Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement

# State of Art

# French research and knowledge on expansive soils

by David MATHON*

* Cerema Normandie-Centre, 11 rue Laplace cs 32912, 41029 BLOIS cedex, France david.mathon@cerema.fr)

*Thanks to Professor Dessouky for inviting me in San Antonio at the University of Texas.*

## Index

# Presentation

The acronym Cerema means Center of Expertise and Studies on Risks, Environment, Mobility and Urban Development. Cerema is a French public agency created in 2014 to help the French government developing and evaluating public policies in France.

3 000 persons are working in Cerema all over France. Its annual budget is about 240 million euros (that is to say 280 million dollars). 85% of the budget is assumed by the State, the remaining 15% correspond to the contracts we can have with private companies, local authorities and research contracts.

The Cerema works in many varied fields (that's what makes its strength) energy climate, mobility, transport, transport infrastructure, prevention of natural and man-made risks.…

For my part, as a geologist, I participate in these last two fields. I am particularly specialized on the geological risks: collapse of the underground cavities, instability of the cliffs and shrinkage-swelling of the clay soils.

I live in Blois in France in a laboratory that works on road infrastructures (earthworks, pavements, bridges), the environment and the risks (floods, stability of dams and structures in the river, acoustics, quality of the air).

France is a country of about 650,000 km² (slightly less than Texas – 695,000 km²) located on the western part of Europe. Its climate is temperate with oceanic influences (for its wide western part), Mediterranean (for its southern part), continental (for its eastern part) and mountain.

On a geological point of view, there are mountains consisting generally of magmatic or metamorphic rocks (shale, granit, etc.) and areas of plains generally consisting of sedimentary rocks or soils (clays, limestone, sandstone, chalk...)

The country is crossed by many rivers including 5 major rivers that have shaped the landscape by erosion (The Seine, the Loire, the Garonne, the Rhone and the Rhine). Blois is located on the river Loire at about 200 km far from Paris.

# Shrink-swell phenomenon

As I told you earlier, I am specialized in the field of geological hazards and more particularly on the shrinkage-swelling of clayey soils. On the other hand, I am not, but not at all, specialist of mineralogy and I ask you to be indulgent with the explanations that I will bring you immediately!

Indeed, clayey soils are soils composed of fine grains (with elements of particle size less than 2 microns). These elements are composed of clay particles whose minerals are organized into ionic layers.

The nature of the ions that make up these layers depends of the type of the clayey soil. Depending on the mineralogical nature of the clayey soils, the nature of the layers is different and we identify large mineralogical families: kaolinites, illites, smectites. The inter-layer space has the characteristic of binding water molecules (dipolar molecule). The attraction of these water molecules has the effect, at the microsocopic scale, of increasing the inter-layer space and at the macroscopic scale to cause variations in the volume of the soil sample.

On a macroscopic scale, therefore, clayey soils have the characteristic of changing their volume according to their moisture. This characteristic has been known and described in the scientific literature for many years. Magnan and Burlon described this behavior at the opening of the SEC 2015 symposium on the illustration 1.

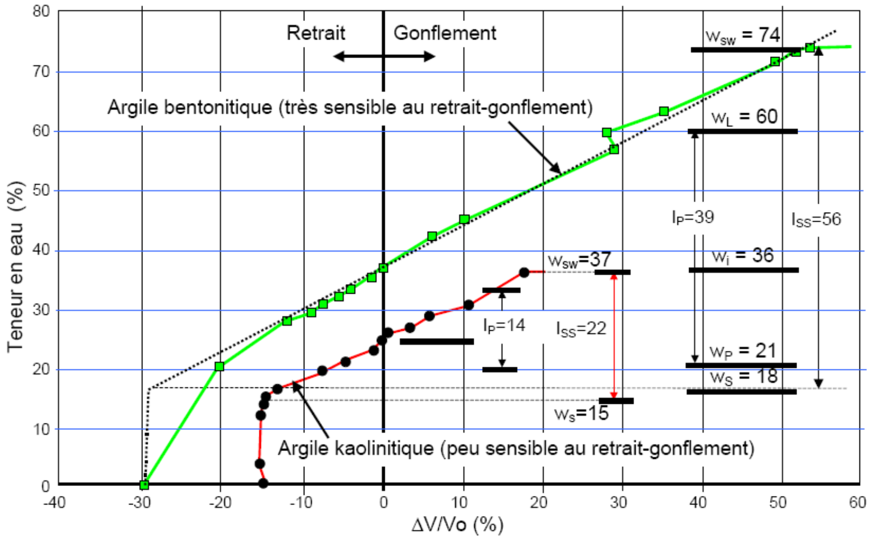



*Illustration 1: relation between volumetric variations and moisture (for two French soils) – Magnan and Burlon*

# ARGIC Project

Soil shrinkage and swelling would not be a real problem if it did not strike buildings. In France, this phenomenon is particularly important and costly since it is the second compensation item of the natural catastrophe insurance system (about 360 million euros per year). French individual dwellings are particularly impacted by this problem.

