Evaluation of sludge consolidation from hydraulic gradient tests conducted in large size columns

Lincar Pedroni
CGM Department – Ecole Polytechnique, Montreal, Quebec, Canada
Michel Aubertin
CGM Department – Ecole Polytechnique, Montreal, Quebec, Canada

ABSTRACT
Consolidation tests have been conducted on sludges produced by an acid mine drainage (AMD) treatment plant. The testing program involves a laboratory system designed and constructed to assess the specific properties of low density slurries. In the tests presented in the following paper, consolidation is induced by applying a controlled vertical hydraulic gradient in an instrumented large size column. The consolidation behaviour is monitored with visual observations of the solid-liquid interface and by evaluating the water content and excess pore water pressures. The experimental data is used to calculate the total pressure, effective stress and hydraulic conductivity of the sludge. Moreover, similar tests have been conducted on a kaolin clay slurry. The paper presents a brief description of the testing setup and procedure, followed by sample test results with a preliminary analysis of the laboratory data.

RÉSUMÉ
Des essais de consolidation ont été menés sur des boues produites par des usines de traitement des eaux de drainage minier acide (DMA). Le programme d'essais implique un dispositif expérimental conçu et construit pour determiner des propriétés des boues de faible densité. Dans ces essais, la consolidation est produite par l'application d'un gradient hydraulique vertical dans une grande colonne instrumentée. Le processus de consolidation est suivi par l'observation de l'interface solide-liquide, et par la mesure de la teneur en eau et de la pression interstitielle en excès. Les données expérimentales servent à calculer la pression totale, la contrainte effective et la conductivité hydraulique. Des essais semblables on été complétés sur une boue de kaolin. L'article présente une brève description du dispositif expérimental et de la procédure d'essais, des résultats types et une analyse préliminaire des données de laboratoire.

1 INTRODUCTION

Mining operations can produce large volumes of acid mine drainage (AMD) treatment sludge, witch must be disposed of in a secure manner. Lined ponds are often built for their storage. The design, construction, and operation of such ponds requires some prior knowledge of sedimentation and consolidation behaviour of the sludge.

In the last years, an experimental setup to study the evolution of low density slurries was designed and tested by the authors and collaborators in their research team. This setup was described by Dromer et al. (2004), and preliminary results obtained on AMD sludge have been presented by Pedroni et al. (2006). The total applied pressure setup described in these publications provides valuable results, but its accuracy decreases when the applied pressure is small. This is partly due to the fact that the frictional stress that develops between the piston and the column wall may be of the same order of magnitude as the applied stress with the piston.

The testing setup used here is similar to the setup previously described. However, in the new tests presented here, the loading path is controlled by a vertical hydraulic gradient instead of an external surcharge (due to added weight). This eliminates friction effects. This alternate option is inspired by the development of hydraulic consolidation cells and related works in finite strain consolidation analyses (e.g. Pane and Schiffman, 1997; Sridharan and Prakash 2001; Kodikara and Rahman, 2002).

The modified testing setup and procedure is briefly described below, with an emphasis on the changes that have been made with respect to the previous laboratory setup (Dromer et al., 2004; Pedroni et al., 2006). The results of two sample tests performed with this modified setup are then presented. One test was conducted on a treatment sludge with an initial gravimetric pulp density P of 7.4% (water content w=1260%, void ratio e=37.1). The other test was done on a kaolinite slurry with an initial gravimetric pulp density of 30% (w=234%, e=5.9). A preliminary analysis of the results is also presented.

2 EXPERIMENTAL PROGRAM

The setup described below is similar to the one presented by Dromer et al. (2004) and Pedroni et al. (2006) (see also Pedroni 2003 and Dromer 2004 for more details). There are some minor differences between the setup used for the water treatment sludge and for the kaolinite slurry.

2.1 General setup description

The testing system shown in Figure 1 includes the column and its support (1), pressure sensors (2a) and piezometers (2b), a digital camera (to record the position of the interface, 3), a density measurement device (4), two reservoirs to control the water level upstream and downstream (5), a Marriott column (6) and an air pressure regulator (7).

