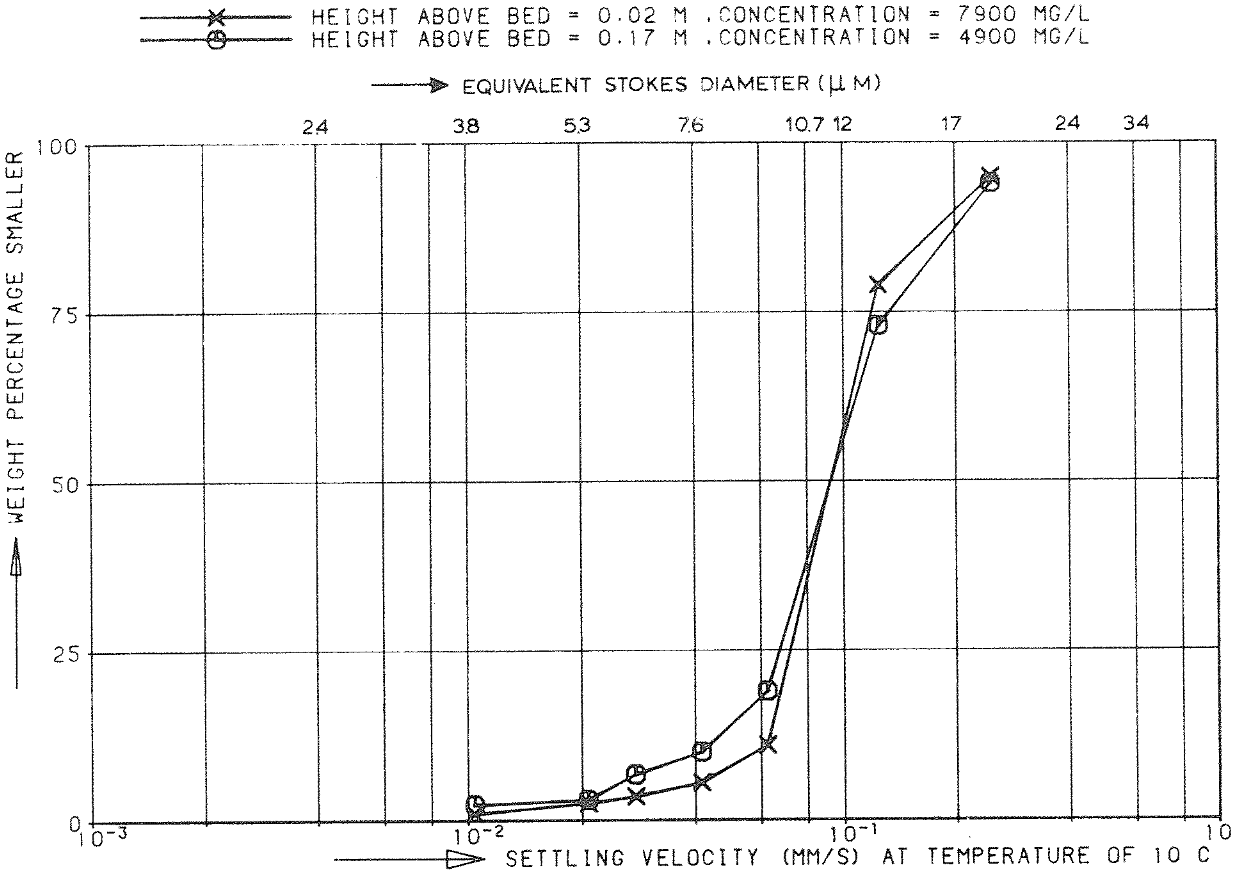

CONCENTRATION PROFILES (SIPHON)

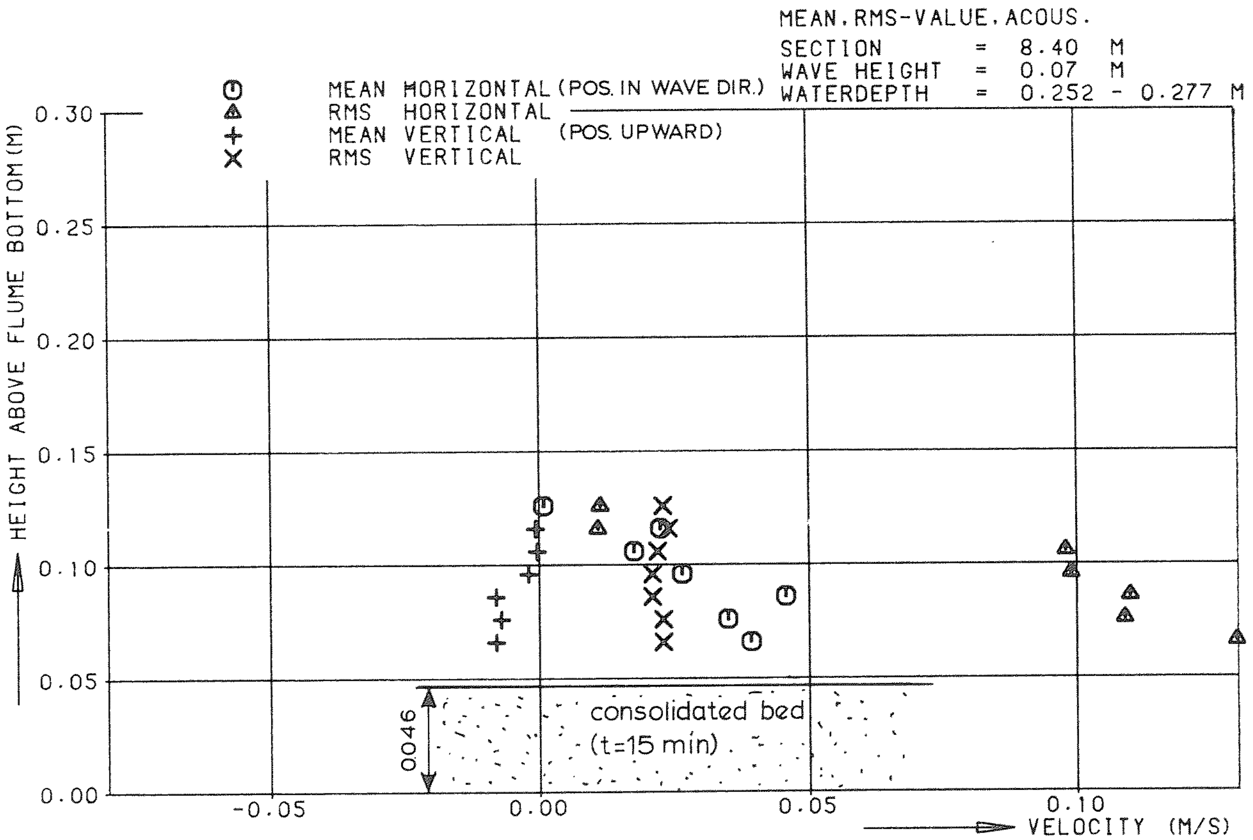
T4-7

DELFT HYDRAULICS LABORATORY

M 2060

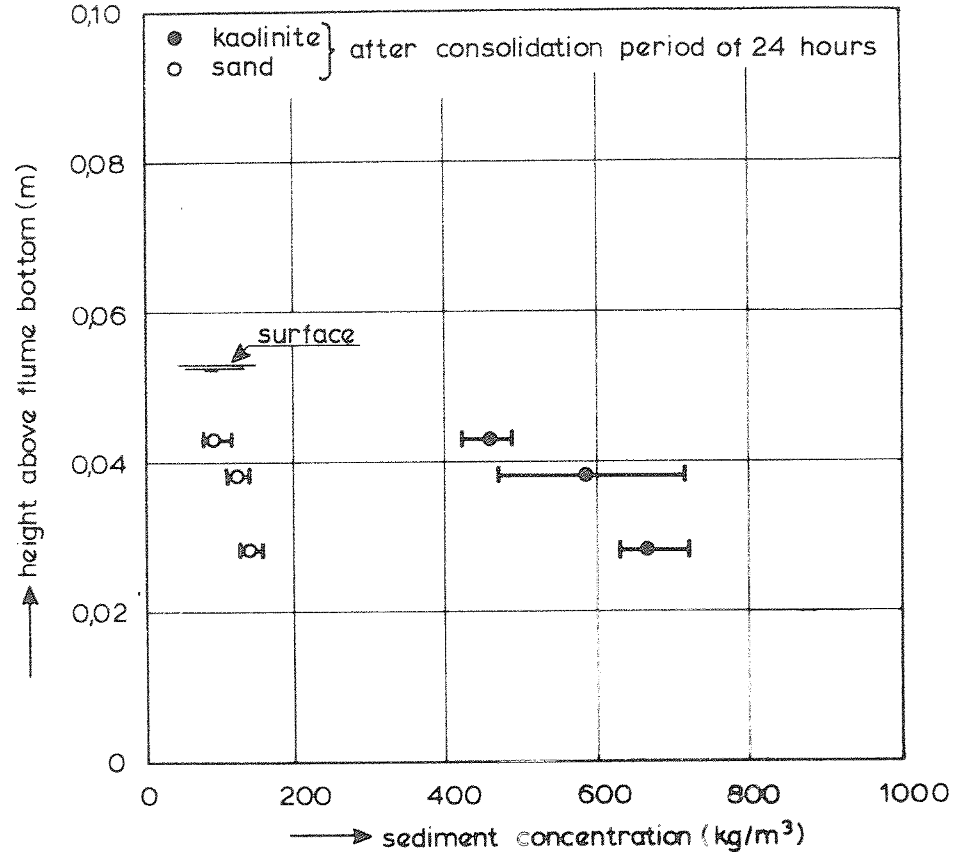
FIG. 40

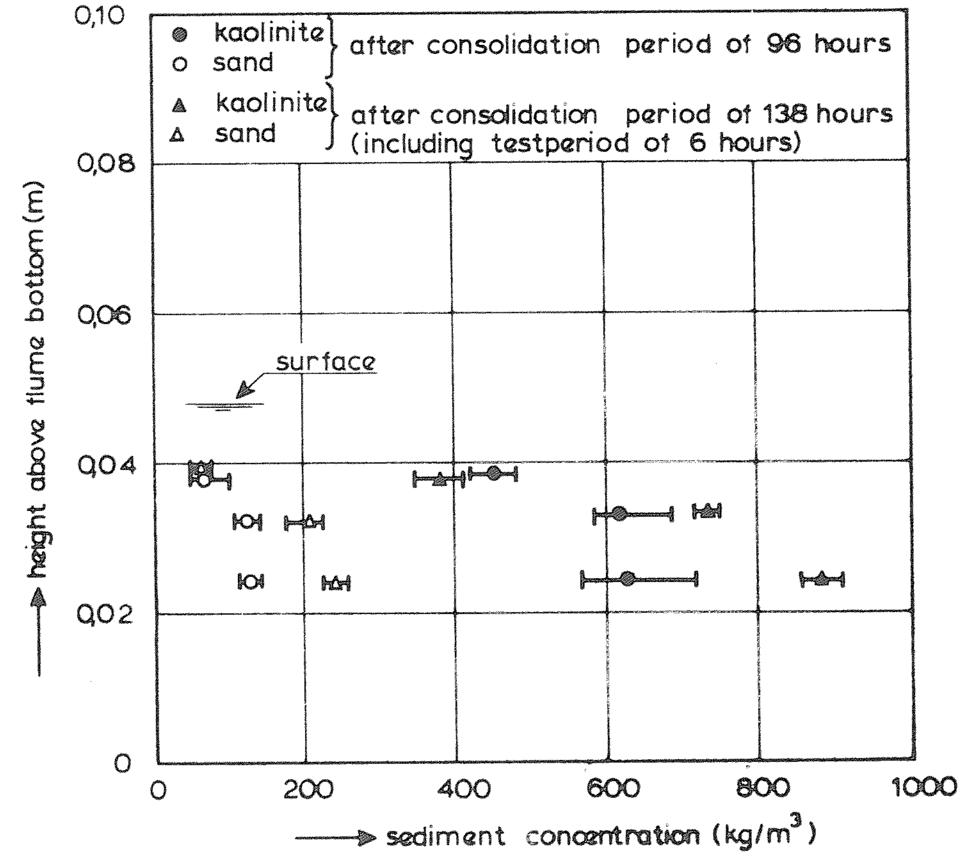



WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 10.00 C

| | | |
|---|---|---|
| SETTLING VELOCITY CURVE<br>VELOCITY PROFILES (ACOUS) | T4-10 | T 4-7 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 41 |