You have to know that, in France, natural disasters are supported by a mixed public-private system that has been the subject of a law since 1982. The French law defines that every French person holding an insurance contract is covered from natural disasters if they result from the "abnormal and unpredictable intensity of a natural agent".

Thus since 1982, it is possible to say that the swelling and shrinkage of clayey soil cost about 10 billion euros. It is also possible to say that the phenomenon endangers the functioning of the compensation system (example of 2003 where the drought caused nearly 2 billion euros of compensation).

These facts led the French government and the French major insurance companies to fund important research programs on drought and shrinkage of clayey soils with the following objectives:

- to understand and quantify the penetration of desiccation in soils
- to characterize the sensitivity of soils to shrinkage-swelling
- to map the phenomenon in France
- to study the impact of shrinkage-swelling movements on French buildings (including roads)

Thus, the ARGIC project (analysis of the shrinkage and swelling of clays and their impact on buildings) was born and brought together 17 French partners (testing laboratories, public and private establishments, which worked from 2006 to 2014 under piloting IFSTTAR and Cerema. The results of this operation were published and fed a good part of the SEC 2015 international symposium which took place in Marne-la-Vallée (near Paris) in June 2015.

I was part of the scientific committee of the SEC Symposium and I invited professor Dessouky from UTSA to the event. He gave us an invited lecture of his work on farm to market road in Texas which are really damaged by geotechnical drought.

I will now detail the main findings of this ARGIC operation and, in a second time, I will talk about experiments in progress in Cerema.

# Experimental sites

First objective of ARGIC was to study the propagation modes of desiccation in clayey soils. The purpose was to characterize it in terms of kinetics, depth and intensity.

13 experimental sites were equipped on the whole metropolitan territory illustration 2, I will here detail two test sites located in the south-west of France near Bordeaux.

*Illustration 2: Location of the ARGIC experimental sites*

## Pessac Site

The experimental site of Pessac followed by the University of Bordeaux (works of Fabre et al.) Allows the continuous monitoring of the mechanical behavior (deformation), water (variation of water content) and thermal (temperature) of the clay to a depth of 5 m between 2008 and 2014. An on-site weather station records cumulative rainfall, air humidity, atmospheric pressure, air and soil temperature and moisture.

The deformations of the clayey soil are measured by two types of extensometer (Telemac and Glötz system) with respectively a manual and automated weekly reading every 3 hours. The results incorporate six years of continuous measurement of deformations and changes in soil moisture (2008-2014), with five cycles of shrinkage and swelling.

From a meteorological point of view, the annual raifall observed during monitoring period was close to the average (about 875 mm / year) but year 2011 is comparable to 2003 and 2005 which were quite dry years in the region (687 mm per year).

Measurements of water content are made using TDR (Time Domain Reflectometry) probes which measure the dielectric constant of the soil in relation to its volumetric water content. The highest annual variations are about 19 to 24% in volumetric water content (12 to 16% moisture). The illustration 3 shows that the moisture variations are observed up to at least 3 meters deep, which means that the shrinkage of the soil can be mobilized up to this depth.

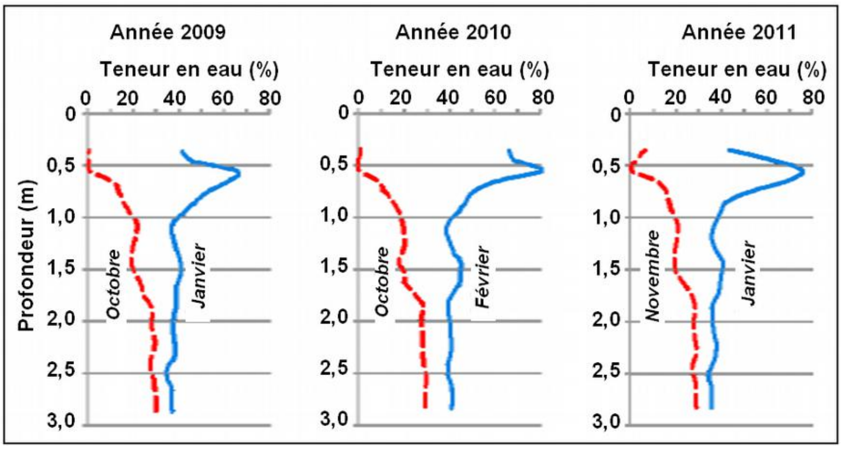


*Illustration 3: volumetric water content profiles over 3 years*

Considering deformation, measurements made with different type of extensometer show similar results (illustrations 4 and 5).

