THE EFFECT OF WAVES ON COHESIVE BED SURFACES

by

L.C. van Rijn, Delft Hydraulics, The Netherlands
C.J. Louisse, Tidal Waters Division, Ministry of Public Works, The Netherlands

ABSTRACT

A laboratory flume study was performed to investigate the effect of waves on a bed of cohesive material. Kaolinite, sand and mixtures of kaolinite and sand were used as bed material. In case of a pure (100%) kaolinite bed a thin fluid mud layer was generated just above the bed. Above this layer, the concentrations were significantly smaller. A bed consisting of 75% kaolinite and 25% fine sand showed a similar behaviour as a pure kaolinite bed. A bed consisting of 75% fine sand and 25% kaolinite did not show the same behaviour as a pure (100%) sand bed. The most striking feature in this case was a strong suppression of the sand ripples and hence a strong reduction of the sand concentrations, while also the kaolinite concentrations remained very small.

1. INTRODUCTION

The presence of a location in the Dutch coastal zone where disposal of dredged mud takes place at a very large scale (about 5.10^6 tonnes per year) provides fairly good conditions for the occurrence of high-concentration mud flows close to the bed.
This conclusion was drawn after having analysed a series of ship-born measurements of suspended mud concentrations, which had not given an indication of significant mud transport taking place in the water column.
Even on places where due to dredge disposal activities some influence on the mud concentrations in the water column could be expected, minor effects were observed.
Therefore it was suggested that the mud could be transported in a thin layer above the bottom. Measurements from a ship were not supposed to be able to detect such layers, not just because measurements at near bottom levels were hardly feasible, but also because major transports of mud were supposed to take place during rough weather conditions, when ships were not able to work.
The mechanism which was suggested to be responsible for generation of such a layer should be the oscillating pressure of surface waves fluidizing the bottom surface. Tidal or other currents should be able to transport a fluid layer.
This discussion stimulated the need of equipment to measure mud concentrations and transports at levels (very) close to the bottom, preferably a self-supporting system to measure continuously during a long period (months).
The first tests with equipment satisfying the above specifications were performed at a location in the North Sea near the Harbour of Rotterdam (see Fig. 1) in a water depth of 7.5 to 10 m (including tidal range and wind set-up). The mud concentration was measured at 0.3 m above the bed using an optical instrument (Partech). The vertical tide, wave and wind parameters were also measured at a quasi-continuous rate at the measuring location DK-I (Fig. 1).
The equipment worked for three months and provided a series of data useful for the interpretation of mud transport events.
An example of a three-days presentation of the data collected is given in Figure 2. A complete presentation of the results will be presented in another publication. Here the occurrence of high suspended mud concentrations up to 1500 mg/l (full scale) during and after periods of relatively high wave energy is emphasi-

zed, indicating at least some relation between wave influence and suspended mud transport.

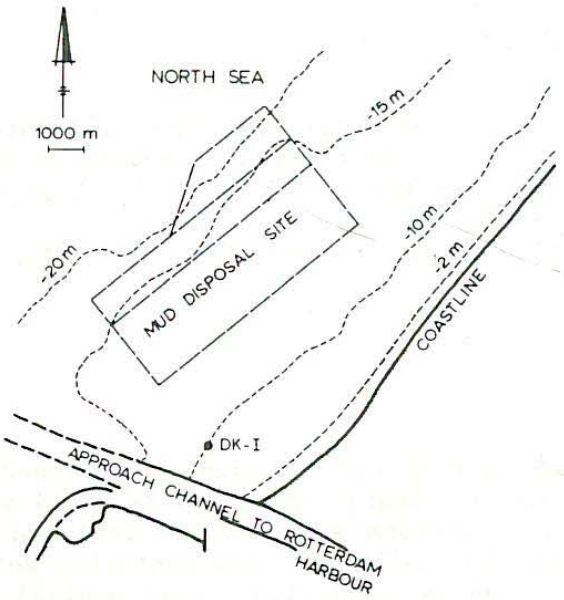

Fig. 1, Measuring location DK-I in North Sea

This knowledge led to the need of experimental support of these observations. Therefore a wave flume was equipped to study the behaviour of a mud bottom under waves. The wave flume experiments should provide a qualitative and as far as possible also a quantative insight into the relation between hydraulic parameters (wave height, wave period, orbital velocities) and bottom parameters (bed density, bed thickness).
The experimental set-up, the methods and the results of the measurements in the flume are presented briefly in the next sections. Detailed information is given by Van Rijn (1985).

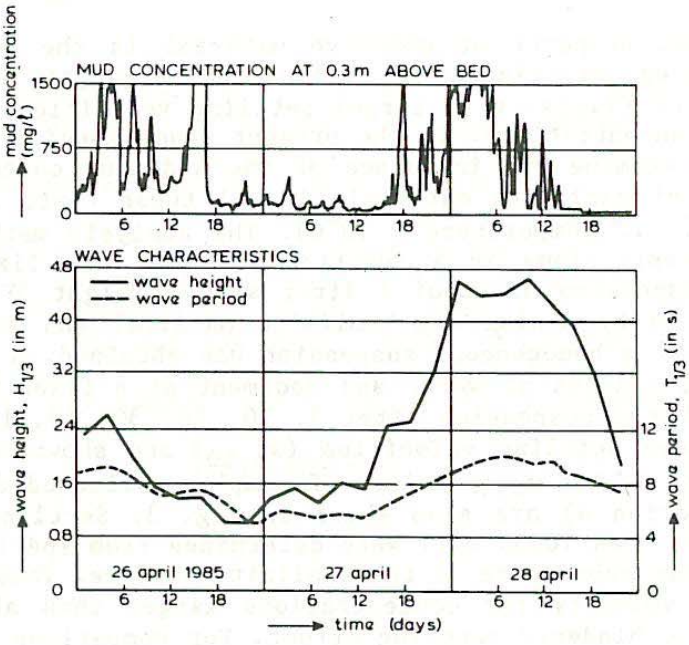

Fig. 2, Mud concentration and wave characteristics at DK-I location

2. CHARACTERISTICS OF KAOLINITE MATERIAL

2.1 Chemical and mineralogical composition

Commercially available kaolinite material and fine sand material were used as bed material in the present study. The chemical composition of the kaolinite material, as given by supplier 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 is as follows: Kaolinite 80%, Illite 15%, Quartz 4%, Smectite 1%.

