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STUDY OF THE PHYSICAL PROPERTIES OF VARIOUS FORMS OF VERY FINE SEDIMENT AND THEIR BEHAVIOUR UNDER HYDRODYNAMIC ACTION

By

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FOREWORD

Pelitic sediment in the form of mud, silt or sludge often reduces the performance of an installation by making expensive maintenance necessary in a reservoir, an access channel, an estuary, a harbour basin or a water purification and distribution station.

On the other hand this same very fine sediment, suitably distributed, is essential for providing a favorable soil structure and thus increasing the production of arable land. Some forms of sediment provide raw material for many industries including the ceramic industries, and may render great service in making a piece of ground watertight and protecting a construction site against infiltration of water or on the contrary making it possible to store large reserves of water in artificial lakes or underground.

Whether pelitic sediment is to be combatted or used, it is necessary to have knowledge of the mineral and chemical nature and the size of the very diverse elementary particles of which it is made, and of its water environment.

Where there are problems of silting, we can with these various kinds of analyses and their sedimentologic interpretation go back to the at times remote origins of the materials, and follow the morphologic and chemical changes, as well as the conditions in which the materials are mixed. It is thus possible to locate the area or areas where they are produced and to decide what kind of measures to take to fight the actual causes of the silting.

However, such a preliminary study of very fine sediment, no matter how elaborate, is not enough to give us a clear idea of its behaviour in nature under various kinds of hydrodynamic action, and we must remember that such material forms underground complexes that are basically variable in time, since they have physical properties that are very different from those of their elementary particles.

Unlike granular sediment such as pebbles, gravel, sand or even silt, pelitic sediment, a category into which I have put all sediment of less than 30μ, can form a multitude, a number that can vary up to infinity, of soils, depending on the nature of the sedimentary components, the water environment in which they lie, the state of maturity of the deposit and the electrostatic forces that bind the particles together. Should one of these factors be changed, a new type of soil will be created that reacts differently under hydrodynamic action.

Only after a detailed study of the physical properties of such complexes in their natural environment: flocculation, structure and fragility of the floc, sinking rate, electric charge of the particles...or duing bedding down under water or in air, bringing deep changes in their rheologic state, we can attack the question of the effect of various kinds of hydrodynamic action: currents, waves, gravity flows, wind action...and try, with full knowledge of what we are doing, to combat silting effectively at the actual location.

Such research is essential also when we wish to reproduce the depositing of mud faithfully, on small-scale models, since we then have to look for a material for models that has, on similar scales, similar physical properties, undergoes the same variations in time and exhibits the same movements under hydrodynamic action as natural sediment.

For a number of years, the Laboratoire Central d'Hydraulique de France (LCHF) has had the opportunity to do such research. The work which was at first oriented to immediate applications of tests on small-scale models and the interpretation of oceanographic and hydrologic measurements carried out by our field study missions, has gone far beyond its initial scope. From all the measurements done in the field or in the laboratory on mud of very diverse origins: from the sea, estuaries, rivers or lakes, and on various kinds of sludge from mine residues and on artificial powders, a number of general trends appeared that enabled us to suggest (with all the reserve necessitated by the complexity of the matter) a few qualitative, empirical laws relating the behaviour of pelitic sediment under various kinds of hydrodynamic action to its physical properties.

After recalling the behaviour of various kinds of elementary particles in pure water, I shall examine successively:

The physical properties of suspensions and deposits of pelitic sediment in calm water:

- flocculation, sinking rate in a water environment, settling,
- rheologic properties of deposits in various stages of settling;

Gravity flows:

- angles of repose of deposits under water or above water,
- sliding and flowing and, by extension, density currents;

The behaviour of deposits under various kinds of hydrodynamic action:

- conditions of erosion by currents,
- movements of suspensions in a theoretic estuary,
- action of swells and wind waves.

I - Physical properties of suspensions and deposits of pelitic sediment in calm water

1. Diversity of the pelitic sediment studied

The studies done in the Laboratory dealt with pelitic sediment of very varied mineral and granulometric origin and composition:

- marine origin: Aiguillon, La Rochelle, Châtelaillon, Conakry, Pointe-Noire, Bombay, Majunga, Kompong-Som;
- esturian origin: La Vilaine, Sèvre-Niortaise, Croix-de-Vie, Gironde, Mahury, Cayenne, Betsiboka, Parana;
- fluvial origin: Durance, Seine, Rhône, Vie, Zemrane, Sebou, Fodda, Hamiz;
- lacustrine origin: Vaine, Geneva;
- mine or quarry residues: Kerkour-Rhi (sludge, phosphate), uranium ore pulp, Provins clay, activated sludge, powdered limestone;
- artificial powders: kaoline technique, bakelite, polystyrene dust and coal dust.

The table shows, as an example, the composition of some of the natural sediment, the physical properties of which will be given special consideration.

2. Behaviour of elementary particles in calm water

The sizes and shapes of the elementary particles in pelitic sediment differ greatly depending on their mineral composition. Measurements by electronic microscope show in particular that argillaceous elements may vary in size from less than 0.1μ to a few microns and their shapes from pellets for palygorskites and halloysites to hexagonal flakes for kaolinites and hydromuscovites.

In the individual state, these particles have extremely small sinking rates that may be less than 1 μ/s. They are frequently represented by a diameter equal to that of a sphere of the same density and exhibiting the same sinking rate in water.

This method cannot give the exact size of the particle because of the actual shape, which may differ greatly, as we have said, from that of the sphere. Also, a particle sinking freely in water sticks to the film of water that surrounds it and which may in some cases have a thickness close to that of the particle (400 Å for a particle of kaolinite that is 1,000 Å thick). The particle and water together therefore have a density very different from that taken for the equivalent sphere.

For fine particles, the sinking rate W is related to the

[Pages 593 and 594 (figures 1 to 6): see original.]

diameter d of the equivalent sphere by Stoke's formula:

$$W = \frac{1}{18} \frac{\rho_s - \rho_0}{\rho_0} \times \frac{d^2 g}{\nu}$$

where ρ_s is the specific mass of the particle,

ρ_0 the specific mass of the water, and

ν the kinematic viscosity of the water.

As a first approximation, we can assume that in pure water at 20°C ($\nu = 10^{-6}$ m^2/s,), the equivalent diameter of a fine particle of density 2.5 to 2.6,

$$d \text{ (in } \mu) = W^{1/2} \text{ (in } \mu/\text{s)}.$$

As an example, a sphere 10μ in diameter would have a sinking rate of 100 μ/s.

The effect of the viscosity of the water on the sinking rate is not negligible, and a slight change in the temperature can double the viscosity:

$$\text{at } 30^{o}\text{C}, \nu = 0.8 \times 10^{-6} \text{ m}^2/\text{s}$$

$$\text{and} \qquad \text{at } 3.5^{o}\text{C}, \nu = 1.6 \times 10^{-6} \text{ m}^2/\text{s}.$$

3. Flocculation. Sinking rate of the floc

The mud, silt and sludge are made up, as we have seen, of elementary particles of greatly varying sizes and kinds, associated with various salts. In suspension in natural waters, such pelitic sediment is in most cases subject to flocculation and forms aggregates whose sinking rate is much greater than that of the elementary particles. Flocculation and its extent depend on a number of factors, some related to the characteristics of the particles, others to those of the water environment.

Generally, flocculation is greater if we increase the electrolytic concentration, the value of the ions and the temperature, and reduce the size of the hydrate ion, the dielectric constant, the pH and the absorption power of the anions.

More simply, a suspension of mud or sludge in the water will, within certain limits, be more flocculated if the elementary particles are smaller and their concentration in the suspension greater, and if the environment contains more flocculent salts.

