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Slump and slide behavior of a dredged harbor sediment

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Abstract :
Dredged sediments, whatever their origin site (harbor, river, waterways, or reservoirs), lead managers to dispose of them in storage areas designed specifically for these deposits before considering their recovery. Once deposited, the sediments will dewater more or less quickly depending on climatic conditions and their removal depends on their water content and the recovery method chosen by the managers. The question then arises as to how to transport them to the site where they are to be reused. The challenge is to determine whether the sediments being dewatered can be shoveled. That is to say, can a working engine intervene and ensure any loading of sediment into a bulk transport vehicle and, above all, according to what criterion related to the state of moisture of sediment? This criterion to be established is linked to the principle of shovel ability.
A laboratory apparatus was specially designed to try to answer this question and to search for a criterion based on the state parameters of sediment. This unconventional test apparatus is first presented with the different possibilities of measurements i.e. *testing procedure*. And then a set of measurements was performed to study the behavior of sediment to slump and slide according to the evolution of its water content which is the state parameter to be considered. The sediment selected is silty harbor sediment with high organic content. This sediment was then subjected to slump tests from a dry state, included in the procedure of the shovel ability meter test, and the same sediment for different moisture states was submitted to slip tests from the shovel ability meter. From these preliminary tests typical slump and slip behavior curves for sediment were established and slump and/or slide patterns were defined from visual observations.

Keywords :
Dredging, Sediment, Slump testing, sliding behavior, Shovel ability meter, Water content, Liquid and plastic limits, Fall cone.

1. Introduction

Sediments, like soils in general, have mechanical characteristics (cohesion c and angle of friction φ) which, depending on the quantity and nature of the fine and coarse particles, give them a cohesive (clays) or frictional (sands) behavior. Fine sediments (maximum diameter<2mm) with a sufficient proportion of clay (>20%) develop a cohesion that varies according to this proportion of clay and the water content. When in contact with a metal interface, these cohesive sediments will adhere to this surface and develop adhesive forces. This adhesion property (a) is often related to the undrained strength of the sediment (Su) by an adhesion factor (α), see table 1 for a soil/steel interface.

Table 1. Common empirical values of factor adhesion α (NAVFAC, 1984).

Soil consistency	***Cohesion range Su (kPa)***	***Adhesion factor α***
Very soft	*0 - 12*	*0 – 1*
Soft	*12 - 24*	*1 – 0.92*
Medium stiff	*24 - 48*	*0.92 – 0.70*
Stiff	*48 - 96*	*0.70 – 0.36*
Very stiff	*96 - 192*	*0.36 – 0.19*

The notion of shovel ability of sediments involves these properties of cohesion and adhesion. Cohesion allows a volume of sediment to be maintained in a compact mass and opposes sliding between the sediment particles. Adhesion, in relation to this cohesion, governs sliding at the interface of a metal plate, as in the simple case of the recovery of sediments using chargers or mechanical shovels. Both properties are highly dependent on water content. Studies have been carried out on adhesion, but they concern soil/structure interaction in geotechnics (retaining walls, sheet piling, foundations on piles, laying of risers on the seabed) or in the field of agriculture (agricultural tools). Laboratory equipment has been developed to measure either the adhesion force or the shear stress at the interface (ABBASPOUR-GILANDEH et al., 2018; AZADEGAN & MASSAH, 2012; BIRCHA et al., 2011; CHEN et al., 2019, 2021; ZIMNIK et al., 2000). To our knowledge, very few studies have investigated the shovel ability of soils, in particular sediments. A procedure for representative measurements of shovel ability has led to the development of a specific tool, called a laboratory shovel ability meter. These measurements concern firstly the settling of a defined volume of sediment and the sliding of this sediment mass after slumping on a flat metal plate. These measurements were carried out on harbor sediment (Port of Cherbourg) using the laboratory shovel ability meter and sediment was considered at different states: from a dry state through plastic and further to a liquid state *i.e. during a phase of humidification*. Typical slump and slide behavior curves obtained together with visual observations are presented and discussed in this paper.

2. The shovel ability meter

2.1 The description of the shovel ability meter

The handling of sediments test (HOST) is based on the use of a laboratory shovel ability meter device. This is a test device for studying the sliding behavior of sediments according to their consistency (LEVACHER *et al.*, 2020, 2021). It essentially consists of a support frame with support (figure 1a) that can be rotated from a horizontal to a near vertical position (figure 1b). The device shown is the manual version which requires visual reading of the rotation angle, the accuracy is in the order of one degree. The roughness involved in the adhesion can be simulated by a plate with a particular roughness or coated with a chosen material (geotextile, steel, rough bottom...). For each test, a volume of sediment is placed on a selected plate with a miniature cone, see figure 1a in the case of a smooth plate.

