A NEW TESTING SYSTEM TO INVESTIGATE THE SEDIMENTATION AND CONSOLIDATION OF SLUDGE AND SLURRY

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ABSTRACT
A system has been developed to study in the laboratory the sedimentation and consolidation of slurry and sludge (pulp). It makes use of a relatively large size column (about 2 meters high) in which the pulp is placed as a suspension at a representative density. The stages of sedimentation and hydrodynamic consolidation are followed with visual observation of the solid-liquid interface, and with measurements of density ρ and pore pressure u. The instrumented column is equipped with pressure transducers that continuously measure u at 10 cm intervals during tests that can last a few weeks. A device has also been constructed so the change in density ρ can be monitored with a gamma ray sensor unit. The tests include stages for self-weight consolidation and forced consolidation following the application of external loads. After recalling the physical processes involved, and some equations used for their description, the experimental set-up is described, and sample results obtained on acid mine drainage treatment sludge are given and briefly discussed.

RÉSUMÉ
Un système développé pour étudier la sédimentation et la consolidation des boues et des pulpes en laboratoire est présenté dans cet article. Le système d'essai comporte une grande colonne (d'environ 2 m de hauteur) dans laquelle on place la boue en suspension à une densité représentative. Les étapes de sédimentation et de consolidation hydrodynamique sont évaluées par des observations visuelles de la position de l'interface solide-liquide, et par des mesures de la densité ρ et de la pression interstitielle u. La colonne instrumentée comprend des senseurs qui mesurent la pression u à intervalle de 10 cm, durant les essais pouvant durer plusieurs semaines. Un système a aussi été conçu pour faire le suivi de la variation de densité ρ à l'aide d'un détecteur de rayons gamma. Les essais incluent une phase de consolidation sous le poids propre du matériau, et une consolidation induite par l'application de charges externes. Suite à une brève présentation des processus physiques impliqués et de quelques unes des équations disponibles pour les décrire, on présente le montage expérimental ainsi que des résultats types obtenus sur des boues de traitement des eaux acides.

1. INTRODUCTION

Various disposal scenarios involve the simultaneous deposition of solid and liquid, as slurry fills. This type of practice is particularly common in the mining industry, as it is used frequently for mill tailings and for water treatment sludge (Aubertin et al. 2002). In the latter case, mining operations producing acid mine drainage (AMD), as a result of sulphide minerals oxidation, have to treat their effluent before discharge. Such acidic waters favour the solubilization of various contaminants, including sulphates and heavy metals found in the host rock. These are then precipitated and recovered in the treatment sludge. The various processes developed for treatment of AMD usually involve the addition of a neutralizing agent such as lime (Walton-Day, 2003; Aubé, 2004). The large volume of sludge produced must be disposed of in a secure manner, so lined ponds are often created for their storage. However, the design of these ponds is largely empirical because very little is known about the hydro-geotechnical behaviour of treatment sludge, which typically contains only 10 to 25% of solids by weight. Hence, there is a need to develop measurement techniques to describe the behaviour of sludge (and other similar slurry fills together referred to as "pulp") after their discharge. The experimental data obtained through such tests can then be used for validating representative constitutive equations, hence providing the tools for analysing in situ behaviour.

2. THE BEHAVIOUR OF SUSPENSION

Slurry type fills, such a treatment sludge and mill tailings, are transported hydraulically to the disposal area. In the impoundment, the pulp shows a behaviour that comprises 3 broad stages. These are shown schematically in Figure 1, representing a vertical column in the impoundment. In the first stage after deposition, the solid particles are suspended in the fluid. Depending on the pulp density, each particle tends to behave more or less independently from the others in the suspended stage. There is then a progressive deposition of the solids, which produces an interface with clear water on top (with little suspended solids), above the sedimentation zone. At the bottom of the column, a zone of accumulated particles in contact

with each other appears, and its thickness progressively increases as the size of the sedimentation zone is reduced.