2.2 Particle size

Particle size analysis was carried out by using a sedimentation method and a laser diffraction method. The sedimentation method is based on the sedimentation of particles in an initially uniform suspension. Distilled water of 20°C was used as the settling medium. Basically, 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 stationary diffraction pattern. Using the measured diffraction pattern, a computer analysis is performed to find the size distribution that gives the closest fitting diffraction pattern. The following values were obtained:
Sedimentation method : D_{50} = 4 μm, D_{90} = 15 μm
Laser diffraction method: D_{50} = 6 μm, D_{90} = 20 μm
Particles larger than 50 μm were not detected.

2.3 Settling velocities

An important sediment property of cohesive material is the settling velocity (w_s). 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°/.., 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 with a height of 0.2 m. 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. The measured mean settling velocities ($w_{s,50}$) are shown as a function of concentration in Fig. 3. The $w_{s,50}$-values of samples collected during the actual flume tests (see Section 4) are also shown in Fig. 3. Settling velocities for concentrations larger than 10000 mg/l were determined from special sedimentation tests by observing the subsidence of the kaolinite surface. These results show a decreasing settling velocity for concentrations larger than about 10000 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 leading to additional flocculation during the settling process.

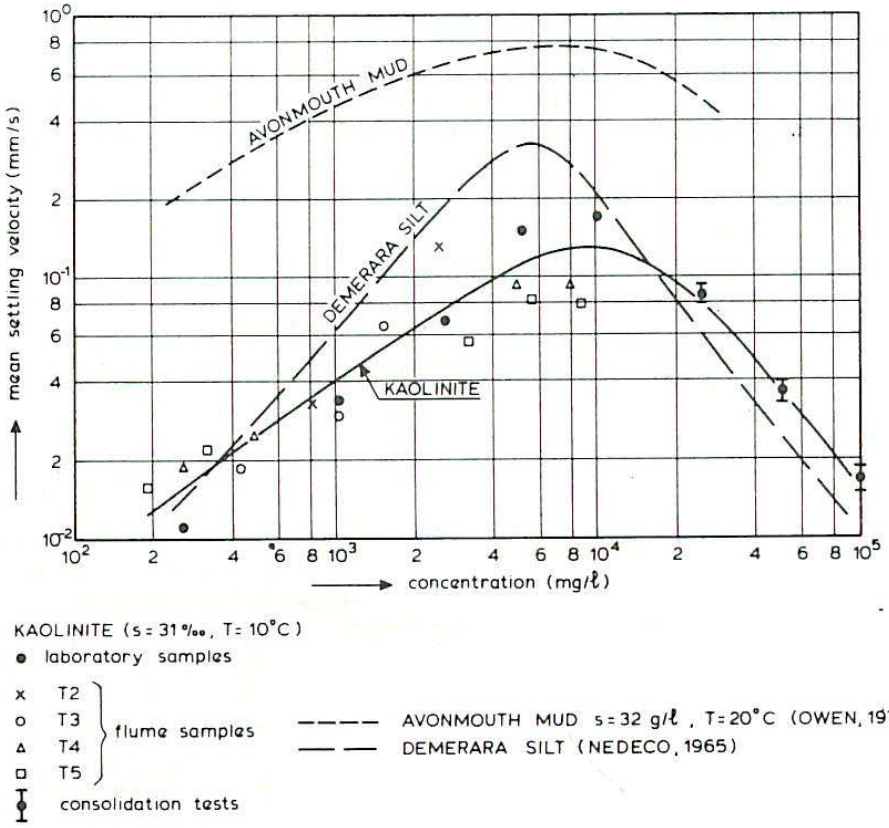

Fig. 3, Mean settling velocity as a function of concentration

3. EXPERIMENTAL SET-UP AND MEASURING INSTRUMENTS

3.1 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 4 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. 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 of about 0.05 m. Then, the flume was filled slowly with saline water (salinity = 31°/₀₀, temperature = 10°C). In all experiments the water depth was about 0.25 m.

3.2 Measuring instruments

Wave heights were measured by using a wave height meter based on the principle of conductivity.
Instantaneous horizontal velocities were measured by a Laser-Doppler method. Time-averaged values and root-mean-square values were determined using a time-

domain analyzer. The Laser-Doppler system was only used in preliminary tests with clear water. Based on these measurements, a relationship between the wave height and the rms-velocity near the bed was derived (van Rijn, 1985).
Three methods were used to determine the sediment concentrations in the test section of the flume, being a siphon method, an optical method, and a pipet method.

