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Instrumentation of a flood zone embankment: Example of the CER experimental embankment

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■ ABSTRACT

In order to evaluate both the risk induced by using water-sensitive soils within embankments located in flood zones and the relevance of a methodology for predicting embankment body deformation, the Rouen-based Road Experimentation Center (CER) and LCPC, in partnership with the SNCF National Railway Company, constructed an experimental embankment made of fine-grained soils 5.40 m high by 10 m long and 21 m wide at its base. This embankment was heavily instrumented, primarily for the purpose of monitoring water movements and deformations. The water content measurement provided the opportunity to implement new or still relatively unfamiliar techniques. Structural behavior was tracked first during the construction phase and then over the two flooding phases at the embankment base.

Instrumentation d'un remblai en zone inondable. Exemple du remblai expérimental du CER

■ RÉSUMÉ

Pour évaluer le risque induit par l'utilisation de sols sensibles à l'eau dans des remblais en zone inondable et la pertinence d'une méthodologie de prévision des déformations des corps de remblai, le Centre d'Expérimentation Routière de Rouen (CER) et le Laboratoire Central de Ponts et Chaussées (LCPC) en partenariat avec la Société Nationale des Chemins de Fer (SNCF) ont réalisé un remblai expérimental en sols fins de 5,40 m de haut sur 10 m de long et 21 m de large à sa base. Ce remblai a été fortement instrumenté, principalement pour suivre les mouvements d'eau et les déformations. La mesure de la teneur en eau a été l'occasion de mettre en œuvre des techniques nouvelles ou encore peu diffusées. Le comportement de l'ouvrage a été suivi durant la phase de construction et les deux phases d'inondation de sa base.

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INTRODUCTION

The objective of this experimental embankment was to supply useful data for evaluating the risk induced by using water-sensitive soils in embankments built within flood zones. A behavioral study conducted on the embankment set up on the CER test site enables assessing the deformation prediction methodology developed by LCPC teams. Implementation of various hydric state monitoring techniques also serves to judge technique relevance within this particular context.

The benefit of such an experimental structure, in time, is to authorize the controlled use of soils available within the perimeter of a road or rail project instead of water-insensitive, so-called noble, materials. The stakes involved are both financial and specific to the principle of sustainable development, by virtue of making use of available soils and avoiding reliance upon aggregate transport from quarries often located far from construction sites.

This experimental campaign has given rise to two research reports [1-2]. The present article will display the type of instrumentation installed in the experimental structure along with the main set of results generated from the monitoring effort.

BACKGROUND

The design of road and rail embankments composed of fine-grained soils is hindered in some contexts by a lack of knowledge on the behavior of these materials during variations in their hydric state. Such is particularly true for collapsible soils whose mechanical strength decreases in the presence of water. This phenomenon is principally due to:

- soil composition (e.g. clay proportion);
- implementation conditions, especially water content or degree of saturation, and the dry mass density after compaction; and
- trends in the external media (position of aquifers or structural flooding, or magnitudes of seasonal drying-wetting cycles).

Current research conducted on these topics is intended, over the long run, to propose computation methods that serve to evaluate structural deformations under various types of loadings (flooding, drying-wetting cycles, etc.) on the basis of suitable laboratory tests. This approach, which for the time being remains confined to the realm of research, could only be applicable to embankment design and dimensioning under the condition of having been validated on actual full-scale structures. This intention has motivated the present research project and construction of the dedicated experimental embankment. In order to examine the collapsible nature of compacted soils, the base of this embankment was more loosely compacted.

The set of embankment instrumentation has been chosen to:

- observe the impact of changes in meteorological parameters on hydric profile variations within surface layers;
- analyze the consequences of embankment base saturation on the height of capillary rising over the body of the structure;
- study the relations between hydric state variations and actual local deformations within the structure, for comparison with laboratory experiments; and
- evaluate, over a long period of time, the relevance and reliability of varying water content and suction in an earthen structure.

THE EXPERIMENTAL EMBANKMENT

■ Embankment construction

The experimental embankment (not including access ramps and ancillary amenities) was sized as follows (see [Figure 1](#)): length 10 m; height (H) 5.4 m; platform width 5 m; base (V) 21.2 m; a talus slope on the order of 3Horizontal/2Vertical.

The various layers ([Fig. 2](#)) were deposited in three phases, as follows.

- First phase: preparation of the soil substratum, installation of the sealant system so as to insulate the embankment from uncontrolled water inflows from the bottom, and placement of a porous base composed of 30 cm of gravel confined within a geotextile.
- Second phase: building of the lower third of the embankment using loams stemming from the A28 motorway construction site. This first third was 1.8 m high and purposely loosely compacted to enable additional settlement during the wetting test performed on the embankment base. The initially-planned fourth layer had to be eliminated so as to double the height of Layer 5 and thereby accentuate the collapsible nature of this part of the embankment.
- Third phase: construction of the two upper thirds with a loam from a quarry operated by the SNEC company. This part of the embankment rose to a height of 3.6 m.

Figure 1
Embankment dimensions
– instrumented zone
(not including ancillary
amenities)