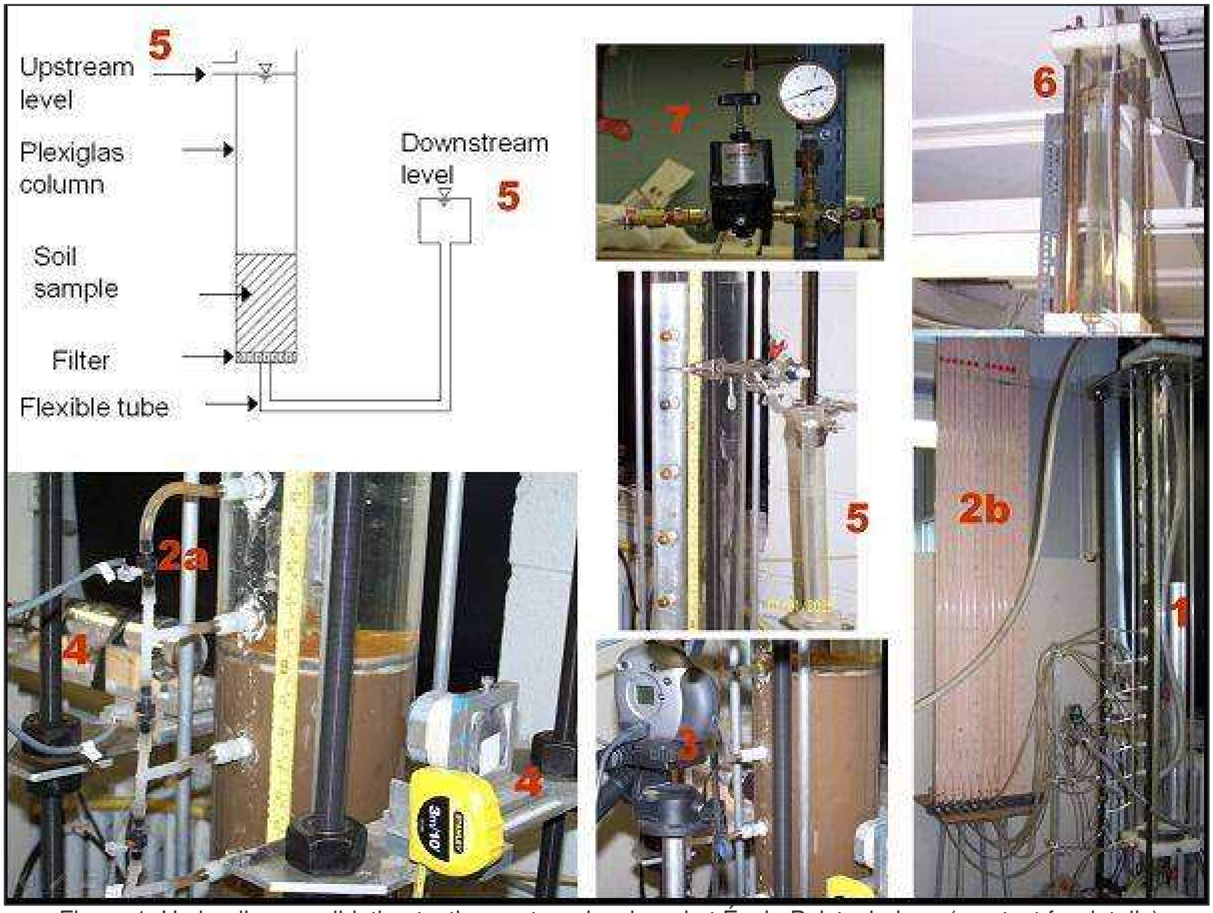

Figure 1. Hydraulic consolidation testing system developed at École Polytechnique (see text for details)

The column is made of Plexiglas. It has a height of 1.8 m, with an internal diameter of about 0.15 m. A filter (geotextile) is placed at the bottom of the column. It is connected to a flexible plastic tube that goes into the downstream reservoir which has an overflow to keep the water level constant. The drainage during consolidation due to self-weight or to seepage can occur at the top of the sample and at the base in the column. Four threaded bolts run along the column (about 0.1 m to the external wall) which allow to move the density measuring device at a rate of about 0.4 m/min.

For the test on treatment sludge presented here, pore pressures are measured with multi-level piezometers connected to the column every 0.1 m, starting at the position of the bottom filter. Each connector includes a cigarette filter to impede the flow of particles. The allowable pore pressure head measurement range is 0 to 2.5 m of water (limited by the height of the piezometers). The accuracy is around 1 mm of water column (or about 0.01 kPa). This is a very significant improvement over the previous system (witch had an accuracy of 0.2 kPa).