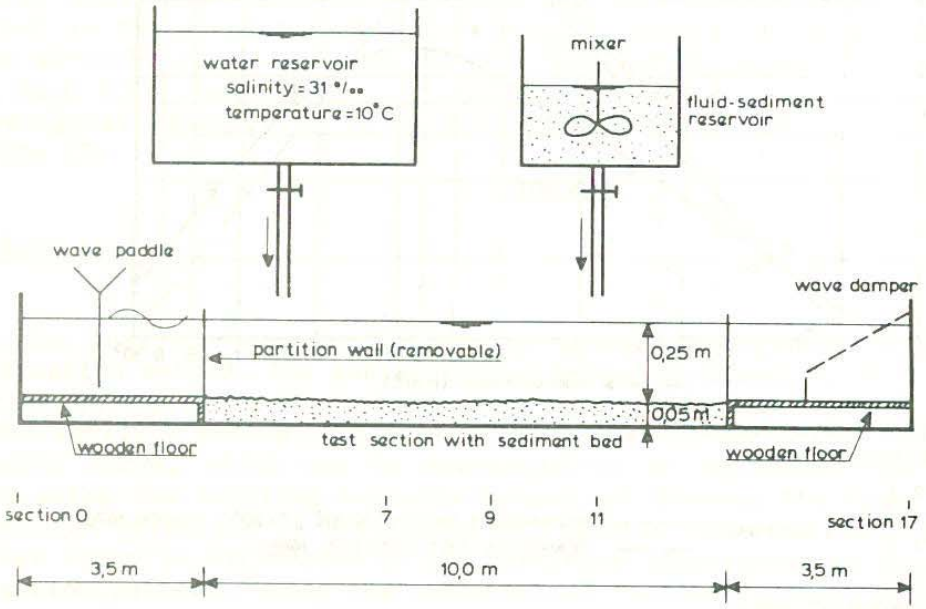

Fig. 4, Experimental set-up

The siphon method consisted of a system of brass intake tubes with an internal diameter of 0.003 m connected to plastic hoses. 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 presenting a vertical mud concentration profile. 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 instrument which is based on the principle of light extinction by the sediment particles, consisted of two vertical legs containing the light source and the light detector. 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. The calibration was done by taking water-kaolinite samples during the flume tests. The samples were transferred to a special (rotating) cylinder and the output signal of the optical probe (placed in the cylinder) was read. After that a small subsample was taken from the cylinder to determine sediment concentration (filtering and weighing). The measuring period of the optical sampler in the flume tests was 30 seconds.
The pipet method was used to collect water-kaolinite samples close to the bed during the flume tests. 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. The pipet was attached to a point-gage (accurate to 0.1 mm) to ensure an accurate determination of the sampling depth. To determine the kaolinite concentration of the siphon and the pipet (20 ml) samples, small subsamples were withdrawn using the 5 ml-pipet. Each subsample was transferred to a small glass tube to be analyzed in a commercially available laboratory turbidity meter. When necessary, the samples were diluted using clear water of the same salinity to fall within the measuring range (0 - 2000 mg/l) of the turbidity meter. Special calibration tests using the same kaolinite material were carried out yielding a relationship between output signal and kaolinite concentration. 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 systematically 10% larger than the prepared concentrations.

3.3 Experimental procedure and conditions

The experimental procedure was as follows:

- preparation of sediment suspension in a container by mixing dry sediment material with saline water (salinity = 31%, temperature = 10°C),
- formation of sediment layer in flume by pumping the sediment suspension from the container into the flume,
- sedimentation and consolidation of sediment layer in flume to obtain a consolidated bed layer of sediment with a thickness of about 0.05 m (consolidation period of about 3 days),
- generation of waves (phase 1) to erode sediment particles and execution of measurements; wave height is constant over a period of about 3 hours and then raised to a higher value (Fig. 7),
- deposition of suspended sediment after stopping the wave generator (deposition period ranging from 20 to 40 hours),
- generation of waves (phase 2) to resuspend the deposited sediment particles and execution of measurements.

Various types of sediment mixtures were tested in the present study. In four experiments the bed consisted of pure (100%) kaolinite material with two different densities. In two other experiments the bed consisted of a mixture of fine sand ($d_{50} \approx 100$ μm) and kaolinite. In the last experiment the bed consisted of pure (100%) sand ($d_{50} \approx 100$ μm). The experimental conditions are given in Table 1.

Test	Bed material	mean dry density (kg/m^3)	wave period (s)
T1	kaolinite	460	1.5
T2	kaolinite	460	2.5
T3	kaolinite	640	2.5
T4	kaolinite	640	1.5
T5	75% kaolinite, 25% sand	790	1.5
T6	25% kaolinite, 75% sand	1700	1.5
T7	sand	1600	1.5

Table 1, Experimental conditions.

4. EXPERIMENTAL RESULTS

4.1 Sediment concentration of bed layer

Pipet samples were taken from the consolidated bed layers to obtain information of the vertical distribution of the dry density (or concentration) of these layers. The results of tests T1, T2, T3 en T4 are presented in Fig. 5, showing typical profiles with low but finite concentrations near the bed surface and high concentrations at the bottom.

The depth-mean concentrations are given in Table 1. The bed layer thickness is about 0.05 m.

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.