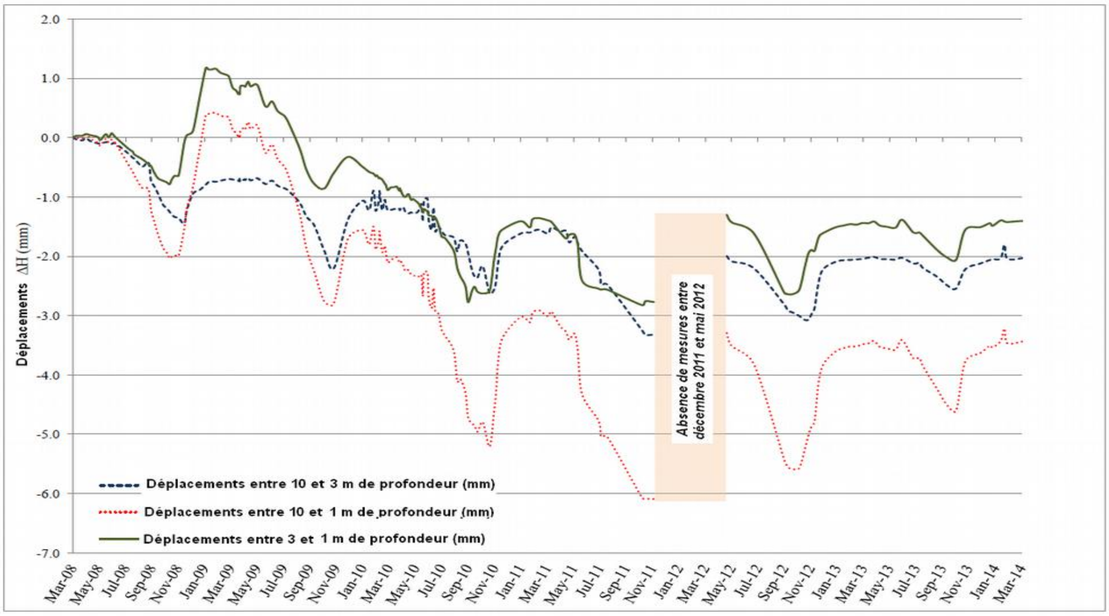


*Illustration 4: deformation between 2008 and 2014 (Telemac extensometer) – Fabre and al.*

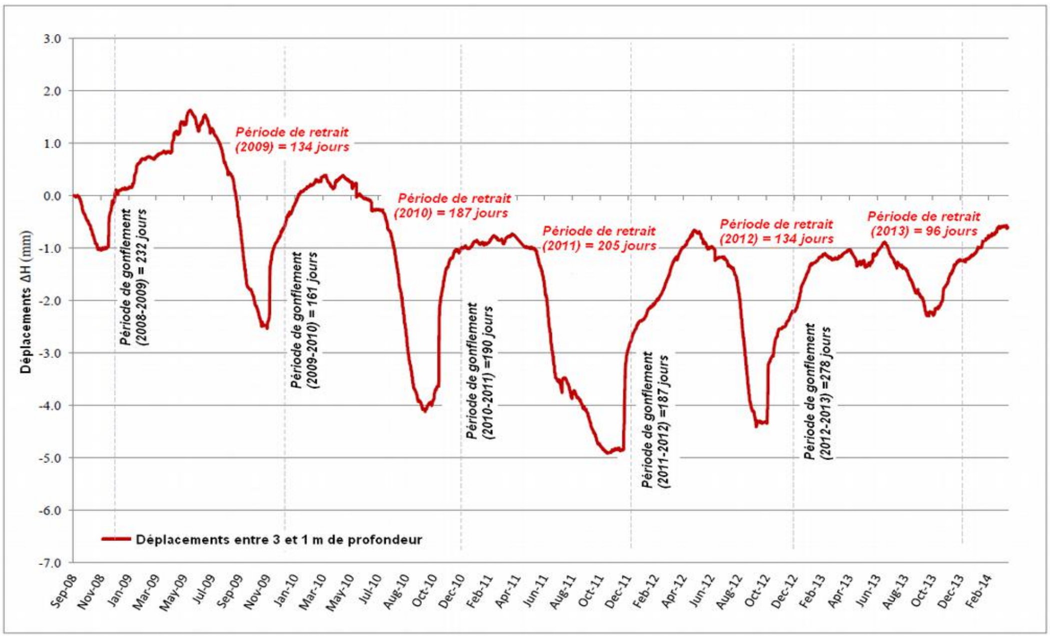


*Illustration 5: deformation between 1 and 3 meter deep (Glötz extensometer) – Fabre and al.*

It showed significative outcommings:

- 50% of the deformations are between 1 and 3 meters deep;
- there is a multi-year cumulative phenomenon that is particularly observed between 2008 and 2011 (shrinkage phase).
- The amplitudes measured are of the order of 5 to 6 mm maximum.

