Structuration of natural muds in a rheological point of view.

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Abstract. This paper discusses the filling of estuary problem which can be defined as the accumulation of fine materials that causes the invasion of muds all over the estuary and that has a direct effect on the fauna and flora in the river, fishing, swimming and the beauty of the landscapes. All this consequences have social, environmental and economic impact. In the context of the study of this phenomena, analysis of the structuration mechanisms of sedimentary materials in estuaries is carried out in order to better understand the fillings estuarine areas and specially to consider sustainable solutions of “cleansing” of these areas. The Rance estuary is particularly targeted by the study. The aim is to provide answers on the rheological behavior of natural vessels by distinguishing the most significant scales to detect structural factors influencing the rheological parameters.

1. Introduction

The filling of water system (estuaries, river) is a natural phenomenon that has been taking place since the end of the ice age and the beginning of the Neolithic era. This phenomenon is due to the accumulation of sediments in rivers.

In this study, we focus on the filling of estuaries. In fact, the estuaries are areas of water and shoreline typically found where rivers meet the ocean.

They are important sites for many biological and physical processes, yet they are often taken for granted. These ecosystems can act as “sinks” for land-based sediments and contaminants. At equilibrium situation (balance between erosion and sedimentation), sediment inputs into water estuaries do not significantly modify the natural ecosystem. The estuary has naturally the capacity to support a quantity of sediments and to return to equilibrium after each natural event. In most cases, industrial and anthropogenic activities or even natural phenomena (violent storms, volcanic eruptions...) disrupt the natural balance of estuary in a way that greatly exceeds the capacity of the system. The equilibrium will be broken.

The health of estuary ecosystems is threatened by the increase of nutrients and algal blooms, the loss of habitat and biodiversity, the contaminants and pollutants, the accelerated rates of sedimentation, the disturbance of acid sulfate soils, the changes to fresh water and tidal flows and the climate change.

The problem of filling of estuaries has been interpreted by many authors by studying the erosion phenomena in estuaries and the transport of sediments to those maritime basins (1), (2).

In this paper, we will discuss the filling of “La Rance” estuary, located in Brittany, northwest France. This estuary suffers from a sedimentary filling, that becomes more complicated after the construction of the tidal power station of “La Rance” in 1966. The main consequence of the sedimentary filling is the disruption of navigation. In fact, muds are widespread throughout the estuary, which reduce the movement of water and hinders navigation in the estuary. This siltation also causes the loss of 1% of the station's capacity per year, as well as flooding, bank collapse, and channel migration. The siltation has a direct effect on the fauna and flora in the river, fishing, swimming and the beauty of the landscapes. All these consequences have social, environmental and economic impact.

Thus, the cleansing of “La Rance” estuary became a must in order to prevent damage in the region. To that end and in order to facilitate the cleansing of this estuary, the association COEUR sets up in 1996 the trap of Lyvet, which creates a privileged area to the deposition of sediments and consequently makes the cleansing of the estuary easier. The trap of Lyvet has undergone several dredging and emptying operations since its construction till now.

In this paper, we focus on the structuration/destruction of sediments in the estuaries to find the elements influencing the sedimentation and to characterize those sediments. This will help us to understand how these zones are filled and to find afterward a better method to clean those fields.

2. From mechanics of fluid to rheology

Usually, in fluid mechanics the structuration/destruction of sediments is studied by identifying the flow properties of the fluid and then the properties of the friction at the interface between fluid and sediments in order to find the shear stress at this interface. Our aim is to use rheology to directly measure this shear stress in the deposited materials. In a first level, measurement of shear stress should be at young age. It means that we will study the variation of the shear stress just before chemical reactions begin. At a second level, we will analyze the influence of time on this stress. Therefore, the possible aging of sediments and the variation of the shear stress with time will be interpreted.

Actually, the transport of sediments and its structuration have been the subject of many studies. The majority of these studies discussed this topic as from a fluid mechanic’s point of view. In the same way, Leo C. Van Rijn (3) discussed lengthily in his book the processes of initiation of motion and suspension in terms of the critical velocities and bed-shear stresses. He presented detailed information of the transport of cohesive sediment materials. Also, Dietrich and Whiting (4) analyzed the boundary shear stress and the sediment transport in rivers.

On the other hand, few studies were dedicated to the rheology of liquid-solid natural sedimentary mixtures maybe because of the complexity of the combined processes and the diversity of the composition of these sediments. However, some authors studied the rheology of sediments as part of determining the sensibility of sediments to erosion and their structural changes (5) (6) (7).

Melingue (8) studied the rheological behavior of the Quiberon Bay muds according to the Herschel-Bulkley law detecting a shear thinning behavior. He proposes a kinetic evolution of the yield stress over time during a maximum aging period of 6 months. Such a result highlights the notion of variability of the erosion threshold as a function of the degree of structuration of the suspensions. This study is the base from which we start, trying to compare the behavior of sediments collected from different places in order to find an estuary signature.