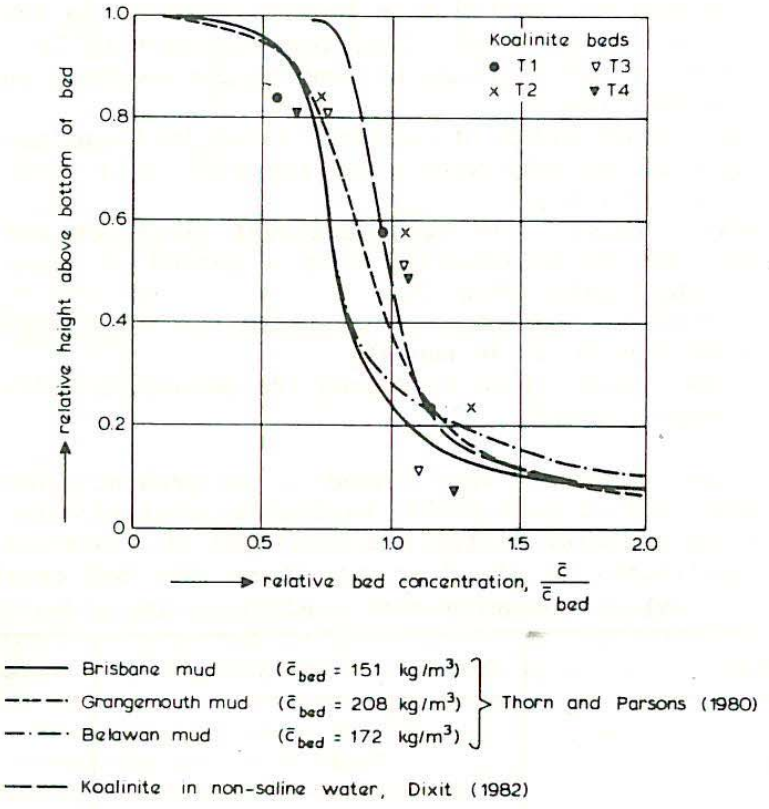

Fig. 5, Sediment concentration profile of bed layer

4.2 Initiation of motion

Initiation 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. Figure 6A 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 ($c_s = 0.5\ \bar{c}_{bed}$).
Figure 6B shows the critical conditions for initiation 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 on critical wave conditions for a kaolinite bed could be found in the literature. Review of the literature showed much information on 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 ($c_s \approx 300$ kg/m³).

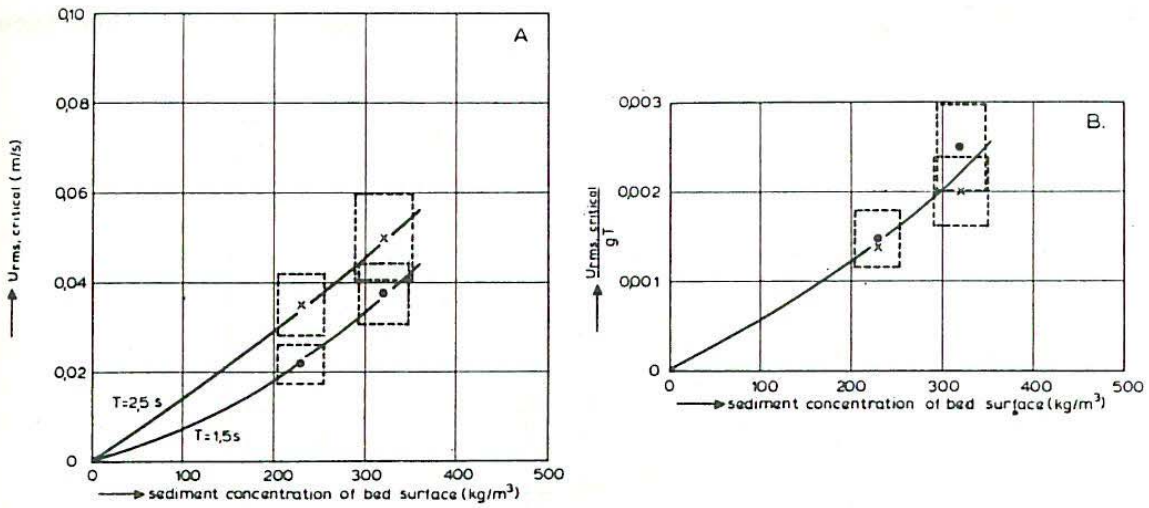

Fig. 6, Initiation of motion for a cohesive bed under wave action

4.3 Erosion of bed surface

Bed surface of pure kaolinite

Each experiment consisted of a sequence of increasing wave heights, starting with a small wave height. At each (constant) wave height, equilibrium conditions were established after a few hours, as shown schematically in Fig. 7. During this period sediment concentration measurements were performed. After that the wave height was increased and the measurements were repeated and so on.

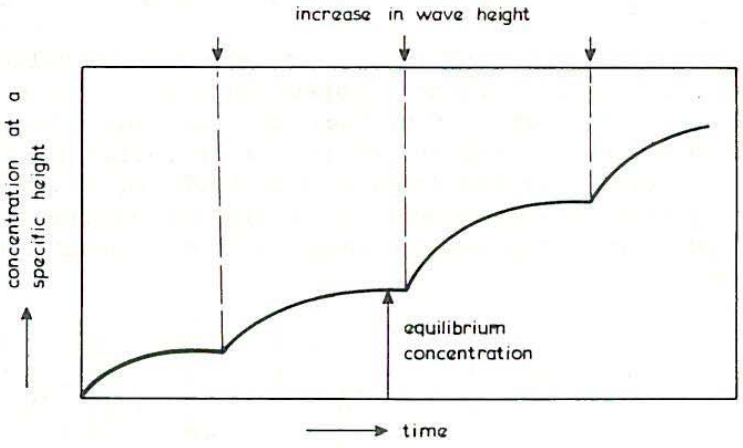

Fig. 7, Sediment concentration at height z as a function of time t

The experimental results of test T4 are used to show the typical erosion phenomena of kaolinite material observed during the T1-T5 tests.
General sediment movement was observed with a wave height of 0.022 m (u_{rms} = 0.05 m/s) during test T4. At the end of this test period a thin layer (0.01 m) of kaolinite suspension was generated in which concentrations of about 100 mg/l were measured. Small vortex motions were also observed (visually). With a wave height of 0.03 m the thickness of the kaolinite suspension layer increased to about 0.05 m. A vague interface was visible. Figure 8 shows sediment concentration profiles (optical samples) at various time intervals. The concentrations

range from about 500 mg/1 close to the bed to about 50 mg/1 near the interface of the suspension layer.