The observations of the deformations are then related to a water index defined by the following equation:

$$CH_{(t)} = PB_{(t)} - ETP_{(t)}$$

with PB Cumulate Rainwater ant ETP Potential EvapoTranspiration

More precisely, Fabre and al. considered the accumulation of CH that is to say

$CHc = \Sigma_{(t0) \to (t)} CH_{(t)}$ .

On illustration 6, there is a remarkable correlation between the representation of CHc and the recorded deformations of the soil between 1 and 3 meters (Glotz extensometer).

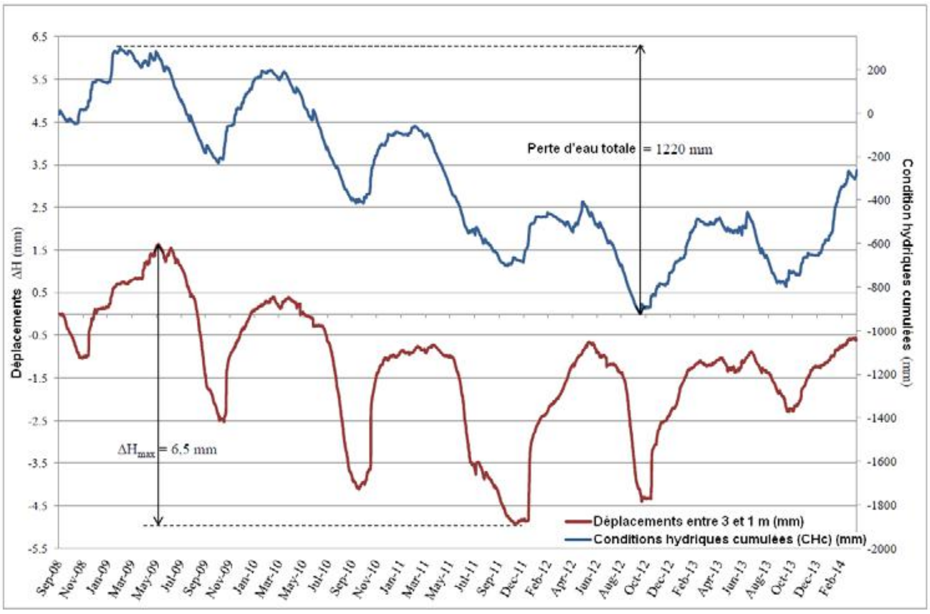



*Illustration 6: Chc Curve and displacements measured between 1 and 3 m deep – Fabre and al.*

Fabre conclude from this finding that the characterization of drought intensity could be achieved indirectly through the simple measurement of meteorological parameters (PB and ETP). For this generalization to be possible, the experiment could be replicated in different geological and meteorological contexts.

### Langon Site

The second experimental site is located in Langon (still in the Bordeaux region). This is a site studied by the University of Bordeaux in association with Cerema, BRGM and a geotechnical design office.

The considered house (illustration 7) was built in 2004 and 2005, it is located in Roaillan in the French department of Gironde at a locality called “le laurier” (Neveu, 2012). It is a ground-floor, L-shaped individual building; its area is about 160 m². Its foundation is a footing anchored between 50 and 80 cm depth under the natural soil. The basement walls are made of concrete blocks and the walls of bricks. The floor is a concrete slab on ground based on the footings.

*Illustration 7: Equipped house*

*Site survey*

The building is located at the center of a rectangular plot of land. The plot area is about 1600 m². The space between the building and the property limits is about 5 m at East and West, 12 m at South and 24 at North. The topography of the plot is rather flat. There is a slight slope towards South of about 3-4%. The plot is tree-filled with old oaks and acacia. We can count eleven oaks, eight of which higher than 15 m, and three acacia higher than 20 m on the North side of the plot. There are two oaks higher than 10 m on the South side. Some of these trees are located less than ten meters away from the house. We note that some trees were cut in 2010 (South-East of the plot).

The site is located on an alluvial formation, coming from the Garonne river. It is composed of sand and quartz gravels wrapped in a clayey, yellow, sometimes red matrix. There is a limestone substratum at a low depth. The BRGM (French Geological Survey) classifies the shrinkage and swelling of clayey soils hazard on this site as weak.
In 2011, the CEREMA carried out four drillings (Mathon, 2013). They confirm the presence of a layer of brown silts more or less clayey on the first 50 to 70 centimeters. Beige or multi-coloured clayey layers are found at 1 meter depth. The limestone substratum is located at 7 m depth. Gravelly deposits are present on each drilling at different depth.