A new pressure sensor system was also tested. This new system consists of 7 small differential pressure sensors (Omega® PX26-001DV), with a maximum range of 70 kPa positive or negative. The excess pore water pressure is obtained from the differential sensor pressure measurements (see details in section 3). The accuracy is about 0.01 kPa (similar to the accuracy of the piezometers). A filter-amplifier (Omega® OM5-IMV-50A-C) is used with an electronic switch (C&K® A20615RNZQ Rotary switch) connected to the differential pressure sensors. For the test on the water treatment sludge, the calibration of the differential pressure sensors was made using the multi-level piezometers. The piezometers were removed for the test on the kaolinite slurry.

A digital camera follows the position of the free water interface with a measuring tape placed along the column. The imaging frequency is adapted to the test requirements (i.e. settlement rate). The images are used to determine the displacement rate of the interface.

The density measurement system was designed in collaboration with the neutron activation laboratory (Dept. of Engineering Physics, École Polytechnique de Montréal). It uses gamma ray emission, transmission and detection (Bedard et al., 1997; Kennedy et al., 2006). Such non destructive techniques are often used to obtain density variations in soft soils (e.g. Alexis et al., 2004; Merckelbach and Kranenbourg, 2004). The gamma energy level was selected according to the mineralogy of the material and the thickness of the sample (internal diameter of the column in this case). The gamma ray source (Samarium, Sm-153 with energy of 103keV, for these tests) is placed in a lead casing on one side of the column. The lead casing includes a small window (0.01 m diameter) that collimates the gamma photons emission. Depending on the density of the sludge, a fraction of the emitted rays is transmitted through the column along its diameter and captured by a detector placed on the other side at the same elevation (on the vertical moving platen). The validity and precision of the system were evaluated under well-controlled conditions (Dromer, 2004; Kennedy et al., 2006).

Density is measured at pre-established locations spaced at 0.05 m intervals along the column (i.e. at the vertical position of the pore pressure measurement points and at mid-points), by raising and lowering the platen (which holds the density measurement device). Such two-fold measurements increase the accuracy of the density data. At the end of each test, samples are taken and analysed in the laboratory. The gamma densitometer calibration is checked by comparing the results of the laboratory analysis with the last recorded scan.

Measurements are not made at distances smaller than 0.05 m from the base of the column and from the sludge-water interface to avoid geometric interference.

A Marriott column, filled with de-aired demineralised water, is fixed at the top of the column to control the upstream water pressure. As mentioned previously, the downstream water level is controlled by using a plastic tube connected to the base of the column. The collected water volume flowing from the base is measured with a graduated cylinder. An air pressure regulator (Fairchild® 0-10 psig pneumatic precision regulator) is used to increase the pressure in the Marriott column to apply the hydraulic head on the sample. The maximum head is limited by the piezometers height (which are used only with the water treatment sludge).

2.2 Testing procedure

For the test conducted on water treatment sludge, the column is first filled with de-aired demineralised water to purge the pressure measurement system (piezometers and filters). Scans are made with water to calibrate the density measurement system. Once equilibrium is reached, the flexible plastic tubes (connected to the filters and piezometers) are fixed to maintain the water head while the column is emptied.

The sludge, which is homogenized mechanically, is then pumped and poured into the column. Samples are taken at the beginning of the test for characterization purposes. The column is filled fairly rapidly (in less than 1 minute) using a centrifuge electric pump. The test starts when the sludge state is static. The multi-level piezometer is open to measure the change of the water head (at equilibrium). The water/sediment interface position, sensor pressures and piezometer levels are registered at short time intervals early in the test (for each hydraulic loading stage). Longer time intervals are used later, as the process evolution slows down.

The radioactive sources (Sm-153, half-life of 48 hours) are activated once a week. As mentioned above, the measurements are made at regular intervals by moving the gamma source-detector system (up and down) along the column. This gives the density profile evolution during the experiment.

A pseudo-steady state (i.e. stable interface position, density, and pore pressure) is typically reached after 3 to 15 days, depending on the material and the initial pulp density. During the sedimentation process (before excess pore water pressure start to build-up), the water level in the upstream and downstream reservoirs is maintained equal. Once equilibrium is reached, the downstream reservoir is lowered slowly to create a hydraulic gradient of 0.1. The resulting water flow through the sample consolidates the particles. During this process of seepage induced consolidation, the upstream and downstream waters are overflowing. When a new equilibrium position is reached, a second pressure increment is applied with a hydraulic gradient of about 0.2 to 0.3. From then on, the hydraulic gradient is doubled at each stage of consolidation, until the limit of the experimental set up is reached (i.e. pressure sensor limit or maximum piezometer height).