The interaction of these factors will lead to reduction of the differences in sinking rate in a flocculent water environment of pelitic particles that in the individual state have very different sizes. Thus mud or silt that in a deflocculated state, ie, as individual elementary particles, shows mean sinking rates of between 10^{-5} mm/s and 10^{-1} mm/s (sinking rate ratio of 1 to 10,000) will, in sea water, and for a concentration of solid particles of 10 g/l, have mean sinking rates for their floc of between 1.5×10^{-1} mm/s and 6×10^{-1} mm/s (sinking rate ratio of 1 to 4).

A - Effect of the diameter of the elementary particles on flocculation

The maximum flocculation factor:

$$F = W_{f\ 50\%}/W_{d\ 50\%}$$

defined as being the ratio between the mean free sinking rate of the floc ($W_{f\ 50\%}$) in a flucculent water environment and

the mean free sinking rate of the elementary particles ($W_{d\ 50\%}$) in the deflocculated state,

varies inversely with the equivalent diameter d of the elementary particles. The flocculation factor will be higher if the particles are smaller.

For a concentration of the suspension of 10 g/l of dry sediment, and in sea water with 30 ‰ salinity, the flocculation factor is given by

$$F \simeq 250 \times d^{-1.8}$$

d being the equivalent diameter in microns or, putting F in terms of the sinking rate (W_d) of the elementary particles,

$$F \simeq 250 \times W_d^{-0.9}$$

Figure 7: see original.

Figures 9, 10 and 11: see original.

This empirical formula tends to show that in practice, a suspension of pelitic mineral elements in a flocculent environment will have mean sinking rates of between 0.15 and 0.60 mm/s, regardless of the size of the elementary particles. It can be seen also that the flocculation is no longer noticeable with mineral particles of a diameter greater than about thirty microns.

B - Effect of the concentration of solid particles in the suspension

The flocculation and sinking rate of the floc are very sensitive to the concentration of solid particles in the suspension. In a flocculent environment, whether it is fluvial water containing traces of salts or sea water, the flocculation factor increases gradually with the concentration of dry sediment in the suspension, up to a critical concentration threshold of about 15 g/l.

At this concentration, the sinking rate of the floc may be ten times as great as the rate that could have been measured for suspensions at 1 or 2 g/l.

On the other hand, beyond the critical threshold of flocculation (about 15 g/l) the sinking of the floc is restricted and the rate tends to diminish.

C - Influence of the water environment

Only very small quantities of flocculent salts (or sea water) are needed for flocculation to appear. Thus, if into a mud suspension with a dry sediment content of 2 g/l dispersed in distilled water we introduce increasing quantities of sea salts, we find that the sinking rates of the floc contained in the suspension increase gradually to reach their maximum value, starting with a 2 per cent concentration of salts. This maximum rate is then maintained at a nearly constant value, up to a salinity of 30^{o}/oo (sea water).

If the initial concentration of the solid particles in the suspension is fairly high (10 g/l and over), macroflocculation can occur for high salinities and lead to a reduction of the sinking rates (velocity restriction); the sinking rate will then be slightly higher for a salinity of 5 o/oo than for one of 30 o/oo.

The action of deflocculent salts such as sodium pyrophosphate in mud suspensions in fresh river water may lead, depending on the quantity of salts introduced, to very different events. One can generally note macroflocculation with the appearance of loosely structured aggregates soaked with water for small quantities of pyrophosphate and a dispersion of the sediment for high concentrations (deflocculation).

The stability or instability of a suspension of pelitic sediment under the action of various salts dissolved in the water may therefore be very complex as the result of the modification of the ionic atmosphere around the particle. It will be possible to use this action of the salts dissolved in the water on flocculation or deflocculation in small-scale models of mud, by adjusting the behaviour of the suspensions to make them similar to suspensions in nature. Also, the pH of the water environment will have a great influence on suspensions of very fine particles.

4. Settling of pelitic sediment.

Settling by gravity, the natural mud floc is crushed under its own weight and gradually loses part of its water.

The network of floc draws in very close, forming a material that is essentially variable in time, as a result of the gradual elimination of the water from the effect of the settling, which may go on for several years. During this settling, the mud exhibits greatly differing physical states depending on its age, or more accurately, its water content. Whether it is liquid, viscous or solid, this same mud can take on the consistency of true stone, after prolonged dessication.

The study of natural settling in various forms of pelitic sediment shows that the mean concentration of a deposit varies as the logarithm of the time with various aspects of settling: velocity restriction, elimination of the interstitial water, drainage and porosity, and state of compression.

In these aspects of settling, the concentration variation T_d is expressed as

$$T_d = \alpha \log t + \beta$$

where t is the time (generally in hours);
α is a factor that depends mainly on particle diameter;
β is a term related to the water environment.

Figure 12: see original.

The density of a deposit ρ_m/ρ may be related to the dry sediment content T_d (in kg/m^3 or in g/l) by the expression

$$\rho_m/\rho = \left(1 + \frac{\rho_d - \rho}{\rho_d}\right) \left(\frac{T_d}{1{,}000}\right)$$

where ρ_d is the specific mass of the sediment in kg/m^3, generally close to 2,500 kg/m^3;

ρ is the specific mass of the fluid in kg/m^3, close to 1,000 kg/m^3 for the water.

We can take as a first approximation

$$\rho_m/\rho = 1 + 0.6 \times 10^{-3}\, T_d$$

Likewise, the water content T_w, the ratio between the weight of water contained in the deposit and the weight of dry sediment is related to the dry sediment content T_d by the relation

$$T_w = \left(\frac{1{,}000}{T_d} - \frac{1}{\rho_d}\right)$$

A - Influence of nature and size of particles

The nature of the sediment: size, form, electric charge...will greatly affect the settling of pelitic sediment.

After a month of settling, the superficial layers of mud may exhibit greatly

Figures 13, 14 and 15: see original.

varying concentrations as outlined in the table below:

ORIGIN	CONCENTRATION (in g/1)
Durance silt	900
Limestone (powdered)	680
Kaolin technique	625
Natural mud:	
- Majunga	480
- Conakry	330
- La Rochelle	320
- Mahury	350
Kerkour-Rhi sludge	250
Provins clay	180

It appears that the factor α of the settling equation increases proportionately to the mean diameter of the elementary particles contained in the deposit. After centrifugation, the settled deposits may have concentrations as great as 1,000 to 1,200 g/1.

B - Effect of the initial depth of the deposit

A deposit of pelitic sediment tends more rapidly to a settling asymptote if the initial depth of the deposit is smaller. But the final concentration will be larger if the depth of the deposit is greater.

C - Effect of the water environment.

The water environment does not greatly change the mean concentration of a settling deposit. It appears, however, that for some kinds of mud the settling is less in sea water than in fresh river water.

D - Effect of sand-mud mixtures

In a homogeneous mixture of sand and mud, the settling can take place with segregation, if the initial concentration of the mud is low, or uniformly if the deposit has an initial concentration of more than 250 g/1. In the latter case, an increase in the percentage of sand does not lead to a more rapid consolidation of the mud whose actual water content remains constant after a given time, no matter how much sand is introduced (less than 30 per cent of the sample).

A deposit made up of alternate layers of mud and sand will settle more than a deposit of mud alone (or of a mixture of sand and mud) if the layer or layers of sand can be drained laterally or vertically.

E - Concentration gradient in the deposits

After prolonged settling, there is a concentration gradient in the deposits between the surface and the bed.

Figure 17: see original.

