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Experimental Bench For Study of Settling-Consolidation Soil Formation

ABSTRACT: A laboratory experimental bench suiting the evolution survey of little concentrated materials in the course of deposition is presented here. The materials concerned can be in formation soils (mud) or any other fine granular materials, however, all characterized by their strong deformability and by their complex behaviour with constant changes from settling to consolidation phases. First, the already available experimental devices are summed up in a state-of-the-art section. The restraints imposed by the material (properties, consistency, quick evolution) have directed the development towards automated settings consisting of a column containing the material studied, a gammadensitometer and a pressure sensor. The device proposed here, the experimental procedures and the result post-processing are described in detail to provide an accurate follow up of the densities and of the interstitial excess pore pressures. The most original feature of the device lies in the possibility to obtain profiles within the first minutes of the evolution. The results, presented here in terms of effective stress and pore pressure, make it possible to delimit the range of validity of the usually adopted constitutive laws better.

KEYWORDS: sedimentation, consolidation, soils, mud, pore pressure, gammadensitometer

Many industrial and scientific domains are concerned by an improved understanding of the settling-consolidation link during the deposition of fine mineral materials. Port and estuary silting, and dredging deposit on shore are among the most striking examples, but it also affects some ore deposits and grout implementation. Theoretical studies (Tan and Scott 1988, Toorman and Berlamont 1991, Alexis et al. 1992, Toorman 1992) have shown the relevance of suiting experimental devices, which can be used to test the validity of the constitutive laws adopted in models.

This paper initially presents a detailed automated experimental device used to measure densities and pore pressure at the beginning of the self-weight consolidation without disturbing the extremely sensitive material. The complexity of the system is dependent on the achievement of the best compromise between the quickness and the accuracy of the measurements. The interpretation of some experimental density and pressure results is presented to show the potential of the system.

The various experimental devices found in the literature are summarized in Table 1. Destructive density measurements (coring, slicing, syringing) cannot be used to follow the evolution of the profiles. Non-destructive density measurement, on the other hand, uses X-ray or gamma sources, the radiation of which through the material is measured in places.

Pore pressure measurements, nevertheless essential for the observation of dissipation phenomena, are not always performed. The non-negligible fluid exchange phenomenon between column and measuring system, which can disturb both the measurement and the material behavior, is the inconvenience of the standpipes. Most authors usually use one sensor for each pressure tapping. The system proposed here, on the other hand, uses one single sensor successively linked to each pressure tapping.

The different translucent columns presented in the literature (Table 1) are not of the same size (the inside diameter ranges from

47–112 mm, and the height from 114–4000 mm). Similarly, the length of the tests varies from a few hours to over four months.

The bibliographic study also shows the evolution of the experimental settings. The first studies, indeed, are characterized by observation and empirical approach of the phenomena (Owen 1970). Then, oedometers suiting low stresses have been used (Monte and Krizek 1976), sometimes coupled with a sampling method (Ume-hara and Zen 1982) or a gamma source and several pressure sensors (Tan et al. 1988). A great step forward was taken when routine tests began to be systematically performed out in columns with an accuracy suiting low densities and stresses better (Been and Sills 1981, Sills 1995). More recent settings (mostly developed within the context of the European Program MAST) are inspired by the preceding one (Menge et al. 1991, Toorman 1992, Berlamont et al. 1992, Alexis et al. 1992, Gallois 1995, Le Bras 2000, Masutti 2001).

Moreover, many references refer to Ph.D. theses (the accessibility to which is often uncertain), whereas the published papers too often present results without justifying the choices, the equipment and the procedures used. That is why, considering the sharp increase in the sophistication of the experimental settings, clarifying the whole experimental process to improve the reproducibility of the tests and, therefore, the scientific and experimental progress, appears essential here.

Settling-Consolidation Bench Design

General Methodological Choices

The study of soils in the course of settling-consolidation is confronted with two antagonistic requirements: quickness and accuracy. The quick evolution of the material at the beginning of the test, indeed, requires performing measurements during the first minutes of the phenomenon. The interpretation of the very low effective stresses and, particularly, hydraulic gradient values (stemming from the difference between two pressures), on the other hand, also requires a measurement accuracy of a few pascals for both stresses

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TABLE 1—*Synthesis of devices and experimental conditions.*

References	Columns			Experimental Conditions			Density Measurement			Pore Pressure Measurement		
	int.diam.*H (mm)	Material	Temp. (°C)	Max. duration (days)	Instrument Type	Translation (mm)	Spatial Resolution (mm)	Accuracy	Sensors	Filters	Accuracy (Pa)	
Alexis et al. (1992)	90*1700	plexiglas	10	62	Γ rays	1200	~10 mm	+/-0.005	7 fixed, 20 kPa.	20, porous bronze	35	
Been et al. (1981)	102*2000	acrylic	Variable	100	X rays	1200 ?	+/-1	0.01	1 + shifting connections, 35 kPa	21, porous stones		
Gallois (1995)	90*1700	plexiglas	10	62	Γ rays	1500	30	?	1 + 10 taps connections	10, porous stones	20	
Imai (1981)	50*250	?	?	3	Slicing	?	~10	?				
Le Bras (2000)	90*1700	pmma	10	32	Γ rays	1500	25	0.001 à 0.005	1 + Pressure multiplexing unit, 2.5 kPa	10, cigarette filters	3	
Migniot et al. (1990)	86*250 to 4000	?	20	62	Γ rays	?	75	?				
Sanchez et al. (1992)	100?*2000	?	21	100	coring	?	?	?				
Sethi et al. (1986)	112.5*320	plexiglas	?	0.12	syringing	?	~30	?				
Shen et al. (1994)	47*114		22 to 27	~7	X rays	?	2	?				
Sills (1995, 1997)	101.6*2000	acrylic	?	142	X rays	1200	1	+/-0.002	Pressure multiplexing unit, 35 kPa		10	
Sridharan et al. (2001)	50x ?	?	?	?	coring	?	?	?				
Toorman (1992)	98*2000	plexiglas	13	93	Γ rays	2000	?	+/-0.03	standpipes	cigarette filters	10	
Wichman (2000)	102* ?	acrylic	?	94	X rays	?	1	0.002	1 + 8 connections	?		
Zen and Urmehara (1986)	55*350	vynil	?	80	slicing	350	?	?	standpipes	porous stones		

and pressures. Both requirements, moreover, can be intensified by the strong sensitivity of the material to disturbances and by its normal evolution during the test, which can disturb the repeatability of the results. All these restraints have directed the researches towards the development of an automated device, based on nondestructive density and pore pressure measurements within a controlled environment, following up the vertical profiles achieved during the evolution of the phenomena (duration of approximately 30 days).