At the end of the test, which may last for up to 2 months, the column is dismantled and the sludge is retrieved in an “intact” state. Tests are then conducted on the sludge samples to measure density, to analyse the chemical composition of the solids and of the pore water, and to assess other characteristics (using a vane and a fall cone test apparatus, for instance, not presented here). The amount of water added to the column during the hydraulic consolidation test is small, so little percolates through the sludge and it can be assumed that it does not affect significantly the chemical equilibrium.

3 TESTING RESULTS

3.1 Water treatment sludge

The test on the water treatment sludge lasted 50 days; and 5 stages of hydraulic load were applied. The hydraulic gradients were 0.1, 0.25, 0.5, 1 and 1.4 (based on the maximum level recorded in the piezometers). As the sample height was changing, the hydraulic load was adjusted using the position of the overflowing level downstream (to keep the gradient approximately constant). Figure 2 shows the water content profiles evolution for the sludge. For this test, the density measurements were done at 0.1 m intervals (up and down) at the level of the pressure sensor connexions.

This density measurement technique gives more accurate readings on the sludge than the ones obtained in previous tests, but these measurements are less accurate than those obtained on the kaolinite test (presented below). Density and pressure profiles measured at the same test time are needed for the results analysis (see section 4). Here, the pore water pressure dissipates relatively slowly, so it can be considered that it does not change significantly during the up and down density measurements. This gives a more precise density evaluation for these tests. In Figure 2, one sees that the water content at the base of the column is reduced rapidly during the self-weight consolidation process (first 17 days). The dotted line represents the water content profile at the beginning of the test. The profile after 2 days shows an increase of the water content, particularly between 0.4 and 0.8 m. This increase is due to the water contained in the piezometers that is moving into the column to reach the equilibrium. This effect appears early, near the central part of the column (away from the surface and the base of the column), and then progressively dissipates.

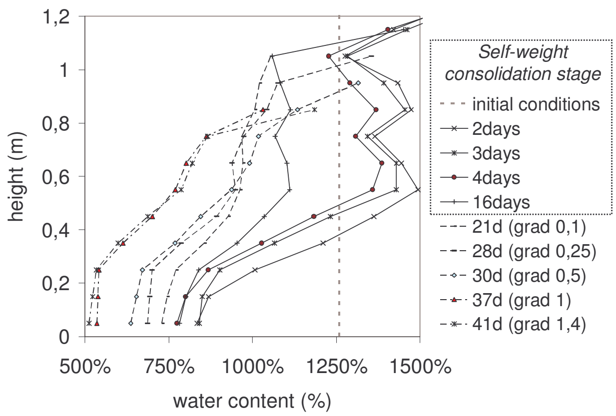

Figure 2. Water content profiles at different times, for the test on water treatment sludge

At the end of the test, the water content was reduced 2.5 times near the base of the column (following the application of the final hydraulic gradient of 1.4).

Figure 3 shows the excess pore water pressure dissipation for the self-weight consolidation stage in the water treatment sludge test. The dotted line represents the theoretical excess pore water pressure at the beginning of the test, calculated as the difference between the initial total pressures (consider hydrostatic) and the pore pressure at equilibrium.

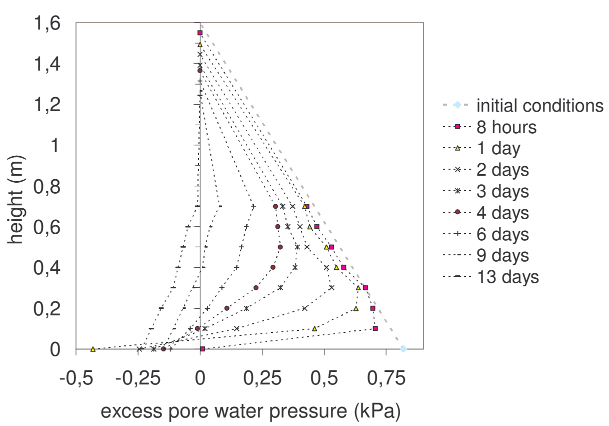

Figure 3. Excess pore water pressure for the self-weight consolidation stage during the test on the water treatment sludge

The negative excess pore water pressures observed at the base of the column on a few profiles are due to small variations between the overflowing levels upstream and downstream. When these levels are maintained constant, the excess pore water pressure becomes nil at the base. This aspect was improved for the test on kaolinite presented below (and for other tests on sludge).