Laboratory analysis show that all soils belong to class A “fine soils” of the NFP 11-300 norm (French soil classification for earthworks). Moreover, the percent passing of elements with a diameter inferior or equal to 2 µm is between 50 and 80 % for clayey layers located between 1 and 7 meters depth.
Atterberg limits were carried out on thirteen samples: 11 show a plasticity index superior to 25. Methylene blue values confirm this trend: they vary between 3.5 and 9.8 g of blue for 100 g of dry soil.
Soils sensitivity to shrinkage and swelling was evaluated by considering plasticity index and methylene blue values and clay activity of the soils. Clay activity is defined by the ratio between plasticity index (or methylene blue value) and percent passing at 2 µm value.

A typical log was established on a depth of about five meters. It contains four layers: clayey brown silts (H1), multi-coloured clay (H2), stiff red clay (H3) and stiff beige clay (H4).

| Lithology | Drilling | Depth | Test values | Activity |
|---|---|---|---|---|
| Clayey silts<br>(H1) | SC1 | 0 à 0,5 m | %80 µm = 66%<br>$C_2$ = 29%<br>$W_L$ = 35 ; $W_p$ = 17 ; $I_p$ = 18 | $A_c^{H1} = I_p / C_2 = 62$ |
| Multi-coloured clay<br>(H2) | SC4 | 1,2 à 3,3 m | %80 µm = 99%<br>C2 = 76 %<br>$W_L$ = 70 ; $W_p$ = 27 ; $I_p$ = 43 ; VBS = 9,6<br>IFSTTAR test:<br>39.4 % < Ass < 46.7 % | $A_c^{H2} = I_p / C_2 = 43$<br>$A_{cB}^{H2}$ = VBS / $C_2$ = 9,7 |
| Stiff red clay<br>(H3) | SC4 | 3,8 à 4,4 m | %80 µm = 100%<br>C2 = 79 %<br>$W_L$ = 60 ; $W_p$ = 26 ; $I_p$ = 34 ; VBS = 9,8 | $A_c^{H3} = I_p / C_2 = 34$<br>$A_{cB}^{H3}$ = VBS / $C_2$ = 9,8 |
| Stiff beige clay<br>(H4) | SC4 | 4,4 à 5,2 m (end of drilling ) | %80 µm = 99%<br>C2 = 62 %<br>WL = 47 ; Wp = 18 ; Ip = 29 ; VBS = 5,5<br>IFSTTAR test:<br>Ass = 28.8 % | $A_c^{H4} = I_p / C_2 = 29$<br>$A_{cB}^{H4}$ = VBS / $C_2$ = 5,6 |

Table 1: Geological model of the site

According to the handbook “Shrinkage and swelling of clays: characterizing a site for construction” of the ARGIC2 project, the soils in the H1 and H2 layers, between 0 and 3.3 meter depths, are “**sensitive to shrinkage and swelling**”.
H3 soils are “low-sensitive to sensitive”, H4 soils are “low or not sensitive”.
This sensitivity difference is underlined by the values of simplified shrinkage and swelling test (IFSTTAR operational mode). The “Ass” value corresponds to the maximum volumetric variation expected for the considered sample. This special operational mode will be explain later...

*Soil Tension and moisture*

Moisture and soil tension are two distinct parameters characterizing a soil hydric state.

Moisture gives a quantitative information on the total water volume in the soil. It is given as a percentage. It is the ratio between the weight of the water in the soil and the weight after heat drying.

Tension is a term used in agronomy (Ton, Chol & Isbérie, 2000). It gives informations about the direction of hydric flows in the soil and on the available water for cultivating. Tension measurement allows to quantify, on a soil given point, the attraction force applied by solid particles on water. It is given in kilopascal and is called, in the soil mechanics field, “soil suction”. Those two parameters are correlated, but it is quite delicate to establish a direct relation between the two. This study shows an attempt to correlate them based on an experimental approach of drying.

With help from the Challenge Agriculture firm, the Cerema proceeded in two steps to installing a soil tension measurement device on the north-west side of the plot in July 2011 and in November 2013. The probes were installed on a 5 meters line between the north-west angle of the house and an oak about ten meters away. They were placed on each side of the presumed location of a root barrier (solution planned by an expert). Depths vary from 80 cm to 5 m. The probes set up is shown on illustration 8.