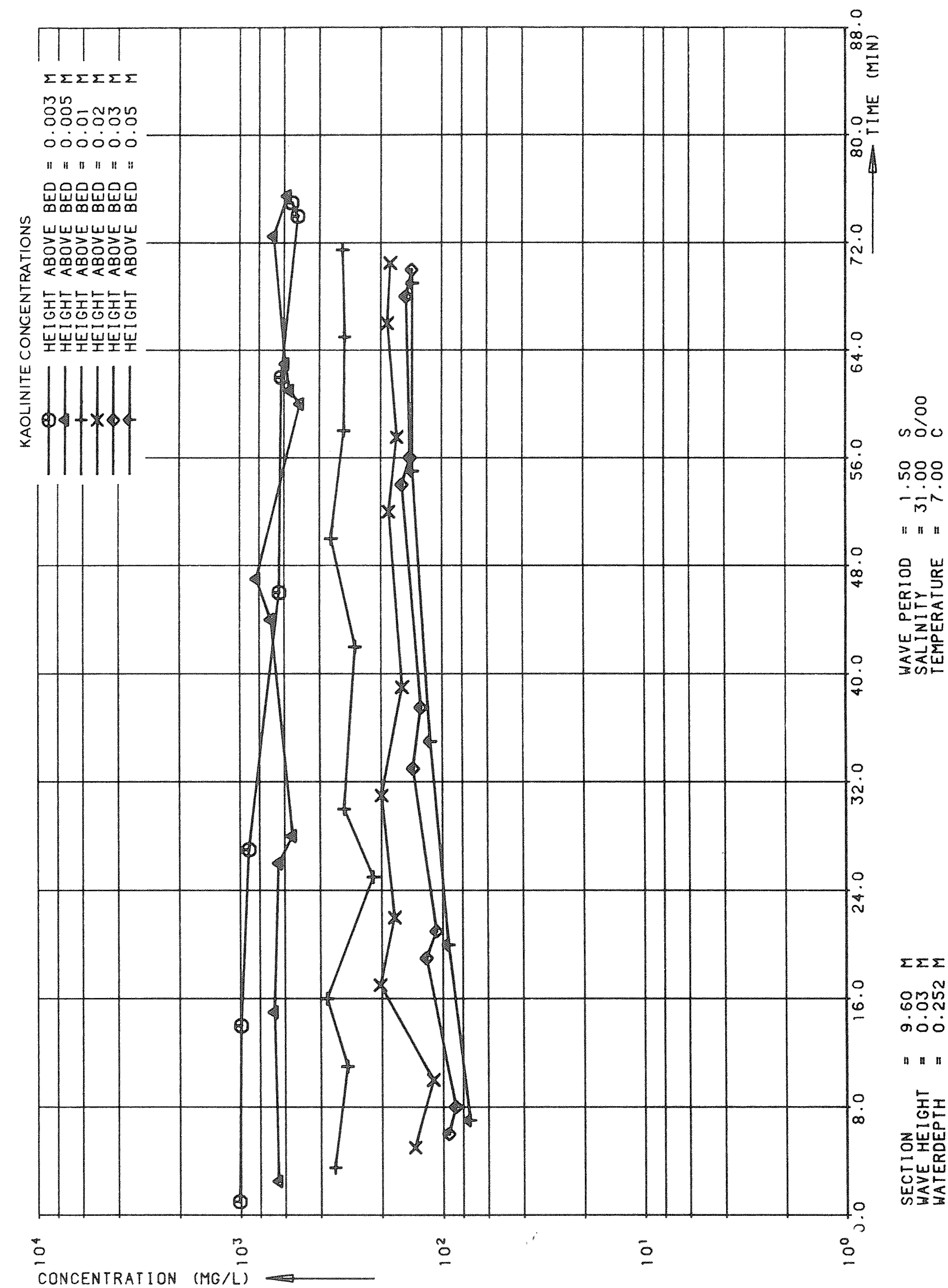

SEDIMENT CONCENTRATIONS IN BED LAYER

T 5

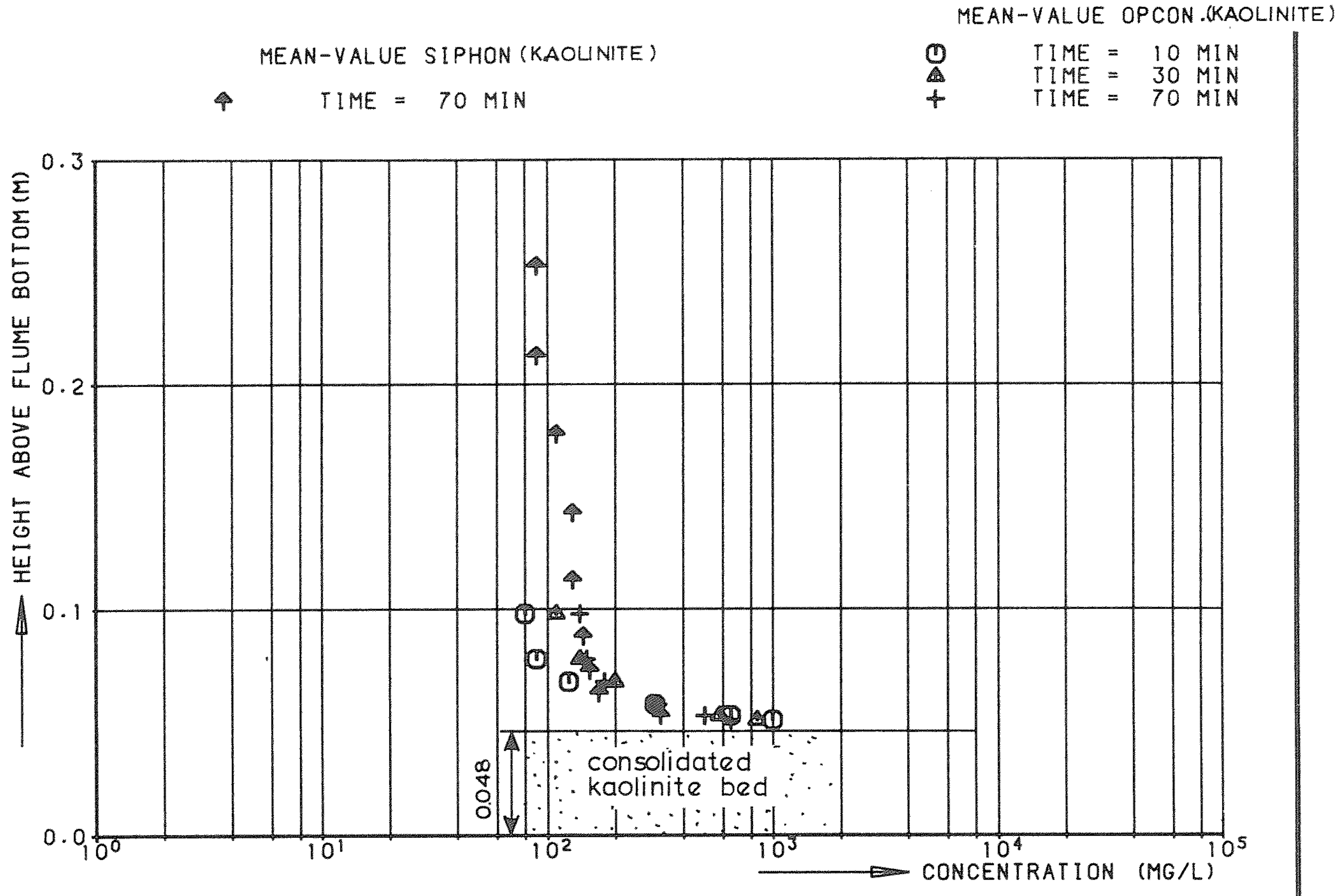
DELFT HYDRAULICS LABORATORY

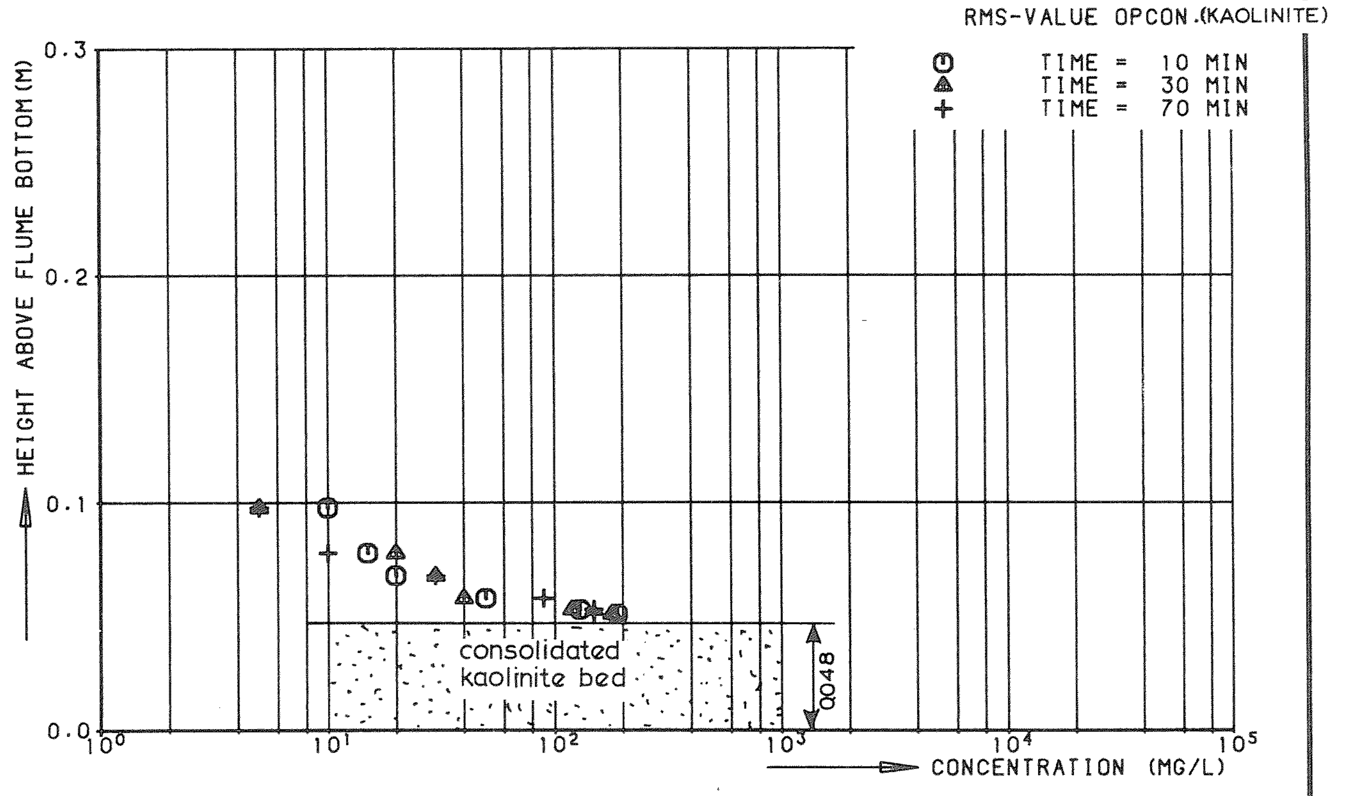
M 2060

FIG. 42




| TIME-CONCENTRATION CURVES (OPCON) | | T 5-3 |
|---|---|---|
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 43 |




| | | | | | |
|---|---|---|---|---|---|
| SECTION | = 9.60 M | | WAVE PERIOD | = 1.50 | S |
| WATERDEPTH | = 0.252 M | | SALINITY | = 31.00 | 0/00 |
| WAVE HEIGHT | = 0.03 M | | TEMPERATURE | = 7.00 | C |

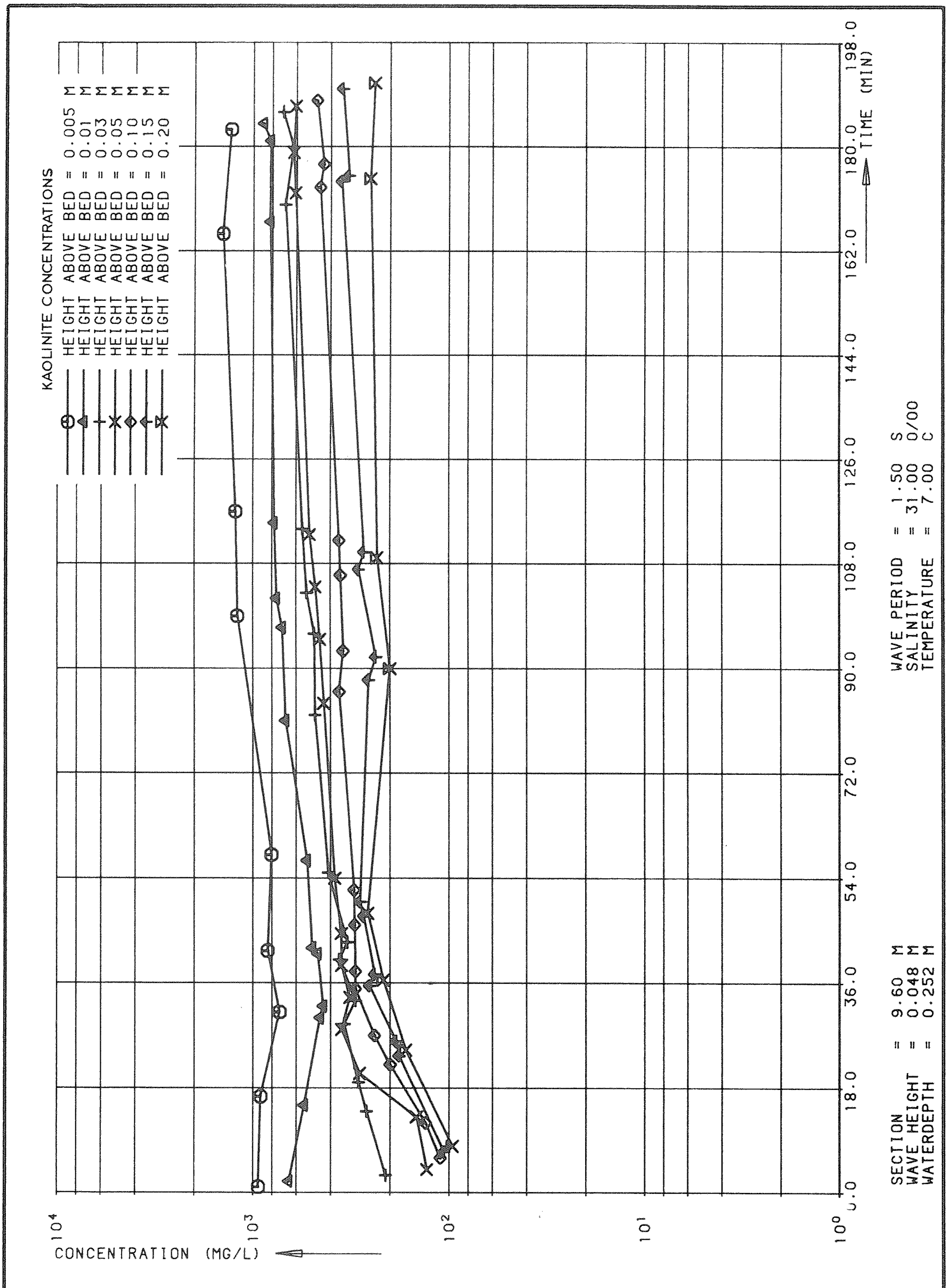
CONCENTRATION PROFILES (OPCON)
CONCENTRATION PROFILES (SIPHON)

T 5-3

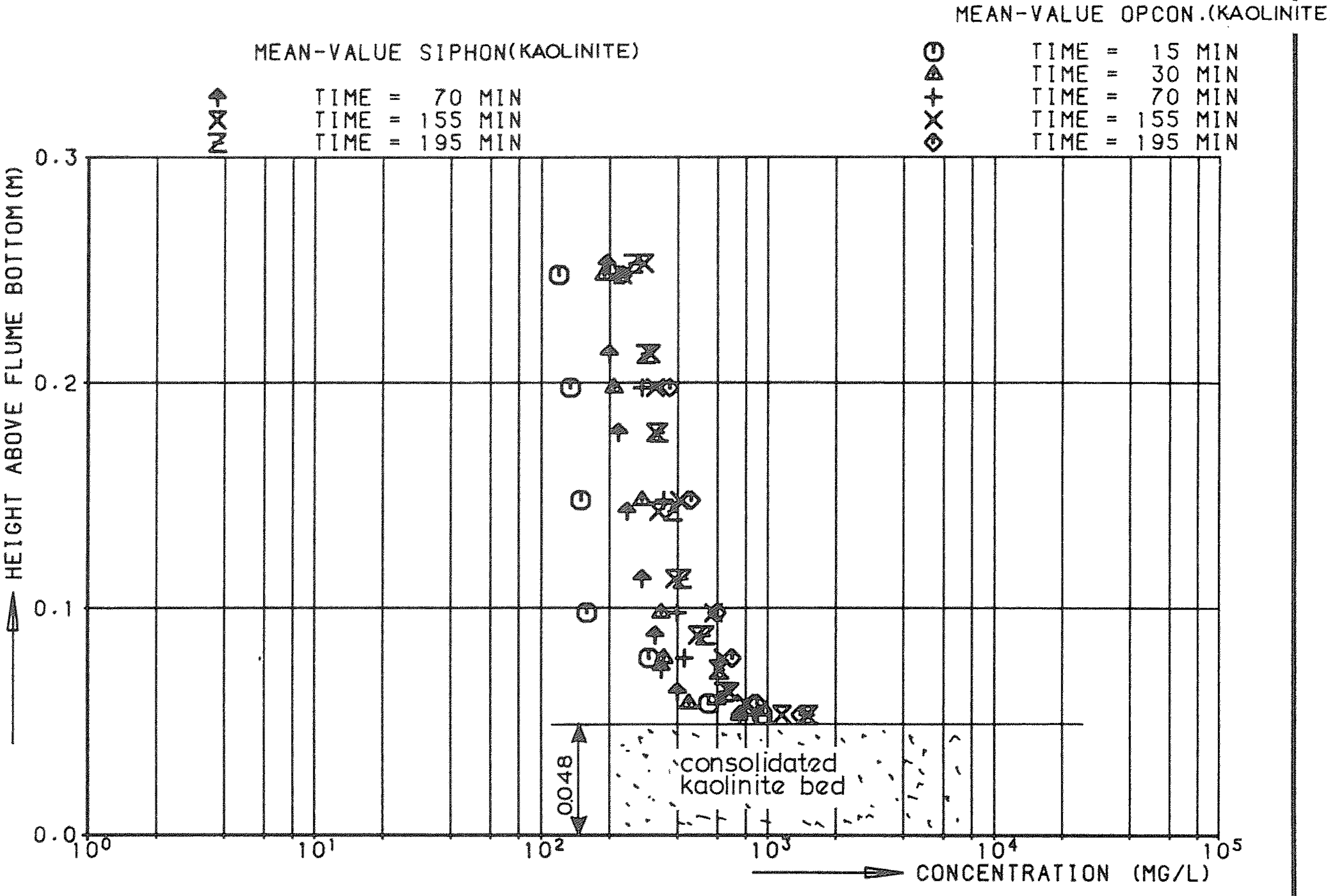
DELFT HYDRAULICS LABORATORY

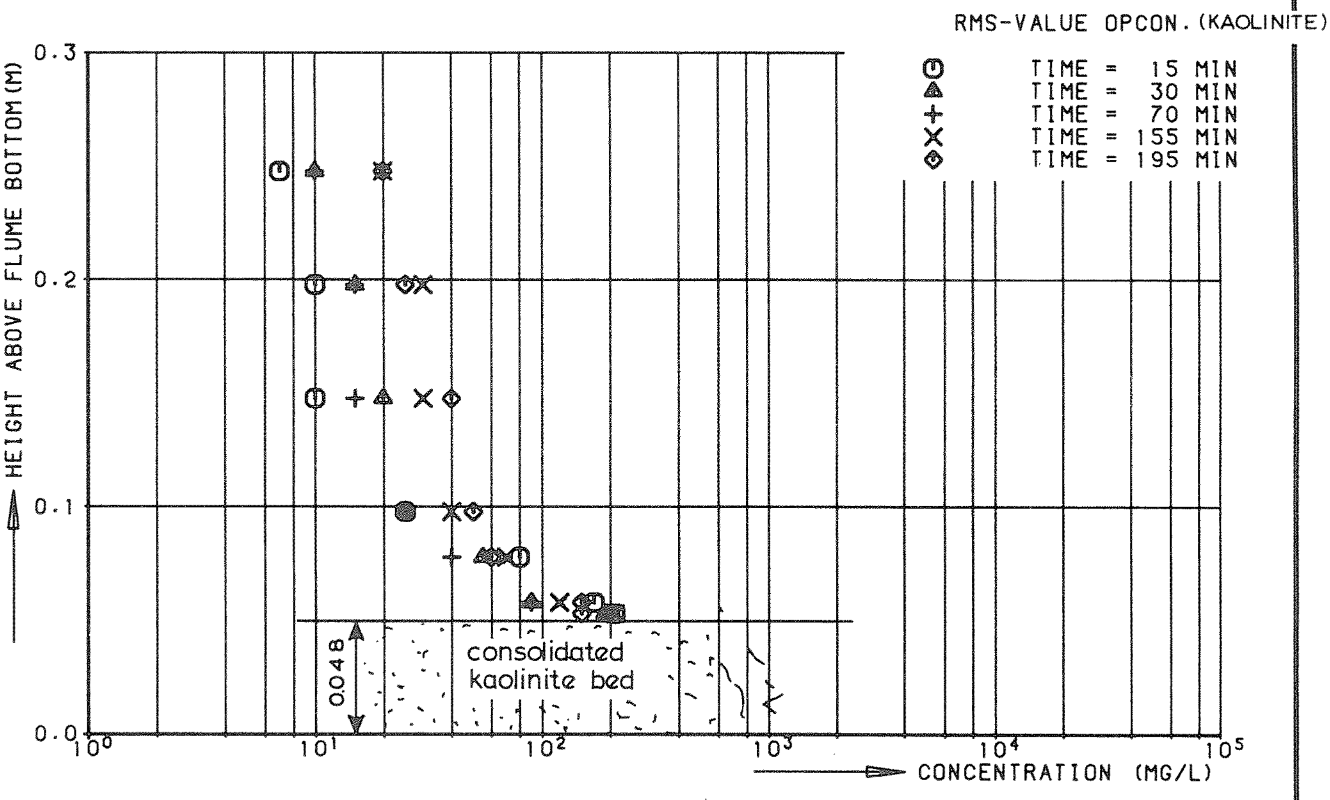
M 2060

FIG. 44




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T5-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 45 |




| | | | | | |
|---|---|---|---|---|---|
| SECTION | = 9.60 M | | WAVE PERIOD | = 1.50 | S |
| WATERDEPTH | = 0.252 M | | SALINITY | = 31.00 | 0/00 |
| WAVE HEIGHT | = 0.048 M | | TEMPERATURE | = 7.00 | C |

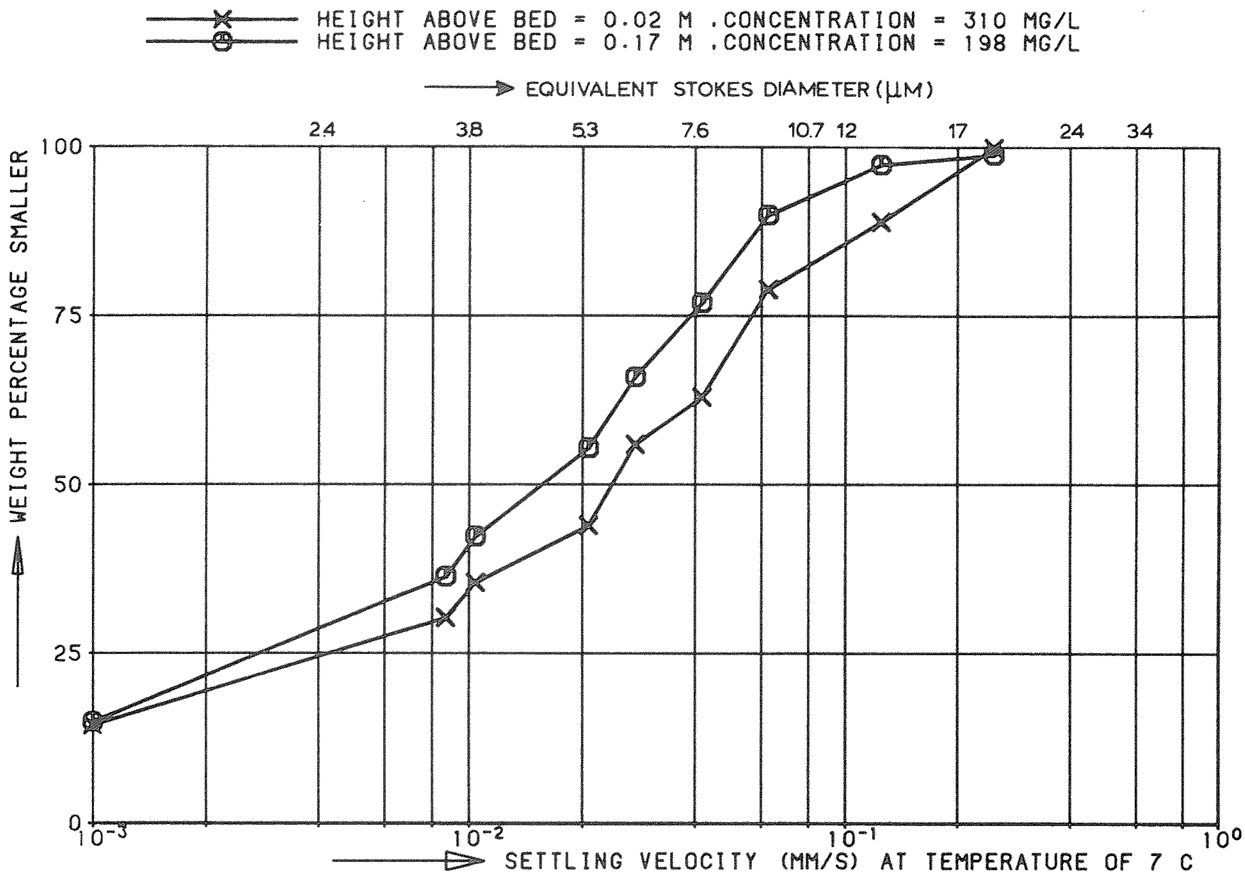
CONCENTRATION PROFILES (OPCON)
CONCENTRATION PROFILES (SIPHON)

