CHAPTER 225

Liquefaction and erosion of China Clay
due to waves and current

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Abstract

A research project was started to study the behaviour of cohesive sediments at the Delft University of Technology in 1989. An existing flume was modified to study the liquefaction and erosion of China Clay due to waves and current. China Clay is an artificial mud, mainly consisting of kaolinite. Among other things, the experimental results showed that fluid mud was generated by wave action if the wave height exceeded a threshold value; the threshold value increases as the consolidation period increases. Waves were significantly damped when a fluid mud layer was present and the damping was only little influenced by a current. Furthermore, the fluid mud is transported very easily by a current and hardly any mud was entrained into the water layer during this process. The pore pressure showed a transient decrease when the mud started to liquefy, succeeded by a gradual build-up of an excess pore pressure to compensate for the vanishing effective stress. Finally, it was found that observations or measurements made at a sidewall during an experiment only give a rough indication of the physical processes away from the sidewall; measurements carried out far from a wall have to be used for a quantitative description of the bulk processes in the bed.

Introduction

In several coastal and estuarine areas across the world the bed mainly consists of

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cohesive sediment, often referred to as mud. The influence of these beds on the coastal environment is usually very large due to the specific properties and transport processes of cohesive sediments such as flocculation, settling, deposition, consolidation, liquefaction and erosion.

Two main hydrodynamic forces drive the transport processes of cohesive sediments in these regions: tidal currents and wind waves. Many researchers have studied the erosion or deposition of mud by currents, because of practical reasons as the maintenance of harbours, for instance. Various empirical relationships were derived from experiments and adopted to simulate the transport of mud (Partheniades, 1984).

However, in shallow waters wind waves dominate the hydrodynamic forcing of the cohesive sediment. The erosion of mud due to waves has also been studied experimentally by several researchers (Maa & Mehta, 1987, 1990). In some of the experiments a layer of fluid mud was formed under the influence of waves (Lindenberg et al., 1989). This phenomenon, which has also been observed in coastal areas, is caused by the varying wave loading. The fluid-mud layer may be transported very easily by a tidal current, for instance, yielding in a relatively large transport of sediment material close to the bed.

A striking observation which can be made at a muddy coastline is the marked wave damping as a result of the dissipation of wave energy in the bed. The energy dissipation depends on the rheological properties of the bed. Such damping phenomenon plays an important role in the protection of these coastlines.

The interaction between both waves and currents and a muddy bed has hardly been studied and is not well understood. In particular the liquefaction mechanism, the near-bed turbulence structure and the influence on wave damping require further study. Therefore a research project was started at the Delft University of Technology some three years ago. A set-up was built to study experimentally the influence of waves on the liquefaction process and the influence of both waves and current on the transport and erosion processes of mud. In the present paper only a brief account of the experimental results will be presented. A full description of the experimental results is given by De Wit (1992).

Sediment

China Clay, an artificial mud mainly consisting of kaolinite, was used as sediment. The main reason for using this artificial mud is to get reproducible measurements. An additional reason is that the small-scale waves in the experiments require a less cohesive mud, which kaolinite is. Furthermore, using natural mud in experiments would involve the use of the natural water. The costs of temperature and light controlled transport and storage of the natural sediment with the accompanying fluid were prohibitive. Several properties characterising this clay were determined and some of them are listed in Table I.

Table 1 *Properties of China Clay used.*

particle size distribution	> 10 μm	14 %
	< 2 μm	41 %
C.E.C.		5.0 meq/100g
density		2593 kg·m^{-3}
specific surface area		29.9 m^{2}·g^{-1}
mineralogical composition		mainly kaolinite

There was no free gas in the sediment, and sodium chloride was dissolved in the tap water used (salinity: 5 ‰) to increase the flocculation of kaolinite and to eliminate the possible influence of small quantities of other chemicals on the characteristics of the mud, as for instance the settling velocity. According to Van Leussen (1988) the settling velocity of kaolinite is maximal for chloride concentrations ranging from 2 to 18‰.