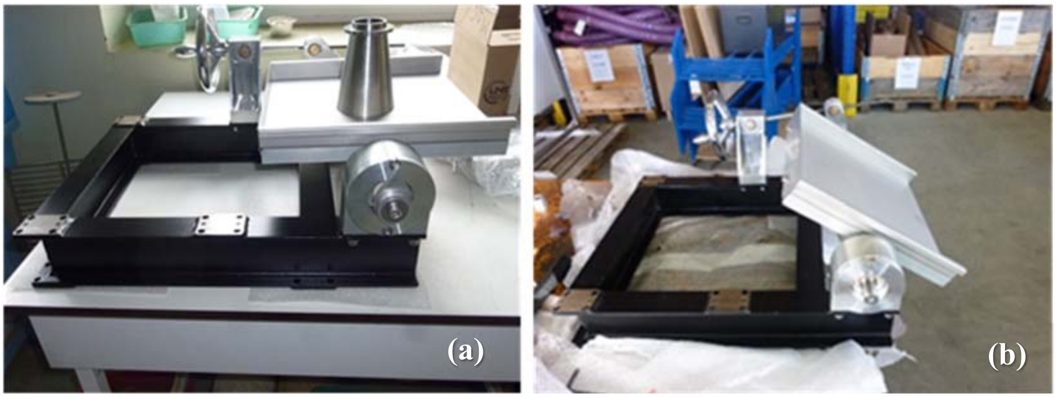


Figure 1. The shovel ability meter with the cone (left) and in sliding position (right).

2.2 The test procedure of the shovel ability meter

The parameters used to try to define a criterion for the shovel ability or transportability of sediments are the water content of the sediment (w), the consistency of the sediment (s), the undrained shear stress or undrained cohesion (Su), and the adhesion of the sediment to the shovel or plate-sediment interface, which depends on the roughness of the latter (μ) and its rotation relative to the horizontal (β). The rotation of the plate makes it possible to highlight the sliding of a mass of sediment of various consistencies, from solid sediment to plastic or even liquid sediment. The behavior of the sediment, depending on its water content, will change from "solid" friction to adhesion-dependent sliding at the interface, and then to flow if the water content increases beyond the liquid limit. The shovel ability criterion is located upstream of the flow of the sediment and is linked to adhesion in part, but also cohesion (displacement or sliding in mass). The measurement of this undrained cohesion can be done with a laboratory vane shear test or a free-fall penetrometer *i.e. fall-cone* at the surface or in the cone respectively, used to measure the slump (A) or consistency (s).

3. Physical properties of harbor sediment

3.1 Origin of dredged harbor sediment

The harbor sediments come from two inner basins of the Cherbourg port: the fishing port and the out port for marinas. The samples were taken in July 2019 using a Van Veen grab and a sampling cone at three similar points selected during a previous campaign conducted in 2005 (DUAN, 2005). They concern the first centimeters on the bottom of the basins. The sediments were stored in sealed barrels and transported to the laboratory for analysis and characterization tests.

3.2 Sediment type and state parameters

As mentioned in the introduction, the nature and state of the sediments play a major role in the study of shovel ability *i.e. slump and slide*. The determination of the nature and state parameters are part of the first analyses carried out on the sediments. It is also these parameters that allow the classification of sediments according to their field of application. The particle size distribution provides information on the composition of the sediment in terms of clay, silt, and fine sand. Other contents are associated with the composition such as organic matter (OM) and carbonates ($CaCO_3$). Clay activity is determined by measuring the absorption rate of methylene blue (MBV).
The state parameters are related to specific water contents that define the state of the sediment by its consistency. They are used in the shovel ability study and could help to establish one or more shovel ability criteria. From a geotechnical point of view, these parameters are given by the Atterberg limits: liquidity limit (LL), plasticity limit (PL), and shrinkage limit (SL). The average values obtained as per French standard (AFNOR, 1993), for a mixture of sediments from the 3 sampling points, sieved to 2mm (removal of coarse particles) from Cherbourg are summarized in table 2. The Cherbourg sediment is a low plastic, low clay but organic silt according to the Casagrande PI-LL chart (geotechnics) or classified as A1 fine soil according to the GTR guide (road engineering) based on the percentage of particles <80µm, the plasticity index PI and the MBV value. Whatever the method used for measuring the liquid limit (LL), the values obtained are very close for the Cherbourg sediments. The organic matter content of more than 15% observed defines the sediment as a highly organic soil which will pose a problem in reuse in construction engineering (HUSSAN *et al*., 2022), in dewatering and shovel ability.