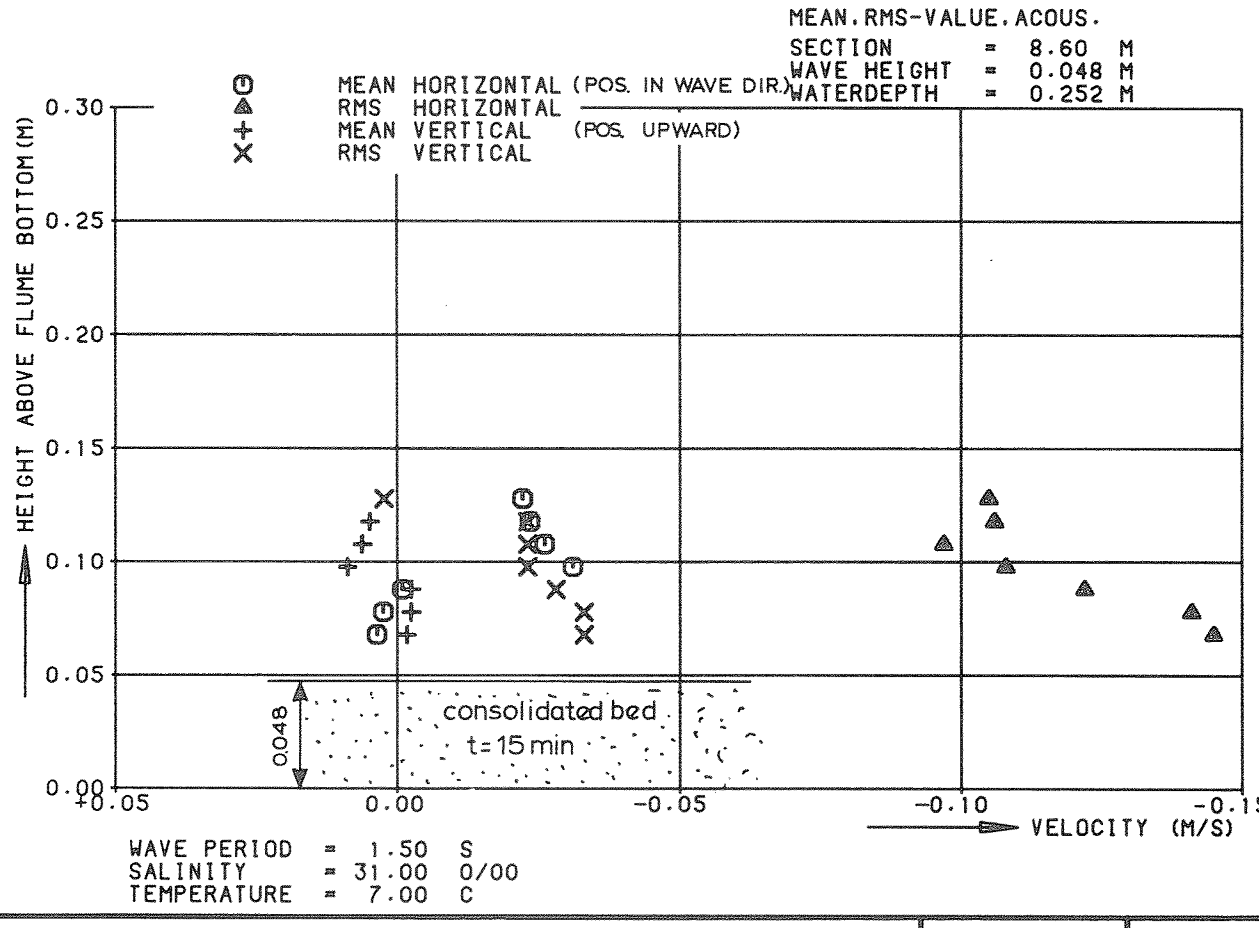
T 5-4

DELFT HYDRAULICS LABORATORY

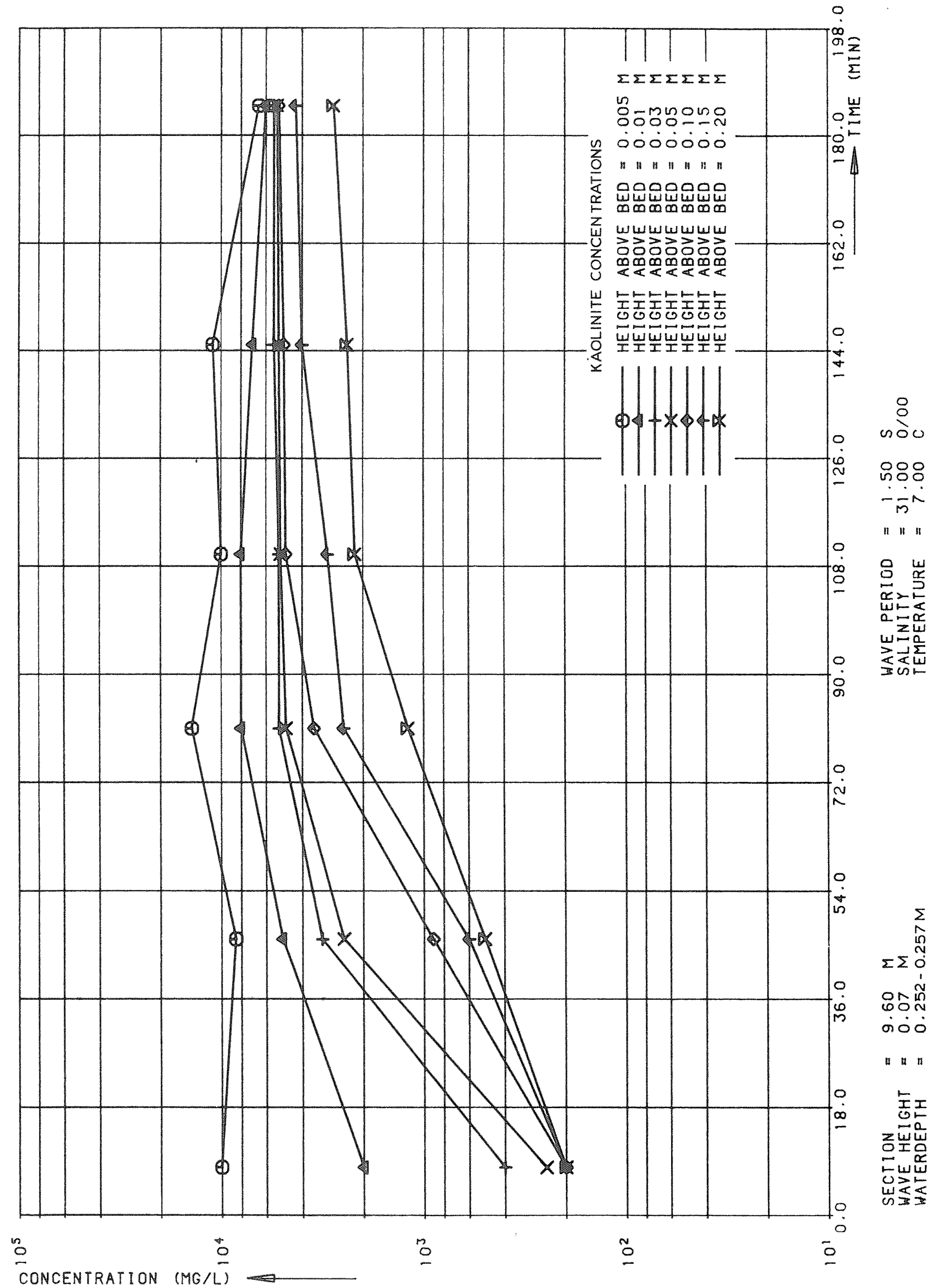
M 2060

FIG. 46

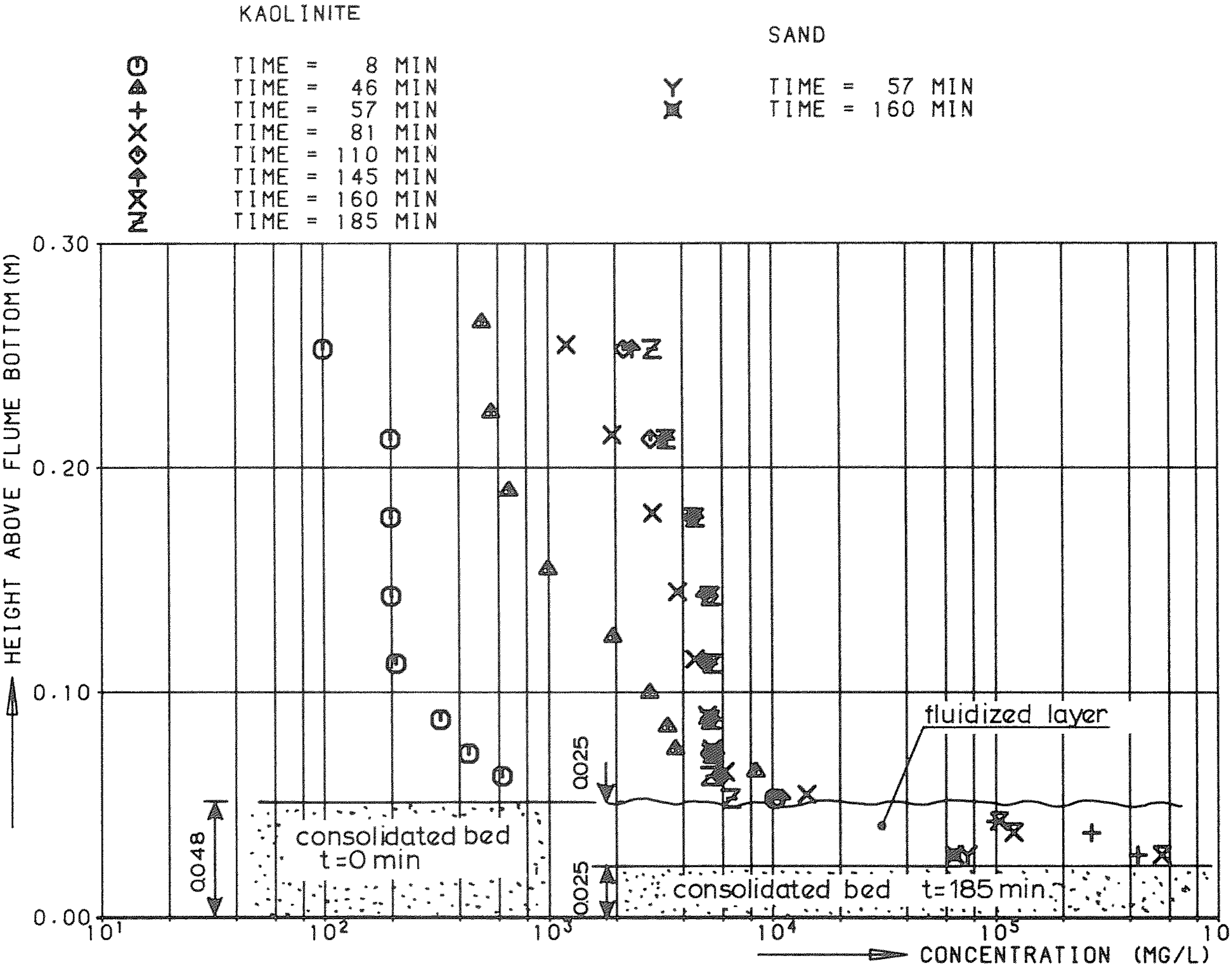



| | | |
|---|---|---|
| SETTLING VELOCITY CURVE<br>VELOCITY PROFILES (ACOUS) | | T5-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 47 |



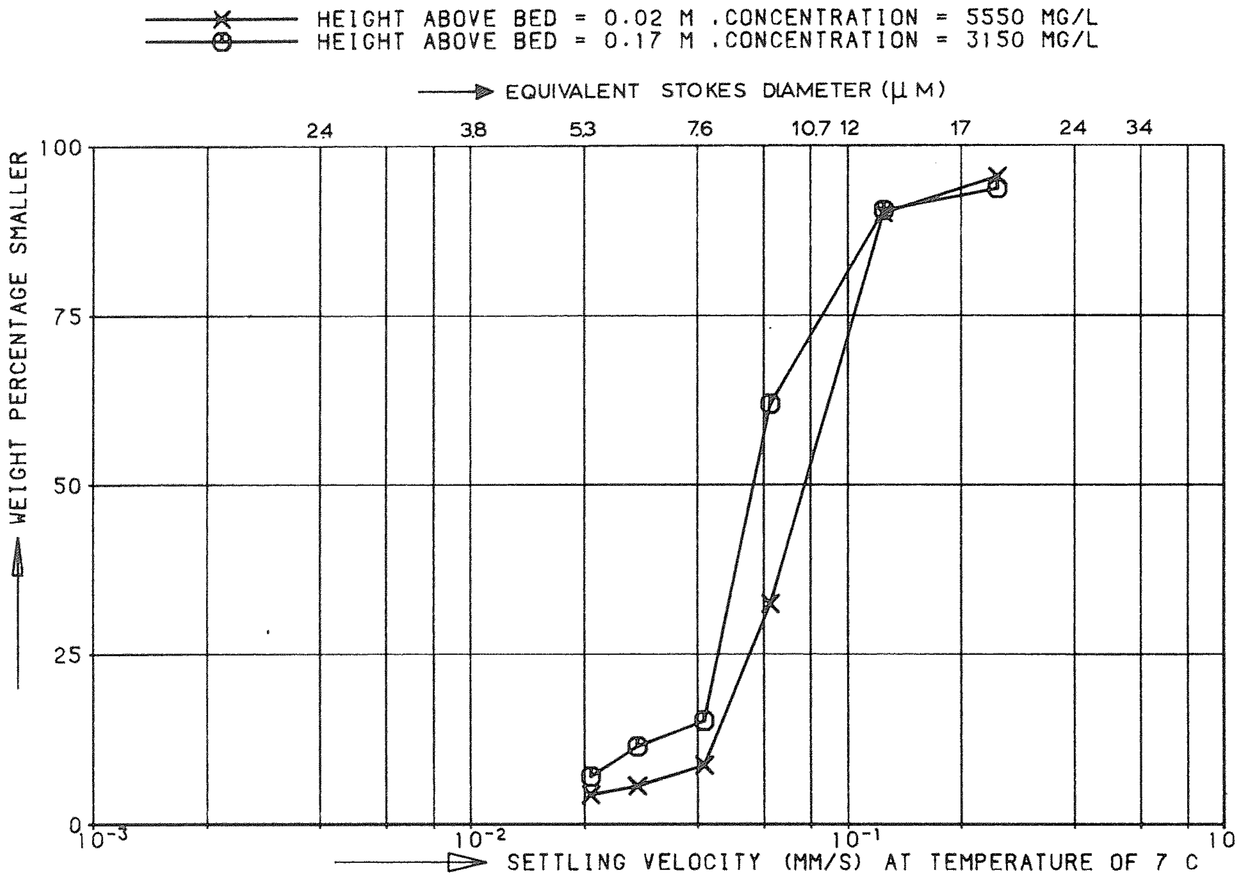

| TIME-CONCENTRATION CURVES (SIPHON) | | T 5-7 |
|---|---|---|
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 48 |