Density profiles are mainly achieved using the vertical shifting of a gammadensimeter along the column containing the material. For bulk, availability, and cost reasons, gamma rays have been preferred to X-rays. It should be emphasized that the use of ionizing radiation imposed some constraints (legal and medical) on the bench scientists.

Because the translation time of the carriage necessarily causes a time delay between the measurements carried out at the bottom and those performed at the top of the column, both an ascending and a descending profile are systematically performed in order to achieve, after processing, a time-centered profile. Reference times (instants where the densitometer is in the up position) have been selected so as to be consistent with the speed of evolution of the phenomenon observed. In this way, reference times are here in a geometric progression with a common ratio of 2 (like in the oedometer test) from 22.5 min to 32 days (12 profiles). To take advantage of the quickness of the system, the first profile spacing is one whole cycle (2.7 min). Consequently, the first five reference times are: 1.33 min, 4.15, 6.9, 9.66, and 12.45 mins. The last two weeks can be used to start a new test with the same equipment on another adjoining column.

In regards to pressure measurements, the most direct method consists of placing a sensor at each selected pressure tapping. Besides its cost, which is not negligible for 10 pressure tappings, this method needlessly measures the hydrostatic pressure (a constant component of approximately 15 kPa) and is sensitive to the unavoidable long-term clock drift of the sensors, which can affect significantly the hydraulic gradient values. To avoid these problems, we use a specific measurement method, which is not clearly described in the literature. This method (called "overpressure mode") uses one pressure sensor only, which connects successively and automatically to each pressure tapping (Fig. 1). The problem of the stabilization time required for each connection, can, however, be settled quickly by conducting pressure profiles simultaneously with density profiles.

The equilibrium at the pressure tapping is given by:

$$u + \gamma_w \cdot (H_0 - x) = u_m + \gamma_{w0} \cdot (x_c - x) \quad (1)$$

where respectively,

H_0, x_c, x : dimensions of the water-air interface, of the sensor, of the pressure tapping,

γ_w, γ_{w0} : the weight density of natural water (in the column), and of clean water (in the tubes),

u, u_m : the excess pore pressure and the pressure measured by the sensor.

Then, the measured pressure is:

$$u_m = u + \gamma_{w0} \cdot (H_0 - x_c) + (\gamma_w - \gamma_{w0}) \cdot (H_0 - x) \quad (2)$$

So, for each pressure tapping, the sensor measures the excess pore pressure plus a constant. Densities of natural and clean water being very close, the measuring range of the sensor can be reduced by positioning it close to the top of the column (low $H_0 - x_c$) while maintaining positive measured pressure values. This method makes it possible to limit the measuring range to 2500 Pa (equivalent to 25 cm of water) and, therefore, to achieve a higher absolute accuracy for a given type of sensor (given relative accuracy).

Regarding the sequence of measurements and profiles, the system automation (Fig. 2) is used to control all the measurement procedures, to provide a better management of time (night, weekends, parallel tests) and, consequently, a better reproducibility of the results. The whole measurement device and the materials are also placed in a $10^\circ\text{C} \pm 1^\circ\text{C}$ climatic chamber to prevent any breakdown of organic matter within natural materials.

Elaboration and Fitting out of the Columns

The main bench characteristics are summarized in Fig. 3. Each column is closed at the top, using a cover valve, equipped with a small tube to maintain a contact with the atmospheric pressure while preventing evaporation. The column has a constant outside diameter without outgrowth to leave the density carriage move freely along the column and, thus, provide density profiles along the whole length of the column.

The pressure nozzle positioning is very accurate (± 0.01 mm are equivalent to a pressure of 0.1 Pa) to cause the accuracy of the pressure measurement no prejudice. The PVC nozzles are hot-welded to the column (using a PVC welding rod). Stabilization annealing is then practiced on the column to minimize the internal tensions

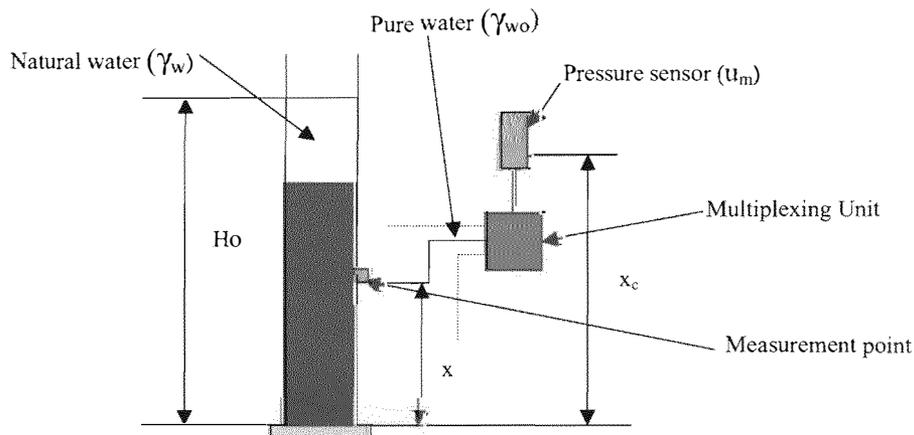


FIG. 1—Excess overpressure measurement method.