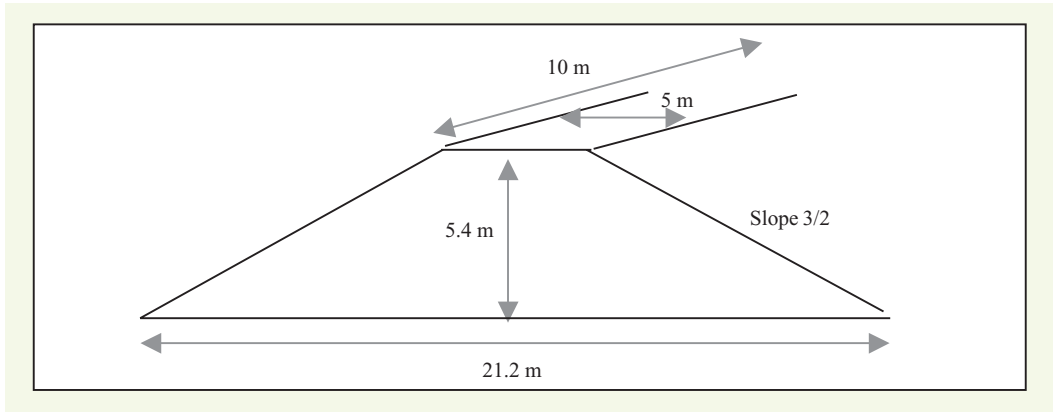
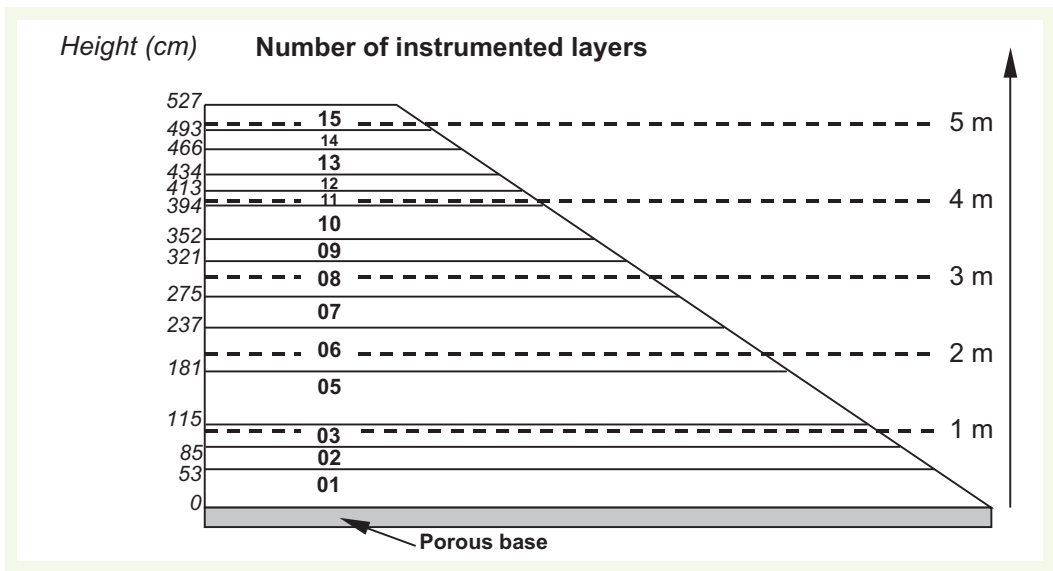
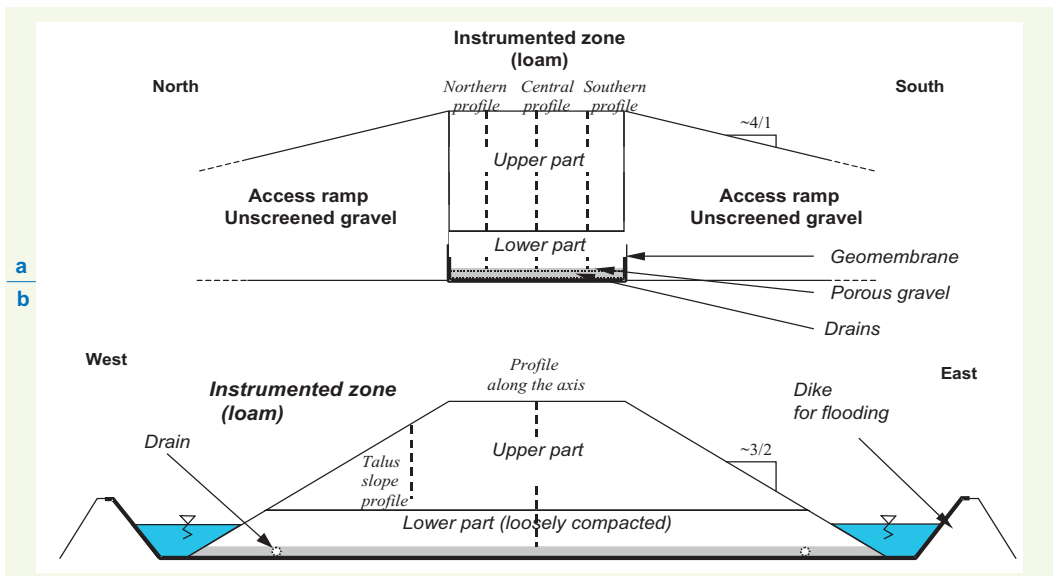


Figure 2
Geometry and numbering
sequence of the various
instrumented soil layers



The instrumented part of the structure, composed of loam, is framed by the access ramps, which are gradually raised over the embankment layers; these ramps are composed of an unscreened gravel available at the CER test site. Between embankment and access ramps, the sealant system is raised by one meter in order to limit leaks via the ramps during subsequent embankment base flooding tests. Two dikes built on both sides of the embankment and sealed by means of a geomembrane connected to the geomembrane located underneath the embankment have made it possible to generate flood basins two meters high (Figure 3).

Figure 3
Schematic profiles of the
experimental embankment
structure
a: longitudinal profile
b: transverse profile

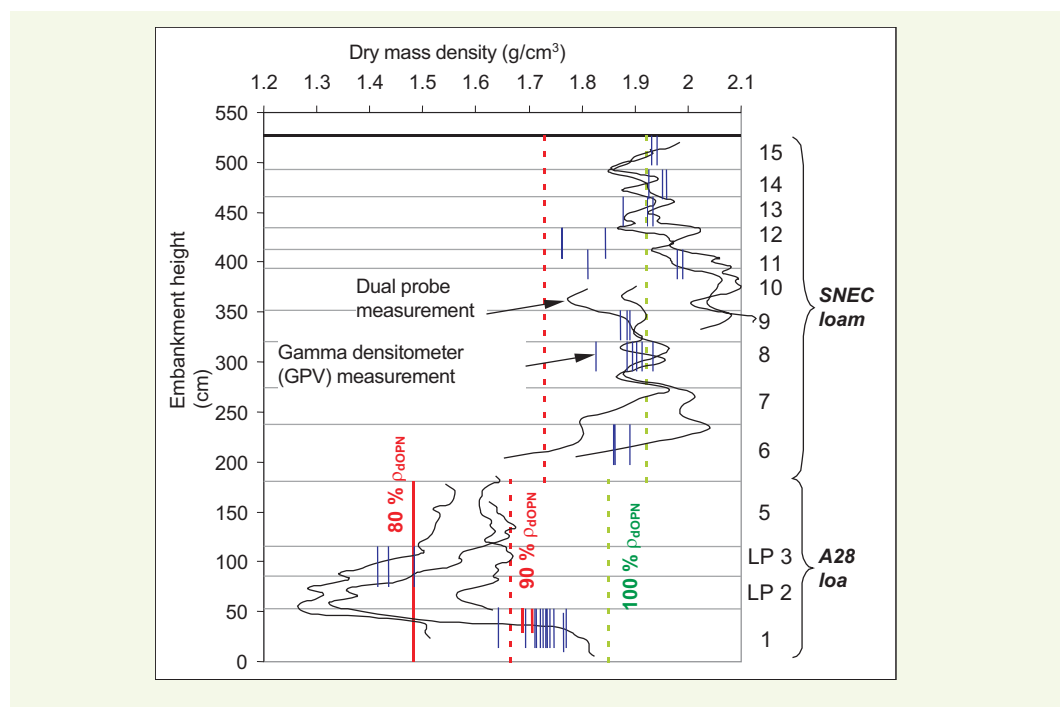


■ Inspections and controls

The mass density measurements, conducted using both a one-shot gamma densitometer (GPV) at each installed layer and a dual gamma probe placed every two meters (Figure 4), reveal that the embankment base was in fact loosely compacted, especially over the first meter where the compaction rate can drop below 80% of the Optimum Proctor Normal (OPN). Between 1 and 1.8 m, the compaction rate does not exceed 90% OPN.

Over the upper part of the embankment, application of compaction rules drawn from the Road Excavation Guide (GTR) enabled reaching at least the target densification objective (i.e. 95% of compaction rate averaged over the entire layer, 92% at the layer bottom). Only Layer 6 (between 1.8 m and 2.4 m), compacted over 60 cm, actually displayed a compaction deficit at the layer bottom.

Figure 4
Results from dry mass density measurements using the GPV and dual gamma probe techniques



INSTRUMENTATION DETAILS

The embankment was instrumented with six types of sensors (see Figs. 5-7):

- Time Domain Reflectometry (TDR) probes for the (indirect) measurement of volumetric water content (40 sensors);
- hyperfrequency loops, which also allow measuring volumetric water content (10 sensors);
- a streamer of embedded electrodes for monitoring water movements by means of the electrical panel method; a second streamer was laid out over the embankment upon each measurement campaign;
- equitensimeters, for measuring the level of suction (15 sensors);
- PT100 type temperature sensors (25 sensors);
- vertical displacement sensors, also called plate settlement gauges (18 sensors); and
- horizontal displacement sensors, based on cable sensors (8 sensors).