Differential and excess pore water pressures evolution over time in the water treatment sludge test, are shown on Figure 4 for the entire test. For the self-weight consolidation stage, the excess pore water pressure is obtained from the differential pressures (Fig. 4a) measured over the column. For the subsequent test stages (with an imposed hydraulic gradient), the actual excess pore water pressure (Fig. 4b) is obtained from the difference between the measured differential pressures and the pore pressure distribution after excess pressure dissipation. There are spikes on the instantaneous values of pore water pressure u when the hydraulic gradient is increased. The delayed response of the piezometers (and connections) affects the magnitude of the spike. This does not happen with pressure sensors only. After a spike, the pressure rapidly becomes stable, so the distribution of the hydraulic head h (h= u + z) in the sludge sample can be followed in Figure 4a.

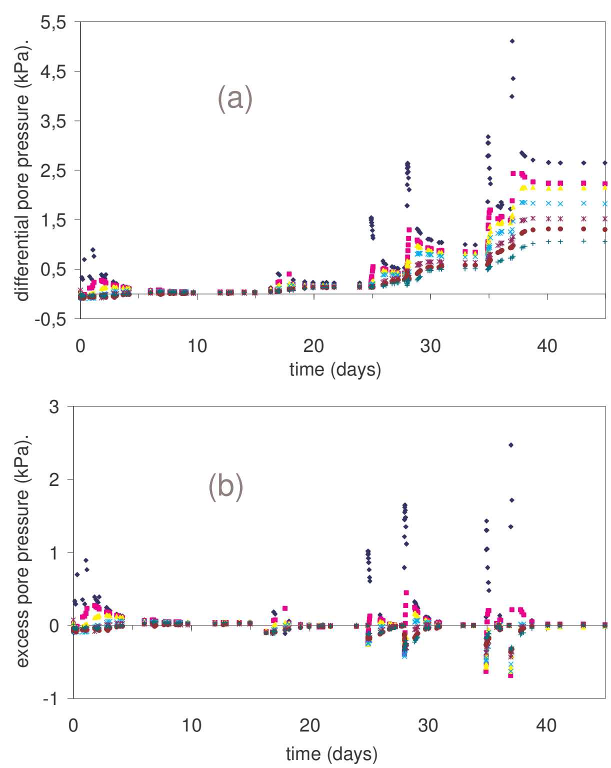

Figure 4. Differential (a) and excess (b) pore water pressures during the test on water treatment sludge

3.2 Kaolinite slurry

The test on the kaolinite slurry lasted 44 days, and 5 stages of hydraulic loads were applied. Each stage approximately doubled the hydraulic gradient of the previous one, starting with 0.5 (and then 1, 2, 4 and 8). The initial gradient applied for this test is higher than for the sludge as the kaolinite is denser after the self-weight consolidation stage (i.e. the kaolinite submerged unit weight at the end of the self-weight consolidation stage is significantly larger). As the pressure sensor readings have been validated, the piezometers were not installed for this test. Calibration and verification of the sensors are made before the test, when the column is filled with water. An air pressure controller is used here to apply higher hydraulic loads. The maximum hydraulic pressure applied during this test was 48.3 kPa (the maximum hydraulic pressure applied on the sludge was 13.5 kPa). By the end of the test, the water content in the slurry was reduced by a factor of 4.5 at the base of the column.

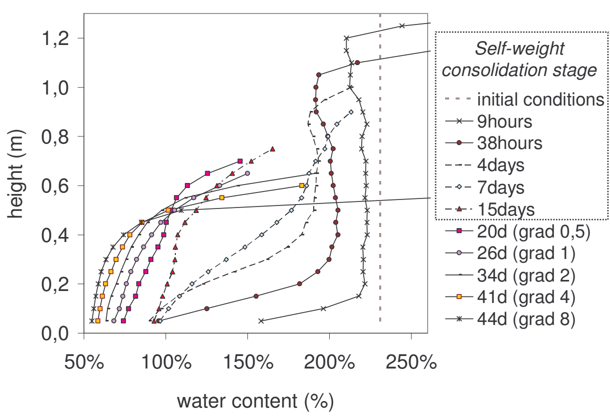

Figure 5. Water content profiles for the test on the kaolinite slurry

In Figure 5, the dotted line represents the water content profile at the beginning of the test (i.e. the water content of the slurry pumped into the column). The curves tend to be horizontal near the water/kaolinite interface. This figure also shows that the rate of decrease of the water content at the base of the sample is larger, which indicates a more rapid consolidation process near the filter (geotextile) and a slower consolidation near mid-height of the sample (as expected). The profiles shown in Figure 5 are becoming shorter as the consolidation process advance (i.e. as the interface water/slurry is moving down).