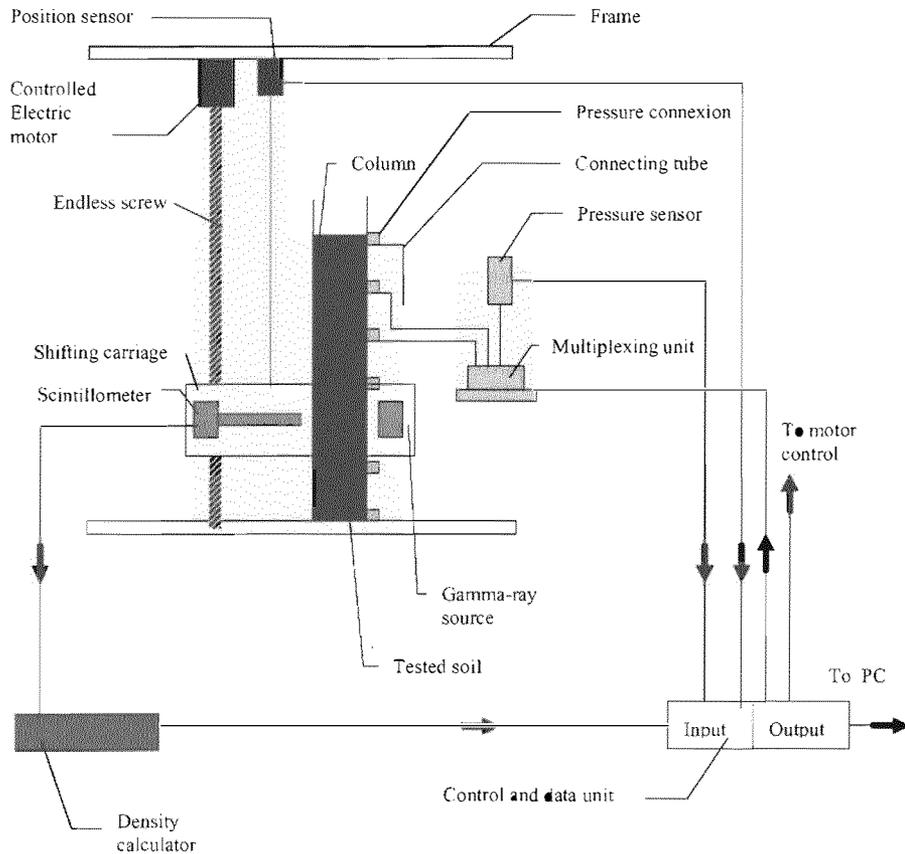


FIG. 2—Schematic of the gammadensitometer bench.

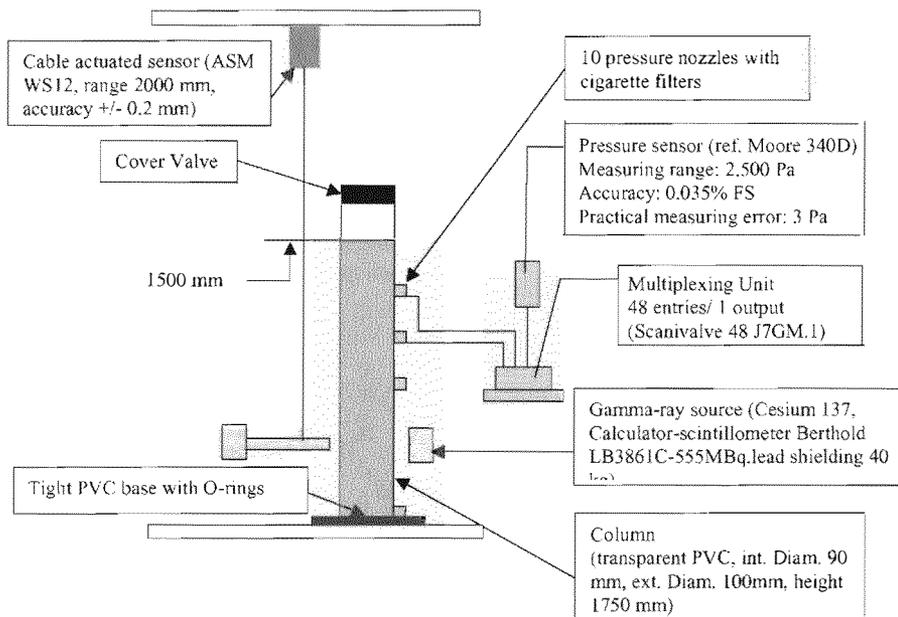


FIG. 3—Gammadensitometer bench characteristics.

induced by welding within the PVC pipe. For pore pressure measurements, each nozzle includes a cigarette filter to prevent the dispersion of the material grains. Sinterbronze filters were first used, but they clogged easily and were difficult to clean. The adopted

filters, made of filter tips and placed in a bronze plunger, performed better than they are replaced in each new test. Each nozzle is connected to a 1.59-mm inside diameter translucent nylon tube filled with distilled water.

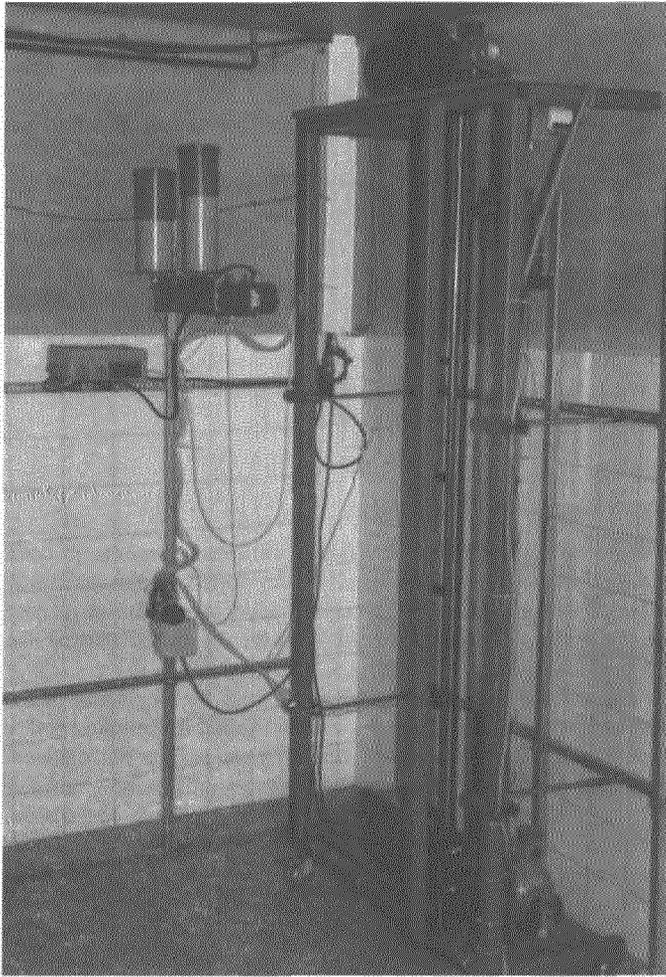


FIG. 4—Gammadensitometric bench.