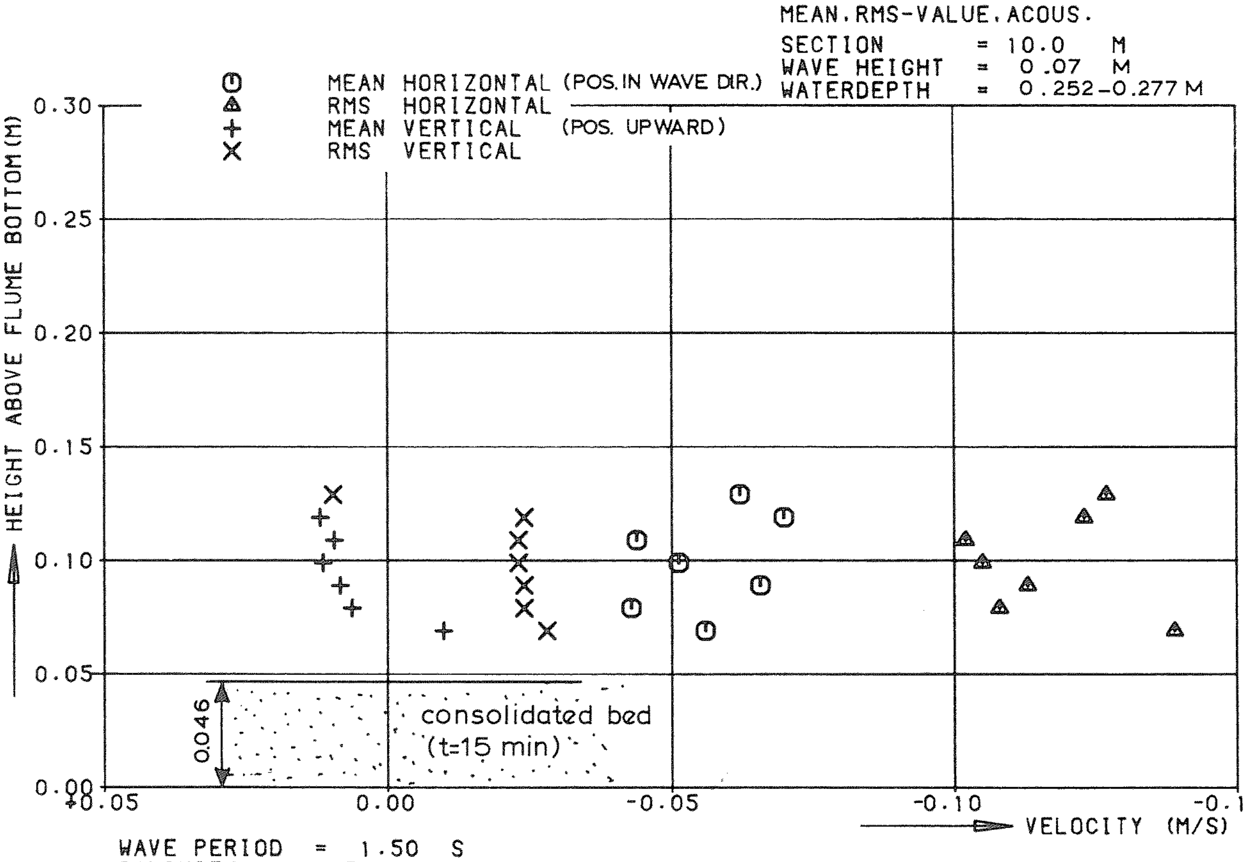



WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

MEAN-VALUE SIPHON.
SECTION = 9.60 M
WAVE HEIGHT = 0.07 M
WATERDEPTH = 0.252 -0.277M

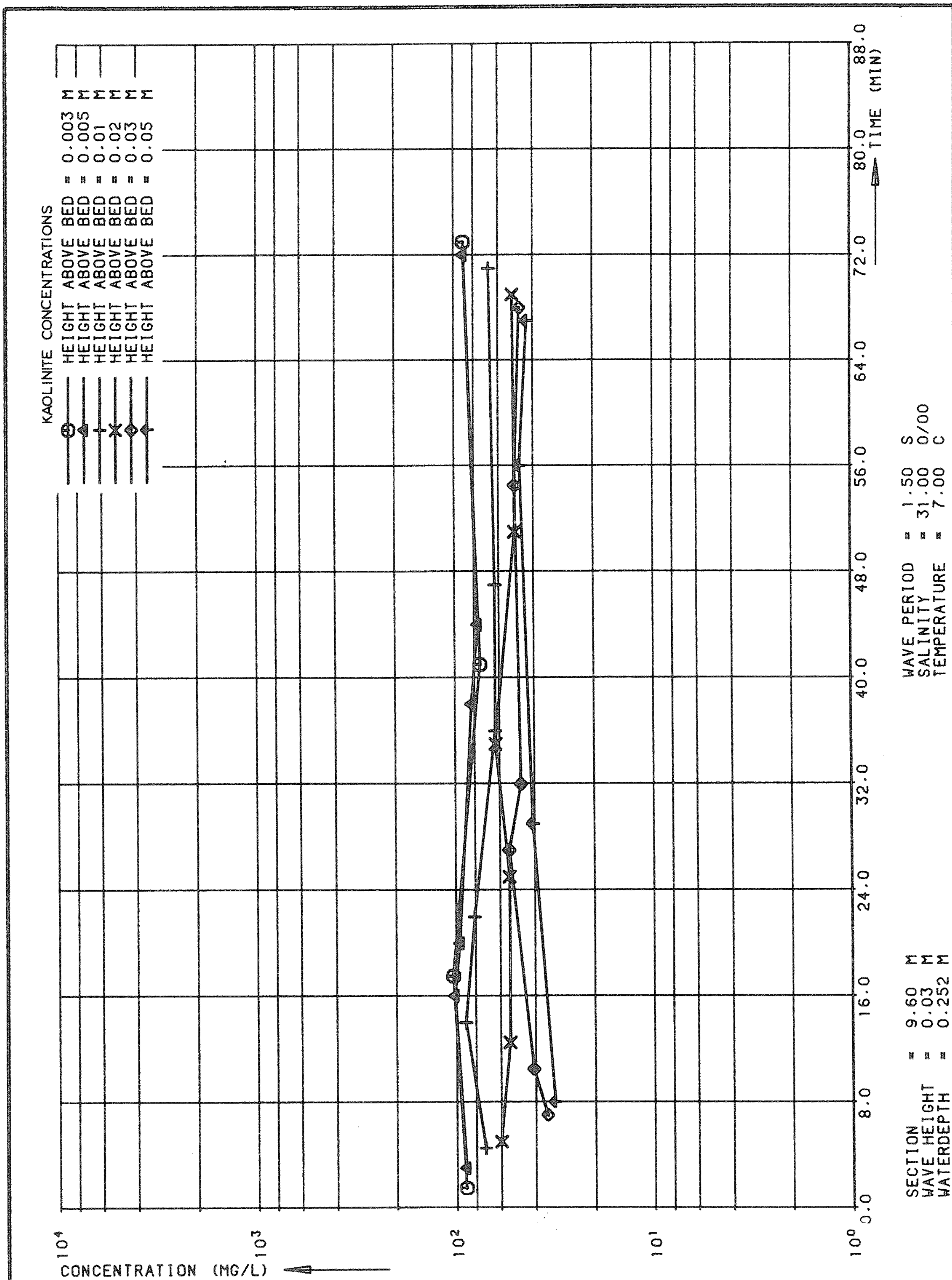
| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON) | | T 5-7 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 49 |



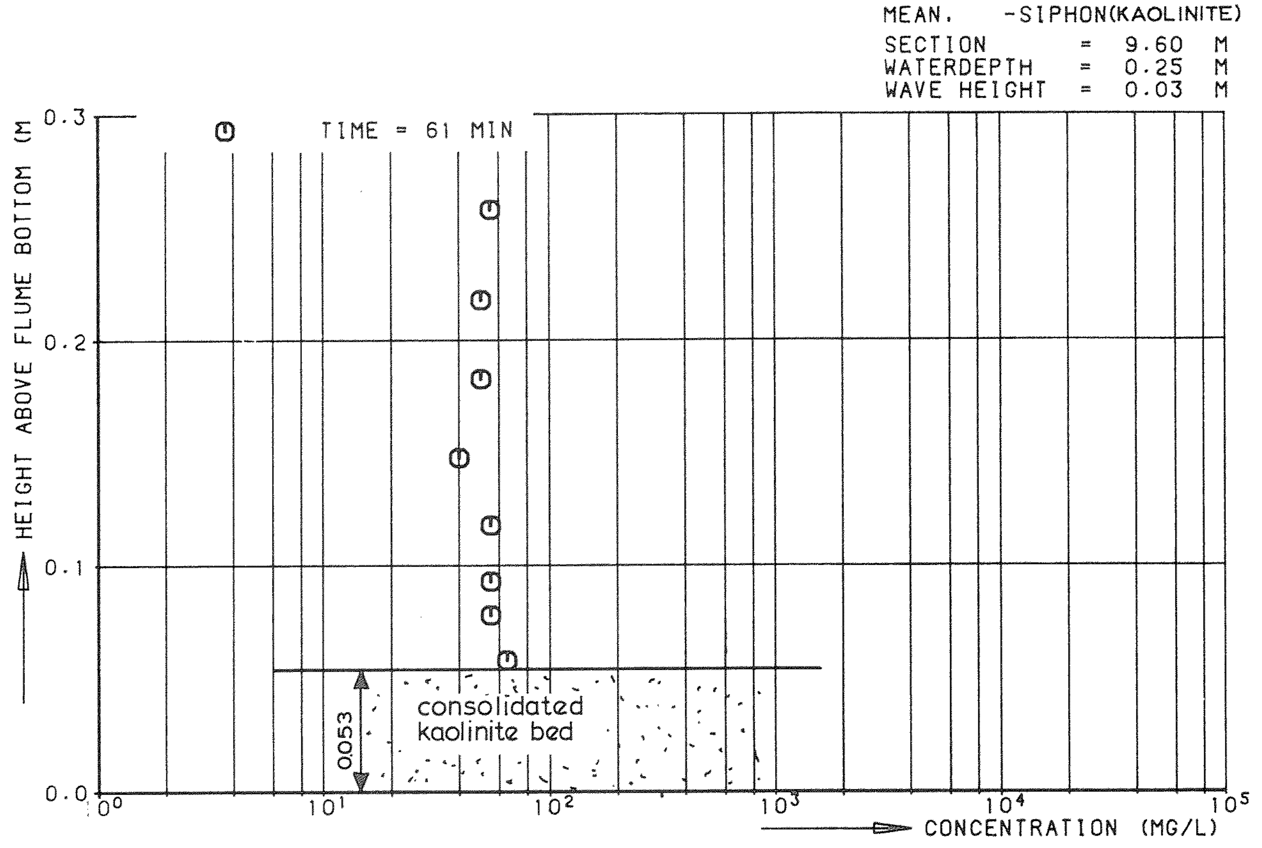



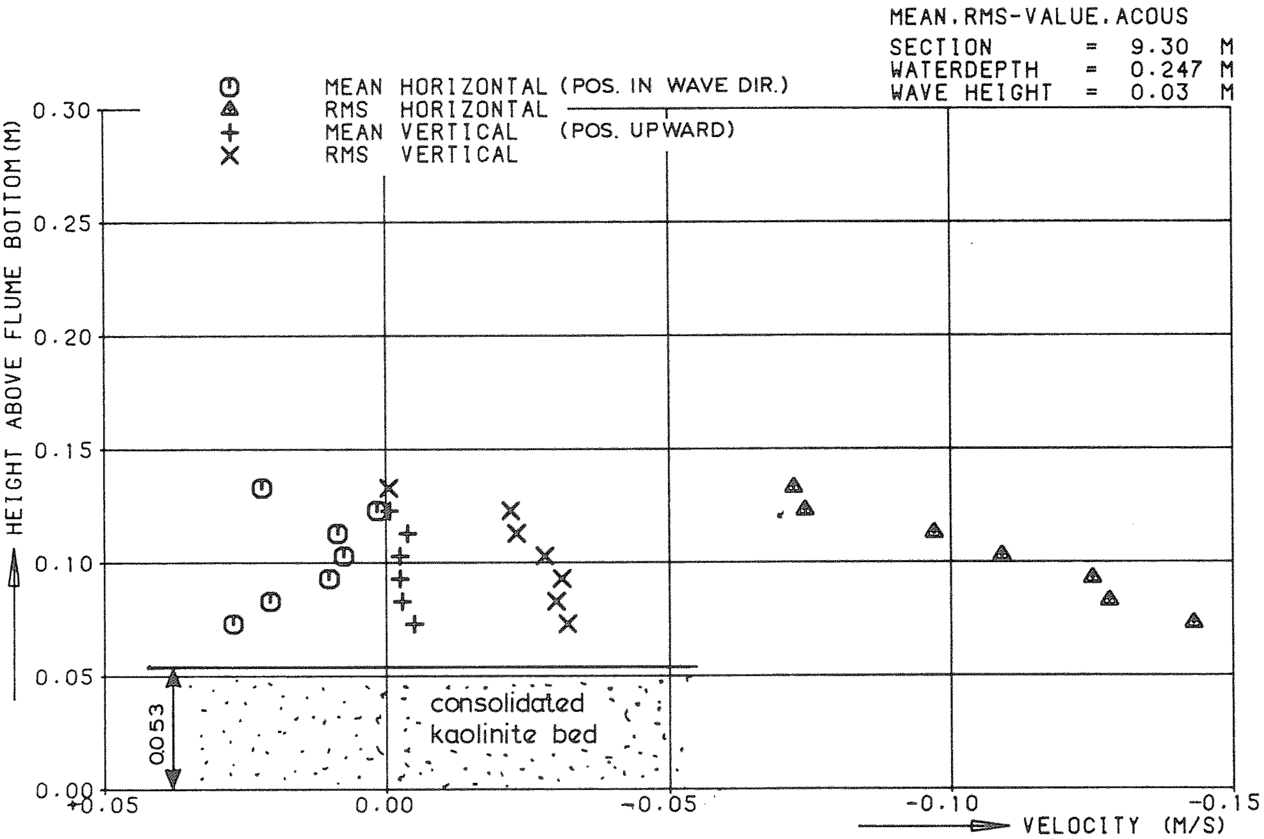

WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

| | | |
|---|---|---|
| SETTLING VELOCITY CURVE<br>VELOCITY PROFILES (ACOUS) | | T 5-7 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 50 |



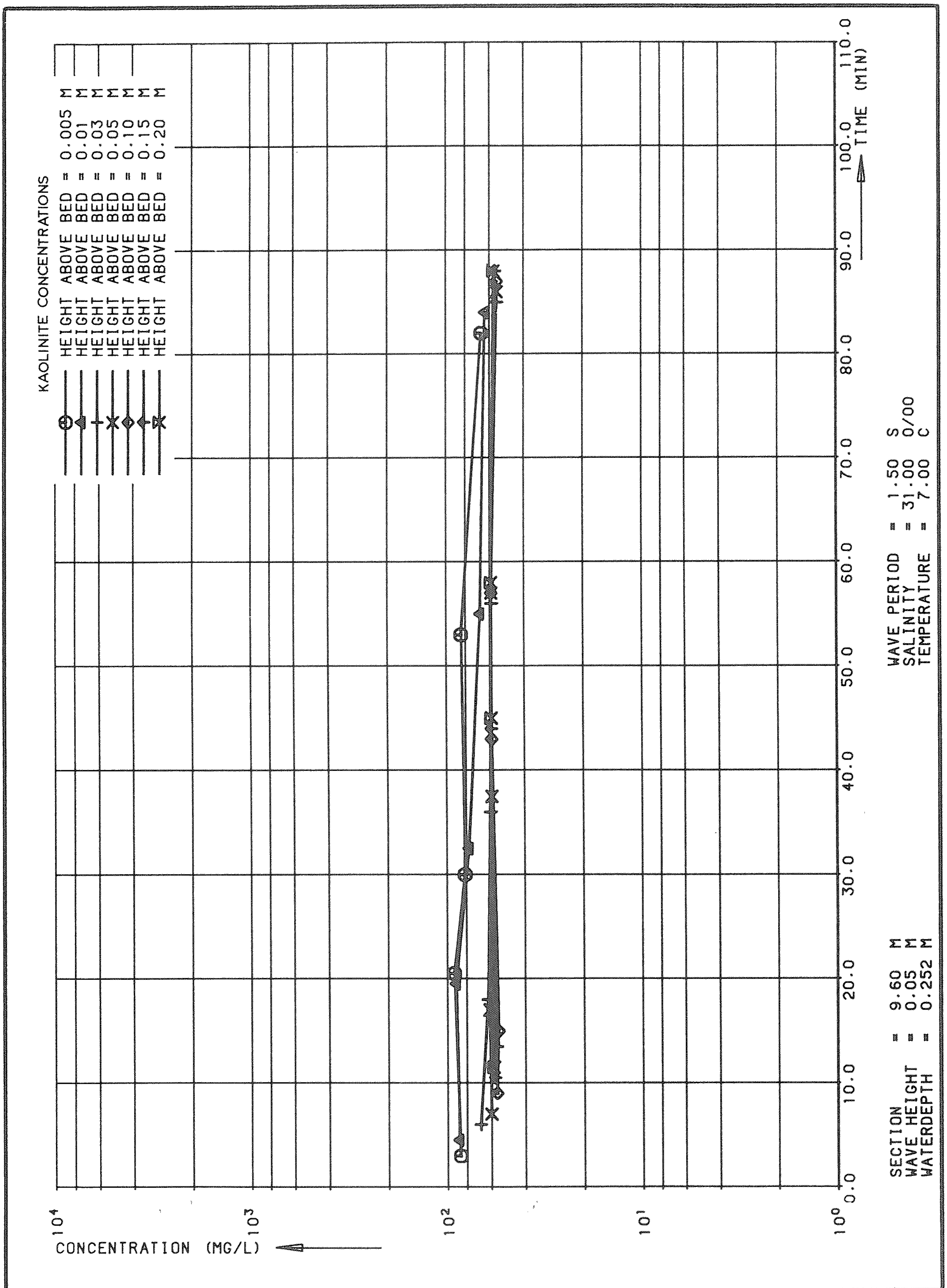

| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T 6-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 51 |



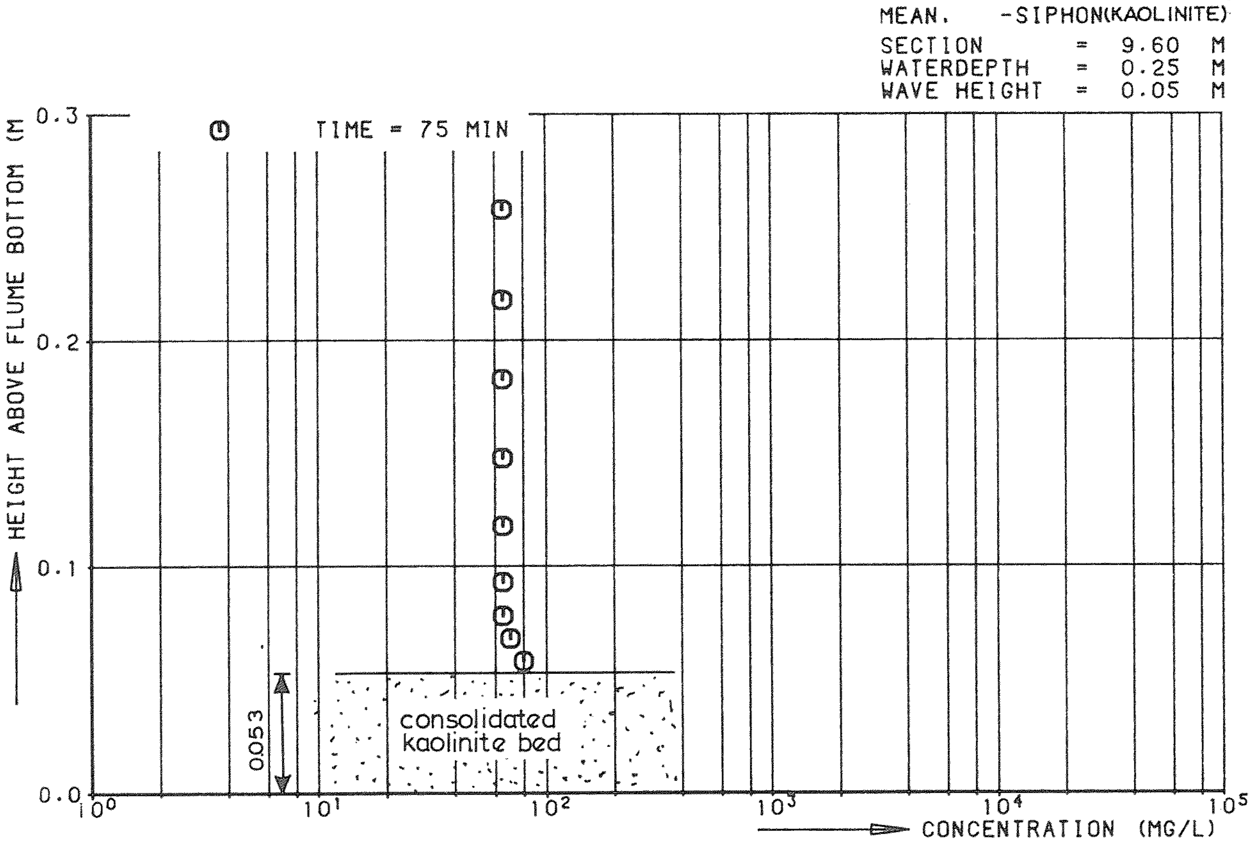



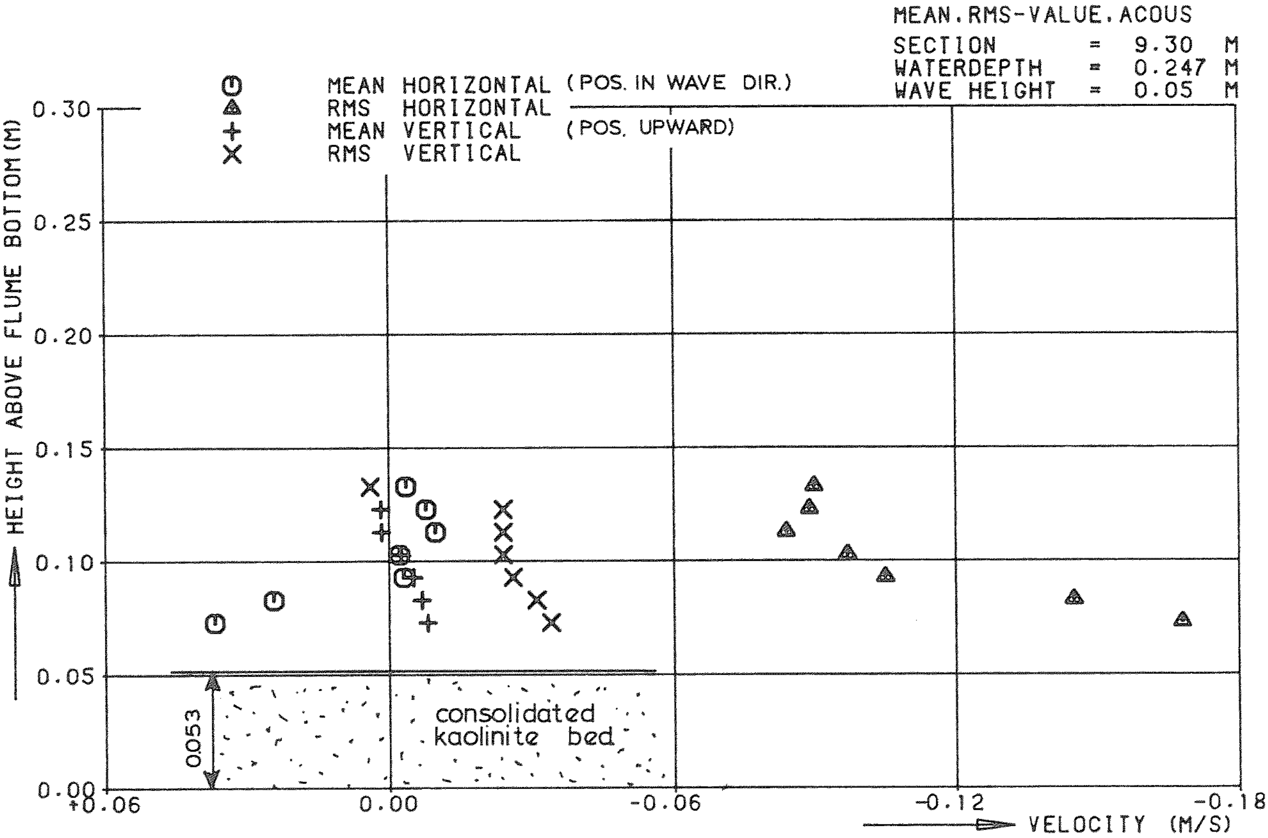

WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON)<br>VELOCITY PROFILES (ACOUS) | | T 6-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 52 |