Figure 6 shows the excess pore water pressure for the self-weight consolidation stage during the test on the kaolinite slurry. The dotted line represents the theoretical excess pore water pressure at the beginning of the test (calculated in the same manner as for the test on sludge – see above).

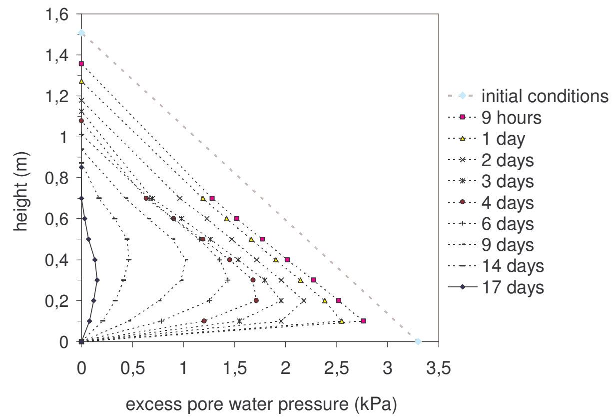

Figure 6. Excess pore water pressure during the self-weight consolidation stage for the test on the kaolinite slurry

Differential pore water pressure evolution for the entire test on the kaolinite slurry is shown in Figure 7. Again, the instantaneous peaks of pore water pressure correspond to the increase of the hydraulic gradient. These are more realistic than those shown on the test with the sludge (Fig. 4) because the pressure sensors response is almost instantaneous. Each peak is about twice the previous one. At the end of each load stage, one can observe the excess pore water pressure dissipation. The negative pore water pressure at the end of the test represents the discharge stage.

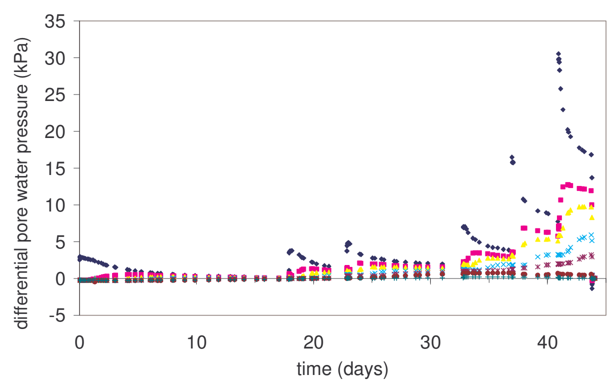

Figure 7. Differential pore water pressure for each consolidation stage for the test on the kaolinite slurry

4 RESULTS ANALYSIS

Figure 8 shows the effective stress-void ratio relationship based on the results of the test on the water treatment sludge.

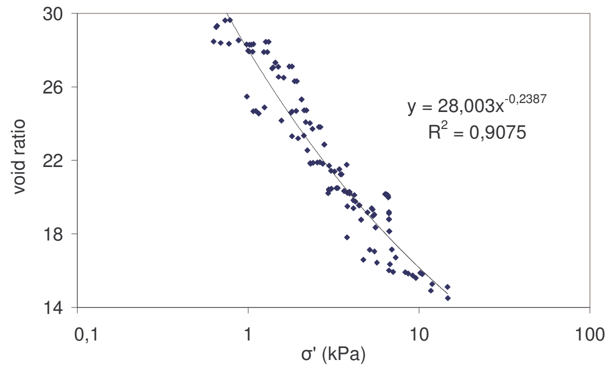

Figure 8. Void ratio vs. log effective stress for the water treatment sludge during the test described in section 3.1

The effective stress was calculated for each layer (i.e. between the position of two consecutive pressure sensor connexions or the top surface and first connexion) using the following equation:

$$\Delta\sigma' = \gamma_{sub} * \Delta z + \Delta u \qquad [1]$$

Where γ_{sub} is the submerged unit weight of the sludge, Δz is the thickness of the layer, Δu is the differential pressure between the bottom and top of the layer (based on the differential pressure sensor or piezometer readings), and $\Delta\sigma'$ is the difference between the effective stress at the top and bottom of the layer. The equation applies for a layer under equilibrium, without considering the effect of friction between the sample and the column wall.