Since the objective of this instrumentation configuration is to study the relations between hydric state variations and deformations within the embankment body, the TDR and suction probes and vertical displacement sensors were placed as closely to one another as possible.

In order to complete the monitoring system layout, a meteorological station was installed on the embankment platform. This station has been used to evaluate a soil-atmosphere hydric exchange modeling method developed by the CERMES Soil Mechanics Teaching and Research Center; it comprises: an anemometer, a weathervane, a solar radiation sensor, a pluviometer, two temperature sensors, two relative humidity sensors, an atmospheric pressure sensor, a dew sensor, and a soil temperature sensor.

Figure 5

Position of the primary sensors (water content w , suction and temperature) within the main transverse profile

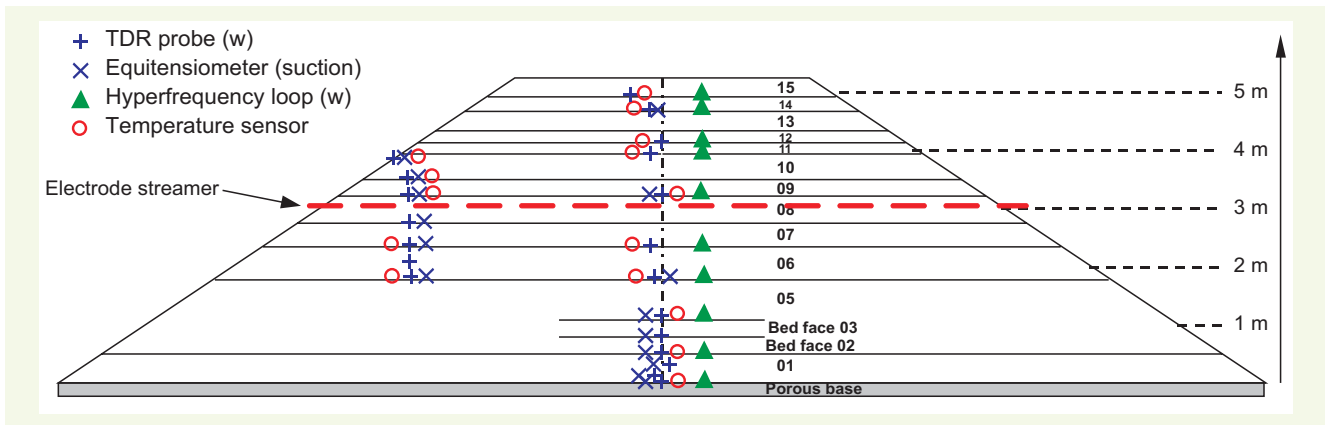


Figure 6

Position of the horizontal and vertical displacement sensors within the central transverse profile

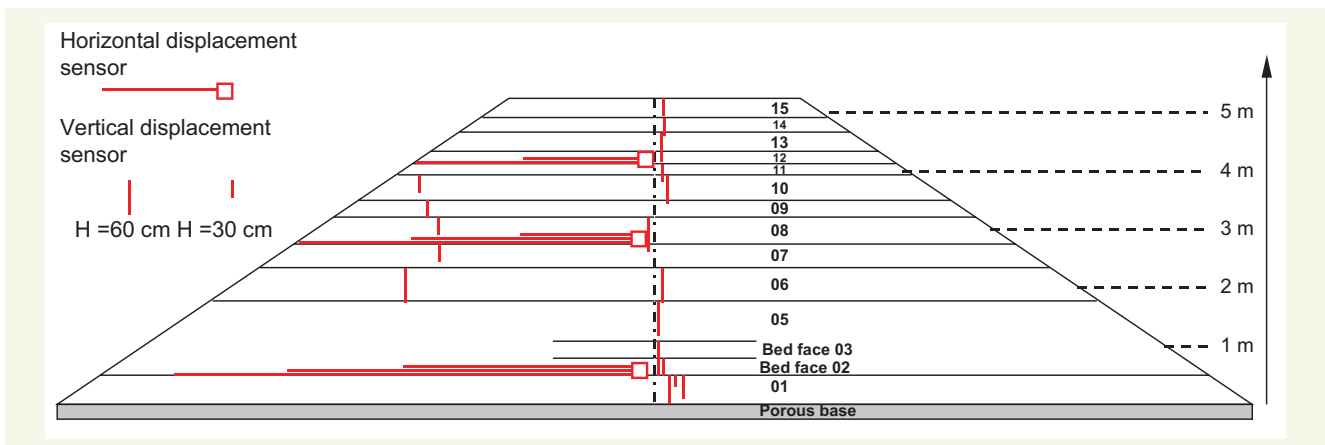
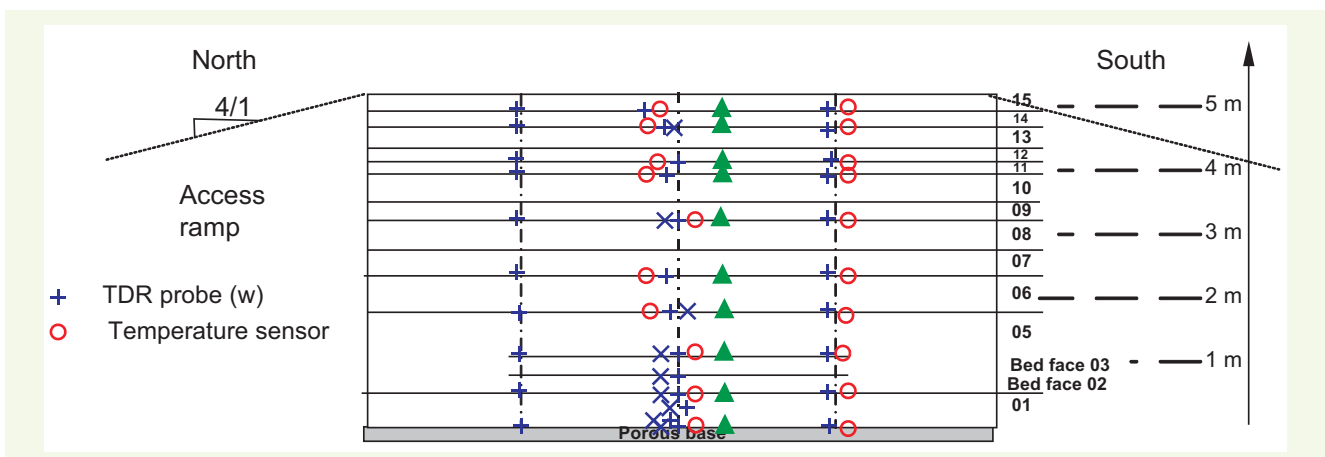


Figure 7

Position of the displacement and water content (w) sensors within the longitudinal profile



■ TDR probes

Measuring volumetric water content via the TDR probe relies upon Time Domain Reflectometry (TDR). The principle behind this technique consists of sending an electromagnetic pulse inside a waveguide (Figure 8) composed of three metal electrodes with known length and then measuring the pulse transit time. Pulse velocity within the waveguide depends on the dielectric constant of the contact material. This velocity drops as the dielectric constant associated with the material rises. Due to the sizable deviation in dielectric constant between the solid soil matrix (1 to 3) and water (80), the apparent dielectric constant Ka recorded by the TDR probe is highly dependent on soil water content:

$$Ka = (t \times c / L)^2 \quad (1)$$

where t is the transit time of the electromagnetic pulse in the waveguide, c the speed of light and L the waveguide length.