Near this bottom zone, the pulp behaviour changes from a sedimentation stage, where particles interact indirectly because of their respective effect on the fluid motion, to a consolidation stage where the grains are in direct contact, thus forming a solid skeleton that behaves as a porous medium. In the latter stage, settlement of the solid surface takes place when water is expelled by the pressure exerted by the self-weight densification of the solids. Above the consolidation zone, the water pressure u is that of the water column above a given position z ($u = z\gamma_w$), while it tends to be larger than its equilibrium (hydrostatic) value in the saturated solid phase. Settlement can continue for a long time, depending on the stress-strain response of the solid skeleton. Hydrodynamic consolidation ends when excess pore pressure (for $u > z\gamma_w$) is dissipated, but solid settlement can nevertheless continue under its own weight due to rheological effects (a settlement stage known as secondary compression).

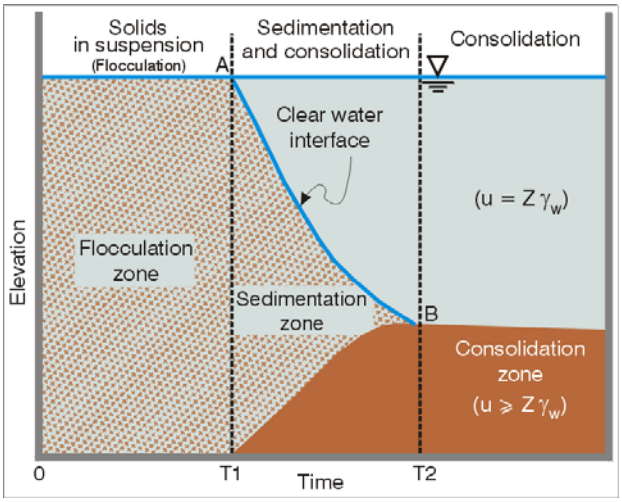

Figure 1. A schematic view of sedimentation and consolidation processes in a vertical column (adapted from Schiffman et al. 1988)

2.1 Basic Equations

In the flocculation zone, the particles would typically obey Stokes' law. The drag force on each particle then linearly depends on its size, on the fluid viscosity, and their downward velocity. The latter may eventually reach a maximum velocity, which can be expressed as:

$$v = \frac{D^2 \gamma_s'}{9\eta} \qquad [1]$$

Where D is the diameter (L) of the particle (taken as a sphere), γ_s' is the submerged (effective) unit weight of the solid grains, and η is the viscosity of the fluid.

In the sedimentation phase, the solid concentration becomes higher, and particles start to interact with each other through their influence on the fluid motion. The behaviour of the pulp is then be defined using the Kynch (1952) equation, which can be expressed as follows (Alexis et al. 1992; 1993; Gallois 1995; Concha 2002; Pedroni 2003; Dromer 2004):

$$\frac{\partial \gamma_d}{\partial t} + \frac{d(\gamma_d v_s)}{d\gamma_s}\frac{\partial \gamma_d}{\partial x} = 0 \qquad [2]$$

where γ_d is the dry unit weight of the pulp, and v_s is absolute velocity of the grains which now depends on the local concentration of the suspension.

In the consolidation zone, the equations typically used ensue from the Terzaghi (1942) theory, developed in soil mechanics (e.g. Holts and Kovacs, 1981). The main equation can be formulated as follows:

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \qquad [3]$$

This equation (which is mathematically similar to the equations used for thermal and molecular diffusion), shows that the variation of pore pressure u as a function of time t and position z is controlled by the coefficient of consolidation c_v. This coefficient can be related (using some simplifying assumptions) to other key properties of the porous media, as shown by the following expression:

$$c_v = \frac{k}{\rho_w g}\frac{1+e_0}{a_v} \qquad [4]$$

where k is the hydraulic conductivity, ρ_w is the water density, g is the gravitational acceleration, e_o is the initial void ratio, and a_v is the coefficient of compressibility. The latter is obtained from the effective stress – void ratio (σ' - e) relationship, as:

$$a_v = -\frac{de}{d\sigma'} = \frac{e_1 - e_2}{\sigma'_2 - \sigma'_1} \qquad [5]$$

where subscripts *1* and *2* identify two different stress states.