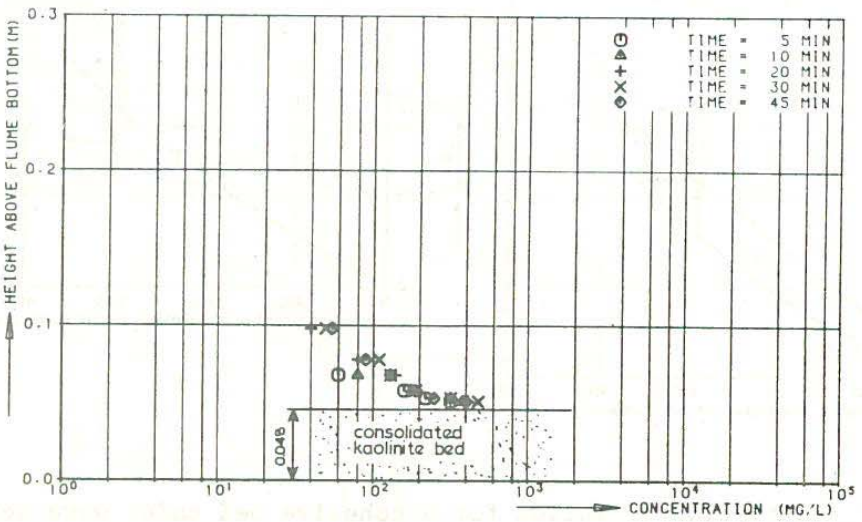

Fig. 8, Sediment concentration profiles, Test T4, wave height = 0.03 m

The wave height was increased to 0.047 m. In the initial stage of this period the kaolinite concentrations were reduced because the suspension layer was diluted by (orbital) mixing with clear water from higher levels. After 30 minutes this process 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 by wave action. Equilibrium conditions were established after about 200 minutes with concentrations in the range of 2500 mg/1 near the bed to 500 mg/1 near the water surface, as shown in Fig. 9.
After this test period the wave generator was stopped and the kaolinite suspension was allowed to settle and consolidate for 43 hours resulting in a relatively clear fluid in the flume. Locally, small scour holes with a depth of 0.02 m were visible at the bed.
In the next test period the wave height was increased to a value of 0.07 m resulting in the generation of a fluidized suspension layer with an initial thickness of about 0.01 m at the top of the bed. The concentrations in this layer were larger than 100000 mg/1. At the end of this test period (after 150 min) the thickness of the fluidized layer had increased to 0.025 m, as shown schematically in Fig. 10. The concentrations above the fluidized suspension layer are in the range of 20000 mg/1 near the bed to about 4000 mg/1 near the water surface (based on siphon samples).

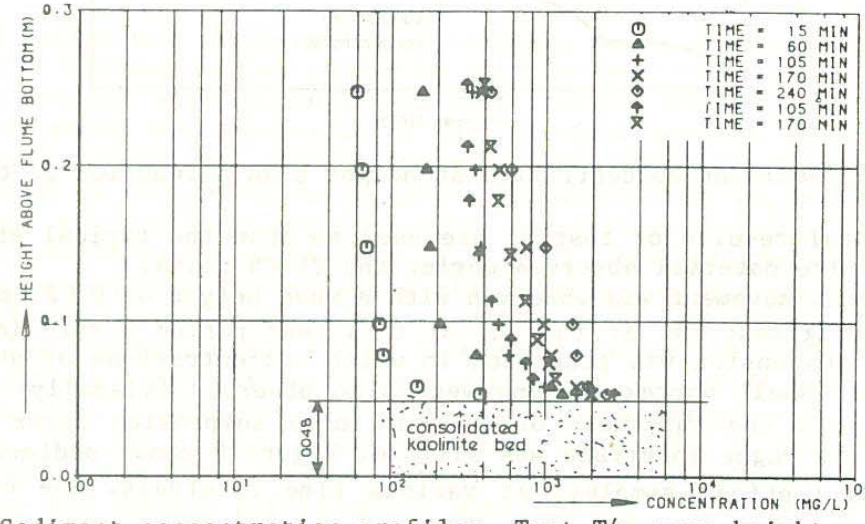

Fig. 9, Sediment concentration profiles, Test T4, wave height = 0.047 m

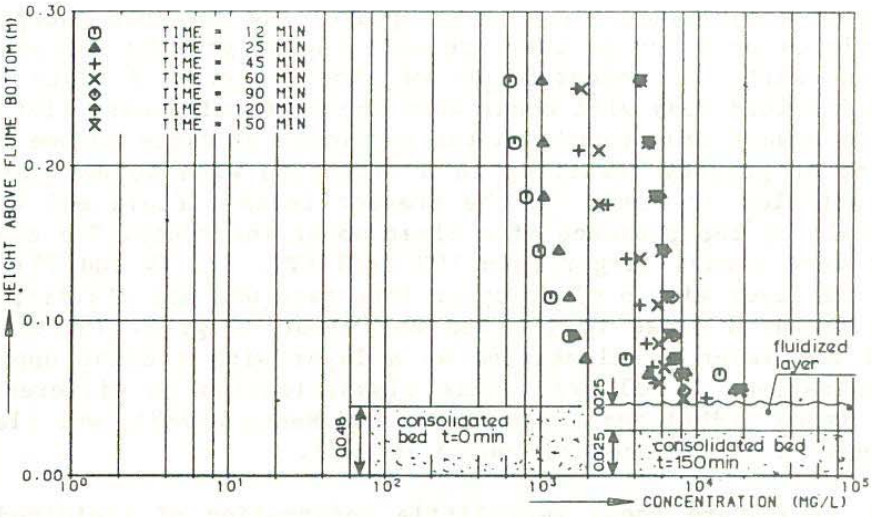

Fig. 10, Sediment concentration profiles, Test T4, wave height = 0.07 m.