The rheological behaviour of the China Clay used was determined with a Haake viscometer; model Rotovisco RV100 and measuring system CV100. It is a viscometer capable of testing materials under either steady rotation, or dynamic oscillation with a frequency range from 0.01 to 9.9 cycles per second. The oscillating strain can be superimposed on a steady shear as well. This device is provided with several sample holders, the so-called sensor systems, such as a

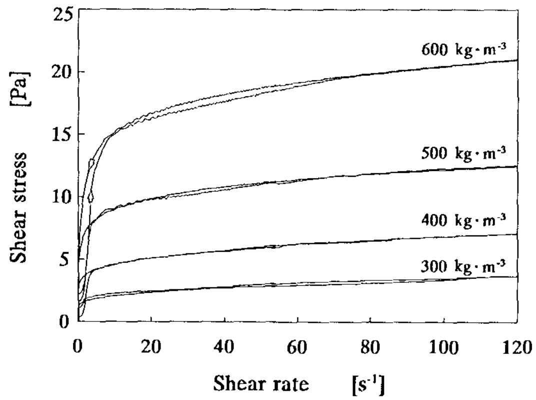

Figure 1 *Rheological behaviour of suspensions of China Clay in saline tap-water (salinity 5‰, sensor type: Q30).*

cone-plate and a plate-plate system. Each sensor system is designed to provide a specific range of shear rate, shear stress and viscosity.

Several suspensions of China Clay and saline tap-water were tested with suspended sediment concentrations ranging from 100 to 600 $kg \cdot m^{-3}$. In the tests the shear rate increased from zero to a maximum value of 125 s^{-1} in 3 minutes and then decreased in the same period to zero again. Several sensor types were used depending on the concentration. The samples were thoroughly mixed and ultrasonically treated during 5 minutes before they were inserted in the sample holder. The temperature of the samples was 20 ± 0.5°C.

Some results are presented in Figure 1. The dynamic viscosity and the yield strength of a suspension can be estimated using these results. Furthermore, dynamic oscillation experiments were made on various clay samples at different concentrations (De Wit, 1992).

Experimental set-up

A flume, length about 40 m, width 0.8 m and height 0.8 m, in the Hydromechanics Laboratory was modified for the purpose (see Figure 2). A simple mechanical wave maker was mounted at one end of the flume in order to generate regular waves, with a maximum wave amplitude of 0.11 m and a period ranging from 1 to 4 s. At the other end a stainless steel wave damper was mounted in such a way that it reduces wave reflection and would not interfere with generating a current. A recirculation pipe and a centrifugal pump were installed below the flume, which makes it possible to generate a steady current. The maximum flow rate is about 0.05 $m^3 \cdot s^{-1}$. The fluid is withdrawn below the wave damper at the end of the flume and it re-enters the flume via a smooth stainless steel duct installed below the wave maker. Wooden parts were used originally but these were replaced by stainless steel ones, because it was found that after a while fungi, algae and other micro organisms were growing on them. In this way the influence of organic material on the measurements is kept as small as possible.

The test section which holds the sediment is 8.0 m long. The vertical endwalls

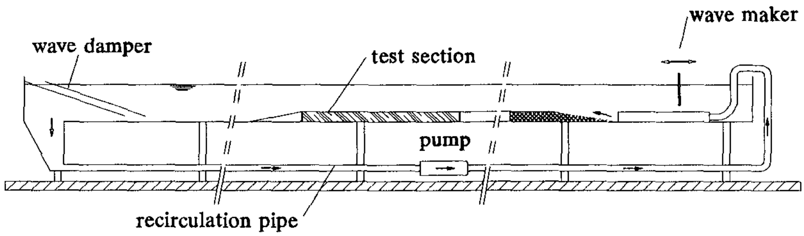

Figure 2 Experimental set-up.

of the test section are 0.2 m high and are formed by stacking four beams of which three can be removed during an experiment. The downstream and upstream endwalls are connected to the bottom and the upstream cement false bottom, respectively, by 2 m long asbestos-cement plates which were made adjustable by means of hinges. In this way the height of the test section can be adjusted during an experiment by removing a beam and lowering the free side of the plate.

Experimental procedure

Prior to the experiments some tests were carried out to measure the wave decay, the wave reflection and the velocity distribution in the flume without sediment. For this purpose a temporary false bottom, made of cement, was placed over the test section. Measurements were also made in this configuration when both waves and current were present. The results showed that there was no significant wave reflection and no significant wave decay above the closed test section. Furthermore, the velocity distribution for a steady current was almost uniform.