Settlement of the solid can also be evaluated based on the use of the compression coefficient, which is typically expressed as:

$$C_c = \frac{-de}{d\log\sigma'} = \frac{e_1 - e_2}{\log\sigma'_2 - \log\sigma'_1} = \frac{e_1 - e_2}{\log\frac{\sigma'_2}{\sigma'_1}} \qquad [6]$$

Hence, by measuring the evolution of the interface position, density, pore pressure, and effective stress state, the parameters that describe the sedimentation and consolidation processes can be obtained.

It should also be recalled that the above consolidation equations were developed for small displacements. In the case of slurry fills, the basic conditions for their application may not be satisfied. For such highly compressible materials, a large strain theory formulation could be better suited; such a theory has been proposed by Gibson et al. (1967; 1981; see also Cargill, 1984; Foriero and Ladanyi, 1998), but it will not be used explicitly in this paper.

2.2 Unifying Theory

Sedimentation and consolidation processes can happen simultaneously, in a continuous sequence in the column. Pane and Schiffman (1985) proposed the use of the following equation to construct a unified theory for these two processes:

$$\sigma = \beta(e)\sigma' + u_\omega \qquad [7]$$

This equation relies on the β parameter (expressed as a function of the void ratio *e*), which controls the magnitude of the effective stress σ' acting on the solid particles. In the purely sedimentation phase, β is nil so $\sigma = \sigma'$, while in the consolidation phase, β is equal to unity so $\sigma = \sigma' + u_\omega$. The transition between the two conditions occurs progressively. In practice however, this transition stage is often difficult to characterize. Once the value of β has been obtained, it can be introduced in the following unified equation (Pane and Schiffman, 1985; Azevedo et al. 1994):

$$\frac{\partial}{\partial e}\left[\gamma_r k_z\right]\frac{\partial}{\partial z} + \frac{\partial}{\partial z}\left[\frac{k_z}{\gamma_r}\frac{\partial\sigma'}{\partial e}\beta\frac{\partial e}{\partial z}\right] + \left[\frac{k_z}{\gamma_r}\sigma'\frac{\partial\beta}{\partial e}\frac{\partial e}{\partial z}\right] + \frac{\partial e}{\partial t} = 0 \qquad [8]$$

where *z* indicates the position along the column. This equation reduces to a formulation similar to the Kynch (1952) equation for the sedimentation stage, when $\beta = 0$. For $\beta = 1$, the large strain consolidation theory of Gibson et al. (1981) is retrieved.

All the information required to deduce the parameters appearing in the equations presented above can be obtained from tests run in the set-up presented in the following section.

3. THE EXPERIMENTAL SET-UP

The set-up developed for this project is loosely based on the one that was put together by Bédard et al. (1997), to which many improvements have been made. The set-up has been installed in the laboratory facilities of the NSERC Polytechnique-UQAT Industrial Chair, in Montreal. Figure 2 shows the main components of the testing system. It includes the column and its support (1), the pressure transducers (2), the digital camera used to follow the position of the interface and the signal treatment system (3), and the density measurement device (4). These components have been described in detail by Dromer (2004), and only a brief summary is given here.

The column, made of Plexiglas, has a height of 180 cm, and its internal diameter is about 15 cm. The base is made with an HMV plastic plate tightly attached to the transparent vertical tube. Holes and tubing have been placed in this base plate for pushing compressed air used for remixing and re-suspending the pulp (when required). Another similar removable plate is placed on top of the column, where the slurry is added before the tests. A small calibration column filled with water is installed below the main column, for verifying the response of the density measuring device. Four threaded bolts run along the column, and serve to fix all the components together. The base of the set up is fixed to an aluminium plate (25 cm x 90 cm) placed on two beams sitting on the concrete floor; there is also a levelling system to ensure the proper positioning and to ensure the column is vertical. The long threaded bolts running along the column also serve for the displacement of a support plate on which the density measuring device is installed; it can be moved up and down the column by the use of an electric motor (equipped with speed control). A steel chain is used to turn sprockets on the bolts, which drives the moving plate at a rate of about 40 cm/min. The bolts are equipped with a lubricating mechanism to ensure a smooth motion of the plate during its vertical course. The entire system is also fixed to the ceiling of the room (by four wires) for increased stability.