Table 2. Main physical parameters of harbor sediment.

Clay (%)	*Silt (%)*	*Sand (%)*	*<80µm (%)*	*SL (%)*	*LL* (%)*	*PL (%)*	*PI (%)*	*MBV (g/100g)*	*OM (%)*	*$CaCO_3$ (%)*
3.83	*53.97*	*42.18*	*>70*	*18.60*	*59.65*	*48.46*	*11.19*	*1.22*	*17.37*	*4.75*

Note: LL = average value obtained by Casagrande and fall cone methods.*

4. Results and discussion on slump and sliding sediment behavior

4.1 Slump test applied to sediments
As defined in the French standard (AFNOR, 2019), the slump test is a standard test used for the study of fresh mortars and concretes, from which the consistency is deduced. This slump test has been adapted into the procedure of the shovel ability test and applied to sediments. Firstly, to minimize the amount of sediment volume to be manipulated but to have a volume representative of a shovel load i.e. *a compact mass*, miniature cones of a smaller scale than the cone used for concrete (height 300mm; lower and upper diameters 200mm and 100mm), were used. The scales are 2/5, 1/3, ¼, and 1/5 as shown in figure 2. The measurements are for the height after slump H and the diameters D1 and D2 relative to the footprint.

Figure 2. Abrams reduced scaled cones and measurement slump parameters.

4.2 Typical relationship of sediment during the slump and moisture content
The measured slump (initial cone height minus H measurement, figure 2) for different water contents from dry to liquid state, allows to establish a typical relationship for each sediment. For this harbor sediment, four zones corresponding to the granular state of the sediment (1) can be observed in figure 3, where the shrinkage limit seems to indicate the beginning of zone 2. In this zone the sediment becomes cohesive or even plastic, the limit of zone 2 is close to the liquidity limit. Beyond this, in zone 3, the sediment becomes like a paste, very plastic, and then takes on a liquid appearance in zone 4.

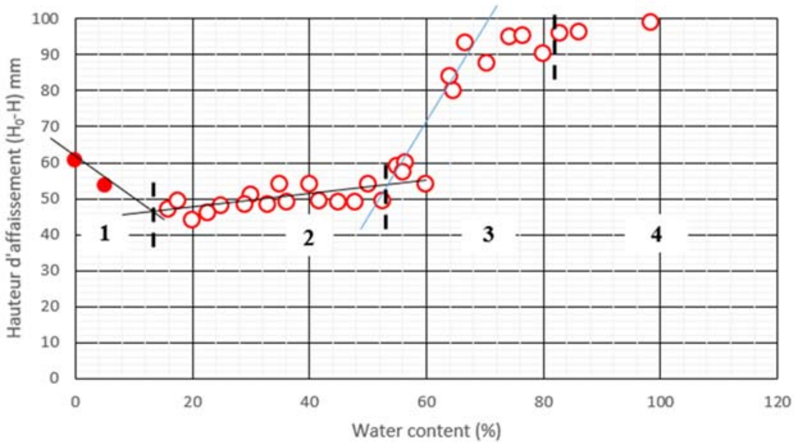


Figure 3. Slump (A) vs water content (w) for Cherbourg harbor sediments.

4.3 Footprint evolution of the sediment after the slump test and moisture content

The footprint left after the slump on the smooth steel plate is measured (average of diameters D1 and D2, see figure 2) for different water contents. The miniature cone used for the slump tests is 1/3 scale, i.e. *a base diameter of 66.67mm*. For this harbor sediment, a typical pattern identical to other sediments (KRAUZMAN, 2022) is observed in figure 4. It is characterized by a footprint equal to twice the base diameter of the cone used until the plasticity limit is reached. Then there is a collapse towards the liquidity limit and then the footprint increases steadily to 30cm, the width of the plate. The consistency states are shown in the pictures (figure 4).