3. Methodology of the work

3.1. Materials

The first step of our study is to collect the sediments from the trap of Lyvet using a shovel and then to analyze their chemical, physical and rheological properties.

Sediments collection was undertaken from different locations in the trap and at two different periods: In 2014 before the last emptying of the trap and then in 2015 during its filling. The comparison of the granular distribution of the samples collected from different locations in the trap and at different depths and at different periods shows that the sediments collected from the entrance of the trap are finest than others. Depth and time of collection didn’t influence the granular distribution of sediments. Although the rheological analyzes afterwards were performed on an average sample created from samplings made at different points of the grab trap.

Once arrived to the laboratory, materials will be dried using a 35°C hot air flow. Then, grinded into a powder and sieved to eliminate particles over 2 mm.

Those sediments have been characterized using chemical and physical techniques. So, we did a particle size distribution analysis which is a fundamental property of any sediment using laser granulometry. Also, X-ray diffraction (XRD) and a scanning electron microscope (SEM) analysis have been carried out to detect the minerals and the crystals present.

Actually, the SEM observations reveal the presence of biogenic elements and various minerals conventionally present in marine sediments: diatoms, calcite (in the form of spicules and shell fragments), quartz, clays and salts.

The particle size analysis of sediments was performed using laser granulometer. Regardless the depth sediments are always composed of silt, clay and fine sand with insignificant variation in proportions. The percentage of clay varies between 11% and 13%, the percentage of silt varies between 71% and 75% and the percentage of fine sand is between 12% and 18%. The maximum diameter is always less than 160 μm , and the median diameter is about 10 μm .

In order to analyze the influence of the diameter on the behavior of the sediments and to detect the inclusions and the binder part possibly existing there, the sediments were sieved and divided to obtain the following granulometry reductions: 0-40 μm , 0-63 μm , 0-80 μm , 0-125 μm and 0-160 μm .

Each of these reductions was characterized and we do not observe explicit differences between them. The grain size distribution curves of sediment reductions are represented in Figure 1.

Figure 1: Particle size analysis for different sediments reductions and natural sediments collected from the trap of Lyvet.

3.2. Method

The second step to understand the structuration of sediments was to study their rheology at young age. Measurements were carried out using a Kinexus rheometer with a Peltier plate cartridge and a 40mm (smooth) parallel plate measuring system. This type of rheometer is used for such a fine material and it allows to carry out a detailed rheological study. The gap is fixed at 2 mm and we use a sandpaper 180 to prevent the "wall slip" phenomenon resulting from a local depletion of the dispersed phase near the geometry walls. All rheology measurements were performed at 20°C.

Thus, this rheological study was performed in order to analyze the visco-plastic behavior of liquid-solid mixtures and to study a possible existence of a binder/granular inclusion relationship.

3.2.1. Preparation of the sample

For a given granular reduction, we weigh between 5 and 10 g of sediments with an analytical balance. Then, an exact quantity of water is adjusted using a pipette to obtain the expected fixed water content (between 120% and the packing). A chronometer had been triggered once the water is added. The mixture is mixed energetically. From the moment the stopwatch is triggered, the end of the mixing must not exceed one minute. This time must be the same for all tests. The mixture is then deposited on the sandpaper of the lower plate of the rheometer. The gap between the plates is then fixed at 2 mm, and the exceeded material of the two plates is eliminated so as to obtain a sample of diameter equal to that of the upper geometry. Finally, the test can be started and the age of the suspension is 4 min.

3.2.2. Experiments procedure

Rheological experiments are applied to samples of granular reductions 0-40 μm , 0-63 μm , 0-80 μm and 0-125 μm . For a sample, three phases will be applied:

- First phase: During this phase, a constant shear stress is fixed during one minute that guarantee a moderated shear rate that can be controlled according to the solid volume fraction of the tested sample. This phase aims to homogenize the fluid in the measurement geometry.

- Second phase: This is the phase of destruction of the material. It applies a linear stress ramp of 30 steps of one minute each. Test duration is closed to 30 minutes. The first part of this phase is generally associated with deformations in the solid regime.
- Third phase: This phase corresponds to a decreasing ramp with 30 shear stress steps of one minute each. It lasts 30 minutes. This phase is used to describe the rheological behavior of the solid suspension. Indeed, it makes possible to reach lower shear rate levels in flow than the destruction curve. For these reasons, only the results of this phase are interpreted in the following. Finally, the obtained average flow curves are analyzed and a rheological model is mathematically adapted.

3.3. Interpretation of rheological behavior of sediments (shear stress sequences)

We applied the experiment described previously for each granular reduction and for different inclusions volume fraction, in order to analyse the influence of these parameters on the viscosity and the limit shear stress. Figure 2 shows the results of the flow curves for the granular reductions 0-63 μm and for different solid volume fraction. At a fixed shear rate, the increase in the solid volume fraction causes a logical increase in the shear stress. The shape of the curves shows a visco-plastic shear-thinning behavior.