The pressure measurements are made with transducers installed every 10 cm, starting at 4 cm from the plastic base plate. These are connected to porous cups inserted in 1.27 cm diameter holes along the column. Quick Connect (Swagelok) fittings made of brass are used to

install the gage transducers (Omega) in the column; the transducer range for pore pressure (positive or negative) measurement is 103 kPa. These transducers are linked, through an AD/DA card, to a data acquisition system controlled by Labtech Notebook (Labtech Corporation) running on a Microsoft Windows system. The transducers are calibrated so that the electric signal (0 to 10 V) can be related (linearly) to water pressure (relative to atmospheric pressure).

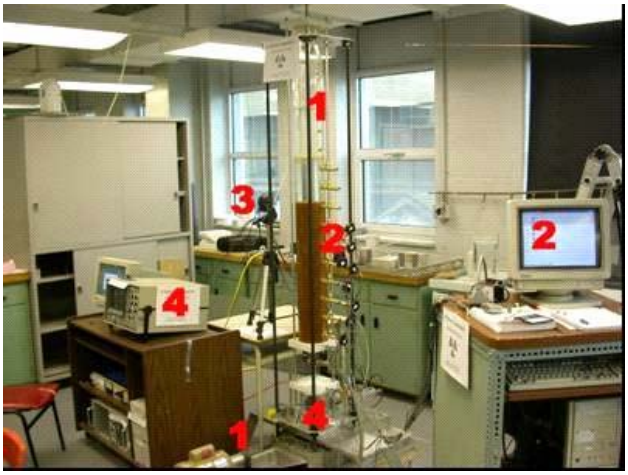

Figure 2. Picture of the experimental testing system showing the main components; see text for details.

The position of the free water interface is measured by a digital camera (Logitech Clicksmart) installed on a tripod located close to the column, and moved regularly to obtain optimum precision. The camera is equipped with the ConquerCam software so the picture frequency can be controlled. A measuring tape has been placed along the column. Images are stored to be analysed so the displacement rate of this interface can be measured precisely.

The density measurement system is the component that required the most effort. This system was designed in collaboration with researchers from the neutron activation laboratory (Dept. of Eng. Physics), of École Polytechnique, using their equipment. It is based on the use of gamma ray emission and sensing, a technique often used for similar purposes (Moens 1981) in various industrial processes. Gamma rays offer some advantages over x-ray devices, also used for measuring density of slurry and sludge (e.g. Been and Sills, 1981; De Campos et al. 1994), as their energy and thus their penetrating power is higher, allowing more precise determination of the actual density of relatively thick media. The active source is ^{153}Sm found in a powder of samarium oxide (Sm_20_3), activated by irradiation with neutrons. The half-life of ^{153}Sm is 46.7 h, and the gamma rays are emitted with an energy of 103 keV. The source is placed in a casing located on one side of the column. The rays emitted are captured by a sodium-iodide (NaI) detector placed on the other side of the column, at the same elevation (on the moving plate). Signals from photons reaching the detector go through a photomultiplier that transforms them into electric pulses, which are counted (Rapin et al. 2002). For the determination of the testing conditions, the number N of ^{153}Sm atoms required was determined according to the source activity A (in Bq). This activity has to be controlled in order to obtain the required precision level, based on statistical analysis of the number of signals (photons) captured by the gamma ray sensor (Moens 1981; Knoll 2000). In these experiments, it was determined that 10^4 photons needed to be detected in the 40 second measuring period in order to obtain a precision of 1% ; this number corresponds to the number of detected events N_d by the sensor. Considering the absorption coefficient k_a of the media (solid and water mixture), which was determined theoretically (based on the chemical composition of the materials) and experimentally (using representative samples), and the distance between the source and receptor, it was estimated that the required number of emitted photons N was about $1.2x10^8$. Taking into account the percentage (about 28%) of gamma rays emitted by Samarium (other emissions are x-rays and electrons), and the actual relationship between activity and density of the media tested in the lab, it was determined that the total activity required was 40 MBq for a precision of 1% (with measurements lasting 40s)

The validity of the system was evaluated under well controlled conditions, using a treatment sludge (site A, located in Abitibi) in a small column installed in the Eng. Physics lab. Typical results are shown on Figure 3, which shows the measured and calculated values of N_d as a function of sludge density; the solid grain relative density D_r of this sludge was 3.4. Tests were also run on bentonite mixtures (not shown here). The results showed the validity of the set-up for measuring sludge density.