Given that this technique is indeed operational, a commercial system (TRASE) was employed. This equipment provides the volumetric water content of soil from the dielectric constant through use of its own calibration curves. Probe calibration in the two materials introduced for this experimental embankment has enabled verifying the 2% measurement uncertainty announced by the device manufacturer.

Figure 8
TDR probe (volumetric water content)



■ Loop antennas

This method serves to determine the volumetric water content of in situ soils and was developed by the LCPC Associated Research Team n°23 of the Rouen regional Ponts et Chaussées Laboratory; it is based on measuring the energy losses of an electromagnetic wave emitted in a buried loop antenna.

The equipment implemented consists of a 10-cm diameter loop antenna (Figure 9) connected to a spectrum analyzer by a hyperfrequency cable with very slight attenuation. The analyzer performs a sweeping of frequencies between 100 and 800 MHz and yields the loss spectrum between emitted energy and reflected energy (Figure 10).

A study of resonance frequencies, i.e. spectrum peaks, leads to determining the dielectric constant of soil in the vicinity of the antenna by means of the following formula:

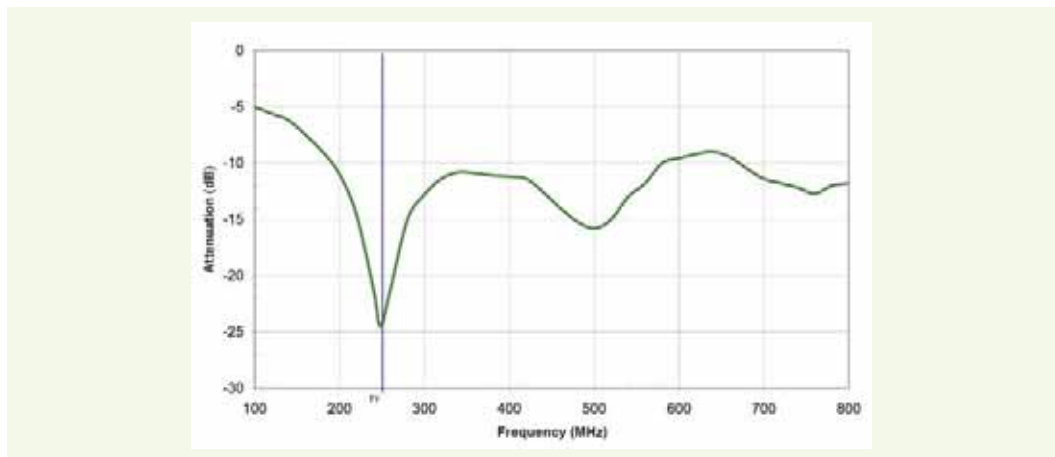
$$\sqrt{\epsilon'} = \frac{c \times k}{Fr \times \pi \cdot d} \quad (2)$$

where k is the order of resonance, ϵ' the dielectric constant of the material, d the loop diameter (m), c the speed of light ($m \cdot s^{-1}$), and Fr the resonance frequency (Hz).

Figure 9
Loop antenna



Figure 10
Example of a spectrum
obtained with the analyzer



Many relations given in the literature allow correlating this dielectric constant with the volumetric water content of the soil. Based on Topp's formula [3], the volumetric water content ($\theta^{\text{Topp}} [\text{m}^3 \cdot \text{m}^{-3}]$) is derived by:

$$\theta = -5,3 \times 10^{-2} + 2,92 \times 10^{-2} \epsilon' - 5,5 \times 10^{-4} \epsilon'^2 + 4,3 \times 10^{-6} \epsilon'^3$$

The CRIM (Complex Refractive Index Method) or Krazewski's model serves to deduce the so-called Labo experimental formula [4] used to obtain volumetric water content ($\theta^{\text{Labo}} [\text{m}^3 \cdot \text{m}^{-3}]$) vs. dielectric constant and wet mass density of the medium (d_w), i.e.:

$$\theta = 1,249 \times 10^{-1} \cdot \sqrt{\epsilon'} - 3,85 \times 10^{-2} \cdot d_w - 1,279 \times 10^{-1} \quad (4)$$

These relations then enable calculating the theoretical uncertainties, which amount to roughly 20% for Topp's model and 7% for the CRIM model [6].

■ Streamer of electrodes (electrical panel)

› Measurement principle

The electrical methods are based on measuring the resistivity parameter, with the resistivity of a given medium being its capacity to oppose the transmission of an electrical current. This parameter is expressed in ohm \times meters. Its inverse, conductivity, is expressed in terms of siemens per meter. In practice, the resistivity of a soil or material is measured using four electrodes. Two of them, A and B, serve to inject direct current of intensity I into the medium, while the other two, M and N, enable measuring a potential difference V induced by the passage of this current. The

apparent resistivity ρ' is the measured potential difference divided by this current and then multiplied by a coefficient k that accounts for device geometry. This parameter is directly deduced from a measurement and integrates a certain volume of ground, whose electrical properties are heterogeneous in space (given that actual resistivity may vary from one point to another):

$$\rho' = k \frac{V}{I} \quad (5)$$

Electrical panel measurements allow automating measurements along an entire series of electrodes (Figure 11). According to a protocol defined by the user, successive measurements are recorded between the various AB-MN couples, which yields a cross-section of the apparent resistivities. An inversion then becomes necessary to generate a model with real resistivities [5].

› Implementation in the experimental embankment

The surface device

For the purpose of conducting measurements by electrical panels according to the typical configurations, it was decided to instrument the embankment at the surface level. The selected set-up comprises 48 electrodes spaced 0.50 m apart, meaning the device features a fully-deployed length of 23.50 m. This set-up was installed transversely to the embankment axis and covers both talus slopes and the platform, which leads to a situation where an electrical panel extends along a very distinct topography.

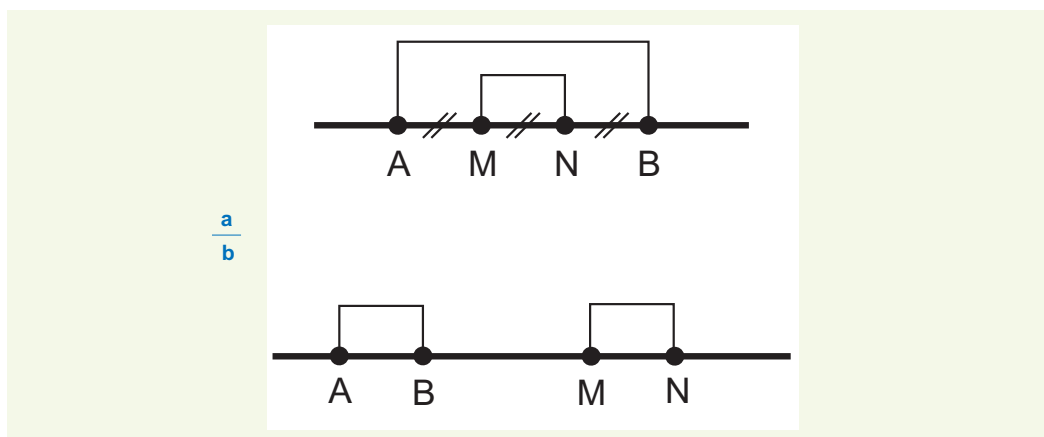
Both the Wenner and dipole-dipole measurement protocols were applied herein (Figure 12). The Wenner protocol consists of measuring the voltage (MN) between the pair of current injection electrodes (AB), with the distance between each electrode remaining constant. The dipole-dipole protocol entails measuring voltage within dipoles (MN) by gradually moving away from the current injection dipole (AB). This technique incorporates a greater measurement depth with respect to the distance between dipoles [8].