The false bottom over the test section was removed and preparations were made for the experiments with China Clay. The China Clay was thoroughly mixed with saline tap-water (salinity 5‰) in a mixing tank. The tank, in which a continuously revolving grid was installed, contained about 3 m^3 of suspension with a concentration of about 250 $kg \cdot m^{-3}$. The suspension was regularly circulated in the tank; the suspension was withdrawn at the bottom and re-entered the tank at the top. After the suspension had been mixed for at least one week, it was pumped to the test section which was separated from the rest of the flume. Then the suspension was mixed again and finally it was allowed to consolidate. After consolidation the mud layer in the test section was approximately 0.2 m thick.

Prior to the preparation of the mud bed, four miniature pore-pressure transducers (Druck PDCR 81) were fixed in a cross-section in the middle of the test section. The measured accuracy of the devices is ± 5 Pa. Furthermore, six wave height meters and three electromagnetic velocity meters were installed in the test section. The sensor of the electromagnetic velocity meter has an ellipsoidal shape (11 × 33 mm) and the sensing area is a cylinder just below the sensor with diameter 33 mm and height 5 mm. Concentrations of mud in the supernatant water layer were measured by an optical method and by taking samples. The concentration in the bed was measured using a conductivity probe. The data were recorded on a personal computer and video recordings were made.

Three experiments with China Clay were made. The composition of the China Clay used in experiment III differed very little from the China Clay used in experiments I and II. In all experiments the behaviour and the processes in the mud were studied and measurements were made for different settings of the wave height (≤ 0.1 m) and water velocity (≤ 0.2 $m \cdot s^{-1}$). The wave period was 1.5 s and the depth of the tap-water above the initial bed was 0.30 m. For a detailed overview of the experimental programmes of the three experiments see De Wit (1992).

During the first, preliminary experiment the configuration was different from the one described above. A description of the configuration used in experiment I is given by De Wit and Kranenburg (1991). In Table 2 the initial heights of the beds and the consolidation periods are listed for the three experiments.

Table 2 *Consolidation periods and initial heights of the bed.*

Experiment No.	date	initial height of the bed [cm]	consolidation period [days]
I	June 1991	18.5	22
II	December 1991	19.8	9
III	June 1992	18.5	6

Results

When waves were generated, it was observed that a layer of fluid mud was formed for wave heights exceeding a threshold value. This value increased with the consolidation period. The consolidation periods for the different experiments are listed in Table 2. The mud in experiment I started to liquefy when the wave height was about 7 cm. In experiments II and III liquefaction occurred when the wave height was about 3.0 cm.

Prior to the experiment the concentration profile of the initial mud bed was measured. In Figure 3 concentration profiles are shown measured at two different places in the test section prior to the experiment and when a layer of fluid mud was present. The latter profile was measured at the down-stream end of the test section. The thickness of the mud layer near the downstream endwall did not decrease very much during an experiment, because fluid mud was transported in the downstream direction by the waves. It can be seen that the bed was quite uniform.

Although sometimes overlooked, the shear stresses caused by the streamwise variation in wave-induced pressures seem to play an important role in the liquefaction process of cohesive sediments (Suhayda, 1984). A rough estimation of these pressure-induced shear stresses is made in the appendix assuming an ideal elastic behaviour of the mud. It is shown that the maximum shear stress increases almost linearly with depth. Using the characteristic values of experiment III it was

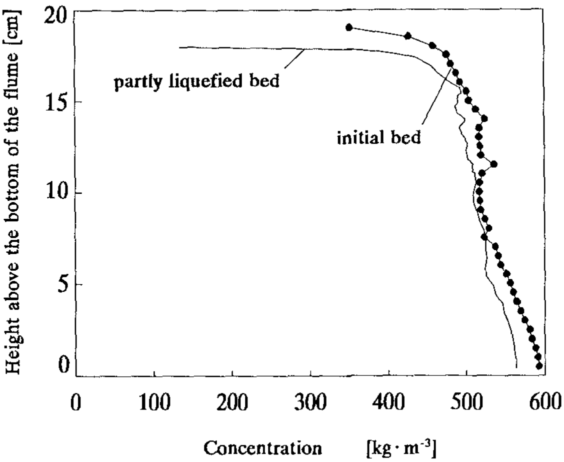

Figure 3 *Concentration profiles of the bed at two locations in the test section during experiment III.*

found that the maximum shear stress at 1 cm below the water-clay interface, for instance, is approximately 3 Pa for a wave height of 3 cm. The initial concentration of the upper part of the bed was about 400 kg·m^{-3}, see Figure 3. In Figure 1 it is shown that the yield stress of mud with a concentration of 400 kg·m^{-3} is approximately 3.5 Pa, which is of the same order of magnitude as the stress generated by the pressure oscillations. At 15 cm below the water-clay interface, the maximum pressure-induced shear stress is about 30 Pa, which is an order of magnitude greater than the yield stress of the sediment at this level in the bed. Only just below the water-clay interface the pressure-induced shear stress is smaller than the yield stress of the sediment. Consequently, the bed will be liquefied immediately after the generation of waves with a wave height of 3 cm, which corresponds with our observations.