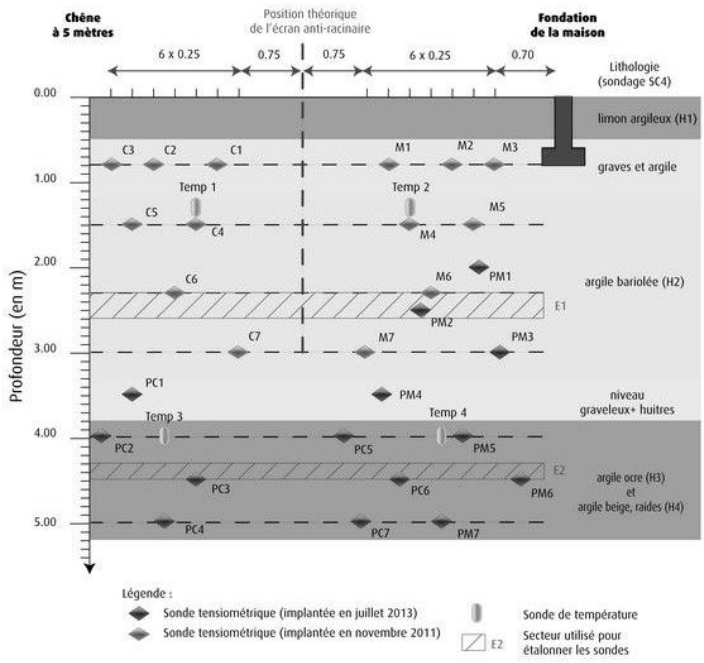



*Illustration 8: Set up diagram of tensiometric probes*

The Cerema conducted calibrating in laboratory in order to find a connection between weight moisture content of soil and tension measured by the probes. This experimentation was conducted on soil samples “multicolor clay H2” and “beige, stiff clay H4” at 2.3 m and 4.3 depths (illustration 9).

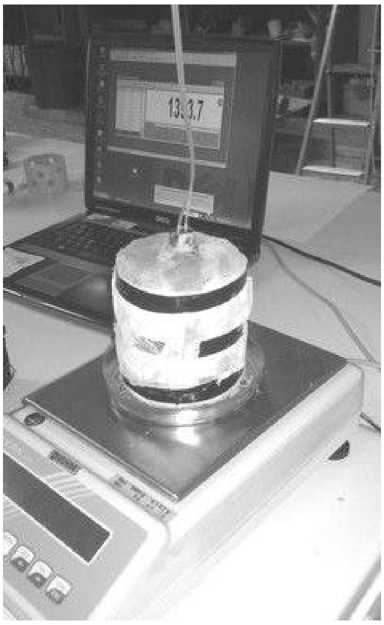


*Illustration 9: Calibrating a soil sample in laboratory*

The calibration consist to monitor the air drying of a previously saturated soil sample. The monitoring consists in measuring tension and its weight every 15 minutes. The graph of weight moisture content as a function of soil tension shows a shape conform to retention curves found in the bibliography (illustration 10). Note the significance of lithology and soil plasticity regarding measured tension values. Exploiting those curves allowed to establish a theoretical relation between a measured tension value and an estimated moisture.

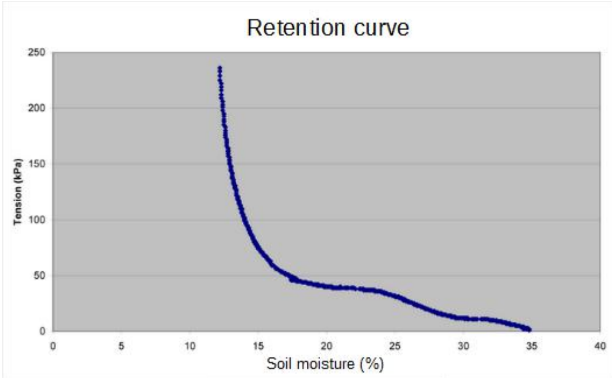



*Illustration 10: Soil retention curve*

*Oak proximity and drying periods*

Tensions measured near the oak are, during the whole year, higher and more irregular than those near the house. Two “dry” periods can be identified, from June 2012 to October 2012 and from July 2013 to October 2013. Each drying period shows a delay of a month between recordings near the oak and recordings near the house.

*Two-dimensional representation*

The cerema produced a chronological atlas of “iso-suction” cross-section for a period going from December 15, 2011 to March 15, 2014. An iso-suction cross-section is a graphic representation of tensions in the plane with isotension curves. We used the spline tool of the ArcGIS software to make these cross-sections. It is an interpolation tool that gives a tension value on every point thanks to a mathematical function, and creates a picture passing exactly through the input points (i.e. tensions recorded by each probe). Note that this method doesn’t take atmospheric variations and soil heterogeneity into account. However, in order to respect the site lithological organisation and the model given in 2.1.4, occasional corrections were made and bound values were added to the model.