Pore Pressure Measuring System

The overpressure measuring system (Fig. 4) consists in a multiplexing unit (used to select each pressure tapping) and in a pressure sensor (positioned to measure overpressures).

At the beginning of the study the multiplexing unit was composed of solenoid valves connected in parallel, but the device was difficult to bleed and could generate transient spurious overpressures. With the adopted multiplexing unit, every next input is selected through an impulse with a maximum rate of 20 selections per second performed by the rotary motion of a perforated disk to avoid spurious overpressures.

Density Carriage

The density carriage (Fig. 5) consists of the radioactive source and the scintillation counter, which is fastened to a strand. The different phases followed by the densitometric signal are: the gamma rays are radiated by the radioactive source, the gamma rays are absorbed by the material depending on its density, the attenuated radiation is converted into electrical impulses by the scintillation counter, and the calculator counts the impulses and calculates the density of the material according to gauging data.

The gamma-ray source presents a maximum actual beam width of 30 mm with the beam standard aperture. The density calculator automatically updates the source ageing effects and stores three calibrations (in 2–5 points).

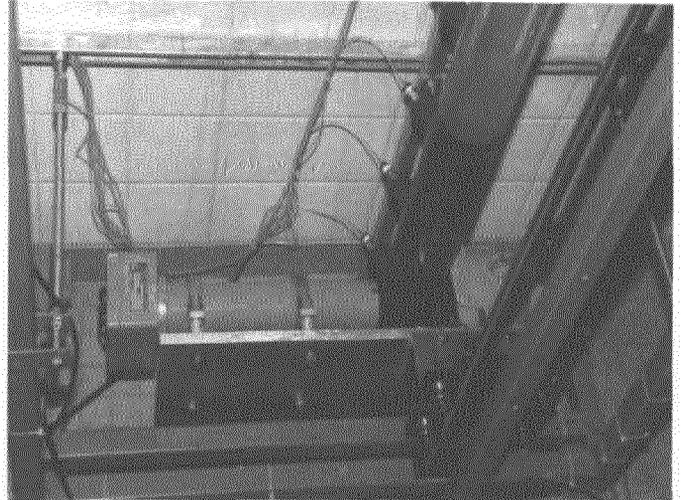


FIG. 5—Detail of settling column and gammadensitometric carriage.

A speed regulator controls an engine, which drives the density carriage into traveling motion. With a time constant of 1 sec. the accuracy of the gammadensitometer is 0.001 in static position, 0.002 at 4 mm/s, and 0.005 at 23 mm/s, which are the carriage velocities used in this study. The position of the carriage is measured by a position transducer (the first transducer used, consisting of a photoelectric cell counting the driving screw turns, was simple and cheap but not accurate enough).

Control and Acquisition Data Unit

The control and acquisition part of the settling-consolidation bench is provided by a data unit, which principally controls the densitometer carriage engine (supplying, direction, speed, acceleration ramp) and the multiplexing unit (pressure tapping selection impulses), manages the profile times according to the preset planning, carries out the measurements from the sensors (relative density, pressure, distance, temperature), stores all measurements and reference values and transfers them towards the PC, and can finally be used to view the parameters in a real-time mode (very useful during the adjustment phases).

The data unit uses a task-level programming technology, which allows much flexibility during the adjustment phase and, apparently, maintains parallel operation during the automatic sequences.

Evolution of a Measuring Cycle

The evolution of a measuring cycle is based on the data unit programming. One whole cycle combines one ascending half-cycle and one descending half-cycle. A half-cycle consists in updating the reference values, completing one relative density profile and one pressure profile. For the user, both profiles seem to take place simultaneously. The profiles are obtained with the repetition of their respective sequence. The pressure sequence is composed of the sensor stabilization delay, the pressure measurement, the pulsing towards the scanner, updating and storage. The density sequence is composed of the distance measurement, the density measurement, updating, and storage.

Most cycles are conducted normally in a low mode. However, in the first 24 h, during which the evolution of all the phenomena is very quick, the cycles are run in the quick mode. In the slow mode, the carriage velocity is constant (4 mm/s) and the sensor stabilization delay is 10 sec. In the quick mode, on the other hand,

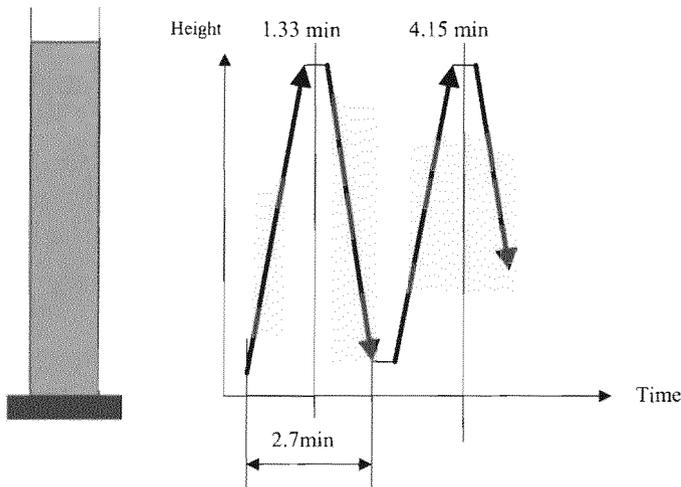


FIG. 6—Shifting cycles of gammadensitometer carriage.

the velocity maintains a 4 mm/s speed for the first 20 mm at the top and at the bottom of the column and reaches 23 mm/s for the rest of the profile, whereas the sensor stabilization delay falls to 4 sec. Consequently, for a 1500 mm high profile, one measuring cycle lasts 2 min. 40 sec. in the quick mode and 13 min. in the slow mode.