Suspension samples were collected at 0.02 m and at 0.17 m above the bed using the siphon sampler for fall velocity analysis. A sedimentation method was used to determine the particle fall velocity of the samples yielding a mean fall velocity of about 0.09 mm/s and an equivalent Stokes diameter of 11 μm for both samples. Since, the original kaolinite material has a Stokes diameter of about 5 μm, a small flocculation effect can be observed.

During the T4-test dye injections were also made near the bed to determine mass-transport velocities, as reported by Longuet-Higgins (1953). The observed mass-transport velocities near the bed of the dye centre were in the range of 0.005 to 0.02 m/s for wave heights of 0.03 to 0.07 m (in the wave direction). These values are half as large as those predicted by the theory of Longuet-Higgins.

So far, only the results of test T4 have been presented. Equilibrium concentrations (see Fig. 7) of all tests with a bed of pure kaolinite (T1, T2, T3, T4) are presented in Figs. 11 and 12. Both figures 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-value (u_{rms}) of the orbital velocities near the bed and the wave period (T). As can be observed in Figs. 11 and 12, 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. 11). 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 large 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 feature 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 (T2, Fig. 11).

Influence of the bed density can be observed by comparing the results of Figs. 11 and 12, indicating a tendency for smaller concentrations for a larger bed density. This can be explained by assuming that a larger bed density is related to a larger erosion resistance as suggested by Thorn and Parsons (1980) and Mehta and Partheniades (1982).

Based on the present experimental results, the following classification for kaolinite suspensions is given (see also Fig. 3):

flocculating mud layers with concentrations	< 10	gr/l
hindered-settling mud layers with concentrations	10-100	gr/l
fluid mud layers with concentrations	100-500	gr/l
consolidated mud layers with concentrations	> 500	gr/l

Hindered settling occurs when there is an upward flow of fluid escaping from between the particles or flocs as they are settling by gravity. According to Fig. 3, this process starts at concentrations of about 10 gr/l. A state of fluidization of the bed (fluid mud) will occur when the vertical upward fluid flow is so strong that the upward drag forces on the particles or flocs become equal to the downward forces of gravity resulting in a situation with no net vertical movement of the particles or flocs. In the present tests a fluid mud layer was always identifiable by the presence of a clear upper interface. The concentrations in this layer were always larger than 100 gr/l (T1, T3, T4 and T5). In the T2-test a fluid mud layer with a clear upper interface was not visible; the largest concentration measured close to the bed was about 60 gr/l. Therefore, in this study a fluid mud layer is classified as a layer with a clear upper interface showing concentrations > 100 gr/l. This classification is different from that introduced by Krone (1962) and later by Maa and Mehta (1986), who classify fluid mud as a suspension with concentrations > 10 gr/l.

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. 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 in saline water with a depth of 0.55 m and a wave height of 0.15 m (period = 2 s). 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. Recently Maa and Mehta (1986) also report the generation of high-concentration mud layers close to the bed (concentrations ranging from 10 to 100 gr/l).