According to the laboratory results, and in test tubes between 0.5 m and 4 m long, the formula for concentration variation within the deposits is approximately as follows:

$$T_{d\,(D)} = T_{d(s)} + n \log D$$

where $T_{d(D)}$ is the concentration in g/1 at depth D beneath the soil level;

D is the depth in cm ($D \geqslant 1$ cm);

$T_{d\,(s)}$ is the concentration in g/1 at the surface of the deposit;

n is a coefficient depending on the nature of the soil-water complex.

For marine mud that has undergone only ascending elimination of the water, the values for n are between 50 and 80. Mud exhibiting a surface concentration of 320 g/1 will therefore have a concentration of 370 to 400 g/1 at a depth of 0.10 m, of 420 to 480 at 1 m and of 470 to 560 g/1 at 10 m.

In nature, the alternation of layers of sediment, rate of deposit and (microseismic or other) external mechanical action will frequently change this formula.

F - Changes in settling

The settling of mud may be changed either, as has been said, by an increase in its drainage (sand or artificial drains), or by the use of chemicals (especially phosphate ions) or by electric processes.

Studies conducted at the LCHF have shown that it is possible, by simultaneous action by electrophoresis (attraction of the particles to the anode) and by electroosmosis (attraction of the water to the cathode), to obtain in a few hours a deposit concentration that is twice as high as what we could have obtained after a year of natural

Figure 18: see original.

settling. In the case of the Kerkour-Rhi sludge, the consumption of electricity is 14 kWh per cubic metre of sludge treated and we obtain appreciably smaller values for mud from the Iril Emda dam; however, electric bedding down of the Bombay sediment entailed expenditures for electricity that were out of proportion to any benefit from the operation.

If we reverse the current flow, it is possible to slow down the settling and to maintain, for a few days, mud that is in a perfectly fluid state; this action works only for a certain time, after which the phenomenon is reversed again.

5. Study of the rheologic properties of mud

In mud rheology, we must remember that suspensions of pelitic elements in different water environments follow different rules according to their degree of settling, or what amounts to the same thing, according to their concentration.

A mud suspension can be Newtonian with low concentrations or resemble Bingham or Casson fluids, for increasingly higher concentrations. Also, deposits of pelitic sediment can exhibit, for some concentrations, thixotropy characterized by a change in their properties under external mechanical action such as stirring or vibration.

The measurement of viscosity or original rigidity (yield value) is therefore extremely tricky and the values may be appreciably different depending on the experimental conditions. The results must therefore be interpreted with caution and, with the types of apparatus we used, ie, Eprecht rotary viscosimeters with fifteen speeds and Brookfield LVT with eight speeds, they remain much more comparative than quantitative. Measurements in conduits, a study of which we have begun, will probably bring more accuracy to these figures.

We are, however, permitted to think that if suspensions or deposits exhibit, for the same particle concentrations and experimental conditions, the same relative values for viscosity and initial rigidity and if in addition their rheologic curves for shearing variation versus the velocity of a rotor immersed in the suspension are comparable, these suspensions will have the same physical properties, ie, the same fluidity, plasticity and cohesion characteristics.

When we did the measurements, we let the mud consolidate around the rotor of the viscosimeter to avoid large re-adjustments of the deposits.

A - Influence of the nature of the pelitic sediment

For equal concentrations of solid particles, the viscosity and initial rigidity of a suspension or deposit may differ greatly depending on the nature of the sediment. The elements with the smallest diameters appear to have the greatest rigidity.

Figure 19: see original.

In fresh water and for concentrations T_d of 250 and 500 g/l, the rigidity measured for various forms of mud was as follows:

See original.

B - Influence of the concentration of the solid particles

The initial rigidity of a given mud or sludge (determined by measurement of the torque required to pull a cylinder immersed in the deposit) increases very rapidly with the concentration. A first approximation might be that the rigidity τ_y varies as the fourth or fifth power of the concentration T_d:

$$\tau_y \simeq nT_d^4$$

where n is a coefficient depending on the soil-water complex.

The relative viscosity varies slowly with the concentration for values less than 200 g/l and very rapidly beyond that. Here again we find a formula in which the increase in viscosity is proportional to the fourth power of the concentration of solid particles in the suspension.

C - Effect of the water environment

The initial rigidity and relative viscosity are, for equal concentrations of dry sediment, greater in sea water than in fresh river water; the rigidity can be 1.4 to 1.7 times greater in a sea environment than in a river environment. The rigidity increases especially quickly at between 0 and 5 ‰ salinity and varies little beyond that.

On the other hand, the initial rigidity can be made much smaller if we add adequate doses of deflocculent salts and the mud may go from a solid state to a fluid state. A deposit of kaolinite, for example, has a rigidity reduced in a ratio of one to ten if 5 g/l of sodium pyrophosphate is added to the suspension. However, the addition of smaller doses (0.5 g/l) of pyrophosphate can have an opposite effect and increase the rigidity of the deposits. We must therefore use judgment in treating suspensions of mud or sludge with chemical salts to change their rheologic properties, especially when trying to adjust the behaviour of a pelitic material on a model to represent natural sediment on a similar scale.

D - Effect of sand content of mud deposits

The initial rigidity of mud decreases when we add sand if we are looking at the overall concentration (mud + sand). However, if we study the initial rigidity versus the sand content of mud of a given concentration (or given water content), we find that with 0 to 30 per cent of fine sand the initial rigidity is not changed by the sand. For example, if we put 25 per cent of sand of a diameter of 0.25 mm into Mahury mud with an initial concentration of 385 g/l, we obtain a sediment with a total concentration of 456 g/l and the rigidity of which remains the same as that of the initial mud (60 to 65 dynes/cm^2 in the case given).

Figure 20: see original.

These results tend to prove that in sandy mud, only the water content of the mud affects the initial rigidity of the deposit. The studies on the erosion of sandy mud by currents will confirm this hypothesis.

E - Alteration of the rheologic characteristics of mud by mechanical action

For some areas of concentration of deposits of pelitic sediment, the rigidity and viscosity are considerably reduced by mechanical action (stirring or vibration).

Page 602 (figures 21, 22 and 23): see original.

Figure 24: see original.

Rigidity measurements on mud having a concentration of 400 g/l and allowed to rest for half an hour, and on the same mud subjected to mixing, showed that the shear rate could be reduced by 10. Mud that is vibrated or subjected to pressure fluctuations by waves can therefore, in some cases, become fluid as a result of thixotropy.

Likewise, it can be seen that after vigorous mixing, the mud becomes fluid, then gradually regains its initial rigidity when allowed to rest. The rigidity increases with time to reach, in most cases studied, an asymptotic value after fifteen minutes of rest. In studies in a flume of the behaviour of mud under hydrodynamic action this property must be taken into consideration.

This overview of the physical properties of pelitic sediment in calm water shows the diversity of the soil-water complexes that can be found in nature and the successive changes that they may undergo in the course of time or under physical and chemical action, since that kind of mud in a given water environment can exhibit very great cohesion or be perfectly fluid, if certain salts in solution are added to the water environment. Likewise, the percentage of organic matter in mud can have a significant effect on its dynamic properties.

Figure 25: see original.

The study of the dynamics of mud as the movement of sediment under the effect of gravity, or of the action of water in the form of currents or waves, must take into consideration the diverse physical properties of such soil-water complexes by defining them not only by their mineral and granulometic nature, as well as the constitution of the associated water, but also by their dry sediment content (or water content) or, if we wish to be more precise, by the initial rigidity and the viscosity of the soil-water complexes.

II - STUDY OF THE ANGLE OF REPOSE OF MUD UNDER WATER AND ABOVE WATER: COLLAPSED MUD, FLOWS AND DENSITY CURRENTS

Under the influence of its own weight, a sedimentary deposit on a rigid, sloping bottom tends to move if the forces of gravity are not counterbalanced by cohesion of the material.