However, at low shear rate we detect a non-linearity in the rheological behavior. This is probably due to a structuration of sediments that occurs at low shear rate. For this reason, the rheological behavior is interpreted from a critical shear rate value. After this critical value of the shear rate, a linear tendency remains very acceptable. Thus, the sediments can be considered as Bingham fluid and will be interpreted using the equations below:

$$\tau \leq \tau_c : \dot{\gamma} = 0 \quad (1)$$

$$\tau > \tau_c : \tau = \tau_c + \mu \dot{\gamma} \quad (2)$$

Finally, these results show for the various granular reductions that the increase in the solid volume fraction increases the shear strength, which is logically in agreement with the results in the literature (9).

Figure 2: Average flow curve for the granular reduction 0-63 μm for different solid volume fraction.

3.3.1. Interpretation of the viscosity

Figure 3 presents the evolution of plastic viscosity μ (Pa.s) as a function of the solid volume fraction (ϕ) and for different granular reductions. It shows a functional link (μ, ϕ) that is not influenced by the different studied granular reductions. So, an average behavior representative of the whole grain size curve is highlighted without really being able to distinguish the influence of addition of inclusions for these dynamic solicitations. This can be explained by the dominance of fine sediments caused by the strong hydrodynamic regime. This behavior describes a divergent trend for the high values of the volume concentration that can be attributed to a packing effect (ϕ_m). In addition, for the low values of ϕ , we note that the link tends

to describe an asymptotic (horizontal) behavior and thus highlighting the rheological properties of the carrier fluid. This functional link is well described by the Krieger-Dougherty model, (equation 3).

$$\mu = \mu_0 \left(1 - \frac{\phi}{\phi_m}\right)^{-\eta\phi_m} \quad (3)$$

Where ϕ_m the maximum packing, η the intrinsic viscosity, it depends on the form of the particles and μ_0 is the viscosity of the medium.

Figure 3: Evolution of the viscosity as a function of the solid volume fraction for the different granular reduction and modeling of the data set with the Krieger-Dougherty model. $\mu_0 = 100,2.10^{-5}$ Pa.s ; $\phi_m = 0,409$; $\eta = 9$.

The fit of the model proposed in Figure 3 is obtained for $\eta = 9$ and $\phi_m = 0.409$. The regression coefficient (by confusing all the data without distinction of grain size reductions) is greater than 0.9; which is very acceptable and representative of the structuring mechanism of the plastic viscosity. Actually, we assumed that the carrying fluid is the water (Meling (8) for the sediments of the Bay of Quiberon, Toutou (10) for the concrete) whose dynamic viscosity is 100.2×10^{-5} Pa.s in normal temperature condition.

3.3.2. Interpretation of the limit shear stress

Finally, we interpret the evolution of the threshold shear stress as function of the solid fraction for the different granular reductions. But we should remind that the values obtained correspond to the Bingham model interpreted at high shear rate. So, results obtained will be a representative value of the threshold stress. In order to asses a better identification of the limit shear stress, other experimental has been then integrated in the protocol. Nevertheless, results are not analyzed in the present paper.

Figure 4: Evolution of the threshold shear stress calculated from the Bingham model as a function of the solid volume fraction.

The results obtained are negative or positive according to the tested volume fraction. The negative values (physically insignificant) of the threshold stress may be a sign of the absence of the plasticity in the sediments and it indicates a viscous behavior. Thus, we can detect a boundary between visco-plastic behavior (positive value) and viscous behavior (negative value) and it is around a critical value of 17% for the solid volume fraction.

On the other hand, we can also say that the threshold shear stress is not function of the granular reductions. So, we consider an overall tendency for the different granular inclusions tested.

Generally, the threshold shear stress is functionally linked with the solid volume fraction. The results show an increment when we increase the solid volume fraction which seems logic and in accordance with the literature.

4. Conclusion

In the present work, we proposed a rheological study of sediments extracted from the trap of Lyvet in “La Rance” estuary in order to better understand some of the structuring/destruction mechanisms of liquid/solid mixtures. This work should help us better understand the filling kinetics of the estuary and optimize prevention operations.

Using a Kinexus rheometer, a dynamic rheological characterization has been carried out by applying a shear stress sequence during the restructuring phase (after a phase of destruction of the mixtures) and then to draw the flow curves for different granular reductions and different values of solid fraction. The flow curves are modeled only at high shear rates using the Bingham model.

The evolution of the viscosity as function of the solid volume fraction is modeled by the Krieger-Dougherty model and we detect a maximum packing about 40%. On the other hand, the analysis of the dynamic shear limit stress showed a fairly functional link with the solid volume fraction. We have also shown that a critical solid volume fraction ($\phi = 17\%$) is distinguished and that marks a transition of a viscous fluid and a visco-plastic fluid. This dynamic characterization doesn't show an influence of the granular reductions of the viscosity.

So far, the results obtained for the threshold stress can't be considered real and will be compared with values measured with vane test (static measurement) to confirm the Bingham model used. This comparison will be presented in a future work.

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