Further validation and calibration tests were also conducted in the actual set-up located in the laboratory of the Chair. This allowed some adjustments to be made to improve the testing and monitoring procedures. During this preliminary experimental phase, much emphasis was placed on the determination of the influence of the boundary conditions, for the top surface of the sludge (or water) and for the bottom plates. These two locations are in fact physical discontinuities in the system, which significantly affect the propagation of the gamma rays. After a series of measurements and data analysis, it was determined that two areas of about 10 cm height (at the top and bottom of the column) were affected by the boundary conditions; hence, readings obtained in these areas were not considered in the data analysis.

More details on these and other verifications of the experimental set-up are presented in detail by Dromer (2004). These verifications ensure that the testing system gives representative measurements.

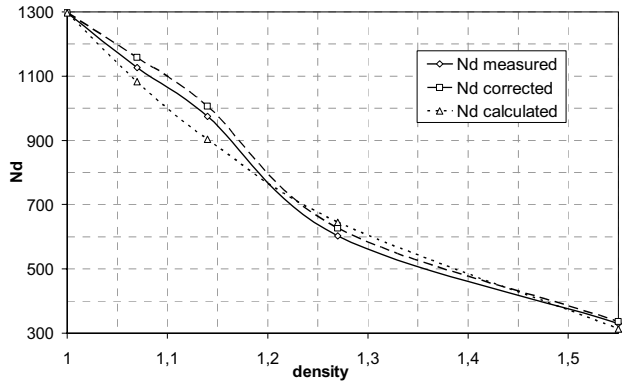

Figure 3. Validation tests conducted on sludge A, showing the calculated and measured number of detected photons as a function of its density (expressed in g/cm3).

4. EXPERIMENTAL PROCEDURE AND PRELIMINARY VALIDATION

After the experimental set up was put together, and the various calibration and verification operations completed, the actual tests were run. The samples are first prepared by mechanically mixing the sludge (or clay slurry) to obtain a homogeneous material. This pulp is put into the column from the top, slowly with a tubing system; the top section above the wet sample is then cleaned for a clear view of the inside of the column. The pressure transducers and digital camera start as soon as the sludge is in the column. These readings are stored in the computer (with regular backups) for the analysis; these data can be retrieved at any time and transferred (with a USB memory stick) to another computer for immediate analysis.

Radioactive samarium sources were activated every two days during the measurements with the École Polytechnique SLOWPOKE nuclear reactor. During the tests, readings are made at regular intervals by moving the source-detector system along the column. This gives the profile of the density (and pore pressure) along the column at different times during the experiment.

Once a pseudo-steady state is reached (when there is no change observed in the interface position, density, and pore pressure), which may take 3 to 15 days depending on the material, external loads are added on top on the column using a rod connected to a perforated plastic plate (covered with a geotextile) placed on the sludge surface. Loads (steel plates) are added periodically, like in a consolidation test, by inserting additional weights along the rod. Upon adding this surface load, the pore pressure is seen to increase suddenly (see below), and then decreases as the water is being expelled upward. Continuous monitoring of the pore pressure, position of the surface, and density of the material along the column provides information for consolidation behaviour analysis.

Figure 4. Pictures of the dismantling of the column and sampling of the sludge

At the end of the test, which may last up to 3 months, the column is dismantled and the sludge is retrieved in an "intact" state (Figure 4). Tests can then be run on these samples to measure the density (and validate final results from the samarium system) and void ratio, the chemical composition of the solids and pore water, and mechanical characteristics using various testing devices (such as vane and fall cone).