Test Methodology

For a given type of soil, the gammadensimeter is previously calibrated in two points (demineralized water and soil density measured by weight and volume, relative densities 1 and 1.28 for these tests). The calculator time constant is set to 1 sec. The column preparation consists of its erection, the bleeding of the pressure system (using gravity while the column is filled with distilled water), water removal from the column and filling with the material, which has been prepared so as to match the required concentration. To be

filled, the column is placed on a balance and the material is poured until the expected mass is reached (± 1 g, which corresponds to 0.1 mm of the filling height). The column, inside which a constant manual agitation is maintained using a ballasted disk to prevent any settling start before the beginning of the test, is then fastened to the stand.

The data unit program is started just when the agitation is stopped. It scans continuously the test elapsed time and starts the cycles by updating the parameters (slow, quick, etc.) to complete automatically and autonomously the profiles at the preset reference instants (Fig. 6). A total of 8800 values are thus measured during one whole 32-day test (17 profiles), among which 2720 density values, 340 pressure values, 3060 measurement instants and 2720 distance measurements. All these values are then processed with a view to the required post-processing objectives.

Experimental Data Processing

Because of vast experimental data collected, a treatment code (in Visual Basic) has been specially developed for the automatic information processing. This code is used to test the sensitivity of the results to the experimental conditions and to analyze the evolution of the material behavior.

The quick evolution of the phenomena at the beginning of the test incited us to run half-cycles (ascending and descending) and to combine density and pressure measurement sequences. Measurements are then achieved at irregular distances and time intervals. For a better systematization of the data processing phase, some nodal values are deduced at the nodes of a regular temporal and spatial meshing at preset distances (about 900 points for 1.5 m) and at the reference times (17 instants for a 32-day test). Density and pressure nodal values are achieved by linear interpolation for relative density and cubic interpolation for pressure (without smoothing) between the distances of the measured values, on the one hand, and by time linear interpolation between the values obtained during the half-cycles (run slightly before and after the reference times) (Fig. 7), on the other hand.

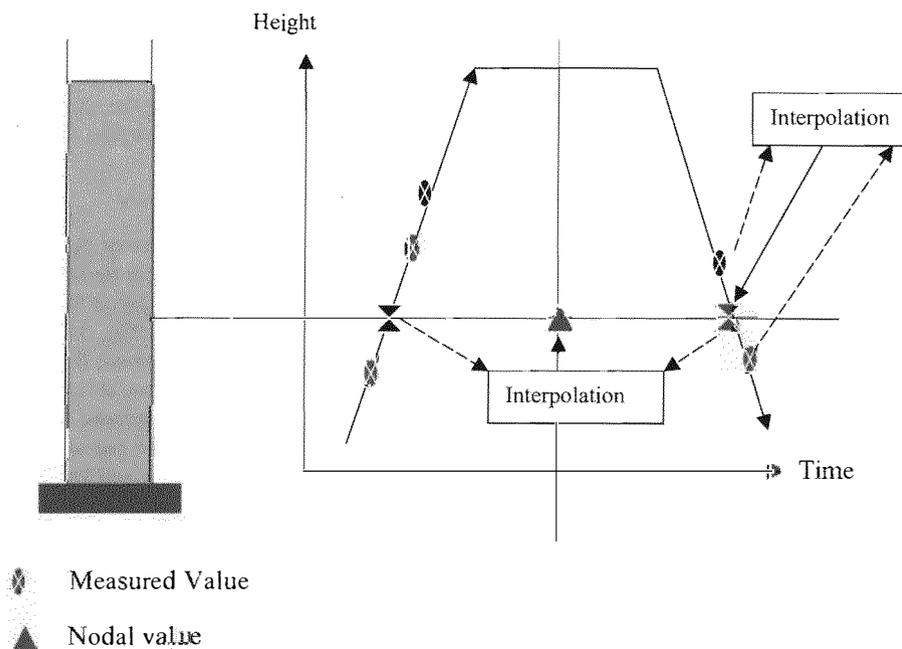


FIG. 7—Definition of nodal values.

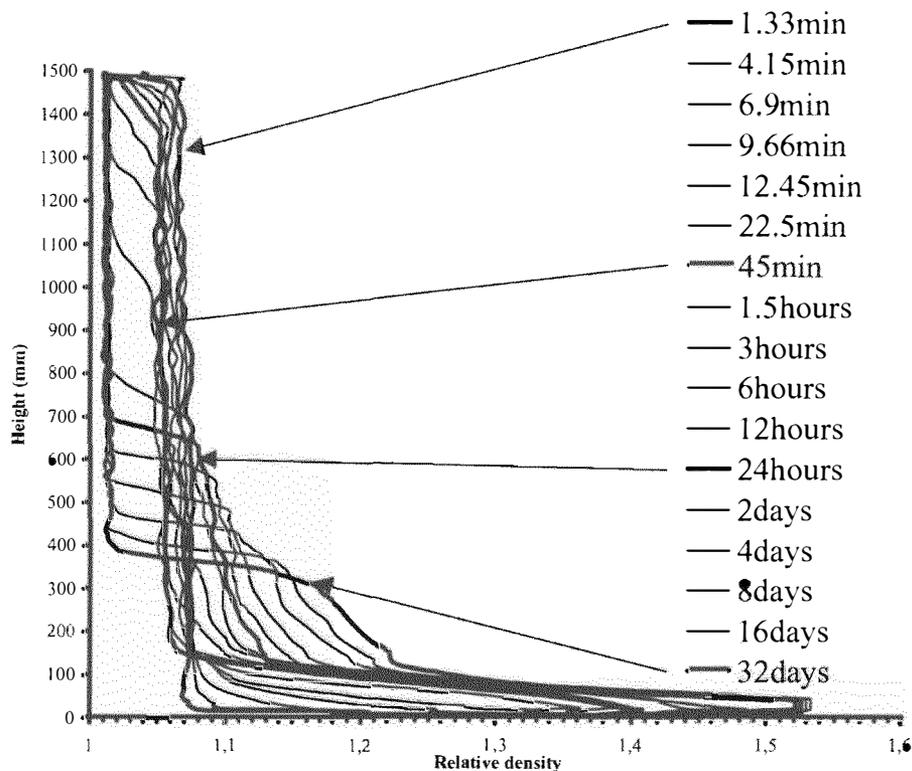


FIG. 8—Relative density profiles.