Results for summer 2012 :
The iso-suction cross-section beneath (illustration 11) show tensions for the drying period recorded in summer 2012 (exactly August 2012).

Two dry areas have to be seen on illustration 11. The first one is located on the upper part of the soil section, between 0,80 m and 1,50 m depth. The other one is located on the lower part, between 1,75 m and 3 m depth. Those two areas are separated by a more moist soil layer.

Continuous tension measurements also allowed to characterize soil drying dynamics in late summer, when rainfall is low. Two recurring phenomena were identified: a strong increase of tension near the oak on the upper dry area and a progression of the two dry areas towards the house. In late summer 2012, the upper area spread till the M3 probe located 0,70 m away from the house. The lower dry area spread well beyond the M7 probe, located 2,20 meters away from the house. The interpolation even shows a drying at 0,70 m from the house. Observations showed that a dry area located deeper than 2 m develops from the tree to the house.

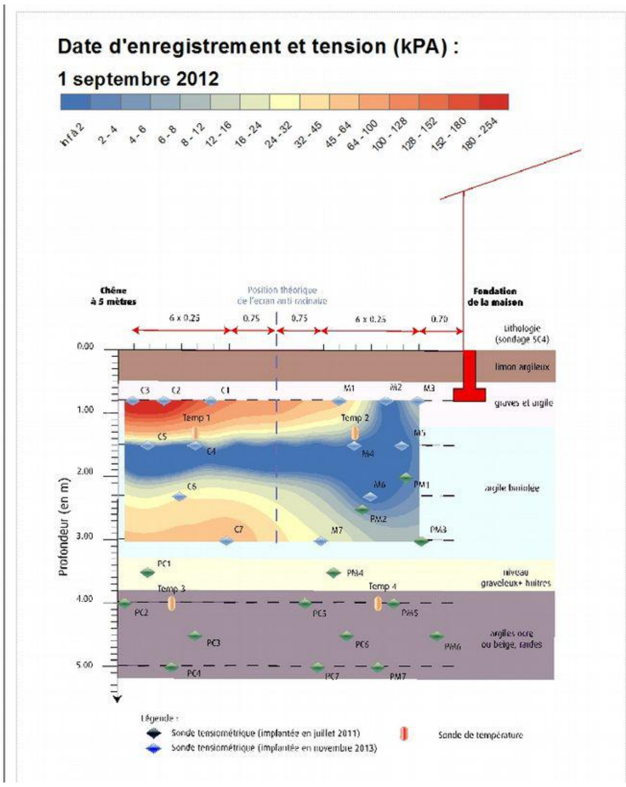



*Illustration 11: iso-succion cross section - August 2012*

*Theoritical assessment of shrinking settlements*

A theoretical assessment of shrinking settlements was carried out for the whole observation period. It is based on the following steps and hypothesis:

- Extracting a profile from interpolations, located at 1 meter from the house foundations;
- Getting a weighted soil moisture value thanks to the calibrating;
- Using the water content variations to get porosity index variations, thanks to the simplified shrinkage and swelling tests results;
- Calculating settlement ($\Delta H = [\,\Delta e / (1+e0)]xH$) on the whole profile height (considering that the soil stays saturated despite the drying).

The following graph (illustration 12) shows the theoretical settlement variations for the period going from mid-September 2011 to mid-March 2014. Three theoretical settlement periods are identified: end of summer 2011, summer 2012 and summer 2013.

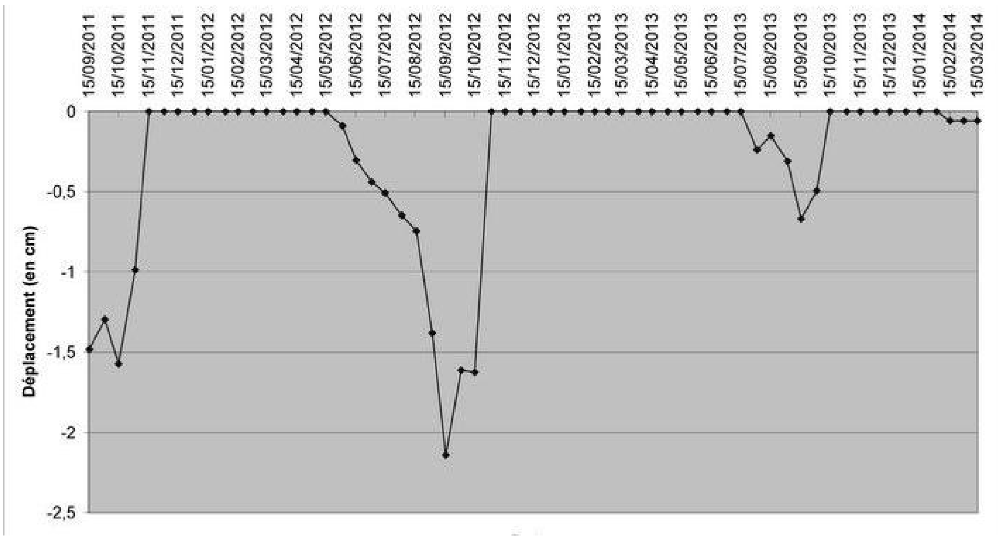



*Illustration 12: Calculated theoretical settlements*

In 2012, settlements began in June and ended in November. The maximum theoretical settlement was calculated around September 15. Its value is -2,14 cm.