4.1 Basic experimental results

The system has been used to conduct tests on a kaolin mixture, and on a sludge obtained from an operating AMD treatment plant located in Abitibi, Québec (sludge B). Only the results obtained on the sludge are shown here.

Based on the chemical and solid content of this sludge (which contains about 26 % iron, the dominating element), a relationship was established between the absorption coefficient and the density. This theoretical curve is required for the interpretation of the results obtains from the Sm system.

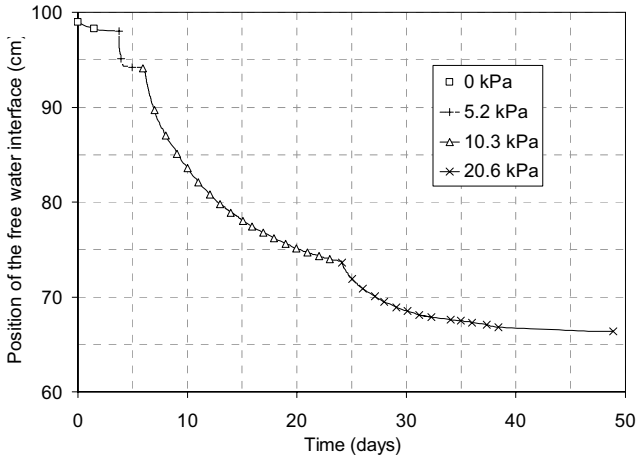

Figure 5. Position of the interface for a test conducted on treatment sludge

The grain size curve of the sludge was obtained by a Malvern Mastersizer® apparatus, available at UQAT. The curves obtained on 3 samples, which were later mixed together for the column tests, are very similar, with a D_{10} of about 1 μm and a D_{60} of about 20 μm. This grain size distribution appears to be fairly similar to others produced by HDS treatment plants used in the mining industry (e.g. Aubé, 2004).

The solid grain relative density for this sludge is about 3.14. Between the beginning and end of one of the tests, the pulp density *P* changed from about 11.4 % to 16.4% ; the water content varied between 776% and 508%, and the void ratio e was reduced from 24.3 to 15.9 (for a maximum applied stress of 21.6 kPa).

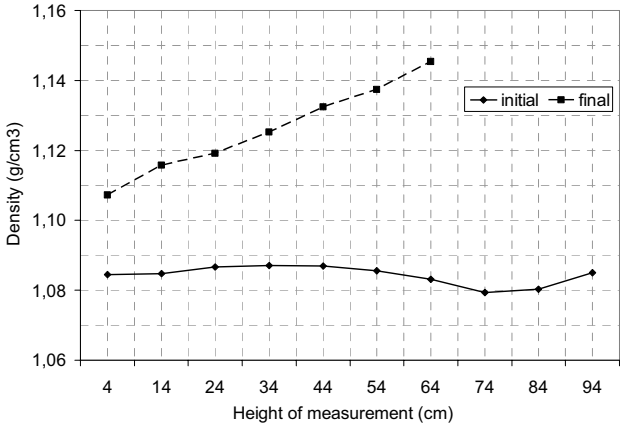

Figure 6. Density at the beginning and at the end of the test measured along the column in sample results for a test conducted on sludge