Soil that is not very compact and has only a small concentration of solid particles, will flow down a very gentle slope, while a very compact soil with high internal cohesion can stay in repose along very steep slopes.

The profile of repose of the bank will depend on the nature of the sediment and of the water environment, of the concentration gradient within the deposits, any overloading, and to a significant extent, the local hydraulic or oceanographic action. For high concentrations, and thus for high initial rigidity, it will take an overload or disturbance to cause a slide with the collapse of blocks of mud which will separate into individual masses but will dilute very little. For average concentrations, the mud will flow over the bed in the form of a homogeneous plastic fluid and the dilution at the water-mud interface will be weak, if the slide velocities are not too great.

However, if the pelitic sediment is very diluted in the water environment (less than 250 g/l), we will go gradually from deposits to suspensions whose initial rigidity will be negligible. Density

Page 604 (figures 26-31): see original.

currents can then appear and travel over the bed to great distances from the spot where they are formed, carrying with them large masses of material.

To give an order of magnitude for these phases of mud flow over the bed, we conducted systematic measurements in one of the glass flumes in the Laboratory, trying to find, on the basis of the physical characteristics of the soil-water complexes, the mean angle of repose of submerged and emergent deposits, the water environment being assumed to be perfectly calm. We also conducted research to define the laws for the formation, propagation and deposit of density currents.

In all cases, the measurements were carried out for a constant deposit depth (0.40 m) and for the same volume of mixture, the profile of the angle of repose being evaluated from a mean value for the inclination of the bank.

The only purpose of this research was to show the influence of the nature of the soil-water complexes and of the concentration on the slope of a deposit and to find the physical characteristic most representative of the slope.

1. Angles of repose of banks of non-cohesive sediment (sand and silt)

For comparison purposes, an initial series of experiments was conducted on non-cohesive sandy sediment with mean diameters of between 0.15 and 6mm.

We found that

- the slope of the sandbank varies between 31 and 40° ($\tan\alpha$ between 0.6 and 0.85), the curve of the slope versus the diameter is parabolic, and it is independent of the time the sand is immersed in the water;
- there is little change in the slope when the water level is slowly lowered;
- the slope is greater when the density of the non-cohesive material diminishes.

These values are valid only for perfectly calm waters and for the maximum slope of the bank. In the sea and along the coasts, the mean slopes of the beaches are much smaller. P Shepard gives slopes for beaches of between 2° ($\tan\alpha = 0.035$) for fine sand 0.12 mm in diameter and 15 to 20° ($\tan\alpha = 0.36$) for pebbles 60 mm in diameter.

Coastal Engineering (1966) gives the following figures for the slopes of beaches:

Diameter (in mm)	$\tan\alpha$
0.2	1/50
0.4	1/15
0.6	1/10
0.8	1/5
1.0	1/4

2. Angle of repose of banks of cohesive pelitic sediment

Unlike non-cohesive sediment, pelitic sediment exhibits angles of repose for its banks that vary considerably depending on how much the deposits have settled, ie, on the concentration of solid particles. The mineral composition of the sediment, the composition of the water environment, the sand content of the sediment and whether the deposits are under water or above water will affect the angle of repose.

A - Effect of the nature and size of the particles of sediment

The mineral and granulometric composition of the mud greatly affects the angle of repose of the deposits. At identical concentrations of solid particles, mud taken at La Rochelle will have a slightly greater angle of repose than mud taken at the mouth of the Mahury, and a much greater angle of repose than mud taken in Algerian wadis like Hamiz and Fodda.

For example, mud from under water at La Rochelle will have in calm (fresh) water an angle of repose of 6° ($\tan\alpha = 0.1$) for a concentration of 335 g/l, whereas mud from the Hamiz wadi will have the same angle of repose for a concentration of 600 g/l.

B - Effect of the solid particle concentration and initial rigidity on the angle of repose of mud under water

The angle of repose of pelitic sediment under water or above water increases very rapidly with the concentration of the deposits. As for the initial rigidity, we find that the angle of repose, defined by its tangent, increases as the fourth or fifth power of the concentration of solid particles.

On the other hand, we can say that the angle of repose of a deposit is directly proportional to the initial rigidity τ_y of the deposit measured with a rotary viscosimeter; these results are valid for angles of less than 60°.

$$\tan\alpha = K\tau_y$$

For mud under fresh water, the value of $K \simeq 0.025$, if we express the initial rigidity in newtons/m^2. A deposit of pelitic elements under fresh water will have an angle of repose of about

$$\tan \alpha = 1$$

ie, an angle of 45^{6}, if the initial rigidity is 40 N/m^2.

$$\tan \alpha \simeq 0.025\ \tau_y \text{ (in N/m}^2\text{)}$$

These various results show also that mud one metre thick under water for less than a month, ie, with low initial rigidity, may flow over the bed and silt up a dragged channel. However, mud, a few months after being deposited, will show initial rigidity of over 5 N/m^2 and can be dragged with a bank slope of $\tan\alpha = 0.10$, if the water environment is perfectly calm.

C. - Comparison between the angles of repose of mud banks under and above water

The angle of repose of mud above water is, for identical concentrations of particles, much smaller than that of mud under water.

For practical purposes, the ratios between the angles of repose of masses under water and above water (characterized by the tangent of the angle the bank makes with the horizon) vary as the ratio of the apparent densities $(\rho_m - \rho)/\rho$ of the immersed or emergent mud.

Figures 32 and 33: see original.

If we compare the angle of repose of mud above water $\tan\alpha'$ with the initial rigidity τ_y of the deposits, we see, as for mud under water, that the slope is directly proportional to the initial rigidity; however, the value of the constant K is smaller:

$$\tan\alpha' \simeq 0.007\,\tau_y \text{(in } N/m^2\text{)}$$

This result is valid, in our experimental conditions, for slopes of less than 45°.

D - Effect of the percentage of sand in the mud deposits on the angle of repose of the banks

Judging from the systematic tests conducted, adding 10 per cent of fine sand (from the bay of the Somme, mean diameter: 0.2 mm) to mud of various concentrations makes virtually no change in the angle of repose of the bank, if we consider the water content (or concentration) of the mud alone.

As an example I give, in the table below, the angles measured under water for pure mud and for the same mud containing 10 per cent of sand (from the Fodda wadi).

CONCENTRATION MUD ONLY	SLOPE MUD ONLY	SLOPE MUD + 10% SAND
T_d (g/l)	$\tan\alpha$	
630	0.27	0.25
600	0.115	0.12
540	0.037	0.04
490	0.027	0.03

These findings are valid for both immersed and emergent mud. However, if we considered, not the concentration of mud alone but rather the overall concentration (mud + sand), we would obtain, as we would for the initial rigidity, smaller angles of repose with sandy mud than with pure mud.

If we increase the percentage of sand contained in mud of constant concentration, we can see that the angle of repose of the bank (immersed or emergent) is virtually unchanged as long as

Effect of various sand percentages on mud at 520 g/l (Fodda)

% SAND ADDED TO THE MUD	Tan δ
0	0.06
2	0.06
3.5	0.059
6	0.051
15	0.051
27	0.044
50	0.135
100	0.61

Figure 34: see original.

the sand percentage does not exceed 30 per cent. Beyond that, we note that the bank becomes steeper (in the experiments and for the initial concentration of mud used).

E - Effect of the water environment

The angle of repose of a mud bank is slightly greater (for equal concentrations of dry sediment) in sea water than in fresh river water. Also, some deflocculent salts, like sodium pyrophosphate, put into the mud in large quantity, considerably reduce the angle of repose.

These results overlap those obtained for the initial rigidity of the deposits, which appears as the most important physical property for defining the angle of repose under water or above water, that can be taken on by different forms of mud or sludge.