The achievement of the density and excess pore pressure nodal values also requires a careful consideration of the specificity of the measurement system. Regarding densities, the positions related to the measured density values are translated from the distance covered by the densitometer carriage during the integration time of the gammadensitometric computer (1 sec.). Moreover, a specific test, conducted on PVC and water only, has shown that the actual width of the gamma radiation actual beam obtained after it went through the column was 30 mm and had a triangular repartition. These significant results demonstrate that the beam also cuts through a different material (PVC column base at the bottom and air at the top) in the lower and upper areas of the column (15 mm). Pore overpressures are inferred from Eq 1.

Total stress values are achieved by integrating the specific gravity nodal values γ (stemming from the density) on the height. The net total stress is defined as the difference between total stress and hydrostatic pressure:

$$\sigma_n(x, t) = \int_x^{H_0} \gamma(\xi, t) d\xi - \gamma_w \cdot (H_0 - x) \quad (3)$$

The net total stress can be considered as a material coordinate, as other authors do (for ex. Gibson 1967, Sills 1995, Toorman 1996). The lines joining places having identical net total stresses can be interpreted as particle trajectories, if relative velocity between different class of grains (segregation) is negligible.

Pore overpressures are obtained from Eq 2. The effective stress is the difference between net total stress and pore overpressure.

The hydraulic gradient and the falling velocity can also be calculated to obtain the permeability (which are not presented here).

Example of Profiles Obtained

Characteristics of Test

For illustration, the results of a test performed on natural estuarine mud (Saint Nazaire, FRANCE) are presented. This material has a 63- μ m undersize material of 77 %, a liquid limit of 84 %, a plastic limit of 53 %, an organic matter concentration of 15 %, and relative density of grains 2.7. The initial relative density of the test is 1.071 (corresponding to an initial concentration of 100 g/l and a void ratio of 26). Estuarine natural water density is 1.01. The material height in the column is 1500 mm. The test total duration is 32 days.

Density and Excess Pore Pressure Profiles

All the relative density profiles (Fig. 8) have a regular shape, which changes from a quasi-vertical group of curves close to the initial relative density (1.07) to values corresponding to natural water (1.01). The final relative density on the bottom is approximately 1.5, whereas the water-soil interface is found at the quarter of the initial height (distance 360 mm). In time, the interface lowers and the density in the lower part of the column increases sharply. In the first 22 min. of the test, the interface has not fallen yet, whereas the density profile has already noticeably changed within the column.

The shape of the excess pore pressure profiles (Fig. 9) is also satisfactorily regular. The profiles change from quasi-linear initial overpressures to quasi-nil overpressures in water and to overpressures within 10 % of the initial values on the bottom, which corresponds to a consolidation rate of 90 % in comparison with the initial values.

The first measured profile (at 1.33 min) is very closed to the theoretical one (straight line from 0 Pa, 1500 mm to 900 Pa, 0 mm),

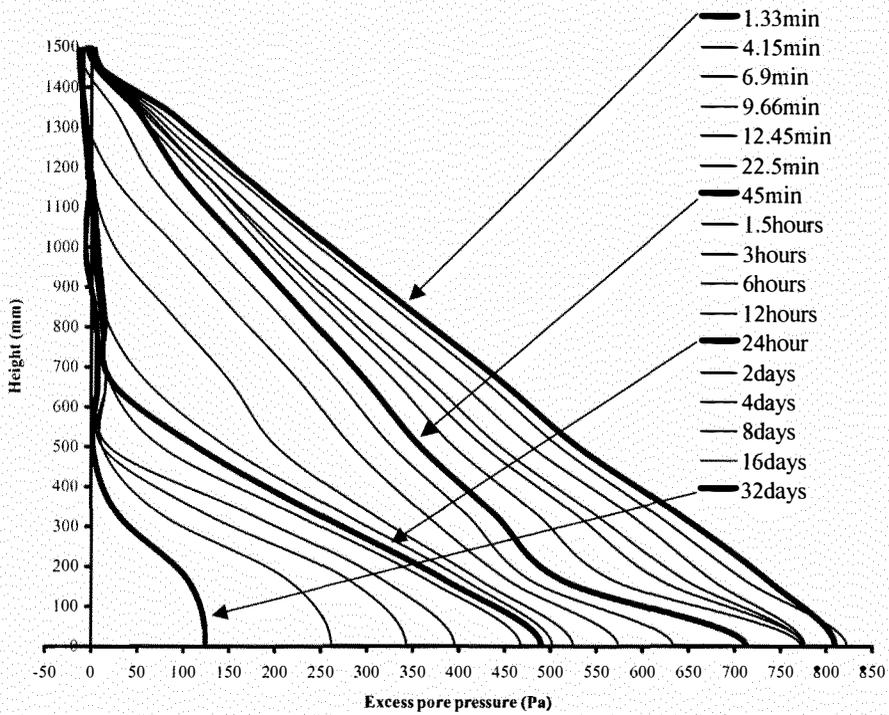


FIG. 9—Excess pore pressure profiles.

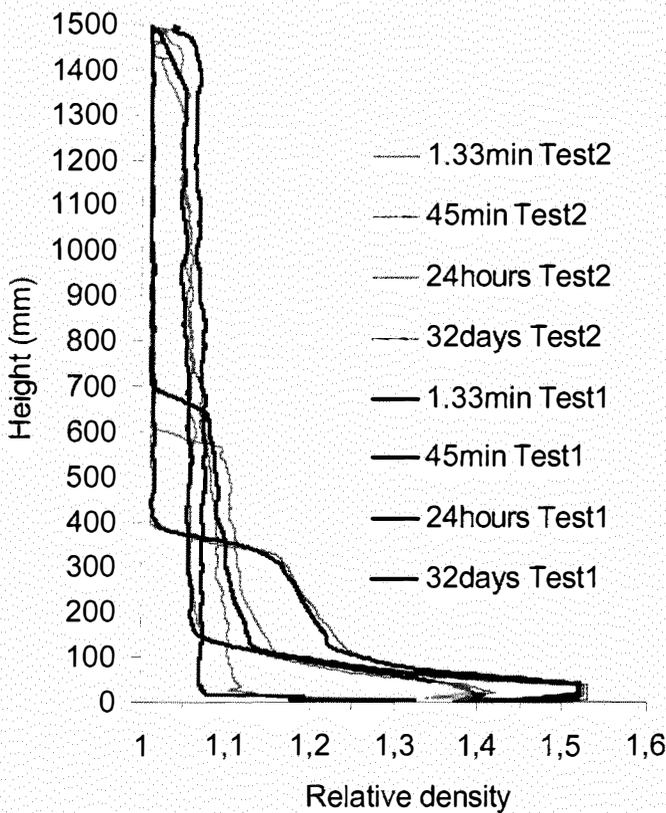


FIG. 10a—Density profiles repeatability.