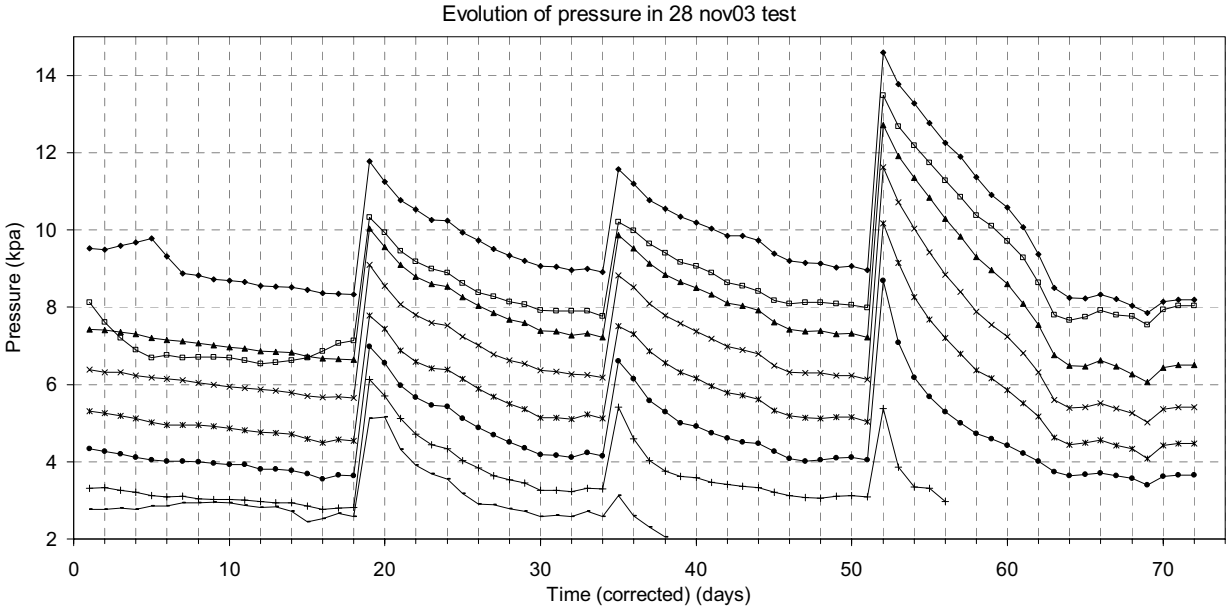

Figure 7. Pore pressure measured during a sedimentation and consolidation test on sludge B.

The position of the sludge surface over the duration of a test is shown in Figure 5; the first level corresponds to the sedimentation stage, which is followed by consolidation due to the added pressure applied on top of the sludge.

Density measurements were also conducted along the column during the tests. Figure 6 shows the value of the density initially and at the end of a test. It is clearly seen that density has increased everywhere, with a larger increase near the top (where water is expelled more rapidly during the consolidation phase).

Pore pressure evolution in one of the tests is shown in Figure 7 (i.e. not the same test as shown in Figure 5 and 6) This figure shows the effect of adding the loads, with a sudden increase of pore pressure followed by a slow decrease (as expected from the consolidation theory).

From these measurements, the effective stress along the column can be calculated as the difference between the total stress and the pore pressure.

4.2 Preliminary Interpretation

Results such as those presented above can be used to obtain key parameters involved in the constitutive laws developed to analyse sedimentation and consolidation. A few relevant values obtained on the treatment sludge tested are presented, following a preliminary analysis of the available results obtained from a test that lasted almost 50 days. It was estimated that:

- The value of c_v was 5 x 10^{-8} to 2 x 10^{-4} m^2/s (average of 4 x 10^{-7} m^2/s); this is somewhat comparable to the coefficient of some soft clays.
- The value of a_v varies from –0.3 to –1.5 kPa^{-1}.
- The hydraulic conductivity is in the range of 3x10^{-5} to 3x10^{-6} cm/s, depending on e; this range would be typical of silty soils.
- The value of C_c varies from 3 to 10, with an average close to 7; this is similar to that of many clays. It has also been observed that C_c is almost linearly related to e_o, as is the case with clays (e.g. McCarthy 2002).

Additional tests on the sludge, sampled after the consolidation test, indicated that the undrained shear strength S_u ranged between 0.36 and 3.8 kPa.

More details and further results can be found in Dromer (2004) and in the ongoing doctoral work of L. Pedroni.

5. CONCLUSION

An experimental set up has been constructed to measure, under controlled laboratory conditions, the properties of slurry and sludge. The system is used to monitor changes during the sedimentation and consolidation phases. The parameters followed include the solid-liquid interface position, pore pressure and density. Upon the dismantling of the column at the end of a test, which can last for months, other properties (such as shear strength) can also be measured. The details of the testing and measuring system are presented, together with some preliminary results. More tests will be run on AMD treatment sludge and other types of slurry, so constitutive laws can be validated or developed.

6. ACKNOWLEDGEMENT

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