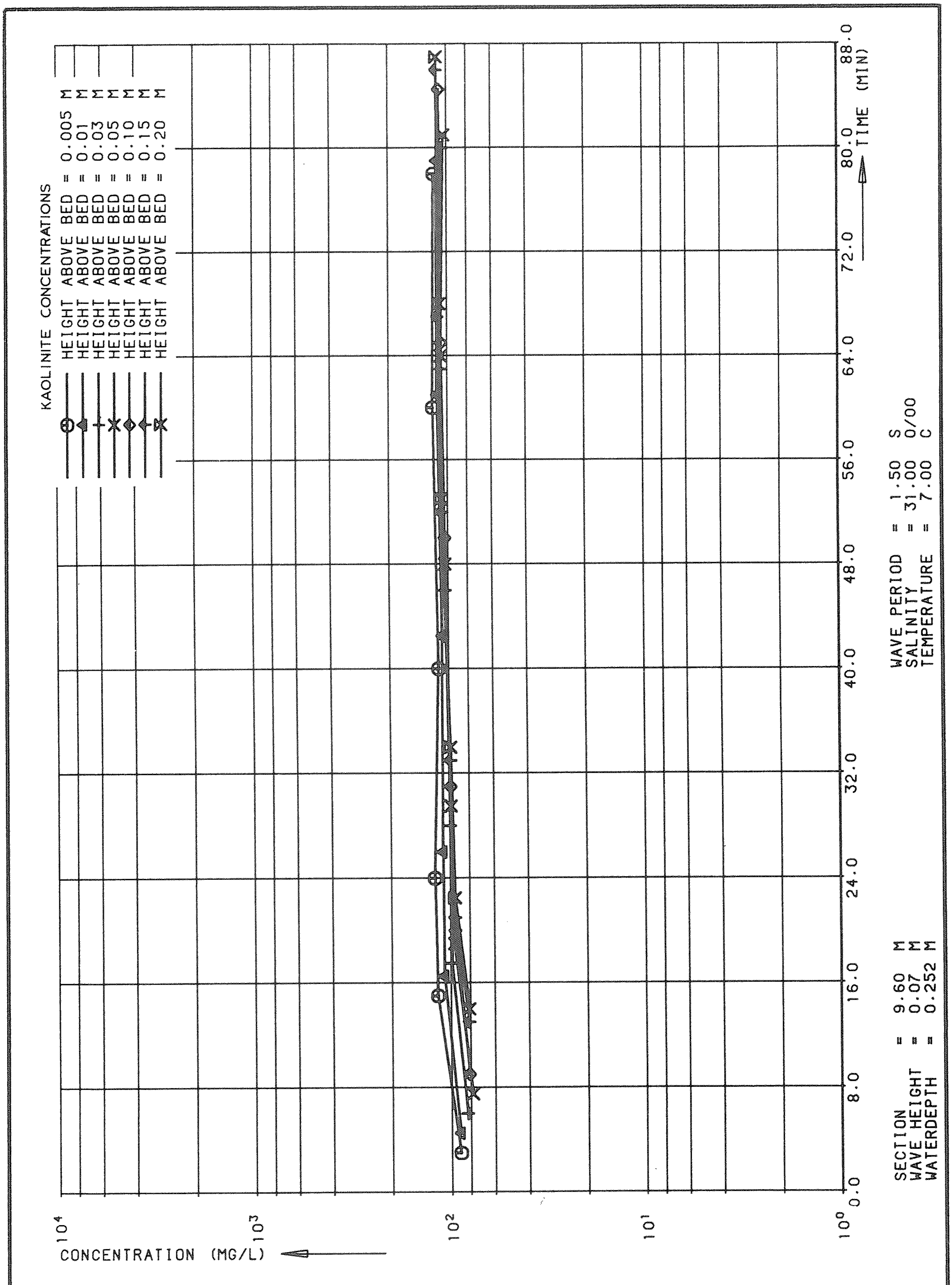

| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T6-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 53 |



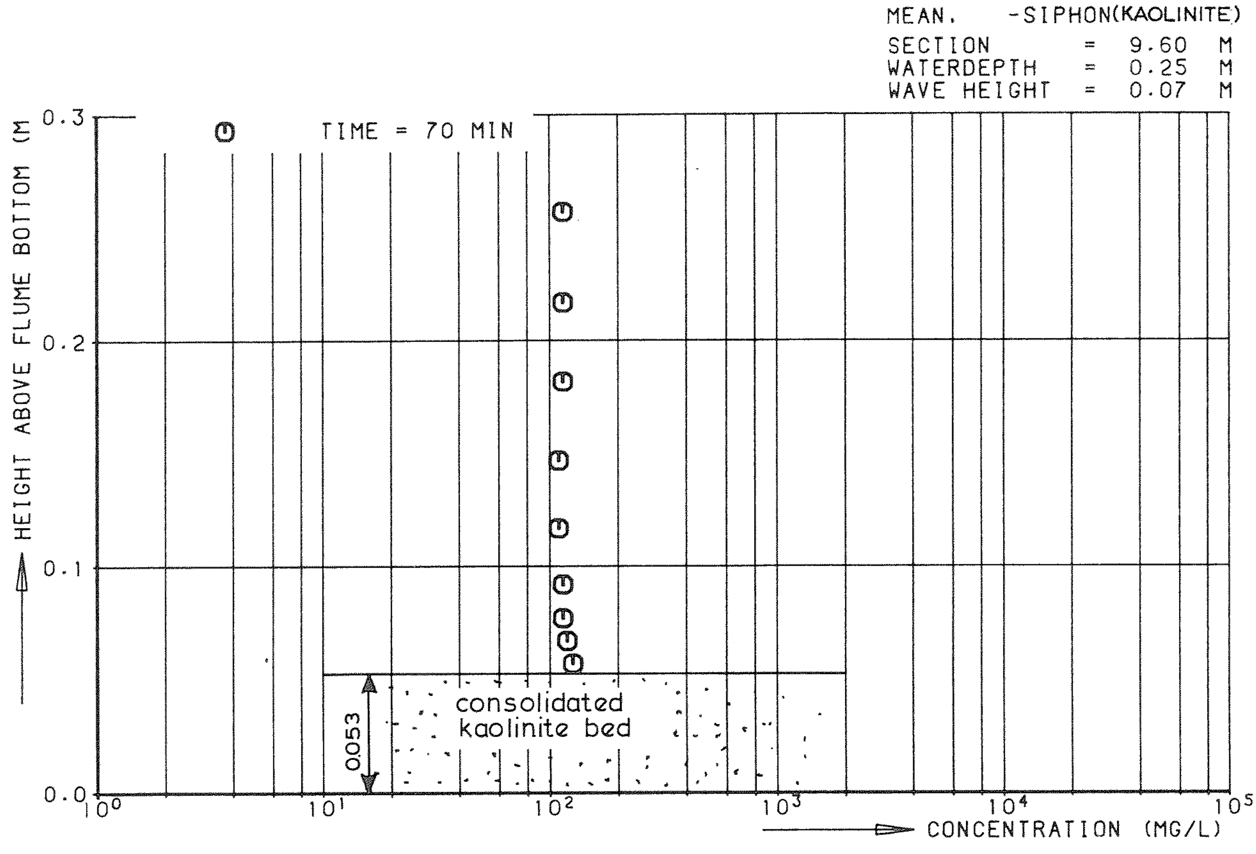



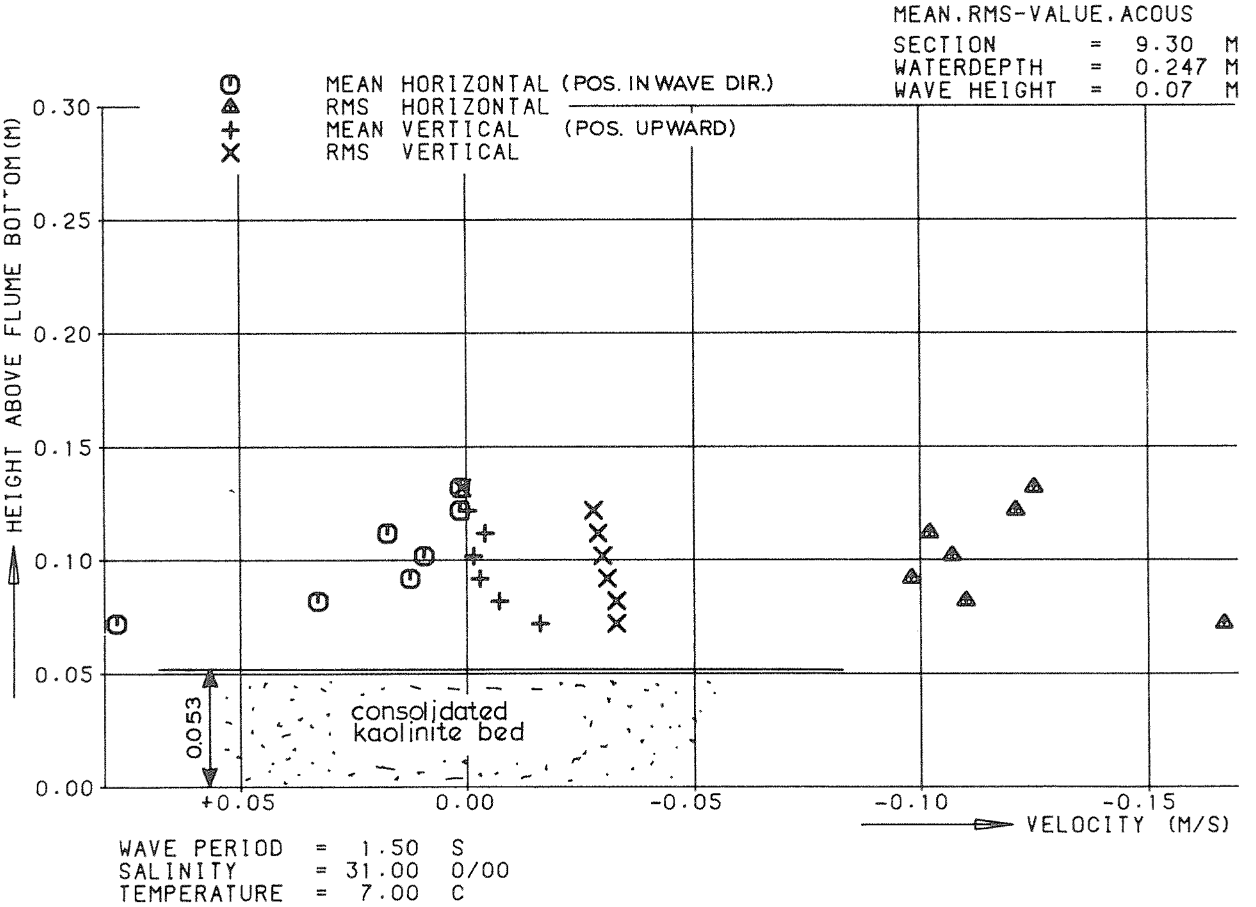

WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON)<br>VELOCITY PROFILES (ACOUS) | | T6-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG.54 |




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T6-5 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 55 |



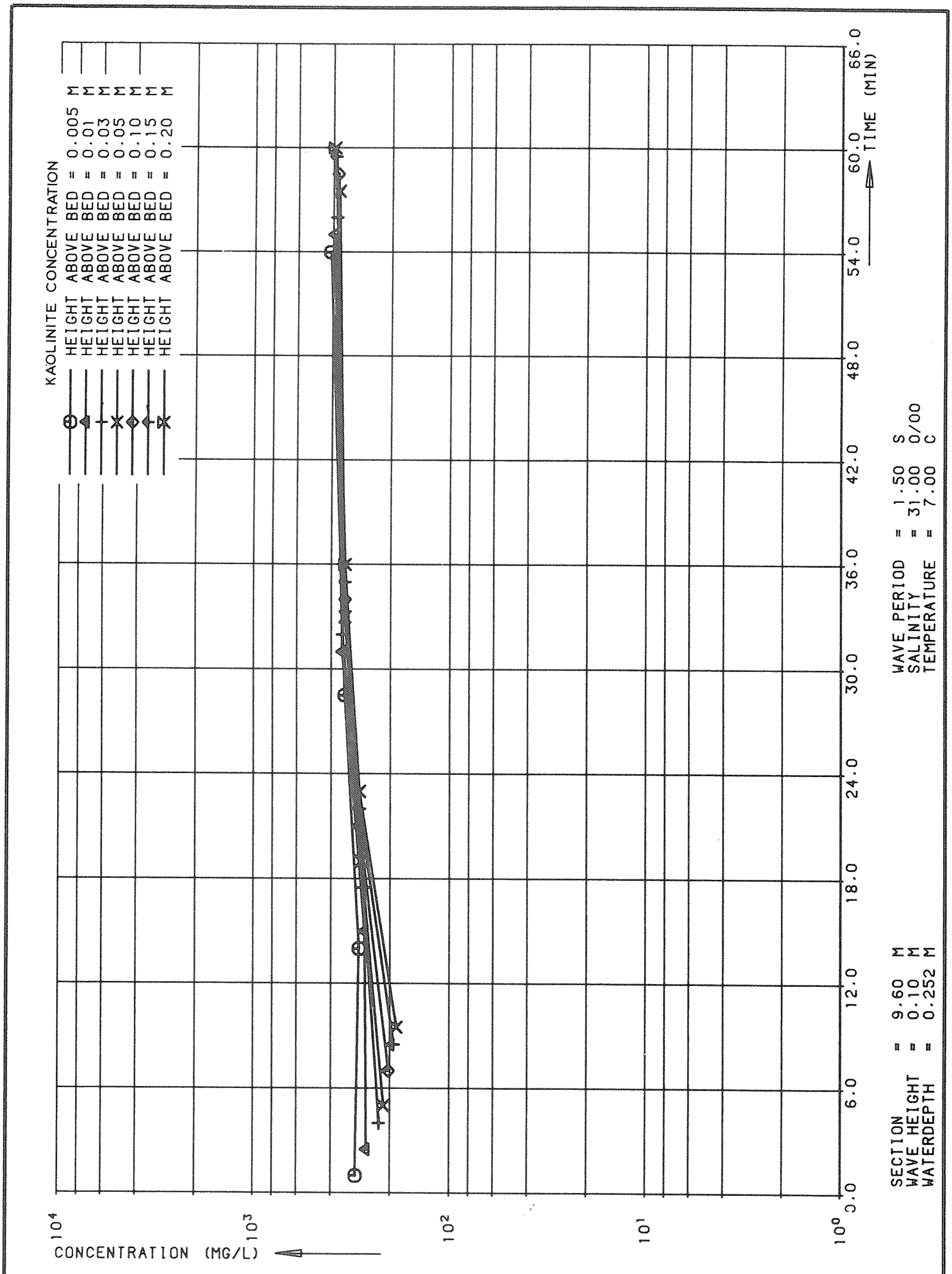

CONCENTRATION PROFILES (SIPHON)
VELOCITY PROFILES (ACOUS)