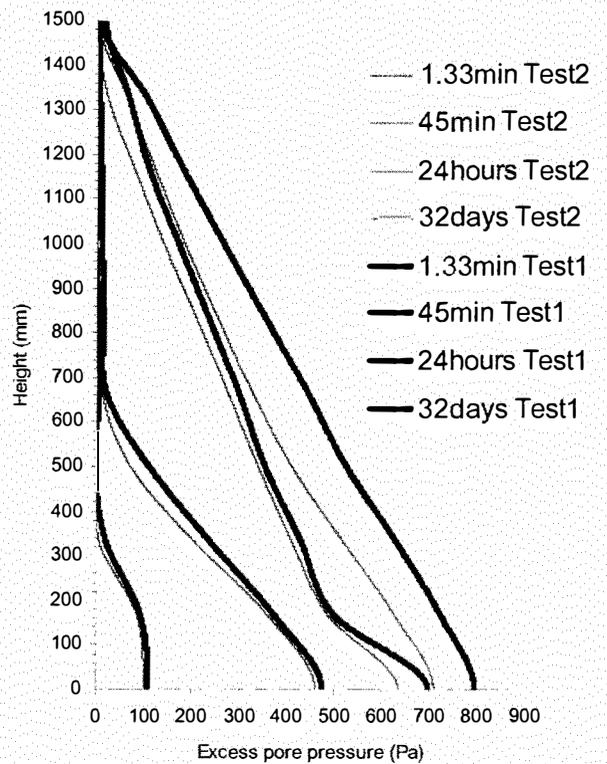


FIG. 10b—Excess pore pressure profiles repeatability.

showing quasi-nil effective stress at the beginning of the test just after the agitation is stopped.

Figure 10a and 10b show the profiles repeatability. Test 2 was performed with the same procedure except that the material was just poured into the column and not then agitated. Although the

initial conditions were not exactly the same, the profiles from 45 min are similar.

Trajectory and Effective Stress

Iso-net total stress curves, which are called “trajectories” for more convenience (Fig. 11), represent the relative density evolution better

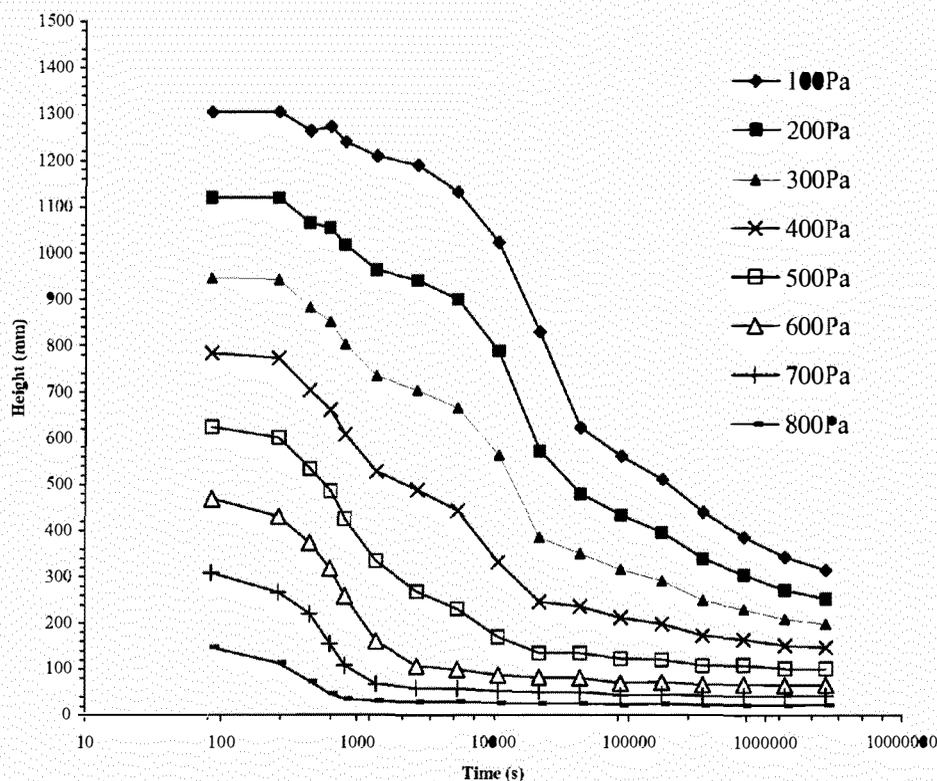


FIG. 11—Particle trajectories.

than the typical relative density profiles, on which many crossings of curves appear.

The study of these lines makes it possible to follow graphically the evolution of the material layers contained between two iso-value lines: lowering and settlement of each layer. The required iso-values are selected within a range according to the amount of material poured into the column (from 100–800 Pa with a pitch of 100 Pa for the presented 100-g/l test).

During the first 22 min. of the test, when the interface has not moved yet, significant evolutions are observed in the lower part of the column. This evolution is much weaker in the upper part. A few hours later, however, there is nearly no evolution anymore in the bottom layers whereas upper layers evolve sharply. Thus, in the first minutes of the test, the particle fall occurs with no pressure dissipation whereas, afterwards, the settlement phenomenon is accompanied by a sharp pressure dissipation.

Figure 12 presents the compared size distribution of initial material and final samples.

These 6 samples were pumped out from the final bed (360 mm height at 32 days).

The bottom sample (0–60 mm) presents a clearly coarser distribution and the other samples a slightly finer than the homogeneous initial material. It shows that partial segregation has occurred during the test.