As soon as a layer of fluid mud had been generated, the waves were significantly damped and the damping increased with the thickness of the fluid-mud layer. The damping was only little influenced by a current (see Figure 4).

Visual observations of dye injected near the bed surface seemed to indicate that the turbulence intensities in the overlaying water decreased when fluid mud was present. Furthermore, the fluid mud was easily transported by a current and hardly any mud was entrained into the water during this process.

In a later phase of experiment I erosion prevented the fluid mud to leave the test section, which then was just a trench in the false bottom. Instead a large circulation zone was generated in the fluid mud. This was the main reason for changing the test section into the present configuration. In experiments II and III this problem did not occur.

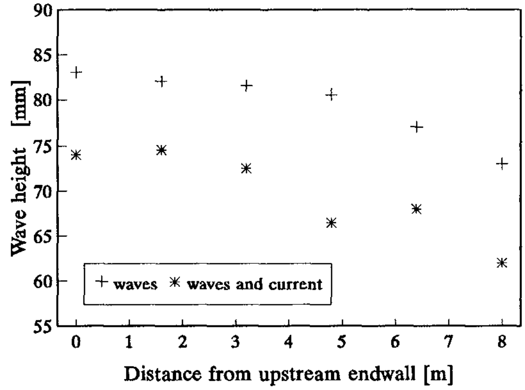

Figure 4 *Average wave heights measured above the test section when waves and both waves and current (10 cm·s^{-1}) were generated. (Experiment II, fluid-mud layer present)*

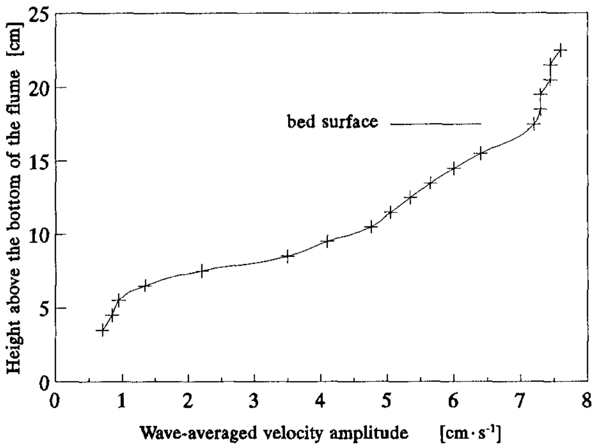

Figure 5 *Wave-averaged velocity amplitudes in and above a partly liquefied bed. (standard deviation: 0.5 cm·s^{-1})*

When a significant layer of fluid mud had been generated due to wave action, an electromagnetic velocity meter was used to measure velocity amplitudes just above and in the bed during experiment III. Although the flow of the fluid mud was disturbed significantly by the velocity meter, it was still possible to measure velocities. The calibration of the electromagnetic velocity meter was checked in towing tests prior to the experiment. According to visual observations at that moment, the bed was approximately 17.5 cm thick; the thickness of the fluid mud layer was when judged at the glass sidewall 4 cm. However, the measured wave-averaged velocity amplitudes shown in Figure 5, indicate that in the centre of the flume the whole mud layer had been liquefied.

In experiments II and III, four miniature pore-pressure transducers were installed. Three of them were fixed at several levels in the bed and one was fixed just above the bed as a reference. Wave-averaged water pressure changes measured just above and in the mud layer after the onset of liquefaction are shown in Figure 6. The pressure above the bed hardly changed during liquefaction. The pore pressure, however, showed a transient decrease which was probably caused by the break down of the aggregate structure. Then a gradual build-up of an excess pore