For the surface device, the number of measurements equals 360 for the Wenner protocol and 822 for the dipole-dipole.

Figure 11
Internal streamer of electrodes for performing electrical resistivity tomography



Figure 12
Measurement protocols
a: Wenner
b: dipole-dipole



Buried device

To obtain resistivity values at the core of the embankment, it was decided to bury a streamer at mid-height of the embankment. The streamer contains 24 outputs spaced 0.50 m apart. Once installed, the set-up therefore runs a length of 11.50 m. This streamer was placed both transversely to the embankment axis and horizontally, positioned in alignment with the surface device. The number of measurements amounted to 84 for the Wenner protocol and 256 for dipole-dipole.

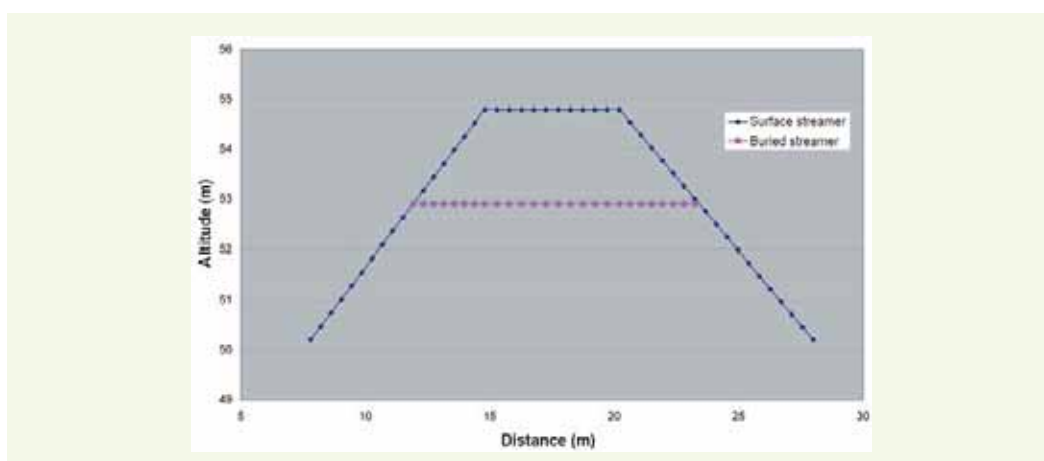
Tomography device

Installation of the two devices (surface and buried) makes it possible to identify a measurement layout identical to that between two boreholes (Figure 13). It was thus decided to conduct measurements between the electrodes buried within the embankment and a portion of the surface electrodes. This set-up is composed of 48 electrodes, 24 in the buried streamer and 24 surface electrodes (i.e. the platform electrodes plus a few of the talus slope electrodes). A specific measurement protocol was devised. The current injection and potential difference measurements were performed between a surface electrode and a buried one.

› Measurement steps

The initial series of measurements was performed using an IRIS equipment of the Syscal type. The remaining series were then carried out with an ABEM device (a Lund multi-electrode system). All elements capable of causing measurement disturbance were taken into account so as to facilitate results interpretation (immersing the embankment base in water, electrodes displaced following immersion, electrodes made inaccessible due to immersion, temperatures, etc.).

Figure 13
Layout of the streamers



■ Equitensiometers

Equitensiometers intended to measure the hydric potential of soil operate according to a principle different from that of standard tensiometers (Figure 14): they do not directly measure a suction, but instead the water content of a porous body inside the probe. This body is characterized by its water retention curve (suction plotted vs. water content). Equilibrium is achieved for suction with the surrounding soil, which serves to modify the corresponding water content. With the retention curve used for calibration, it thereby becomes possible to determine soil suction by measuring water content of the porous body. Suction values are expressed as negative pressures.

As opposed to conventional tensiometers, whose measurement limit lies around 90 kPa, these sensors, adapted to measuring suction in dry soils with average clay content, are capable of measuring suctions ranging between 0 and – 1,000 kPa with an uncertainty of ± 10 kPa over the 0 to – 100 kPa interval and of $\pm 5\%$ from – 100 to – 1,000 kPa. According to their use principle however, these devices are not capable of measuring positive pore pressure.

Figure 14
Equitensiometer (suction sensor)



■ Displacement sensors

The vertical and horizontal displacement sensors have been prepared to measure respectively:

- elementary layer settlement (settlement gauge), via LVDT (Linear Variable Differential Transformer)-type sensors (Figure 15);
- the horizontal deformation of a single layer over several meters, via cable sensors (Figure 16).

the intrinsic uncertainty of the various sensors used equals 0.2%. The host assembly in conjunction with implementation in the embankment body lead to higher overall uncertainty.

■ Instrumentation installation

The installation of TDR probes, hyperfrequency loops, the electrode streamer, equitensiometers and temperature sensors has simply entailed digging just slightly into the compacted layer surface, placing the sensor and covering with material removed during the excavation. For each water content probe, material was extracted to determine weighted water content at the level of the probe, for the purpose of calibrating the origin of hydric monitoring.

Installation of plate settlement gauges requires more finesse since they measure height variations of a given soil thickness. This installation step was thus carried out by carefully position-