T 6-5

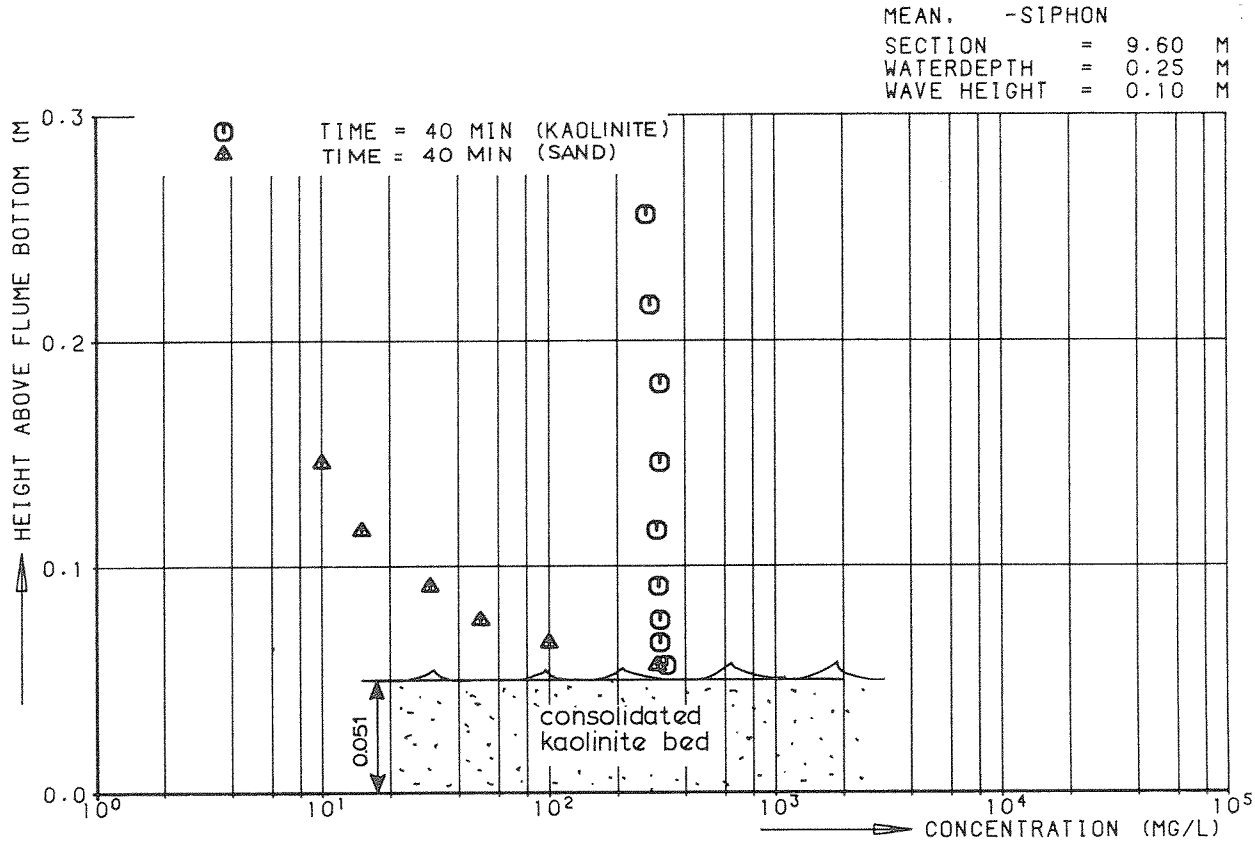
DELFT HYDRAULICS LABORATORY

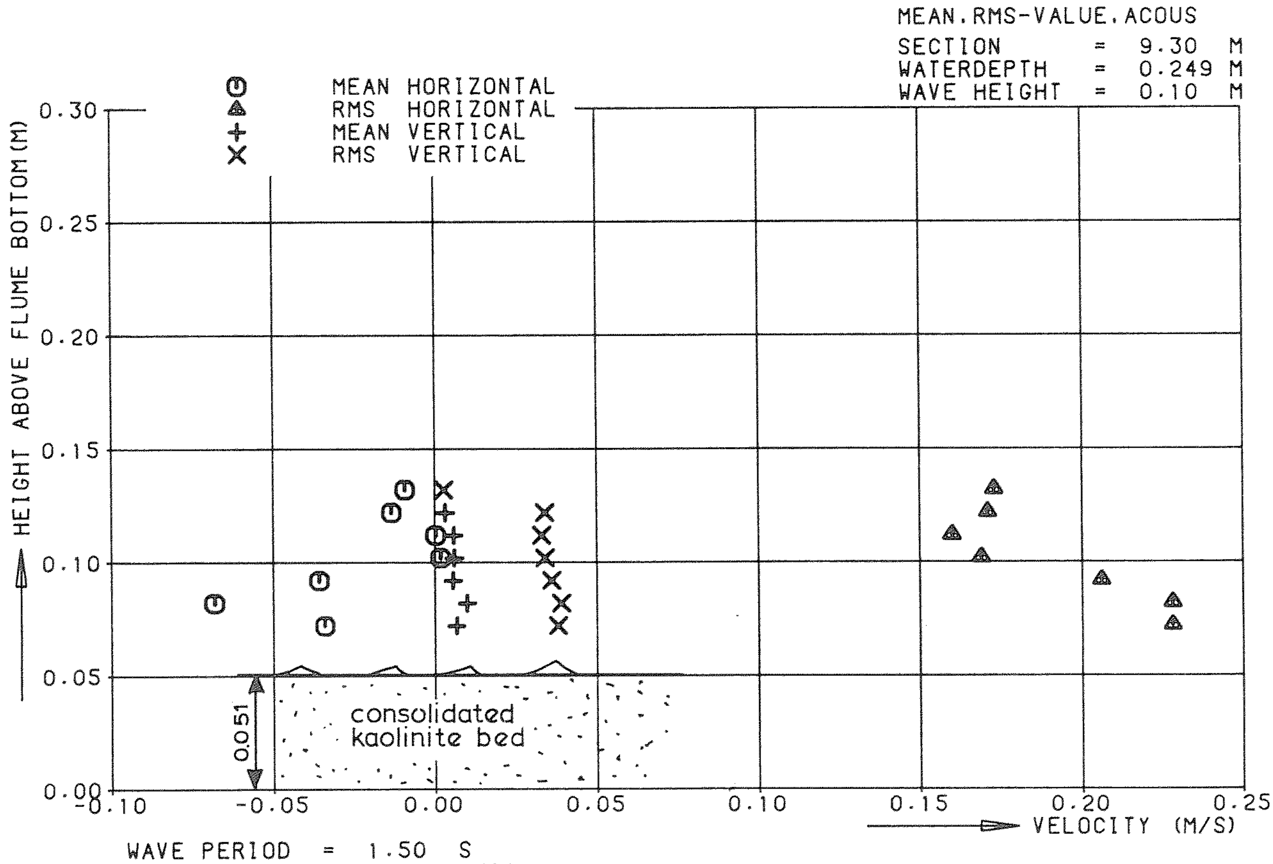
M 2060

FIG. 56




| | | |
|---|---|---|
| TIME-CONCENTRATION CURVES (OPCON) | | T 6-6 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG.57 |




WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

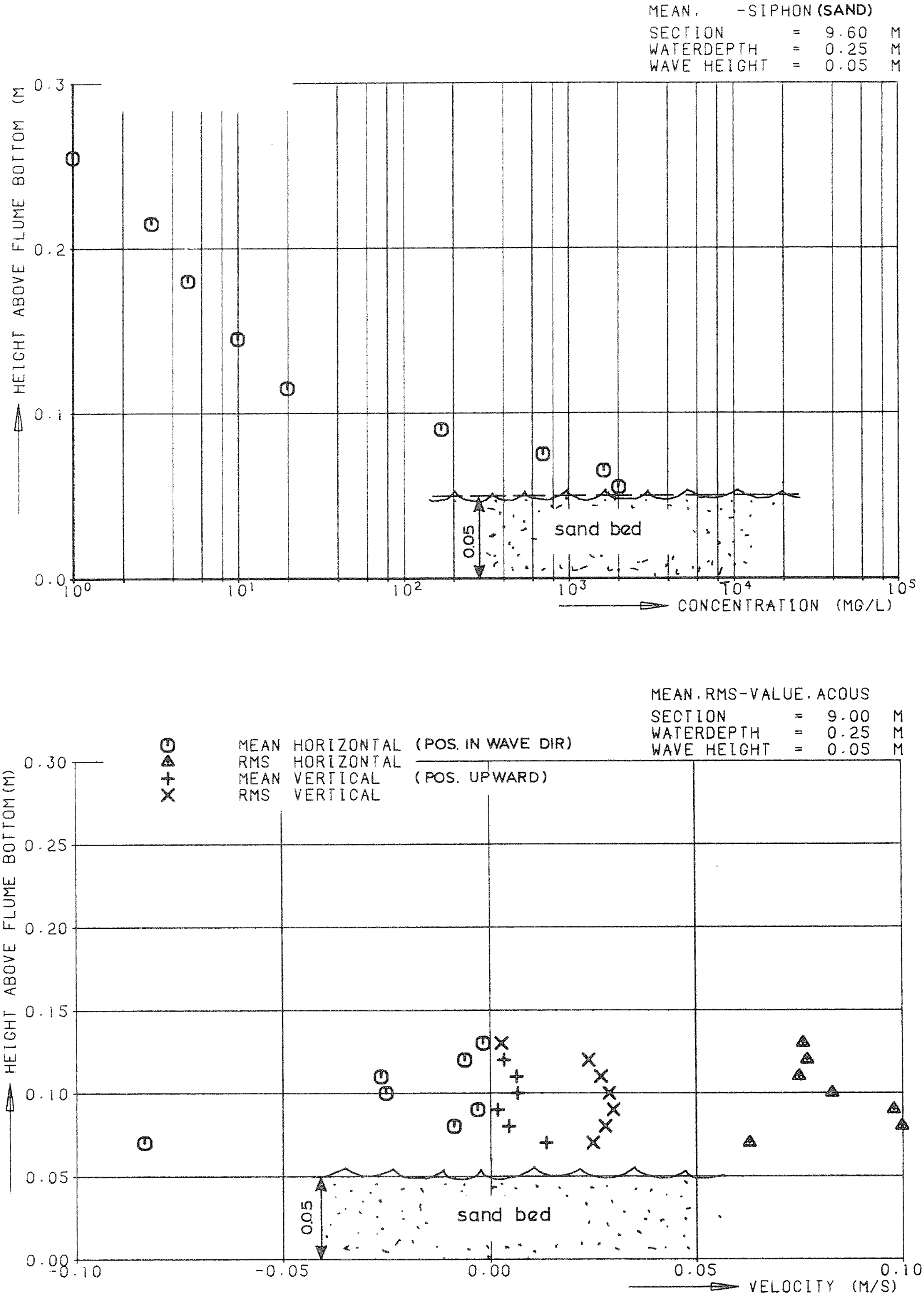
CONCENTRATION PROFILES (SIPHON)
VELOCITY PROFILES (ACOUS )

T6-6

DELFT HYDRAULICS LABORATORY

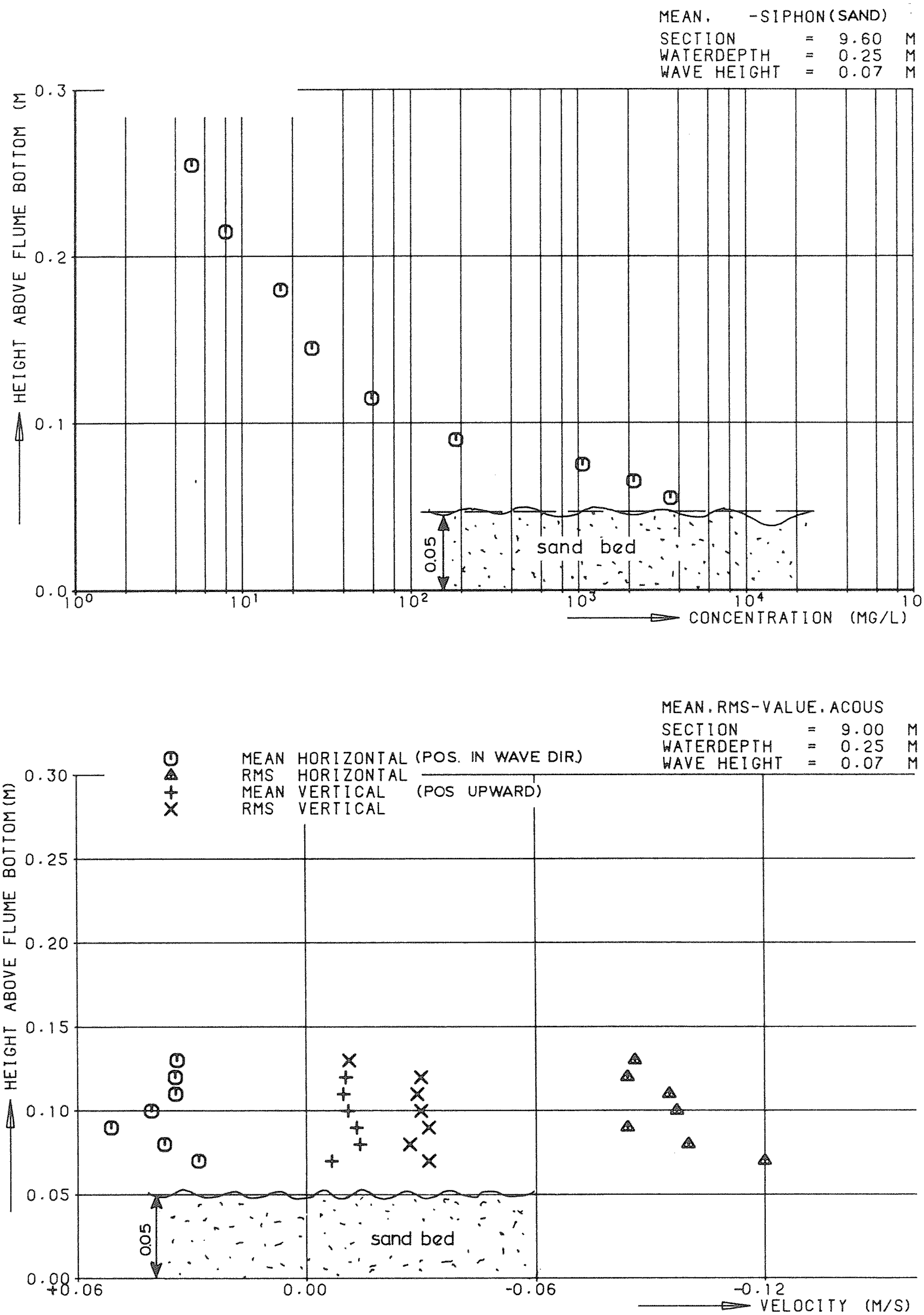
M 2060

FIG. 58



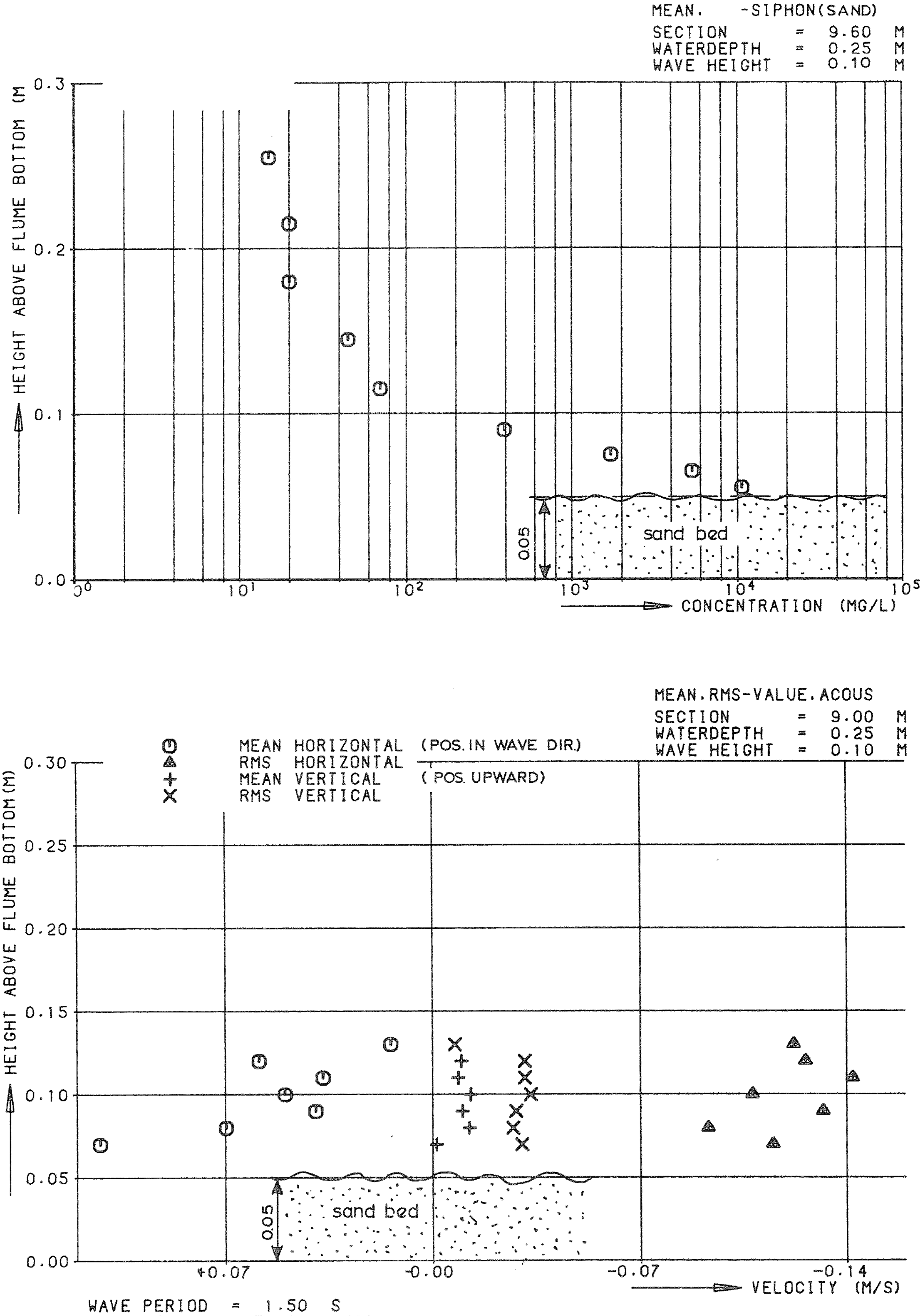

WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON)<br>VELOCITY PROFILES (ACOUS) | | T 7-2 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 59 |



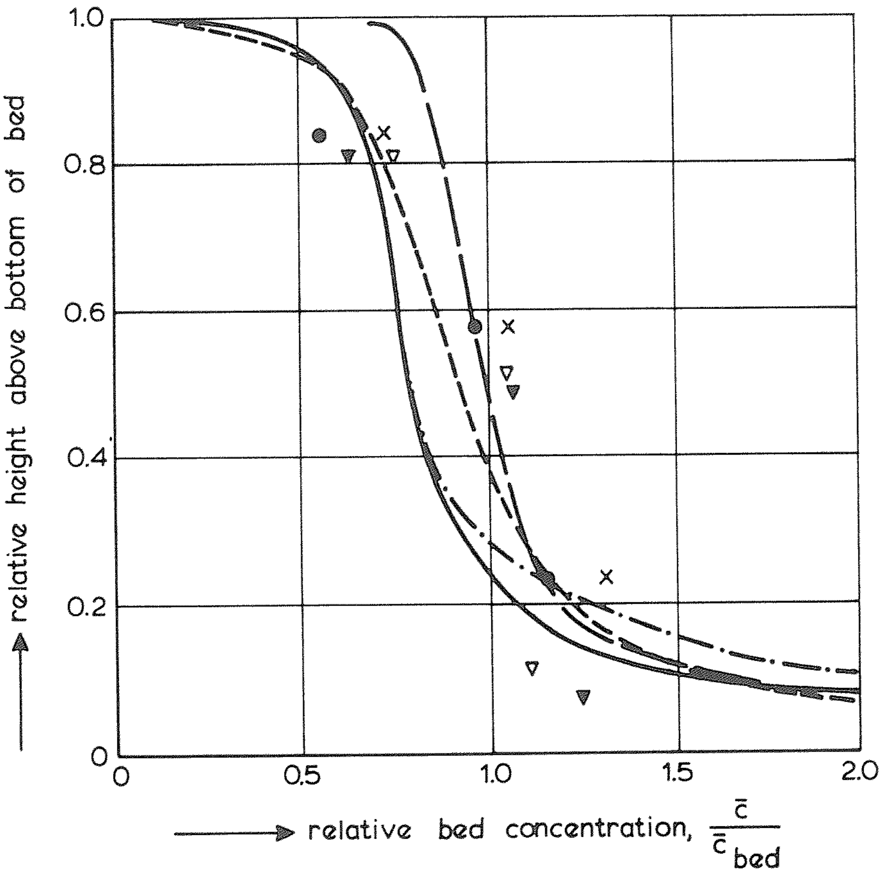

WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON)<br>VELOCITY PROFILES (ACOUS) | | T 7-3 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 60 |