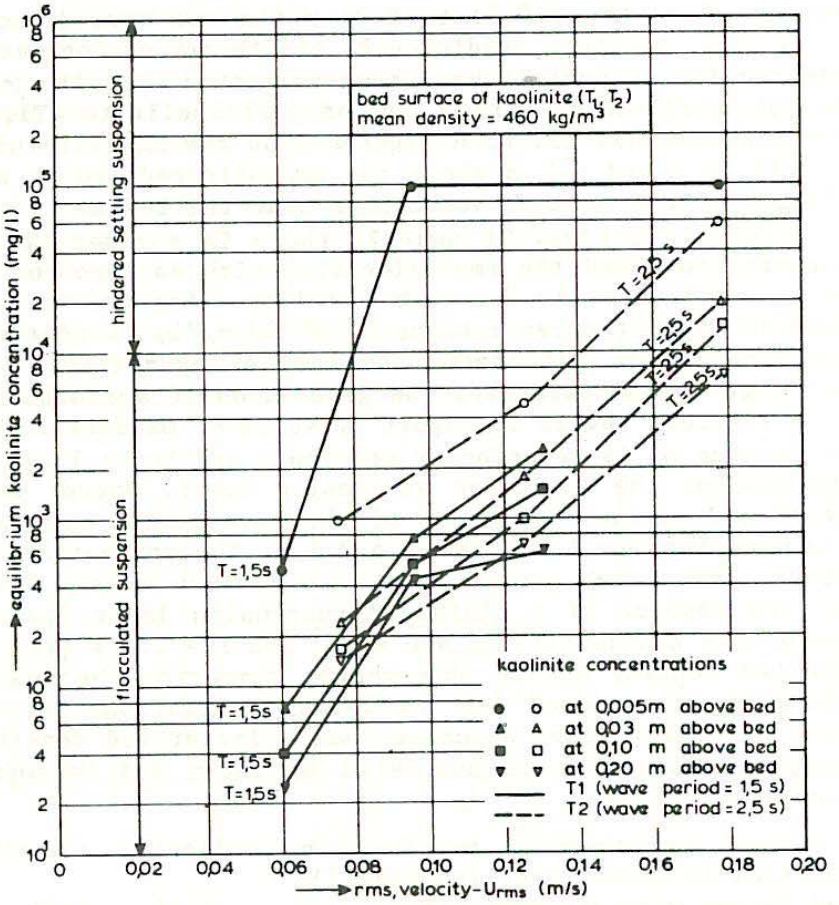

Fig. 11, Sediment concentrations as a function of u_{rms} and wave period T

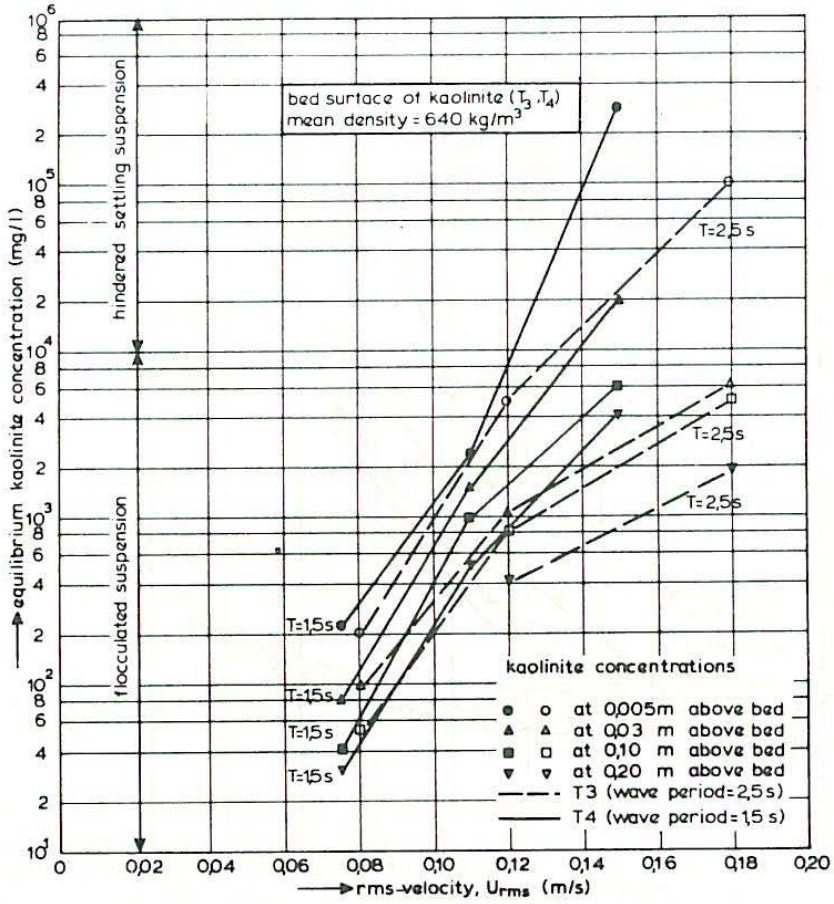

Fig. 12, Sediment concentrations as a function of u_{rms} and wave period T

Bed surface of 75% kaolinite and 25% sand

The sand particles were mixed through the kaolinite material to obtain a homogeneous mixture. The consolidated bed was subjected to waves of increasing heights (in steps). Fluidization of the top layer of the bed was observed at a wave height of 0.07 m. The thickness of the fluidized mud layer was about 0.025 m. A typical phenomenon observed before the onset of the fluidization process was the formation of (isolated) patches of accumulated sand particles. The patches were estimated to have a diameter of about 0.005 m and a height of 0.001 m. During fluidization of the bed surface, the sand particles disappeared in the fluidized kaolinite layer. Above this layer no sand particles were observed. Equilibrium kaolinite concentrations are presented in Fig. 13, showing similar results as those of test T4.
Summarizing, it is concluded that a small amount (25%) of sand particles does not have a significant effect on the erosion and fluidization of the kaolinite bed material.

Bed surface of 75% sand and 25% kaolinite

The sand and kaolinite materials were mixed thoroughly. Because of the relatively large specific area of the kaolinite particles, the sand particles were covered by a film of kaolinite material yielding a muddy-looking mixture. This mixture was pumped into the flume for sedimentation. Then the tests were performed.