3. Density currents

The essential difference between slides, flows and density currents is related, judging from the experiments that the LCHG was able to carry out, to the rheologic properties of the environment.

Density currents arise in suspensions that have no inherent initial rigidity, whereas sludge flows are related to already compact, plastic or solid soils.

The first can cover very great distances on an almost horizontal bed, and erode the bed only if the bed is hardly at all consolidated; they carry large quantities of materials and are sedimentation agents. The second arise from a break in the angle of repose of the soil, ie a slide, and can be changed into underwater avalanches, with high erosive power, if the slope of the bed is big.

Density currents are due to the difference in density between the fluids present, ie, between the suspensions containing quantities of sediment. This difference in density causes, in the vicinity of the bed, a pressure difference directly proportional, if one of the fluids is pure water, to the turbidity T_d of the suspension.

If the depth of the turbid water in contact with the clear water is D, the velocity of formation of the density current is given by the expression

$$V = K\sqrt{g'D}$$

with $$g' = g \frac{\rho_m - \rho_0}{\rho_m}$$

where g' is the small acceleration due to gravity,

ρ_m is the specific mass of the suspension, and

ρ_0 is the specific mass of the water.

For a mud suspension at 50 g/l, we can see that

$$\frac{\rho_m - \rho_0}{\rho_m} \doteq 0.029$$

The value of K, in our experiments in the flume, was 0.7 for low viscosity suspensions, and slowly diminished when the viscosity increased, to disappear abruptly when initial rigidity appeared, ie, for concentrations and suspensions equal to or greater than 250 or 300 g/l, according to the mineral composition of the sediment.

For a concentration of 50 g/l and a suspension depth of D = 1 m, the maximum density current velocity would be 0.37 m/s; it would be 1 m/s for a suspension depth of 10 m.

The switching of the density currents to muddy flows can be defined by the appearance of an initial rigidity in the suspension, which sharply alters the conditions of formation and propagation of the suspensions over the bed.

On a horizontal bed, the density current velocity that is not maintained decreases more rapidly if the initial concentration of the suspension is greater or, more accurately, if the viscosity of the suspension is higher. It appears, judging from a number of experiments, that a decrease in velocity $\Delta V/\Delta L$, in relation to the distance L, varies proportionally with the viscosity of the suspension.

Also, it seems that density currents deposit their materials as soon as the Reynolds number of the density flow becomes lower than

$$R = \frac{Vh}{\nu} \leq 2,000 \text{ or } V \leq \frac{2,000\nu}{h}$$

where h is the height of the density current above the bed,

v is the velocity, and

ν is the kinematic viscosity of the suspension.

A density current formed with Mahury mud having a concentration of 100 g/l would deposit its materials as soon as its propagation velocity is less than 1.0 m/s (assuming the thickness of the density current to be 1 m).

Finally, the dilution of the density current at the suspension-water interface will depend on the relative velocity V_r of the flows. If the density current velocity increases, or if a current of pure water opposes it, dilution will appear and tend to reduce the motive force maintaining the density current. The density current velocity should not be able to exceed a certain critical threshold.

The importance of density currents in the transport and depositing of sediment must not be overlooked and some kinds of silting can be explained only by such processes.

Figures 35 and 36: see original.

III - BEHAVIOUR OF DEPOSITS OF PELITIC SEDIMENT UNDER VARIOUS KINDS OF HYDRODYNAMIC ACTION

There are many papers dealing with the conditions of entrainment of mobile non-cohesive materials under the action of currents or waves. However, less is known about the conditions of erosion and transport of pelitic sediment under various kinds of hydrodynamic action; the first studies done by the LCHF go back about a dozen years.

Since that time, the LCHF has been pursuing research in this area, taking into consideration the nature of pelitic sediment, the characteristics of the water environment, the effect of the various sand contents and especially the extent of bedding down of the deposits characterized, as for the angles of repose of the mud banks, by the concentration of solid particles and their initial rigidity.

1. Study of the erosion of pelitic sediment by uniform currents

A - General

The beginning of entrainment or erosion of a soil can be defined

- by the mean velocity of the water $\bar{U}$:

$$\bar{U} = \frac{Q}{S}$$

where Q is the flow of liquid, and
S is the transverse section of the flow.

With this parameter we cannot have great precision, since the critical velocity of entrainment $\bar{U}_c$ will depend on the height of the water H above the material. $\bar{U}_c = fH^{1/6}$. For example, if $\bar{U}_c = 25$ cm/s, for a water height H = 0.10 m, U_c will be 36 cm/s for a water height of 1 m and 55 cm/s for a height of 10 m;

- by the entrainment force τ_0 exerted on the bed:

$$\tau_0 = \rho . g . R_H . i \qquad (1)$$

where ρ is the specific mass of the water (in kg/m^3),
g is the acceleration due to gravity (in m/s),
R_H is the hydraulic radius (wet section; wet perimeter, in m), and
i is the slope of the waterline;

- by the friction velocity U_*, such that

$$U_* = \sqrt{\tau_0/\rho} \qquad (2)$$

The friction velocity U_* can be related in a uniform system to the mean velocity $\bar{U}$ by Chézy's coefficient C:

$$\frac{\bar{U}}{\bar{U}_*} = \frac{C}{\sqrt{g}} = \frac{KR_H^{1/6}}{\sqrt{g}}$$

In our experiments (height of water in the glass flume = 0.40 m), the coefficient $C \simeq 75$ and $U = 24\ U_*$; Strickler's coefficient K is close to 100.

$$\bar{U} = KR_H 2/3\ i^{1/2}$$

In theory, it should be easy to measure the friction velocity, U_*, since we need only determine, in the established system, the hydraulic slope i and the draught H, and from equations 1 and 2 deduce the value of U_*, or learn the mean velocity $\bar{U}$ and Chézy's coefficient to determine U_*, from equation 3.

In practice, the measurement of the slope i in a short experimental flume is very imprecise and we are forced to determine U_* from the velocities U at various depths y of the bed and the value of Nikuradse's roughness factor [?] k_s.

(k_s: diameter of the contiguous spheres that would give, for a rough, turbulent system, the same friction on the bed.)

$$\frac{U}{U_*} = 5.75 \log \frac{y}{0.108 \frac{\nu}{U_*} + 0.33\ k_s}$$

for $y \leqslant 0.16$ H (H is the total depth).

If we take for the viscosity ν a value of $1.15 \times 10^{-2} cm^2/s$ (temperature = 13°C), and assume that on a smooth mud bed the coefficient k_s is negligible, we obtain in the cgs system the simplified equation

$$\frac{U}{U_*} = 5.75 \log 800\ yU_* \qquad (4)$$

As an example, if $U_* = 1$ cm/s, we should have U = 16.6 cm/s at 1 cm from the bed and 22.5 cm/s at 10 cm from the bed.

For non-cohesive gravel, pebble or sand sediment, the studies conducted by various research workers show that on the average, the entrainment force τ_c required to erode the bed is proportional to the particle diameter

$$\tau_c \text{ (in N/m}^2\text{)} = KD \text{ (in mm)}.$$

According to the authors, the coefficient K may vary between 1 (Shields) and 0.3 (Liu-Chang).

For cohesive mud, silt or sludge sediment, the particle diameter will not be enough for a determination of the recovery rates [?] and consideration will have to be given, as has already been said, to the degree of bedding down of the soil-water complexes.

B - Experimental conditions

The measurements were made in the LCHF tilting flume.

- length	12	m
- width	0.40	m
- height	0.60	m
- possible tilt	1/12	
- maximum flow	250 l/s	

- control by gate downstream, stilling chamber [?] upstream

The mud is arranged in the centre of the flume over a length of 3 m and a thickness of 12 cm; it is carefully homogenized and levelled.