Figure 15
Schematic diagram of a
settlement gauge

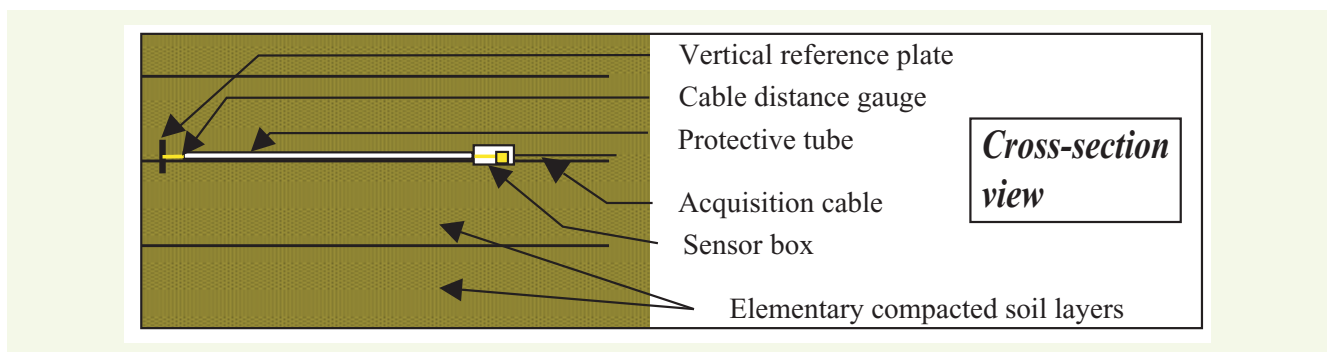
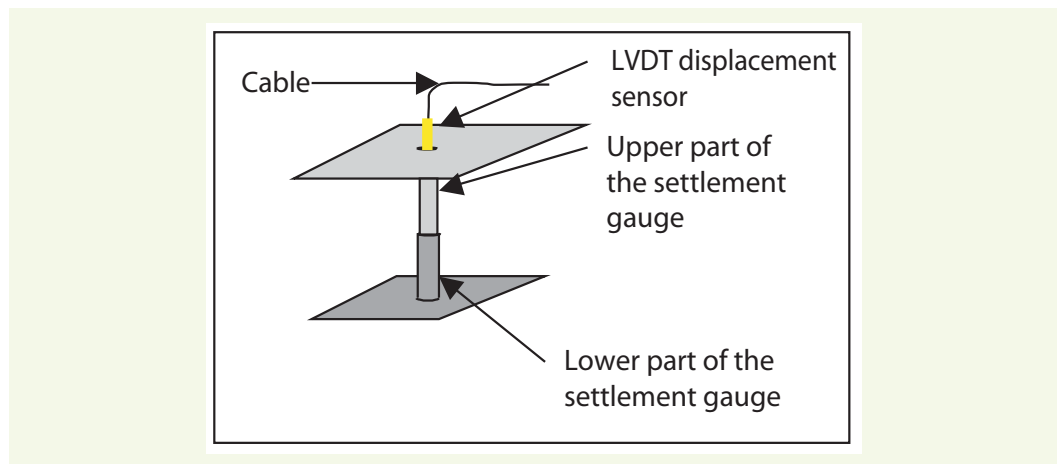


Figure 16
Schematic diagram of the
horizontal deformation
measurement

ing the lower plate at the bottom of a parallelepiped excavation at known depth (Figure 17a). Once the plate had been set, the excavated hole was filled by restoration as closely as possible to the initial state (i.e. mass density value of the specific layer, Figure 17b). A counter tube serves to hold a place for introducing the sliding tube attached to the upper plate. The dimensions of the upper plate make it possible to cover a larger surface area than that of the excavation, so as to ensure that the settlement measurement takes into account a sizable volume of untouched soil. Once the upper plate had been positioned (Figure 17c), the displacement sensor could be installed inside the device (Figure 17d) and then adjusted for definitive fastening. Next, the first sensor reading associated with the inter-plate height was processed.

The horizontal displacement sensors measure, by means of tensioned cables, the distance separating rigid plates fastened vertically into the soil. Two or three sensors were set up in an airtight box (Figure 18a), from which differently-sized cables exited with protection from PVC tubes. Once the entire configuration had been installed on the compacted soil, the device length was measured and associated with the initial reading. A layer of material was then manually placed and a protective steel case positioned on the sensor packing box (Figure 18b). The overlying layer could then be introduced.

INSTRUMENTATION MONITORING PHASES

The initial monitoring phase focused on the period from the completion of construction (end of 2004) until preparation of the first flooding (beginning of 2006) in order to observe embankment behavior under actual meteorological conditions. The two subsequent monitoring phases corresponded to flooding at the embankment base beginning of 2006 and end of 2006.

Flooding at the beginning of 2006 took place in three stages:

- saturation of the porous base: the objective of this stage was strictly to observe the consequences of a rise in water table on capillary rising in the embankment base;

Figure 17

Placement of a plate settlement gauge

- a: excavation for lower plate installation
- b: filling of the excavation hole
- c: installation of the upper plate
- d: following installation of the LVDT sensor

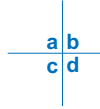


Figure 18

Horizontal displacement cable sensor

- a: packing box
- b: view after installation



a | b

- basin filling on both sides of the embankment with a hydraulic load on the order of 1 m; since this phase had been intended to produce complete saturation of the collapsible embankment base for observing the consequences of saturation in terms of settlement;
- basin drainage and observation of water content variations in the embankment base.

The second flooding (end of 2006) took place on just one side of the embankment. To produce this effect, the dikes were sealed with the same geomembranes used to create the basins at the time of the first flooding; they were then disassembled to place a one-sided water retention system so as to

ensure maintaining a flooding level of greater than 1.5 m for 4 weeks. The objective of this second loading was to observe the consequences of asymmetric flooding on the embankment along with its hydric state.

MAIN MEASUREMENT RESULTS

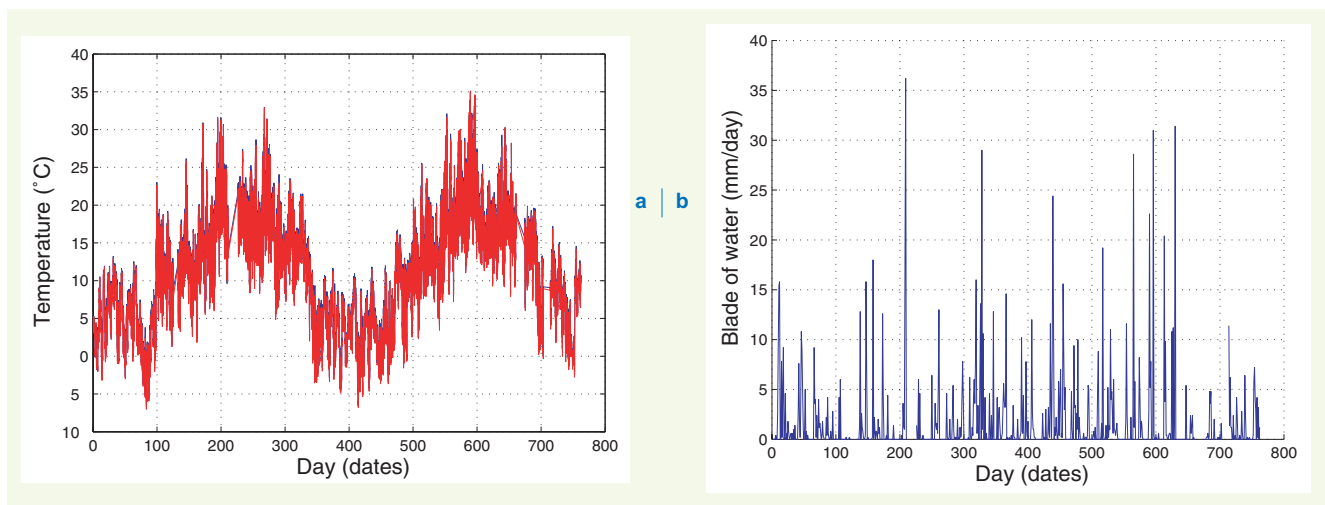
The origin of observation phases (Day 0) corresponds with the completion of embankment construction.

Figure 19

Meteorological field recordings over the period: beginning of December 2004 to end of December 2006
a: air temperature
b: precipitation readings

■ Meteorological conditions

The evolution in both temperature and precipitation recorded by the weather station positioned on the embankment platform is shown in **Figures 19a** and **b**.



■ Temperature probes

The temperature probes were installed on three vertical profiles (southern axis, central axis and western talus slope). They were programmed to provide information:

- on heat transfers taking place within the soil, for input into the soil-atmosphere exchange model;
- on temperature in the soil, so as to correct electrical resistivity measurements.

Figure 20 illustrates the temperature monitoring conducted over two years in the central axis. The temperature values indicate a much stronger variability nearer the surface (4 to 25°C) than at the embankment base (10 to 15°C). These measurements enable proceeding with a slight correction of the electrical resistivity measurements.