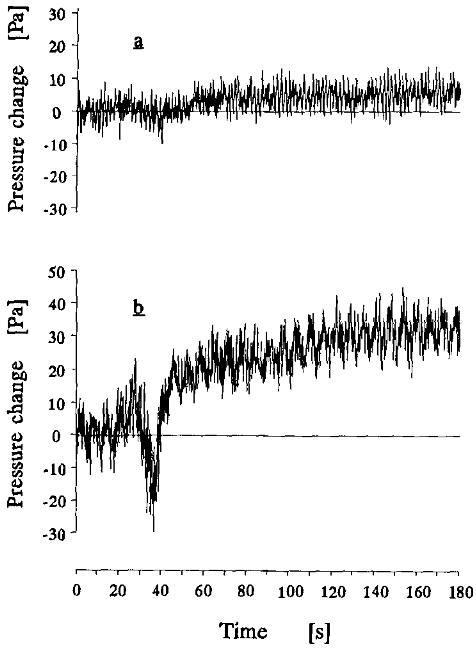

Figure 6 *Wave-averaged pressure changes during liquefaction; a pressure at about 23 mm above the bed, b pore pressure 21 mm below the bed surface.*

pressure was observed. Due to the low permeability of the mud layer the excess pore pressure did not dissipate, but rose to a final value corresponding with a zero effective stress.

Discussion and conclusions

In each experiment a layer of fluid mud was generated due to wave action. However, the threshold value of the wave height at which liquefaction occurred depends on the consolidation period of the mud; the threshold value increased as the consolidation period increased.

Although the assumption made in the appendix of cohesive sediment being an elastic material is not quite appropriate, the estimate of the maximum pressure-induced shear stress given shows these stresses play an important role in the liquefaction process of mud.

The wave height was damped significantly as soon as a layer of fluid mud was generated and the damping was only little influenced by a current. Furthermore, dye injections seemed to indicate that the turbulence intensities decreased when a fluid mud was present. However, measurements using laser doppler anemometers or electromagnetic velocity meters are necessary to validate this observation.

The fluid mud was transported very easily by a current and hardly any mud was entrained into the water layer.

Usually visual observations and pressure measurements are made at a transparent wall of a set-up. However, from the measurements made with an electromagnetic velocity meter in the experiments carried out so far it is found that observations or measurements made at a sidewall are not representative of the actual physical processes away from the sidewalls. Only measurements carried out far from a wall give a quantitative description of the bulk processes inside the bed.

Pore-pressure measurements showed a transient decrease possibly caused by the break down of the aggregate structure, succeeded by gradual build up of an excess pore pressure so as to compensate for the vanishing effective stress.

This work will be continued by examining the liquefaction of sediments composed of other clay minerals. Furthermore, mathematical models relating the wave damping to the rheological properties of the bed are being tested.

Acknowledgements

The authors wish to thank Delft Hydraulics for making available their Haake viscometer. This project was partly funded by the Commission of the European Communities, Directorate General for Science, Research and Development under MAST Contract no. 0035 (G6 Morphodynamics research programme).

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Appendix

Wave induced shear stresses in the bed

Waves are capable of generating shear stresses in the bed. The total shear stress is a superposition of the shear stress caused by the oscillating flow and the shear stress caused by the streamwise variation in the pressure on the bed. The shear stress imposed upon the upper bed surface by the oscillating flow can be calculated from viscous flow theory for laminar flow or an empirical equation for turbulent flow. The pressure-induced shear stress is sometimes overlooked, but seems to play an important role in the liquefaction process of cohesive sediments (Suhayda, 1984). This shear stress can be estimated in the following way.

Consider a two-dimensional semi-infinite isotropic linear-elastic solid in the domain $z \geq 0$. The x-axis of the cartesian coordinate system is in the streamwise direction. In the origin of this coordinate system a vertical point force is applied. Boussinesq derived a solution for the resulting stress components at any point in the solid in 1885 (Timoshenko, 1951). Using the principle of superposition the maximum value σ_{max} of the shear stress σ_{zx} can be calculated for a sinusoidal pressure distribution $p = \hat{p}\sin(kx)$, where k is the wave number. It is thus found that

$$\sigma_{max} = \hat{p} k z \, e^{-kz} \tag{1}$$

The maximum shear stress is found for $kz = 1$, but liquefaction may start at higher level in the bed because usually the strength of the bed increases with depth. Approximating for small kz, equation 1 gives $\sigma_{max} \simeq \hat{p} k z$ which was also found by Maa & Mehta (1990).

The pressure amplitude $\hat{p}$ at the upper bed surface generated by progressive waves with amplitude a as calculated using linear short-wave theory is

$$\hat{p} = \frac{\rho g a}{\cosh kD} \tag{2}$$

where ρ is the density of the fluid, g the gravitational acceleration and D the water depth.