The velocities are measured with Hydrotechnica miniature current meters 1.5 cm in diameter, with automatic recording over the whole depth (every 5 mm up to 15 cm above the bed, and every

Page 610 (figures 42, 43 and 44): see original.

cm beyond that, up to the surface).

The slope and draught of the water are taken with limnimeters above the container of mud and at the ends of the flume.

Finally, the water turbidity is determined at the various depths above and below the flume (measurement by colorimetry).

The mud is prepared in a special type of mixing vat and mixed with the soakage water for at least three hours before being put into the flume. Each time the mud is put into place and the flume filled (slowly), a period of fifteen minutes is allowed for the deposits to become rigid again without any mixing.

C - Erosion of the various kinds of mud by currents at their various stages of consolidation

Depending on the concentration of the mud deposits, ie, their degree of settlement, the beds can be eroded in very different ways:

- For very low concentrations, which can relate to mud that was deposited during a slack and therefore did not have the time to consolidate, the suspension behaves like a true viscous fluid (creamed mud), and at the interface of the water and the mud there is a discontinuity where there arises a waviness due to the difference of velocities between fluids.

If the current velocity is sufficient and much greater than the phase velocity of the waves, we can see a successive change in the discontinuity leading to a separation into discrete eddies and mixing of the fluid mud and the water.

We can also see in the mud a general shift in the direction of the current and a downward change in the slope of the bed upstream and an upward change downstream, if an obstacle interrupts the flow.

- For medium concentrations, it is hard to make out discontinuity waves at the mud-water interface.

The surface of the mud becomes puckered, showing rips in the surface film, which may be torn from the bed and totally diluted in the water. The motion travels downstream and the eroded pelitic sediment is carried in suspension in the water with a concentration gradient from the (heavily loaded) bed to the surface.

After the current has acted for a time, the whole surface of the mud is puckered and covered with tiny wrinkles.

If we stop the action of the current, the surface marks remain visible, but we can see that the mud, which had been stretched downstream by the tangential forces acting on the bed, retracts upstream exactly like a plastic body.

- For high concentrations, ie, mud that has been piling up for several months or at the very least several weeks, it takes very great velocities to tear away bits of consolidated mud. It is very difficult for these bits of mud to become diluted in the water and they are carried in the form of pebbles of low density but high cohesion.

In most cases, the erosion begins at a preferred point (sand particles, drainage wells,...) and extends downstream, forming a gradual flare horizontally and an increasingly larger pit vertically.

D - Effect of the mineral composition and grain size of the pelitic sediment

It must first be made clear that the critical threshold for the putting back into suspension (or re-erosion) of mud is fairly well marked. Below the critical recovery rate there is no movement; above it, we can get a large amount of mud back into suspension.

Also, unlike what can happen with coarse sediment like pebbles, gravel and sand, once the mud has been put back into suspension by the current and diluted in the water, very low velocities are needed to keep the mud in suspension. This holds true as long as the initial rigidity of the mud is low; for high rigidity (mud pebbles), however, the depositing can take place as soon as the current velocity decreases.

When we compare the critical friction velocities U_* that are needed to put the various forms of mud (La Vilaine, Mahury,

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Figures 45, 46 and 47: see original.

Provins, Aiguillon, Hamiz, Fodda,...) into suspension again, we find the mineral composition of the mud has a very great effect.

In fresh river water, it takes a friction velocity U_* of 2 cm/s (about 0.50 m/s mean velocity) to erode a mud from La Vilaine having a concentration T_d of 200 g/l, whereas the same velocity will put back into suspension Hamiz or Fodda mud having concentrations of 450 g/l.

As things are now, it is not possible to define accurately the effect of the mineral composition of the deposits. Systematic experiments on pelitic sediment of simple mineral composition like powdered quartz, powdered limestone, kaolinite or montmorillonite and mixtures of these in varying proportions may provide the answer to this problem in the near future.

E - Effect of the concentration of particles and the initial rigidity of the deposits

Interpretation of the measurements of critical entrainment velocities for the mud versus the concentration of solid particles in the deposits tend to show, as a first approximation, that:

- for old deposits, the critical scour velocity U_* varies as the square of the concentration T_d:

$$U_* \simeq K T_d^{\,2}$$

where K depends on the nature of the soil-water complexes and may vary greatly from one form of sediment to another (in a ratio of 1 to 5, or even 1 to 10);

- for recent deposits that are imperfectly consolidated, the scour velocity varies in proportion to the concentration of sediment:

$$U_* \simeq K' T_d$$

If we plot the critical scour velocities U_* against the initial rigidity τ_y (measured as has been said with a rotary viscosimeter), we can see that all the measurement points, no matter what kind of soil-water complexes are examined, are grouped around two straight lines corresponding to the rigidity values lying on both sides of about 1 to 3 N/m^2.

For initial rigidity values above 2 N/m^2, ie, for consolidated deposits, the critical scour velocity is given by the approximate expression

$$U_* \simeq 0.016 \tau_y^{1/2}$$

if U_* is expressed in m/s
and τ_y is expressed in N/m^2;
and $$U_* \simeq 0.50 \tau_y^{1/2}$$
if U_* is expressed in cm/s and τ_y in dynes/cm^2.

For deposits having an initial rigidity of less than 1 N/m_2, ie, for plastic unconsolidated deposits, the critical scour velocity U_* will be related to the initial rigidity τ_y by

$$U_* = \tau_y^{1/4}$$

if U_* is expressed in cm/s and τ_y in dynes/cm^2.

Figure 48: see original.

F - Effect of water environment on the velocity of mud erosion

The water environment has a very great effect on mud erosion conditions.

For identical concentrations of solid particles, and for the same sediment, it requires

- a current velocity about 1.7 times greater to erode mud in sea water than mud in fresh water;
- a current velocity about seven to eight times weaker to erode Provins clay in fresh water containing deflocculent salts than the same clay in sea water.

Here again we can find exactly the same results as we had in the measurement of the initial rigidity and viscosity in suspension of the same sediment in various water environments.

G - Effect of various sand contents of mud

Various percentages of fine sand were put into Fodda mud of constant concentration (470 g/l) and systematic measurements were taken of the critical recovery rates of the currents.

Table: see original.

From these results it appears that only the water content of the mud around the sand particles is of great importance; this result is valid up to a sand content of thirty per cent. After that the critical velocity U_* tends to decrease.

These results agree with those obtained by examination of the effect on the initial rigidity of various percentages of sand in a suspension of pelitic elements.

H - Passage of sand, gravel and pebbles over mud of various degrees of consolidation

The preceding studies have shown that the critical scour velocity of mud deposited over a fairly long period could be much higher than that required to entrain coarse sediment.

Thus mud with an initial rigidity τ_y of 10 N/m^2 will not be eroded for current velocities U_* of less than 5 cm/s, whereas coarse sand or fine gravel can shift at this current velocity.

Systematic measurements made at the Laboratory made it possible to define the conditions for the transport of sand, gravel and pebbles over mud beds of various degrees of consolidation, so as to shed some light on some sedimentologic problems.

During these experiments, it was found that

- for mud deposits of low concentration, ie, mud deposited for a short time, sand particles in transit could be trapped in the mud. This happens when the initial rigidity of the deposits is less than 1 dyne/cm^2;
- for mud of higher concentrations, the sand could pass over the mud without being trapped, as could the gravel and small pebbles, as soon as the initial rigidity exceeded 1 N/m^2. Such displacements can occur by sliding, or by saltation, of the points of impact that mark the surface of the mud at the time.

Consolidated mud is therefore not an obstacle to the passage of sand and gravel, and we can very well have coarse sediment passing down over the mud banks in a river or estuary.