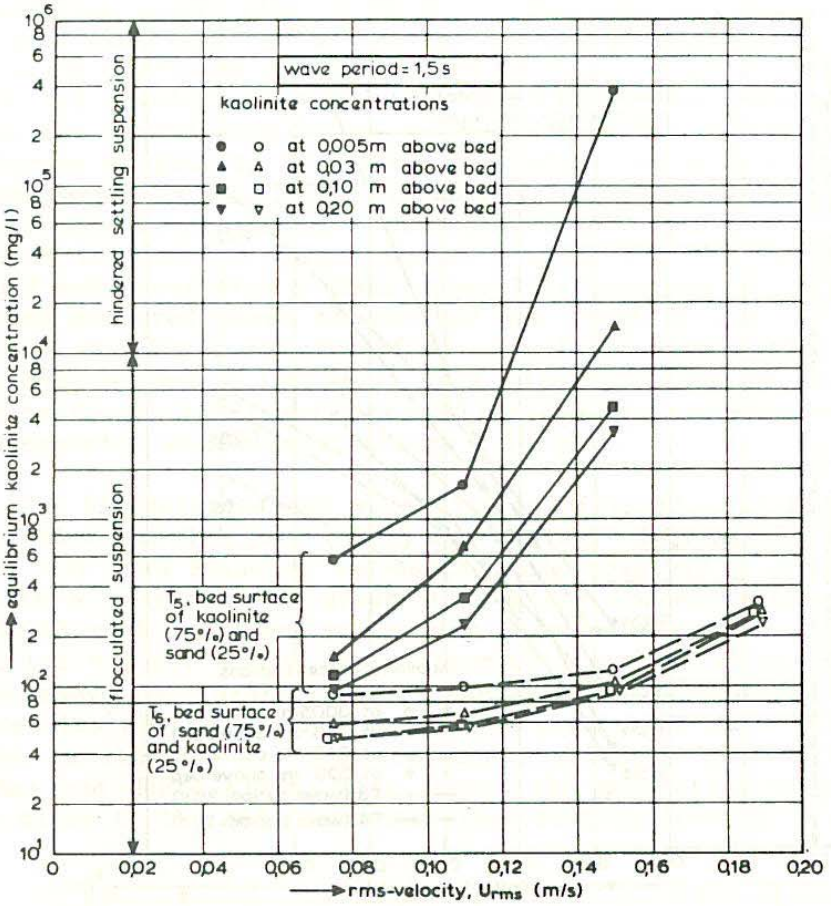

Fig. 13, Sediment concentration as a function of u_{rms} and wave period T

The kaolinite concentrations, shown in Fig. 13, remained very small because only the top layer of the bed was washed out. Even, at a relatively large u_{rms} of 0.19 m/s (wave height of 0.10 m, water depth = 0.25 m) the kaolinite concentrations were not larger than about 300 mg/1. For comparison the results of the T5-experiment (75% kaolinite) are also plotted, showing much larger concentrations (factor 10 to 100). The concentration profiles were almost uniform, because the concentrations were too low to cause significant flocculation. After the kaolinite material has been washed out of the top layer of the bed, 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 kaolinite particles in the ripple-troughs.
The maximum ripple height was only 0.002 m, which is very small compared with the ripple height of about 0.01 m 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 concentrations were reduced from about 10000 mg/1 to about 300 mg/1 close to the bed (factor 30), as shown in Fig. 14.
Summarizing, it is concluded that a small amount of cohesive particles in a sand bed causes a large reduction of the sand concentrations and transport, mainly because the ripple heights are suppressed by the cohesive material which acts as a binding agent for the sand particles.

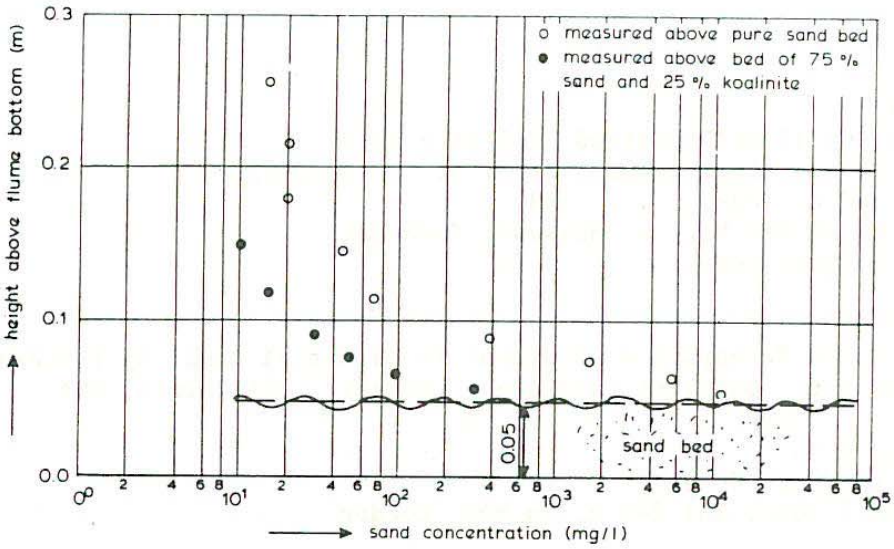

Fig. 14, Sand concentration profiles, Test T6 and T7, wave height = 0.1 m

5. CONCLUSIONS

Relatively large waves acting on a consolidated bed of kaolinite material can fluidize the top layer of the bed and generate a thin fluid mud layer with concentrations > 100 gr/l. The generation of a fluid mud layer seems to have a stabilizing effect on the vertical upward sediment transport. This is caused by the absence of large velocity gradients and hence large stear stresses at the fluid mud interface. The sediment concentrations above the interface of the fluid mud layer are much smaller (factor 20 to 50) than in the fluid mud layer itself.
Relatively small waves acting on a consolidated kaolinite bed can only wash out the top layer of the bed resulting in small concentrations which are distributed rather uniformly over the depth.
A consolidated bed consisting of 75% kaolinite and 25% fine sand showed the same erosional behaviour as a pure (100%) kaolinite bed.
A bed consisting of 25% kaolinite and 75% fine sand did not show the same behaviour as a pure (100%) sand bed. Because of the presence of the kaolinite material acting as a binding agent, there was a strong suppression of the sand ripples which were not larger than 0.002 m while values of 0.01 m were observed for a pure sand bed at the same wave height. As a result the sand concentrations above the bed were much smaller (factor 35) than those measured in case of a pure sand bed. The kaolinite concentrations were not larger than 300 mg/l, because only the top layer of the bed could be washed out.

6. REFERENCES

DIXIT, J.G. 1982
Resuspension Potential of Deposited Kaolinite Beds
Coastal and Oceanographic Eng. Dep, Univ. of Florida, USA
KENDRICK, M.P. and CLIFFORD, J.E., 1981
Hydraulic Studies of the Port of Belawan, Indonesia
Proc. Seatec III, Singapore

KRONE, R.B., 1962
Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes
Hydr. Eng. Laboratory, Univ. of California, Berkely, California, USA

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

MAA, P.Y. and MEHTA, A.J., 1986
Mud Erosion by Waves: A Laboratory Study
16th EBSA Symposium, Plymouth, England

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

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

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

RIJN, L.C. van, 1985
The Effect of Waves on Kaolinite/Sand Beds
Delft Hydraulics, Report M2060, Delft, The Netherlands

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