WAVE PERIOD = 1.50 S
SALINITY = 31.00 0/00
TEMPERATURE = 7.00 C

| | | |
|---|---|---|
| CONCENTRATION PROFILES (SIPHON)<br>VELOCITY PROFILES (ACOUS) | | T 7-4 |
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 61 |




Koalinite beds

● T1 ▽ T3

× T2 ▼ T4

—— Brisbane mud ($\bar{c}_{bed}$ = 151 kg/m$^3$)

– – – Grangemouth mud ($\bar{c}_{bed}$ = 208 kg/m$^3$)

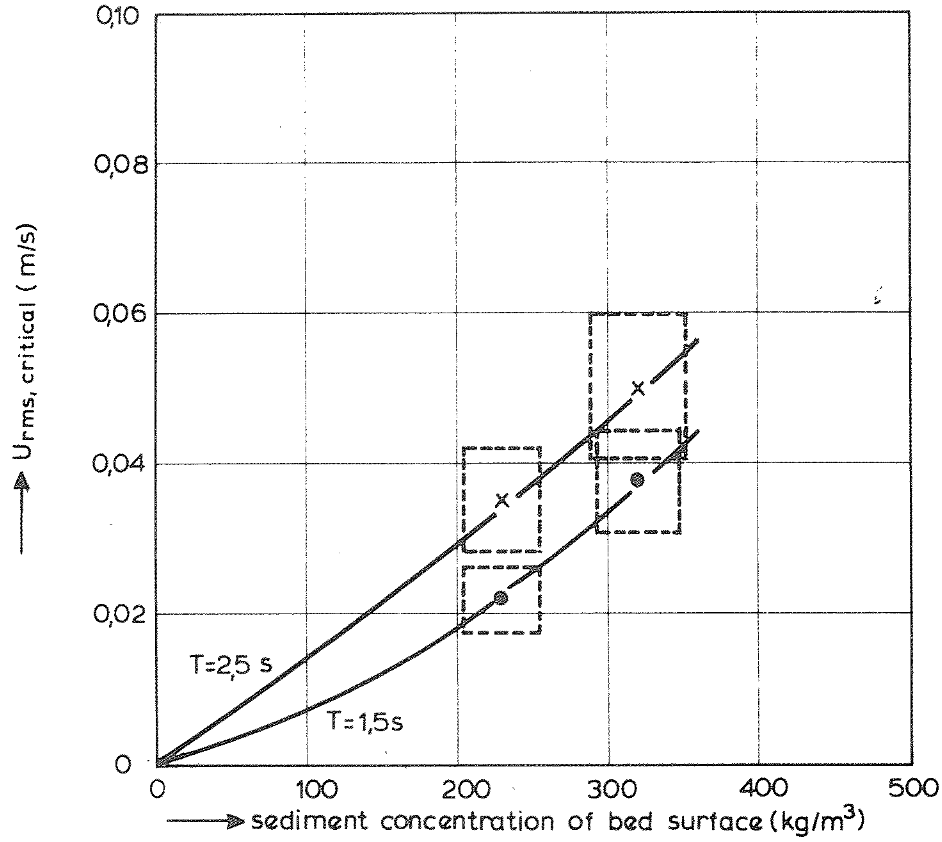
—·— Belawan mud ($\bar{c}_{bed}$ = 172 kg/m$^3$)

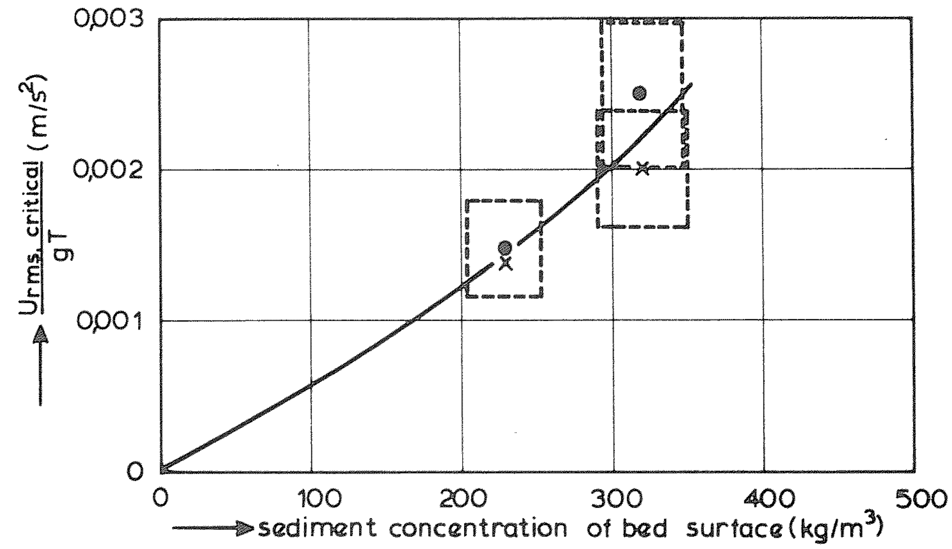
} Thorn and Parsons (1980)

— — Koalinite in non-saline water, Dixit (1982)

SEDIMENT CONCENTRATION DISTRIBUTION OF BED LAYER

DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 62



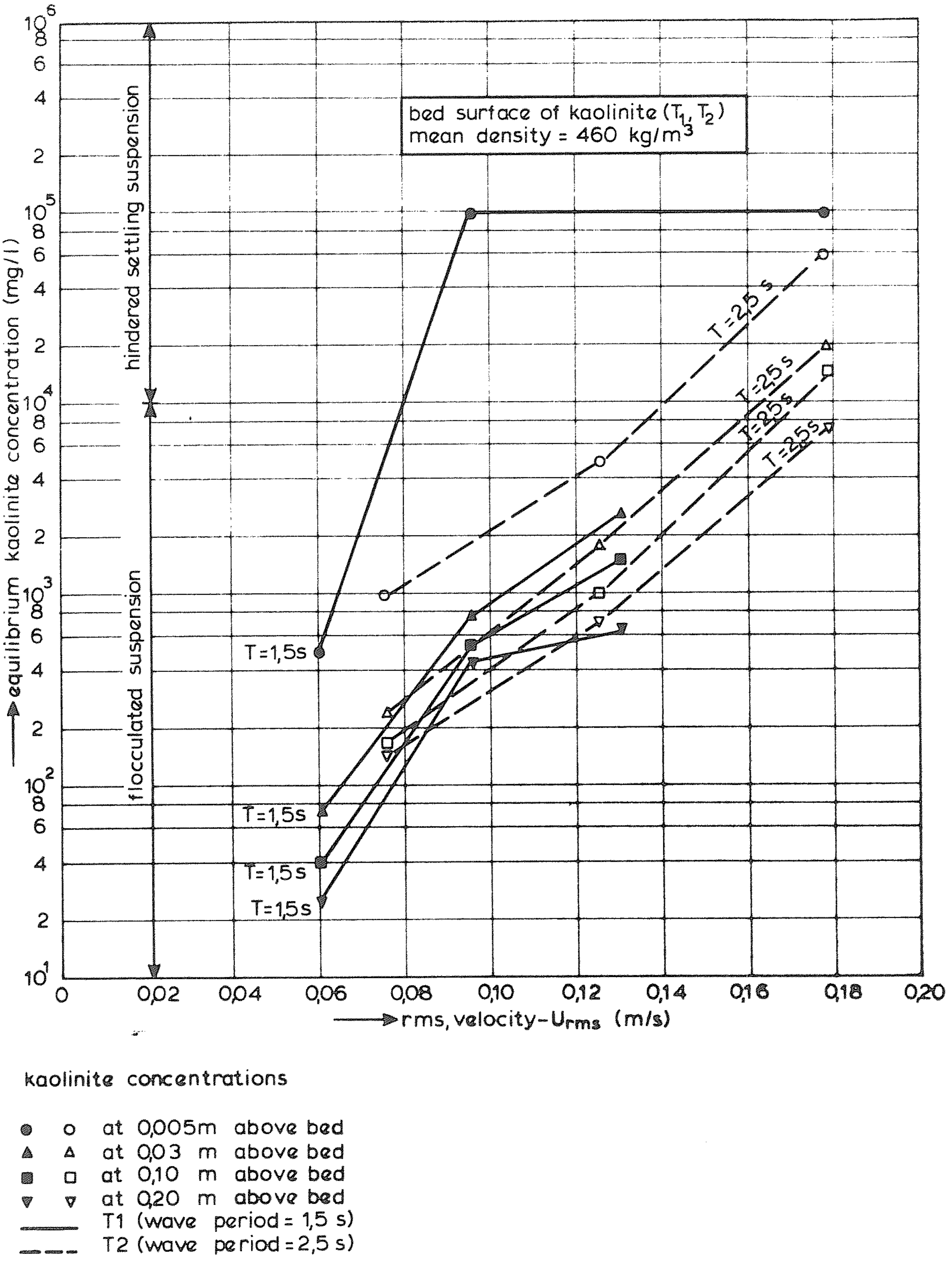




CRITICAL WAVE CONDITIONS FOR A
CONSOLIDATED KAOLINITE BED

DELFT HYDRAULICS LABORATORY

M 2060

FIG. 63

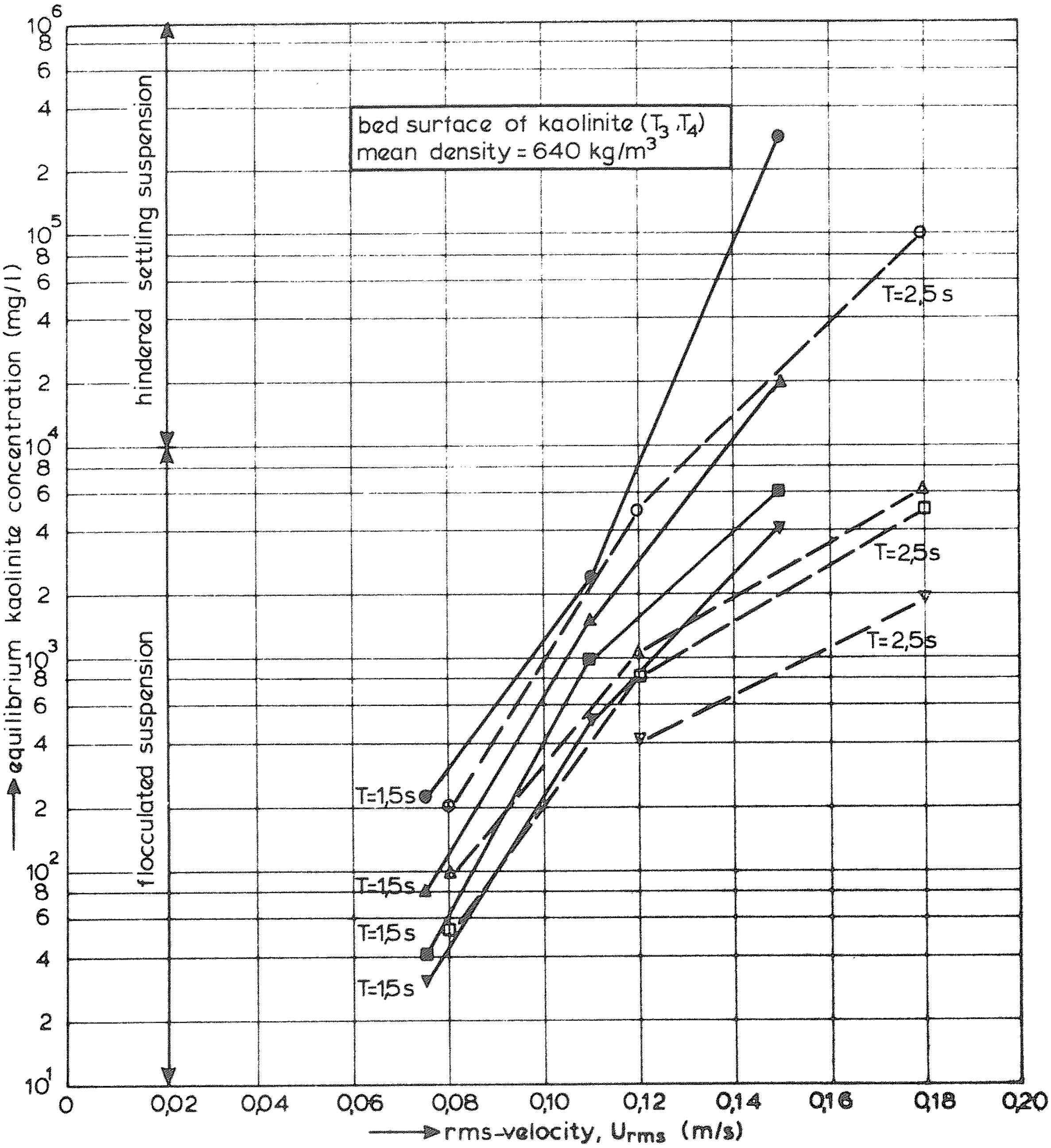



KAOLINITE CONCENTRATIONS

DELFT HYDRAULICS LABORATORY

M 2060

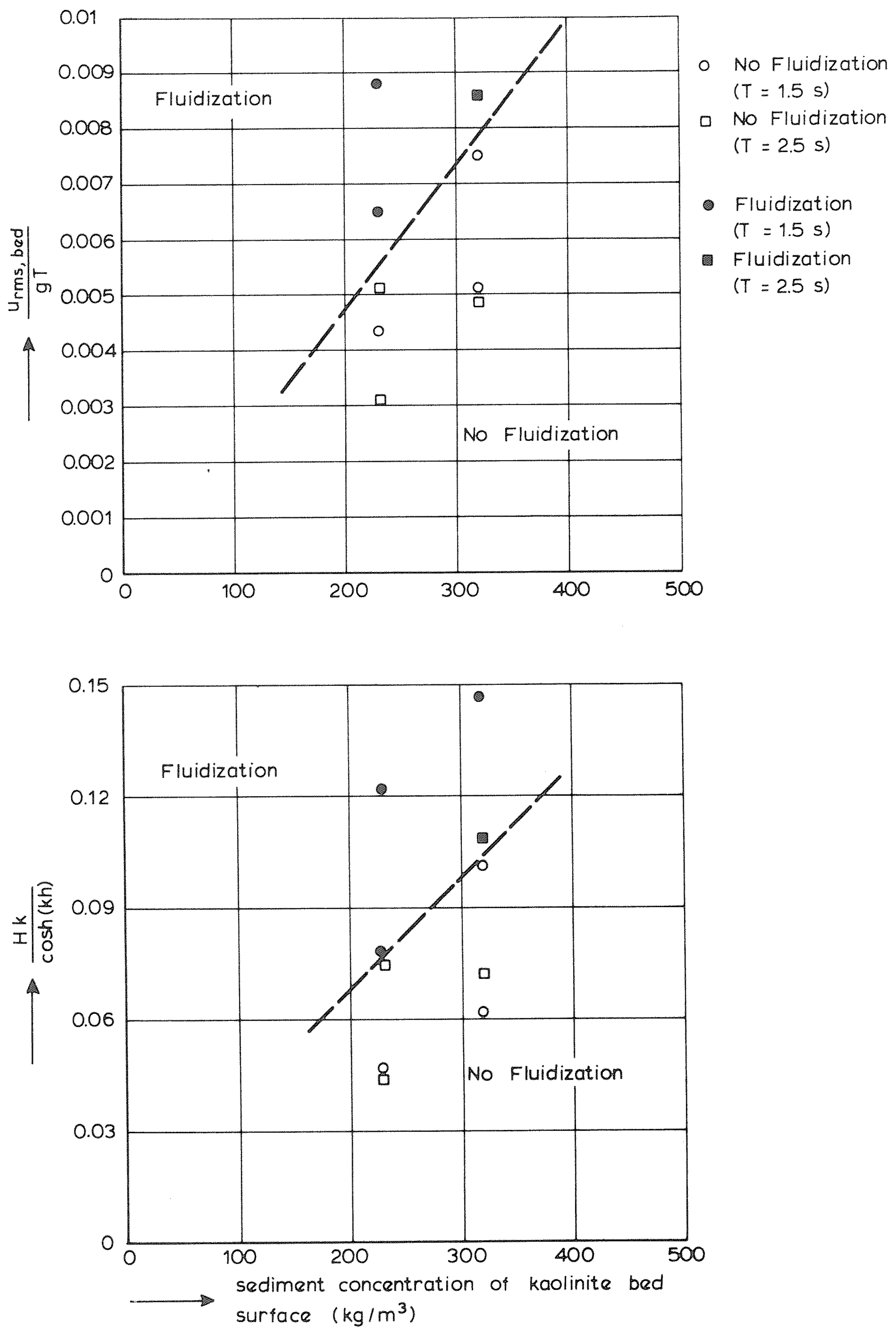
FIG. 64




kaolinite concentrations

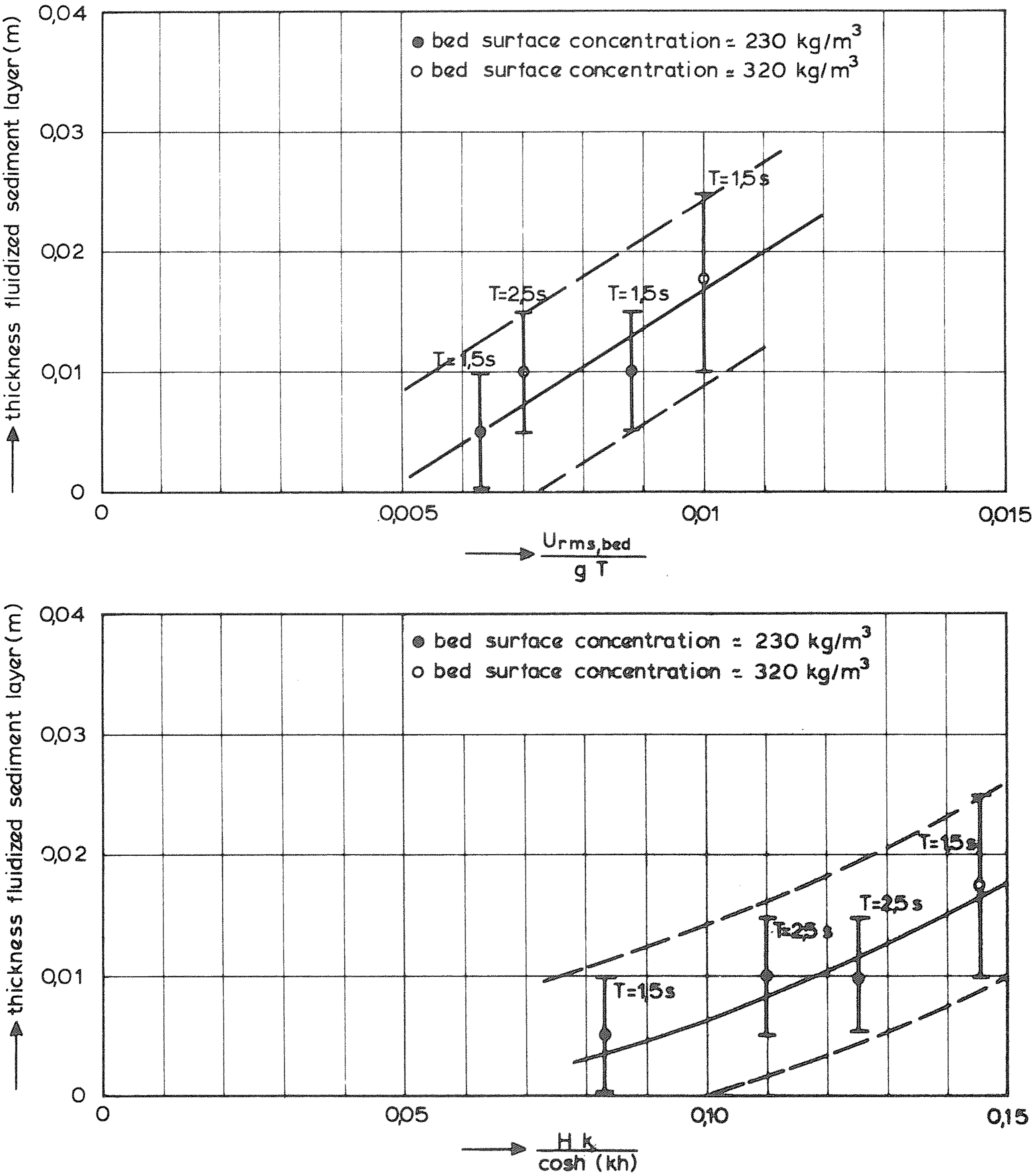
● ○ at 0,005m above bed
▲ △ at 0,03 m above bed
■ □ at 0,10 m above bed
▼ ▽ at 0,20 m above bed
— — - T3 (wave period = 2,5 s)
——— T4 (wave period = 1,5 s)

| KAOLINITE CONCENTRATIONS | | |
|---|---|---|
| DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 65 |