2. Study of the displacement of pelitic sediment by tidal currents.

With a view to later studies of the similarity of silt and other very fine sediment, research was done a few years ago at the LCHF for the purpose of examining the conditions for depositing and putting back into suspension various soil-water complexes in a theoretic estuary.

This was a regularly converging estuary 40 m long, 8.85 m wide at the downstream end and 0.25 m wide at the upstream end. The tide represented was of the river type and was about 1/3 floodtide and 2/3 ebbtide.

The tests covered various types of pelitic sediment dispersed in water environments containing varying proportions of flocculent salts (MgCl) or deflocculent salts ($Na_4P_2O_7$). The material was assumed to be of marine origin and was put in at the downstream end of the model.

The tests were conducted in some cases without any river flow and in other cases with a weak river flow. The variations in the beds obtained on the model were followed by means of systematic measurements over time, and we were thus able also to study the effect of the various hydraulic factors on the movement of the sediment.

This research on a small-scale model was paralleled by and compared with a number of measurements taken by our field study teams.

The various results obtained on the model and in the field enabled us to make a number of assumptions on the displacement of mud under the action of tidal currents.

A - Study on a sedimentation model of a theoretic estuary by the addition of material of marine origin (without river flow)

Under the action of tidal currents acting in an estuary that was assumed to be dredged [?] uniformly very deep, compared to the amplitude of the tide, and not subject to river flow, we can see that the pelitic

Figure 49: see original

sediment supplied at the downstream end has moved upstream.

At first the sedimentation occurs only in the downstream part of the estuary, where the bed gradually rises. Since the velocities are boosted locally in this area, the sedimentation gradually reaches the sections farther upstream. At a certain stage (time t)--and for a given type of soil-water complex--the estuary depth will be constant over its whole extent; the bed is horizontal at a point H below the mean water level.

Beyond this stage, the sediment is deposited in the upstream part of the estuary, and there is a regressive sedimentation in the downstream direction.

The sedimentation is therefore at a maximum at the downstream end of the estuary, as long as equilibrium is not reached, and becomes greater upstream, when this sedimentary stage is passed.

The depth H below the mean water level, and the time t at which the bed starts to be horizontal over the whole estuary, depends--apart from the hydraulic characteristics--on the physical properties of the pelitic sediment and its water environment. The critical depth H will generally be greater if the soil-water complexes show smaller initial rigidity τ_y at their various stages of settling.

By acting on the characteristics of the water environment, it will be possible, on a small-scale model, to adjust the values of H and t, and thus to adapt the soil-water complex to the requirements of similitude.

B - Movement of pelitic sediment in a theoretic estuary, without a supply of mobile materials and without river flow

Under the action of the tidal currents, a theoretic estuary the mean depth of which is uniform over its whole extent and less than the critical depth H previously defined, will be subject to large rearrangements if the initial rigidity of the deposits is less than the entrainment force on the bed.

The sediment will be carried upstream by the currents and in some cases may emerge. The final profile of the bed will be a gentle slope in the downstream direction which in our experiments was 1.4 per thousand when the new state of equilibrium was reached.

C - Effect of a weak river flow without a supply of mobile materials

Adding a weak river flow at the upstream end of the estuary (1/30 of the volume of oscillating water) greatly changes the profile of the estuary bed. This effect is greater if the initial rigidity of the deposits is smaller.

Under the action of the weak river flow, the bed is eroded at the upstream end and tends to build up slightly toward the downstream end, the rest being pulled toward the sea (outside the limits of the model).

If we stop the river flow and resupply the model at the downstream end, the transgression of the sediment begins again and the bed builds up again in the upstream direction.

There is therefore a permanent change in the bed of an estuary under the effect of the river flow if the deposits are not well consolidated.

D - Displacement of the pelitic sediment in the estuaries in nature.

In nature, what happens is very complex and bears very little resemblance the simplified arrangements of a theoretic model.

From all the natural estuaries studied, Betsiboka, Cayenne, Mahury, Sèvre niortaise and La Vilaine, to which can be added the alternative action of the currents before Conakry, it can be seen that:

- at a given point in an estuary, the maximum turbidity during a tide grows exponentially relative to the range A of the tide (square or cube of the range). It can be a very small for a small coefficient and large for coefficients over 70;
- it does not appear that in a tide the turbidity can be directly related to the mean current velocity at the same point. It can very frequently be seen (La Vilaine, Bombetoke, Mahury) that the turbidity rises sharply near the bed, after the low stand, although the currents can still have a low absolute value. We can believe that there then exists a large velocity gradient close to the bed, capable of creating a strong turbulence favouring the putting back into suspension of the fluid mud;
- the turbidity gradients between the bed and the surface seem larger at flood tide that at low tide, and at the upstream end of the estuary than at the downstream end;
- the turbidity increases likewise when we go up the estuary, then decreases again when we approach the limit of the river-sea stretch;
- the resultant of the movements of sediment is generally in the upstream direction, during low-water periods, and large amounts of mud can be carried up from the mouth many dozens of kilometres (silting of the Redon sector in La Vilaine, of the upstream part of Degrad-des-Cannes at Mahury...). On the other hand large amounts of mud may slowly pass downstream in the flood period. If there is little

- sediment coming from the outside, the estuary, although in perpetual motion, is dynamically stable;

- the presence of a salinity gradient or of a salty spot can very greatly alter the movement of the pelitic sediment in an estuary.

These natural schemes are in harmony with the observations made in tests on the models of theoretic estuaries. Because of the complexity of what goes on, however, we cannot suggest any precise formulas and will need many measurements to arrive at that stage.

3. Action of swells and wind waves on mud deposits of various degrees of concentration

Wind waves and swells have a considerable effect on mud-beds of various degrees of consolidation.

Depending on the characteristics of the material and of the wave, large volumes of mud can be carried up from the bed and moved along the littoral in the form of moving bars or banks having their individuality and exhibiting a definite mud-water interface or on the contrary, be put back into suspension in the water, forming along the edge of the littoral an immense river of muddy water that can carry large quantities of mud in suspension in the littoral currents and add to the sedimentation of the estuaries.

This double aspect of the contribution of the wave in the transport of mud was studied for the first time at the Laboratory in 1956-57 and was demonstrated mathematically in 1958 by P Lhermitte (Contribution à l'étude de la couche limite des houles progressives).

The wind waves and swells act directly on the movements of the mud; the mud on the other hand modifies the rules for the propagation of the swells and can, in some cases, cause total damping of the waves, which are completely absorbed in the soft mud before reaching the coast.

In nature, the various interactions of the waves and the mud are of great importance along the coasts.

A - Experimental conditions

The effect of wind waves and swells on mud beds of various degrees of consolidation was studied in the Laboratory's large glass flume.

- width	1 m
- length	60 m
- depth	1 m

Because of the size of the problems raised, the investigations had to be limited to a number of simple cases.

Thus among other things, the thickness of the deposits of pelitic sediment was not systematically studied and our results are therefore applicable only to deposits at the surface or of fairly small thickness, whereas in nature we can find mud deposits that are very thick and consequently have a consolidation gradient between their surface and the bed on which they are sedimented.

B - Propagation of waves on the mud beds

The rules for the propagation of waves on a bed of unconsolidated mud are not the same as for those propagated on a perfectly rigid bed. The water depth that has to be taken into consideration in the classic formulas giving the wavelength for a given period will be more important than the thickness of the layer of clear water above the water-mud interface. It can be estimated from the results of our experiments that we need an initial rigidity of over 20 N/m^2 for the bed to behave like rigid soil; for smaller values, it will be assumed that the wavelengths can be slightly larger than those resulting from a direct computation based on the depth of water above the mud bed.