Figure 13 presents curve families showing the evolution of the effective stress vs. the material void ratio following the iso-net total stresses. The first points (1.33 min.) of each line are placed on a quasi-horizontal straight line, which represents the homogeneity of the initial mixture. It is possible to analyze the curves with roughly two areas. First, the area of low effective stresses (less than 50 Pa) where the incertitude (± 10 Pa) is visible. This area also corresponds to the beginning of the test when the segregation

may have occurred, and then induces an increase in void ratio for the upper layers. In this area, the material coordinate is not strictly valid. Second, the area of high effective stresses (more than 50 Pa) where the bottom layers (coarser) have a different behavior than the upper ones (finer). In this area, the effective stresses are high enough to prevent the continuation of segregation (and then the material coordinate becomes valid again).

The results of the test presented here show the material complex behavior, which is characterized by dissimilar evolutions, principally in the upper and lower parts of the column. These evolutions tend to show a quick particle fall of the coarse grains during the first minutes (rise in the void ratio at the top and decreasing at the bottom) followed by a consolidation phase within each layer, whose coarse size fractions are not identical anymore (fine material at the top, coarse material at the bottom). Considering the measurements achieved here, the phenomena could be addressed (and modeled) in terms of segregation and sorting.

Conclusions

A new test bench for the study of settling-consolidation soil formation has been described here. Although it is inspired by devices already available, this bench presents the original feature to be able to carry out density and excess pore pressure profiles from 1.33 min. along the 1.5 m length of the test column. The overpressure measurement method applied, moreover, maintains an accuracy of a few pascals. Measurement automation makes it possible to respect the same measurement procedure over several tests. The collected data are processed by a specific treatment code taking the specificity of the system and the types of representation required for the mechanical interpretation of the material behavior into account.

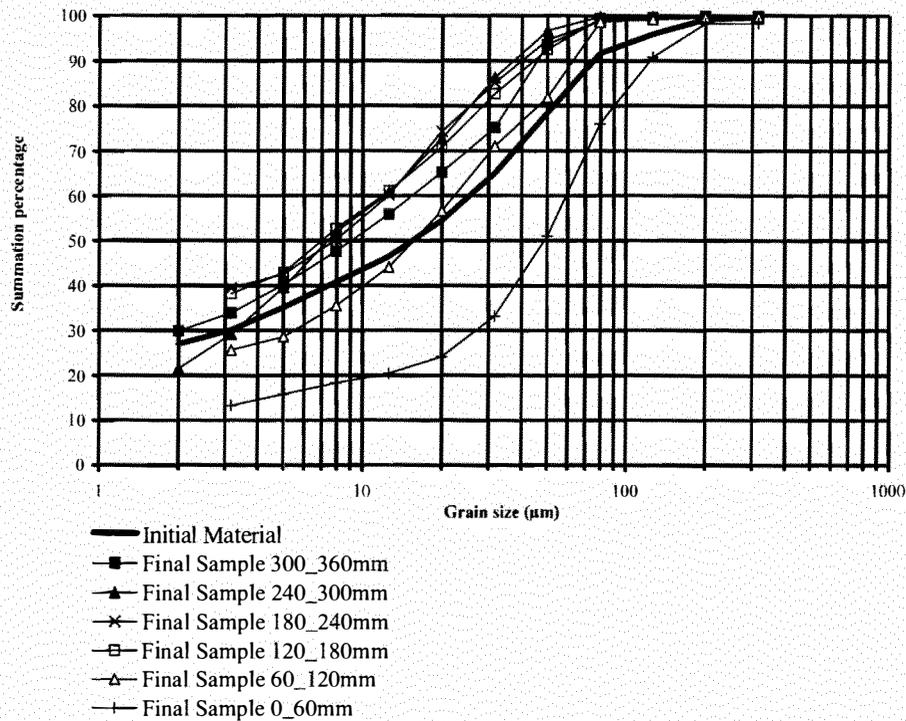


FIG. 12—Initial and final (32 days) particle size distribution.

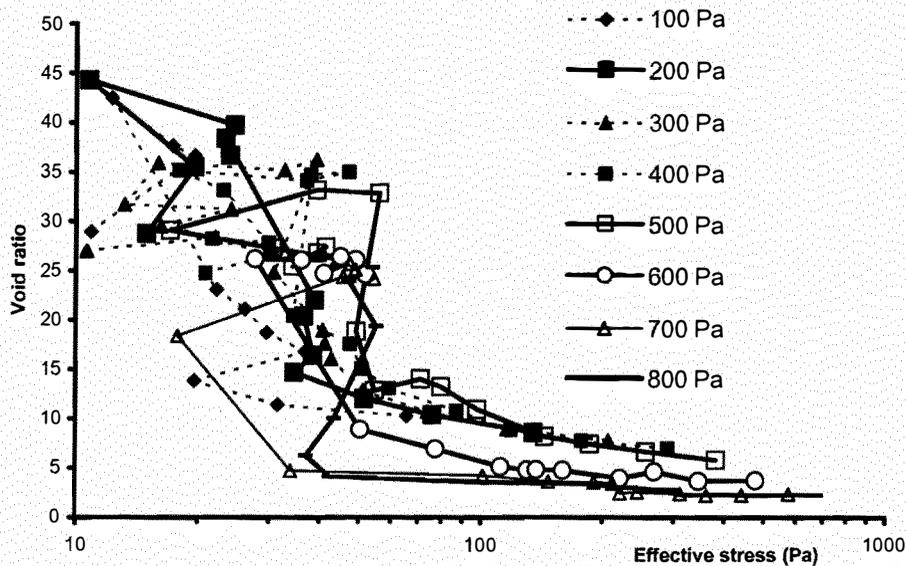


FIG. 13—Effective stress and void ratio.

The example of results presented in this paper demonstrates, through the regularity of the profiles achieved, the reliable adaptation of the setting to the problems. The chosen spatial and time resolutions make it possible to analyze the evolutions at different fineness levels.

The results tend to show that low effective stresses at the beginning are not sufficient to prevent the coarser particles to fall. The evolution of the different parameters directs the research towards a better consideration of the segregation (or sorting) phenomena for natural materials, which will make possible the interpretation of the effective stress vs. void ratio curves with the help of the local size distribution.

In the future, this test bench will be used to study other types of material with a view to building up an experimental database, which becomes essential for the better representation and prediction of the behavior of soils in the course of formation.

Acknowledgments

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