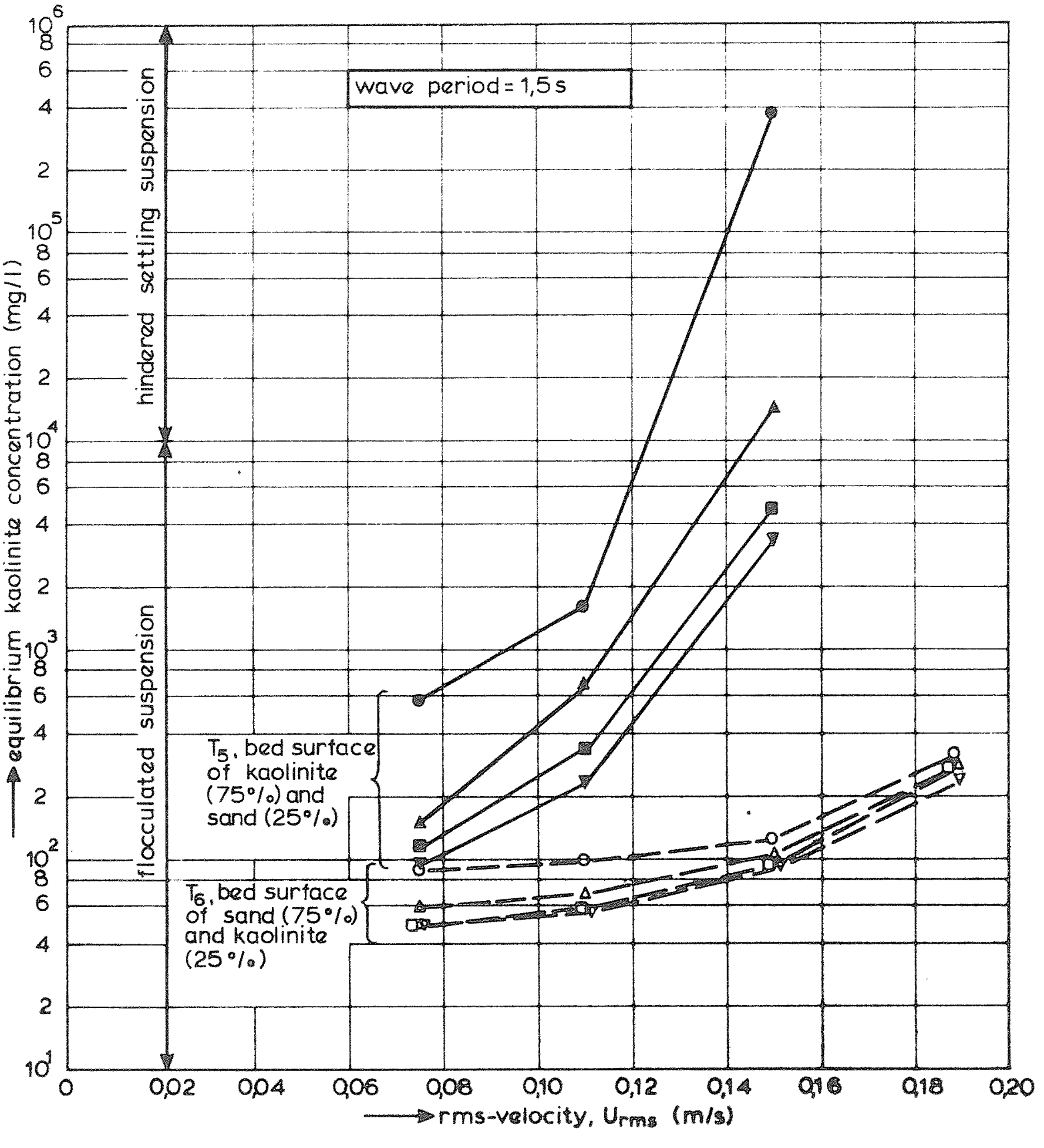

ONSET OF FLUIDIZATION OF KAOLINITE BED SURFACE

DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 66




THICKNESS OF FLUIDIZED SEDIMENT LAYER

DELFT HYDRAULICS LABORATORY | M 2060 | FIG. 67




kaolinite concentrations

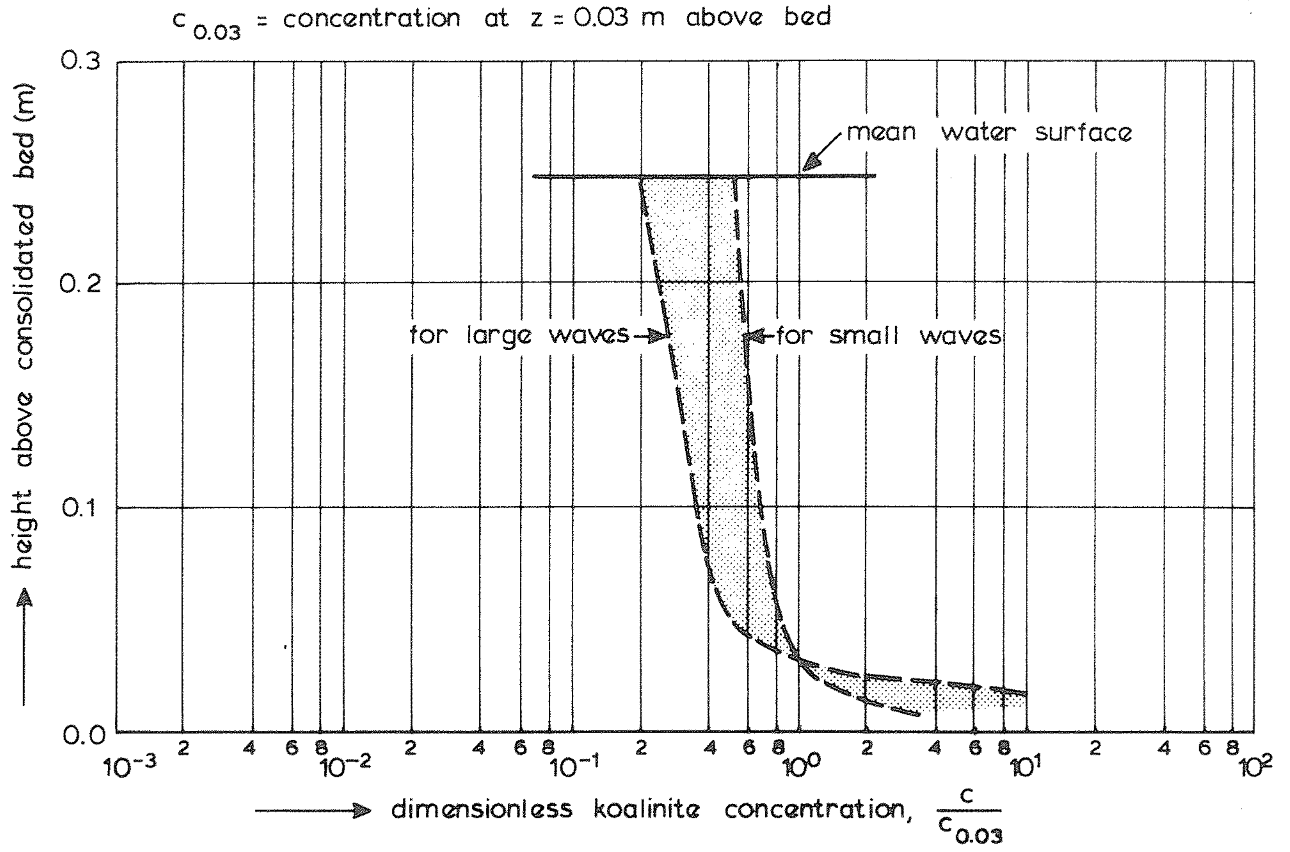
- ● ○ at 0,005 m above bed
- ▲ △ at 0,03 m above bed
- ■ □ at 0,10 m above bed
- ▼ ▽ at 0,20 m above bed

KAOLINITE CONCENTRATIONS

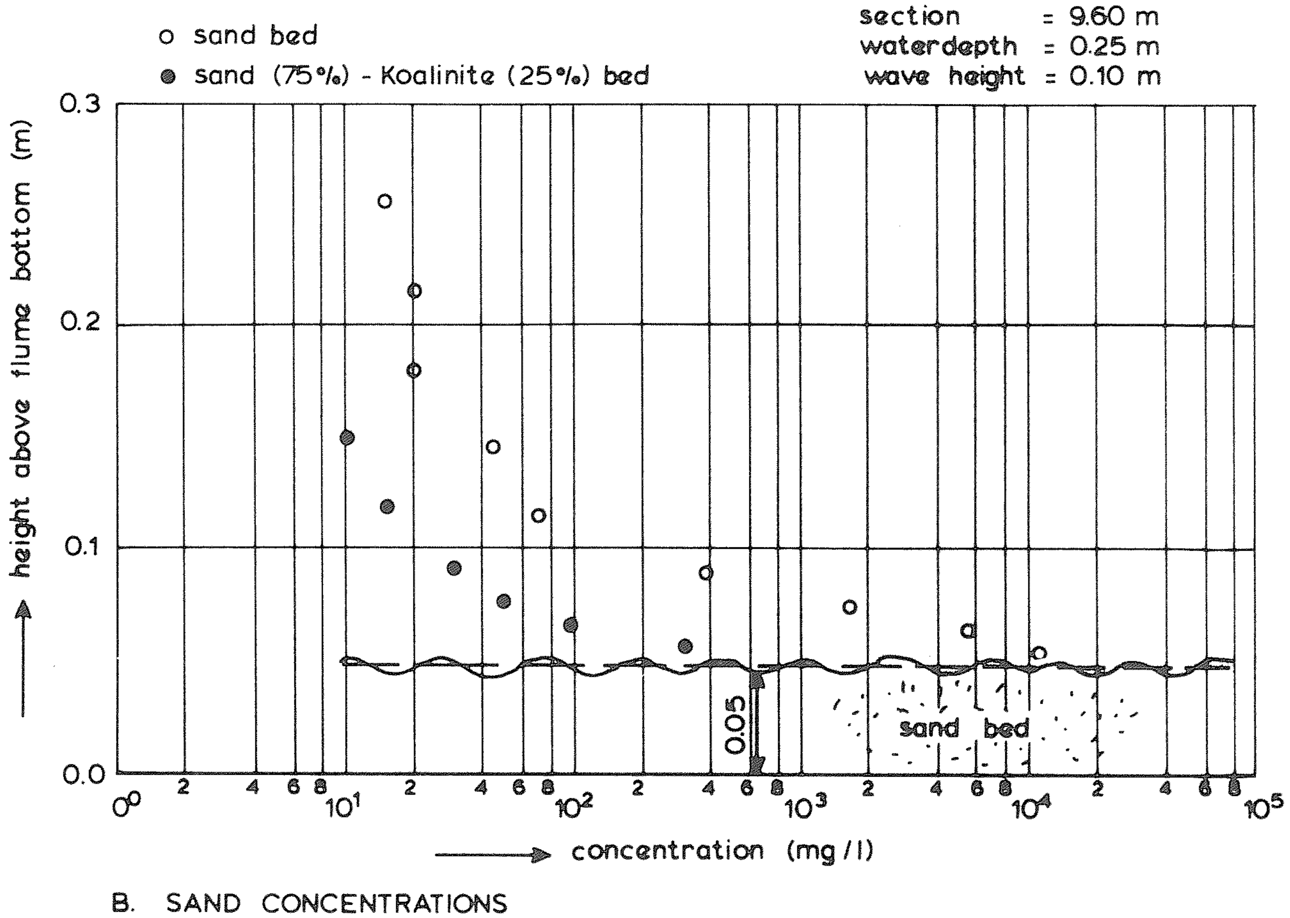
DELFT HYDRAULICS LABORATORY

M 2060

FIG. 68




A. KOALINITE CONCENTRATIONS




B. SAND CONCENTRATIONS

CONCENTRATION PROFILES

DELFT HYDRAULICS LABORATORY

M 2060

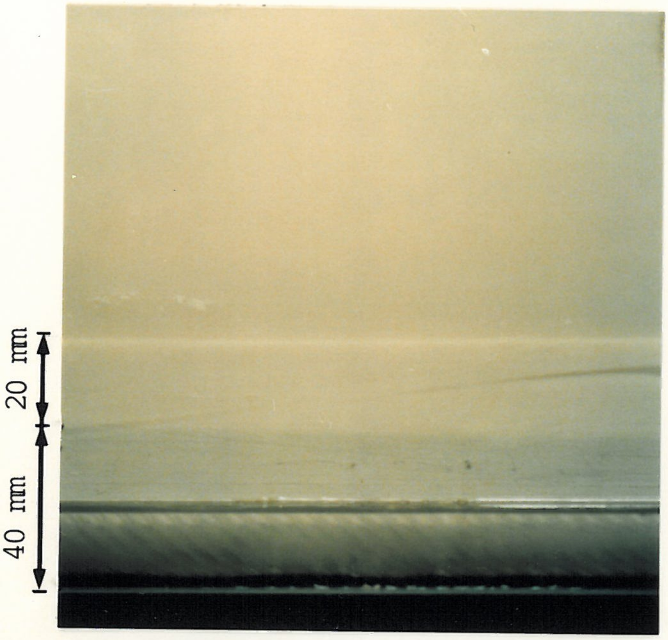
FIG. 69

no 1. Siphon sampler (left)
acoustical sampler (middle)
and optical sampler (right)

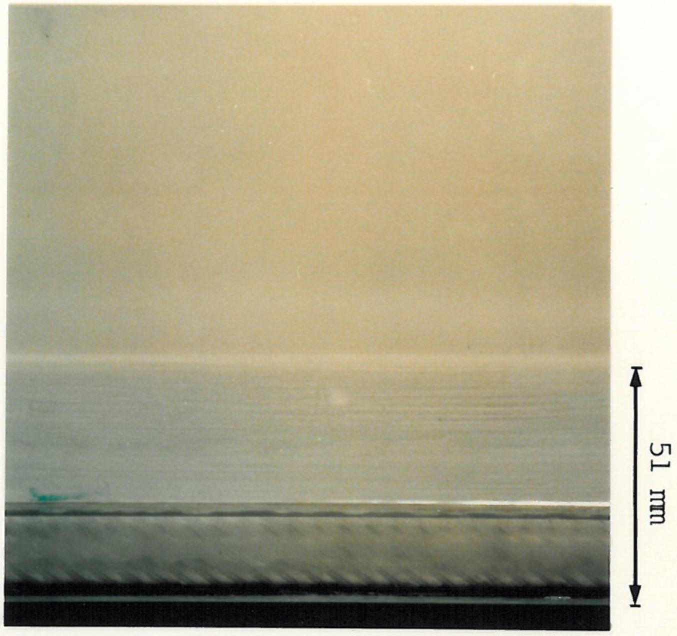
no 2. 5 ml-pipet sampler above
sand (yellow) and kaolinite
(white) bed

no 3. 20 ml-pipet sampler


no 4. Turbidity meter




no 5. Fluidized suspension layer (≃20 mm) above consolidated bed (≃40 mm) in section 11 (T3-4)

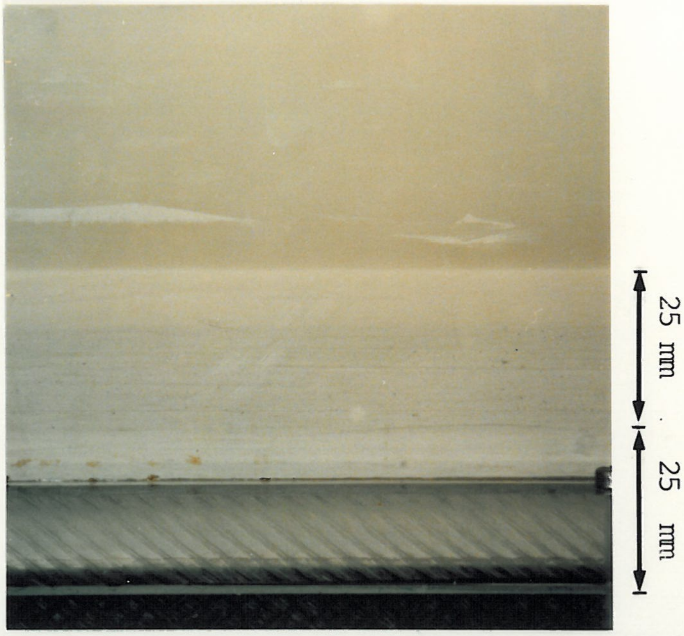



no 6. No fluidized suspension layer above consolidated bed (≃51 mm) in section 9.6 (T3-4)

no 7. Vortex motions above consolidated bed (T3-4)

no 8. Vortex motion above consolidated bed (T3-4)

no 9. Sand spots on koalinite bed (T5-4)




no 10. Fluidized suspension layer (≃ 25 mm) above consolidated bed (≃ 25 mm) in section 9.6 (T5-7)

no 11. Wave action in suspension layer

no 12. Wave action in suspension layer

p.o. box 177 2600 mh delft the netherlands