C - Effect of waves on the physical properties of mud

The sinking rate of pelitic sediment floc can be greatly altered by the action of waves. This extremely fragile mud floc becomes disaggregated and forms smaller elements with a resulting decrease in the mean sinking rate of the floc which can be five times as small under a wave as under calm water.

Likewise, the orbital movements of the wave can develop in unsettled mud causing considerable stirring of the deposits.

The effect of this stirring is to substantially diminish the chances of the mud's settling and to cause older deposits to become fluid because of the thixotropic properties of some forms of mud.

The orbital movements in the mud will be larger if the wave is larger, the depths smaller and the rigidity of the deposits less.

Here again we find that there is interaction between the physical properties of the deposits and the hydrodynamic action of the waves.

This action of the waves on the chances of the deposits of pelitic sediment consolidating is found in nature. We find, for example, a gradual decrease in the water content of the deposits as the water gets deeper. In French Guyana, our field study teams were able to measure the following variations:

Table: see original.

D - Shoreward drift of mud under the action of ocean swells

Superimposed on the orbital motion in the mud, a motion of mean translation of the particles can arise and, without putting them into suspension, carry a large quantity of materials in the same direction as that of the propagation of the swell by a process comparable to that found in the boundary layer.

In our experimental conditions, ie, for a certain type of wave and between certain limits of the bed viscosity, there is a relationship between the velocity U_T of translation of the mud particles and the maximum velocity U_{fv} of the oscillatory motion in the mud. This relationship takes the form

$$U_T = 0.02 \quad U_{fv}^{1.6}$$

P Lhermitte showed that it was necessary only that the pressure gradient be of the order of magnitude of the initial rigidity of the mud for the process to occur and that what we see is a slow drift of the mud toward the littoral.

However, if a certain critical threshold of agitation is exceeded, or if we get into the shallows, the motion in the mud can be amplified and lead to the putting back into suspension of the sediment above the bed.

Figures 51, 52 and 53: see original.

Page 618 (figures 54-57): see original.

Also, if the bed is subject not to swell but to wind waves, there can be a strong turbulence near the bed and the mud can be put back into suspension without any shoreward drift.

In the breaker zone, as a result of the strong turbulence, the materials that have come in from the sea in the translation current will be put back into suspension over the whole depth of the water, which will then be heavily loaded between the breaker point and the shore. A density current may then arise in the coastal zone, superimpose itself on the compensation currents due to the wave, and travel out toward the deeper areas where the particles will form deposits.

There can, however, be exceptions to the mud's being put back into suspension. In some cases, the wave will die on the shore without breaking; its motion will then be transmitted to the underlying layer of fluid mud and travel into the mud itself where it will be weakened by the viscosity of the material. The continually supplied coast will then receive heavy deposits.

Under the more complex action of the wave on a bed consisting of pelitic sediment, we can always find the same effect of the characteristics of the materials, their water environment and their degree of settling. Essentially variable in time, the dominant physical properties of such deposits are their initial rigidity and their viscosity.

IV. - CONCLUSIONS

The comparative study of the physical properties of pelitic sediment of mud, sludge or silt and of its behaviour under hydrodynamic action shows that, despite the complexity of events, there are a number of simple relationships among the various characteristics that are representative of soil-water complexes.

Knowledge of the mineral and chemical characteristics and size of the elementary particles is essential to a search for the origin of a deposit and to any assumption about the conditions for its settling at a given point. Confirmation of this can be provided by the detection of natural tracers consisting of oligo-elements contained in the sediment, and by modern methods with radioactive tracers.

However, to define the dynamics of these very fine forms of sediment in their water environment, it is essential to state a number of fundamental physical properties. Research conducted at the LCHF on behalf of various French and foreign authorities as well as for private companies tends to show that the three basic physical properties are:

- flocculation of the suspensions and, by extension, the sinking rate W_f of the floc at various concentrations of solid particles and in various water environments;
- the settling of the deposits in the course of time, characterized by the mean variation of the particle concentration T_d and the concentration gradient vs the depth;
- the rheologic properties of the deposits at various stages of settling and more especially, the initial rigidity τ_y and the viscosity vs their concentration of solid particles.

If these three physical properties are close for different soil-water complexes, their suspensions and deposits will behave in the same way under hydrodynamic action.

In particular, the slope tan α of a mud bank under or above water will be proportional to the initial rigidity τ_y of the deposit:

$$\tan \alpha \; K \tau_y$$

where K is close, for certain measurement conditions and for deposits under water, to 25/100 if τ_y is expressed in dynes/cm^2 and to 7/100 for deposits above water.

Also, the critical friction velocity over the bed U_* as a first approximation can seemingly be related to the initial rigidity by

$$U_* = 0.5 \tau_y^{1/2} \text{ with } \tau_y \text{ in dynes/cm}^2$$

for deposits having an initial rigidity of over 10 dynes/cm^2.

The same effect of initial rigidity and viscosity of the deposits can be found in the behaviour of various forms of pelitic sediment in water environments under the action of tidal currents and of the swell.

The flocculation, settling, rigidity and viscosity of deposits apppear in all cases as physical factors characteristic of soil-water complexes changing under the various forms of hydrodynamic action. Attention must, however, be drawn to the difficulty we still have in precisely defining such factors, since their quantitative values are dependent on the measurement conditions and must be extrapolated with great caution before they are generalized.

DISCUSSION

Chairman: Mr Talureau

The chairman introduced Mr Migniot, an engineer at the Laboratoire Central d'Hydraulique de France where his research on movable-bottom small-scale models for the study of the problems of sanding or silting in a river or ocean led him to a more detailed study of the behaviour of very fine sediment in these various environments.

Mr Chamboredon asked what the effect was of organic matter, often contained in mud, on the properties that were studied.

Mr Migniot said that in the mud that was studied the percentage of organic matter fluctuated between 0.12 and 2 per cent; it is mainly the rigidity that is affected; for further particulars he referred to a study made by Mr Rivière of the Laboratoire d'Orsay on the effect of organic matter on various types of clay.

Mr Johnson commented that the values for initial rigidity τ_y used by Mr Migniot in establishing the formulas he presented for the entrainment velocity and for the angle of repose of mud were obtained from tests with a viscosimeter; they therefore corresponded to the characteristics of reshaped material. However, the rigidity of untouched mud could be fairly different from that of the same mud after it has been reshaped.

Mr Johnson asked whether Mr Migniot had had a chance to make comparative measurements of both states of the same mud by using for the measurements a crossbar scissometer [?] or the new apparatus described by Mr Biarez.

Mr Migniot acknowledged the value of such measurements, but was able only to compare the values of the initial rigidity, obtained by various laboratories by pressure measurements, with those given by rotary instruments; the numerical values are different, but the laws of change exhibit the same trend, so that the values of the coefficient K are not the same.

Mr Migniot explained also that the results given in his paper concern laboratory tests in flumes and the measurements in situ on mud for these tests were made with a rotary instrument. These measurements, possible in a laboratory, are difficult in the field, but do not seem impossible; one may think that in both cases the laws are appreciably the same, at least qualitatively.

Mr Biatez made the following comments:

1. The measurements with a scissometer can be very different for the same mud in the laboratory and in situ. This depends particularly on the thixotropy; but the latter can be very variable from one form of mud to another. The difference depends, moreover, on the method of mixing and on the time of repose in the laboratory. In a few special cases, we have found variations of 1 to 5;

2. The angles of stability of the mud slopes must vary greatly with the height of the banks.

Mr Migniot confirmed the effect of the height on the slope of a bank, but recalled that all the measurements he had mentioned had been made in the laboratory with a constant height (40 cm).

The Chairman thanked Mr Migniot.