■ TDR (volumetric water content) probes

TDR probes are basically sensors capable of measuring the volumetric water content of host soils. Given that volumetric water content is the product of water content weighted by the dry mass density, this parameter is therefore sensitive to mass density variations. In the present experiment, the observed variation intervals for dry mass density are narrow. Measurement results provided by TDR probes primarily reflect variations in weighted water content.

In the lower part of the embankment, i.e. the collapsible base, the majority of probes do not reveal significant variations in volumetric water content during the first 300 days, except for

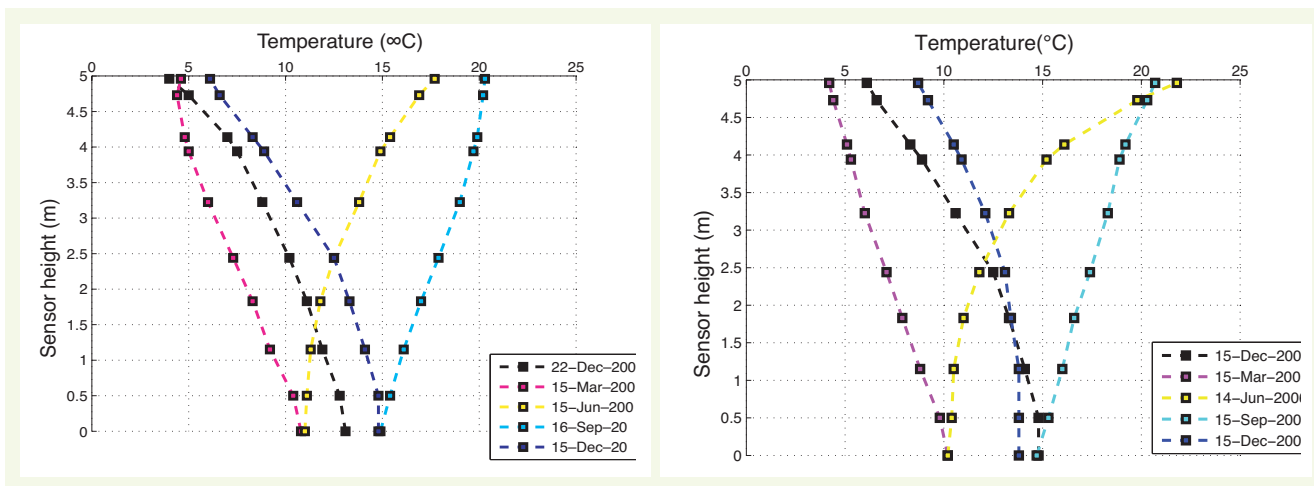


Figure 20
Evolution in temperature profile along the central axis
a: year 2005
b: year 2006

the one positioned in the least compacted layer (Probe 2W9 on **Figure 21**), which does undergo settlement. The settlement gauges placed in this zone make it possible to assign two water content points to the evolution, with the remainder due to water infiltration via the talus slope.

Water movements caused by flooding at 430 and 720 days are clearly recorded by the TDR probes. The shape of curves indicates water saturation of the soil over the lower part of the embankment, at a height of between 0 and 30 cm (Probes 0W1 and 1W4). Saturation is confirmed by a lack of reaction from these probes during the second flooding.

■ Loop antennas

Figure 22 shows an example of volumetric water content computations using the formulas presented above, in comparison with measurements conducted with TDR probes. Results obtained, especially those stemming from the *Labo* method, are close to those found from TDR, which serves as the reference method for this experimental campaign. The deviations recorded between methods may be explained by the fact that probes are not measuring the same soil sample despite being placed in very close proximity. The relative soil heterogeneities in both water content and mass density are actually accounted for in the results.

Figure 21
Evolution vs. time of volumetric water content measured by TDR probes in the collapsible embankment base

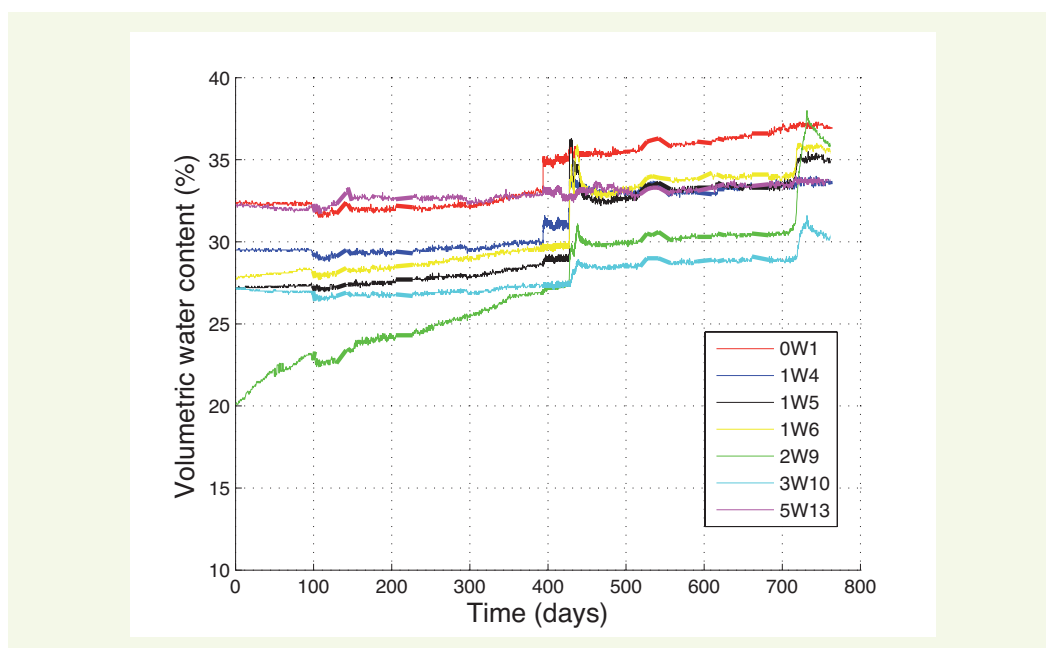
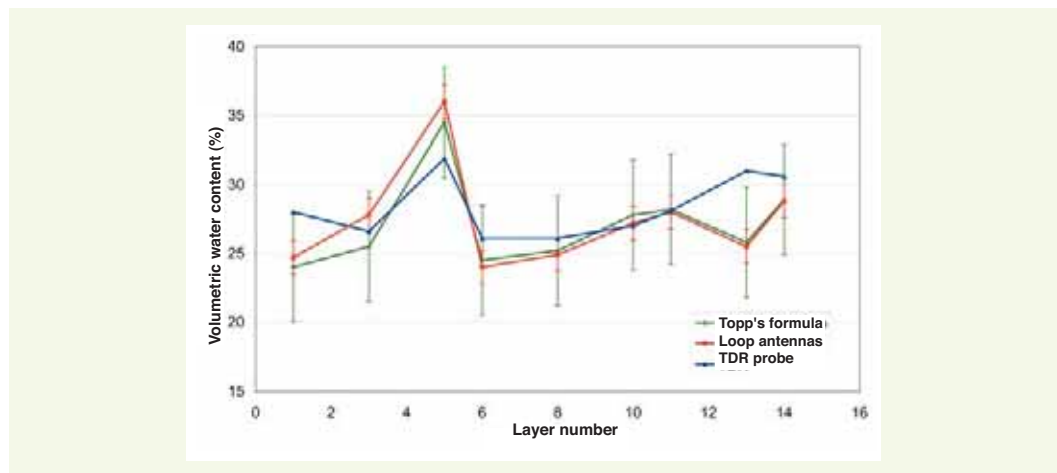