The calculations start at the top of the sample, in the layer between the water/slurry interface and the first pressure sensor connexion (measurement point). For this layer, γ_{sub} is calculated from the water content profile. For this layer, Δz is the difference between the position of the water/slurry interface and the first connexion; Δu is then calculated as the applied hydraulic pressure minus the summation of all others pressure sensor readings. $\Delta\sigma'$ (Equation 1) for this top layer represents the effective stress at the first connexion, as the effective stress is nil at the surface.

For the layers below, γ_{sub} is obtained as above. The value of Δz is 0.1 m. The pore pressure differences Δu are directly obtained from the readings of the differential pressure sensor. The effective stress increase $\Delta\sigma'$ is simply the difference between the effective stresses at two adjacent connexions.

The trend observed in Fig. 8 is typical of porous media with a very high void ratio (e.g. De Campos et al, 1994).

During these tests, the water content w has been obtained from measurements made with the gamma ray sensors at the position of each pressure sensor measurement point. The void ratio can then be calculated from the water content using the following equation:

$$e = w * G_s \qquad [2]$$

(G_s is 2.95 for the water treatment sludge, and 2.5 for the kaolinite slurry)

The flow-rate is obtained by measuring the volume of water at the downstream reservoir over times. This flow-rate was adjusted for each "layer" (0.1 m-thick), between two connectors of pressure sensors. The adjustment is made by calculating the volume change for each layer (from the change in the voids ratio) during the downstream flow-rate calculation. The outflow rate from a given layer is then calculated; at the base of the column, this rate is directly given by the downstream flow-rate. The incoming flow-rate for each layer is the outflow rate from the layer above, plus the rate due to the volume change in the layer. The same calculations are made from the base to the top of the column. The maximum flow-rate adjustment required (around 30% to 70%) occurs when a new hydraulic load is applied. More details on the calculation procedures are included in Pedroni (2008 – Ph.D. Thesis, to be submitted).

The hydraulic conductivity k is calculated using Darcy's law with the hydraulic gradients between the various sensors. The hydraulic conductivity is plotted as a function of the average void ratio for each layer between measurement points in Figure 9 for the water treatment sludge.

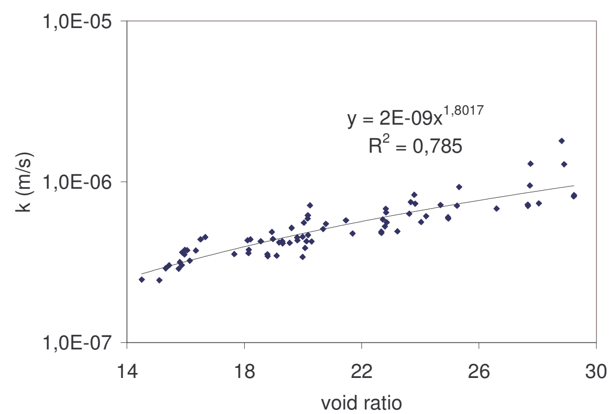

Figure 9. Log hydraulic conductivity vs. void ratio for the water treatment sludge

The data in Figure 9 was obtained from piezometer readings at equilibrium (i.e. after the rapid change in elevation was stabilized). This figure also shows a trend that is commonly observed in porous materials with a very high void ratio (e.g. De Campos et al, 1994).

Figure 10 shows the void ratio vs. effective stress relationship for the kaolinite. Once again, the trend is generally clear, but there is more uncertainty for small values of the effective stress (less than about 0.4 kPa for this test). This phenomenon was also observed by others who conducted column tests on slurries (e.g. Been and Sills, 1981; Bartholomeeusen et al., 2002; Hawlader et al., 2008).