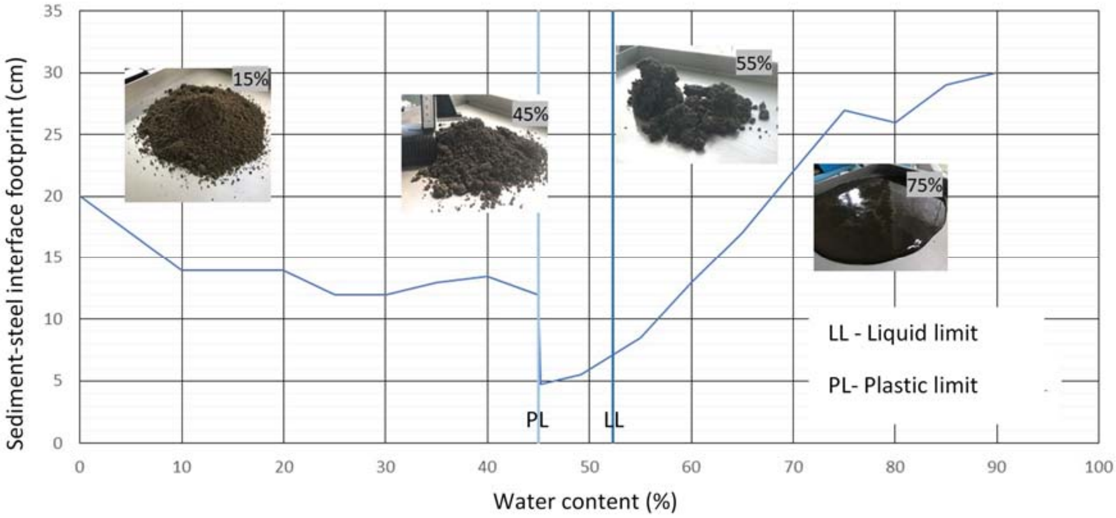
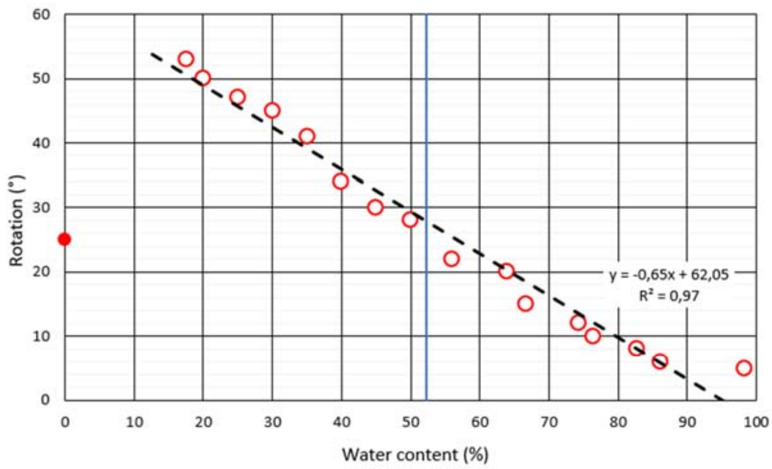


Figure 4. Footprint left by Cherbourg harbor sediments vs water content.

4.4 Sliding behavior

With the help of the shovel ability meter, the slip angle of the deposited sediment mass after the slump is measured directly when the metal plate is rotated. This measurement is accurate to ± 0.5 degrees. These measurements were taken for different water contents, i.e. *different consistencies*, as shown in figure 5. It can be seen that the angles of rotation initiating sliding decrease as the water content increases and this variation is almost linear whatever the consistency of the sediment, see figure 5 for the Cherbourg harbor sediment. In this figure 5, the point at 0% corresponds to the dry state of the sediment which, after drying, is in the granular state (photo on the left of figure 5). Then the water added successively to the sediment gives it cohesion by capillarity, then by intergranular bonding, but to this cohesion must be added adhesion at the plate-sediment interface. Above a certain water content (>LL), the sediment takes on a liquid consistency (photo on the right, figure 5). This linearity has been observed on other tested sediments, (KRAUZMAN, 2022).



Consistency of Cherbourg harbor sediment just before sliding
Figure 5. Rotation angle just before sliding vs water content (above).

4.5 Sliding modalities

When measuring the angle of rotation at the time of incipient sliding, and depending on the consistencies of the tested sediments, different sliding modes could be distinguished. In the dry state, it is a classic granular flow whose angle at rest can be determined. Then, for low values of content (10-30%), discontinuous agglomerate slumps are observed. Between the Atterberg limits (PL-LL), a continuous slip sets in (middle photo, figure 5). Towards water contents (>75%), material (sediment) flows.

5. Conclusions and perspectives

A laboratory shovel ability meter was designed for the study of sediment shovel ability and transport. A test protocol was tested that combines a slump test and a sliding test of sediment with controlled water content. For sediment going from a dry and granular state (0% water) to a liquid state (water content >> LL), the following phenomena were observed: (1) the slump-water content relationship shows a typical bilinear pattern beyond the shrinkage limit or at the end of the granular behavior; (2) the footprint at the contact of the sediment and the steel base decreases from the dry, granular state to the plastic state (the sediment becomes coherent) and then increases beyond the liquid limit; (3) the rotation angle relationship (incipient slip) decreases linearly with increasing water content. These trends have been observed and confirmed for other sediments from waterway and dam sites (KRAUZMAN, 2022).

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