Figure 22
*Sample comparison
 between measured and
 computed water content
 values*



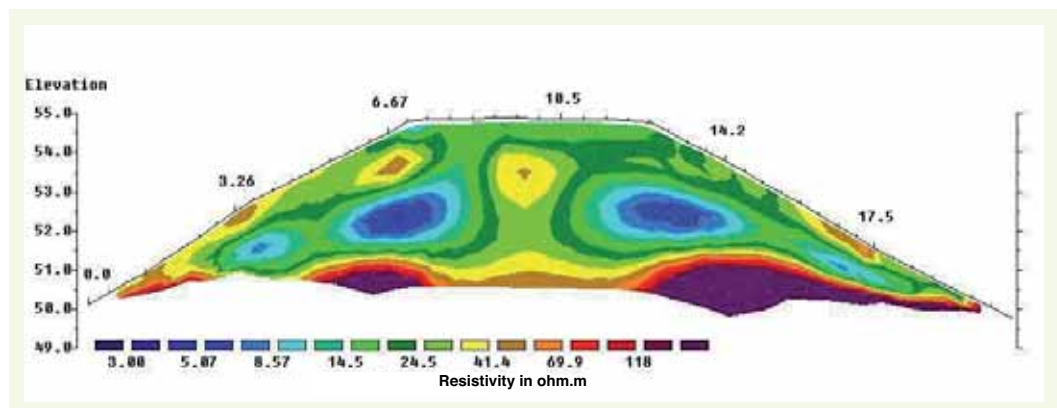
■ Streamer of electrodes (electrical panel)

The objective of this instrumentation set-up is to assess the capacity of the electrical panel type of resistivity measurements in evaluating hydric state variations of materials within an earthen engineering structure. At present, the electrical panels generated from the surface have given rise to an inversion using the Res2DInv software, in including topography (Figure 23). These panels reveal resistivity variations from one measurement series to the next.

The interpretation sought however proves to be much more complex. Resistivity actually varies as a function of temperature, hence corrections are required by taking into consideration temperature values inside the embankment at the time each measurement series is processed. This step still needs to be performed.

Similarly, measurements conducted using the buried streamer or those carried out in tomography cannot be utilized by current software products on the market. A finite element computation module within the CESAR-LCPC code should in the near future allow inverting these measurements and evaluating the performance of this method for monitoring hydric variations within a soil.

Figure 23
*Sample result
 Variation in resistivity
 inside the embankment*

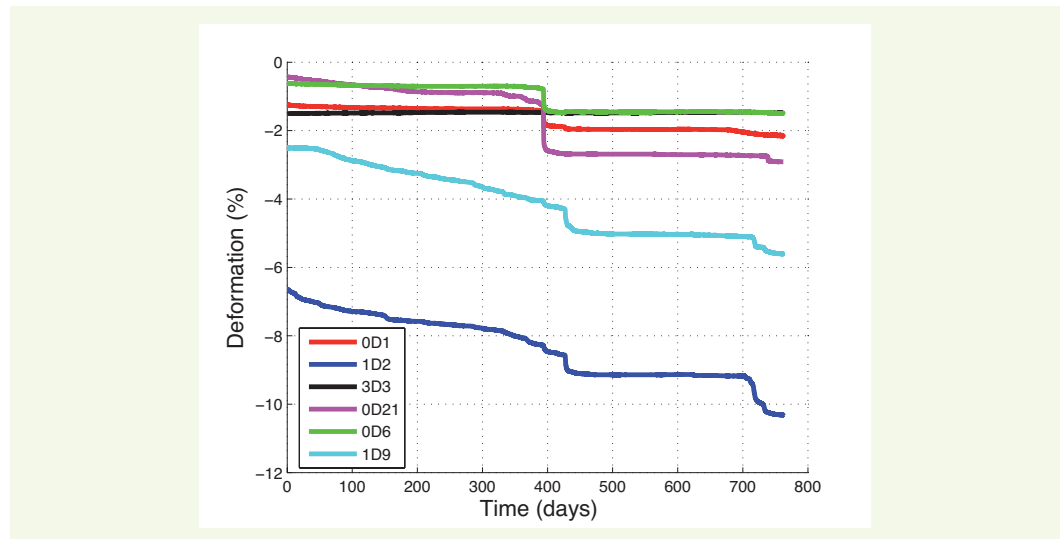


■ Vertical displacement sensors

Figure 24 displays vertical displacements inside the embankment base that have been converted into deformations. It can be observed that deformations inside the embankment base are solely settlements and that the magnitude of these deformations reaches high values (up to 8%) over the least compacted zone (Sensors 1D2 and 1D9), and this even before flooding. In analyzing TDR probe results, it could be demonstrated that these pre-flooding settlements stem in particular from an increase in water content of the collapsible base.

The two flooding phases are reflected by additional settlements, which for the least compacted zone (Sensors 1D2 and 1D9) lead to a total settlement capable of exceeding 10%; within these settlements, only two deformation points are due to flooding. This finding suggests that the collapsible base had acquired 80% of total settlement prior to flooding. It can moreover be noted that the second flooding (at 720 days) generated a new settlement greater than that caused by the first (430 days), as measured by Sensor 1D2, with the indication of quasi-stability between the two flooding events.

Figure 24
Evolution in vertical displacement within the collapsible embankment base vs. time



CONCLUSION

Instrumentation of the experimental embankment took place under favorable conditions and led to a valuable set of results. The sensors could be installed in strict respect of pre-established procedures and in situ controls. These advantageous conditions resulted in detecting only very few sensor malfunctions. The bulk of losses was observed at the end of embankment construction, upon resumption of power shoveling on the talus slope: the 3H/2V slope found represents the result of applying the excess method. A total of 7 sensors were lost out of the 109 initially installed (not including the electrode streamer).

Problems were encountered for measurements stemming from the equitensimeters and a portion of the settlement gauges. Due to a change in soil (A28 motorway loam) occurring after their control step, the equitensimeters were operating within a suction interval on the order of 5% of their typical range, and measurements thus remained within the uncertainty range of these sensors. For some settlement gauges, measured displacements were considerably lower than those obtained by means of computation; the cause may be attributed to sensor installation, which likely led to excess densification of the soil lying between the two plates.

The volumetric water content measurement method using loop antennas yielded results comparable to the TDR method. In analyzing underground antenna response vs. injected frequencies, the use of loop antennas is also intended, over the long run, to comprehend other soil parameters, such as the bound water-to-free water ratio, mass density and medium conductivity.

Subsequent to this experimental campaign, only a qualitative assessment of the electrical panel method was actually undertaken. The new processing resources under development will enable evaluating water movements, especially over the non-instrumented parts of the embankment.

Despite being just partially applied, these experimental results are already sufficient to validate the deformation prediction method for engineering structures in fine-grained soils. Moreover, they allow concluding that a slightly plastic, fine-grained soil compacted in accordance with rules applicable to common embankment bodies may undergo, within a relatively short embankment, flooding without displaying major settlement detrimental to its platform geometry.

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