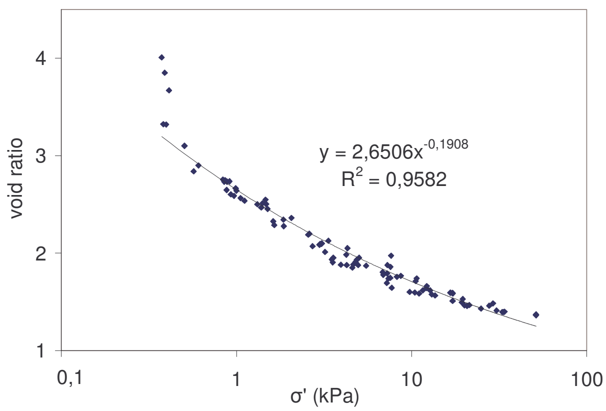

Figure 10. Void ratio vs. log effective stress for the test on the kaolinite slurry

Figure 11 shows the void ratio vs. hydraulic conductivity relationship for the kaolinite. One can observe (Fig. 11) larger variations of the hydraulic conductivity for larger void ratio values.

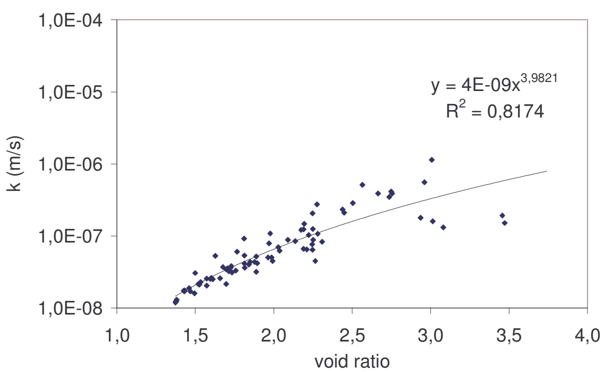

Figure 11. Log hydraulic conductivity vs. void ratio for the kaolinite slurry

5 PRELIMINARY INTERPRETATION

The non-linear finite strain consolidation theory (Gibson et al., 1981) is generally considered as the state of the art for describing consolidation in engineering applications. The prediction of the consolidation behaviour is however largely influenced by the details of the constitutive equations introduced into the theoretical model. Several authors have proposed constitutive relationships that can be applied to highly porous media; Bartholomeeusen et al. (2002) and Hawlader et al. (2008) have recently reviewed some of the existing formulations. Other authors (e.g. Al-Tabbaa and Wood, 1987; Aubertin et al., 1996; Chapuis and Aubertin, 2003) have presented more specific models to estimate the k - e relationship, which is often required to solve a variety of geotechnical and hydrogeological problems. Based on the above, the authors propose here very simple relationships to represent the data shown in Figures 8 to 11.

For the water treatment sludge the follow relationships represent the data fairly well:

$$e = 28 * \sigma'^{-0.24} \qquad \text{(with } \sigma' \text{ in kPa)} \qquad [3]$$

$$k = 2 * 10^{-9} * e^{1.8} \qquad \text{(in cm/s)} \qquad [4]$$

For the kaolinite, the follow relationships have been obtained:

$$e = 2.65 * \sigma'^{-0.19} \qquad [5]$$

$$k = 4 * 10^{-9} * e^{3.98} \qquad [6]$$

Further analyses are underway to develop more complete relationships.

6 CONCLUSION

An innovative large size hydraulic consolidation testing set up has been presented with results obtained on two materials having a very high void ratio. The testing procedure described here, which relies on the application of a varying hydraulic gradient, is different from the one used in previous tests that made use of an external applied pressure (Dromer et al., 2004; Pedroni et al., 2006).

This paper shows typical test results obtained on AMD treatment sludge and kaolinite slurry during self-weight consolidation and after the application of increasing pore pressures (that simulates layer deposition).

The results presented show a larger hydraulic conductivity change in the kaolinite slurry (where k varies by about 2 orders of magnitude, from about 10^{-6} to 10^{-8} m/s) than in the water treatment sludge (k goes from about 10^{-6} to 10^{-7} m/s). This is most probably due to the larger hydraulic loads applied in the kaolite slurry (about 3 times higher). Moreover, the higher void ratio in the water treatment sludge (e = 30 to 14) than in the kaolinite slurry (e = 3.5 to 1.3) may also influence these parameters. The results obtained on the treatment sludge and kaolinite slurry are used to define simple k - e and e - σ' relationships. The results presented in the paper indicate that the hydraulic gradient technique is a valuable alternative to total load increments to simulate a layered deposition.

Results obtained from the column tests are being used to simulate sludge behaviour in ponds using numerical calculations.

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