In 2013, settlements began in August and ended in October. The maximum settlement is -0,66 cm at September 15.

*Calculation limits and results consolidation*

A -2,14 cm settlement may seem high (in absolute value) given the weak disorders observed on the construction for this period (small cracking). However, it is a global settlement value on an exposed area and not a differential one. Thus, this value seems “realistic” to us.

Those theoretical settlement calculations give a better perception of the impact of the probe calibrating and simplified shrinkage and swelling tests. More generally, besides uncertainties on tests, local variations of lithology (silty or sandy layers) have a crucial importance on settlement assessment.

Another important parameter as well: the quality of tension measurements and interpolation. A tension measurement error of 1 kPa may modify the settlement value of 0,46 cm for 1 meter of soil. In order to strengthen the results, it would be interesting to carry on the experimental monitoring and to confront the future results with direct measurements made by the extensometer set up in 2013 by Bordeaux’s university.

Likewise, the precise measurement of the drilling lithological cut needed to set up the extensometer can increase the quality of the “model”.

## Global finding about experimental sites

After purchasing 12 experimental sites, it returns that drought penetration depends on climate (obviously), human surface occupation, soil lithology and vegetation. This last parameter has been highlighted as an important issue by the ARGIC projects and should be one of the main motivation for very interesting future research works, especially for a better understanding of the root role and the induced suction in the soil.

# Characterize the sensitivity of soils to shrinkage-swelling

In order to characterize sensitive (or expansive) soils and to analyse their mechanical behaviour, different kind of measurement were performed by ARGIC partners.

## Shrinkage and swelling direct measurement

An original laboratory test procedure is proposed in order to set a new shrink-swell test method that can be used for the foundation design and the characterization of expansive soils.

This test is issued from an Australian method (Method of testing soils for engineering purposes. Method 7.1.1: soil reactivity tests – Determination of the shrinkage index of a soil – Shrink-swell index.). The assessment of the ground movements due to the moisture variations requires to perform simultaneously a shrinkage test and a swelling test (illustration 13).

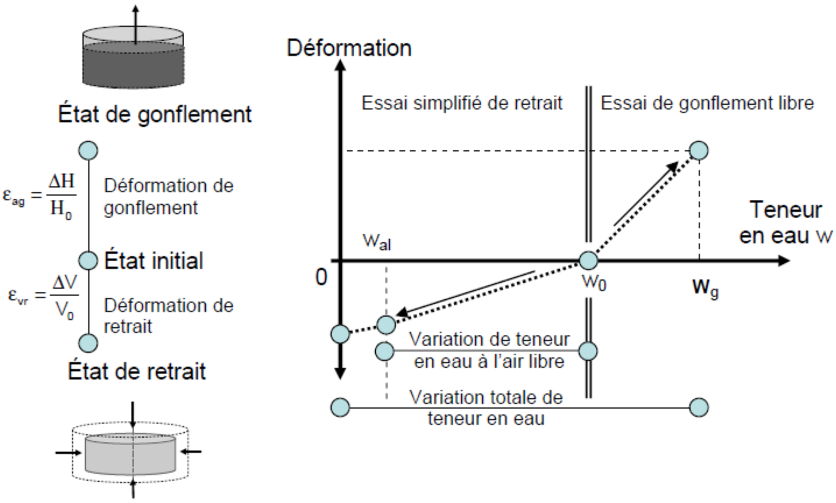



*Illustration 13: Shrink and swell test on two separate samples*

The shrinkage test consists in allowing a sample to air-dry for 4 days by regularly measuring its dimensions and weight (illustration 14). The sample is then dried to define the moisture and void index of the soil.

The swelling test is a free swelling test in an oedometric frame (illustration 15). The test is stopped when the swelling is stabilized. The height of the sample is then measured as well as its weight (to find its moisture).

*Illustration 14: shrinkage test*

*Illustration 15: free swelling test*

The collected information defines a total index of shrinkage-swelling which characterizes the soil. This index is called Ass (for Amplitude Swelling and Shrinkage).

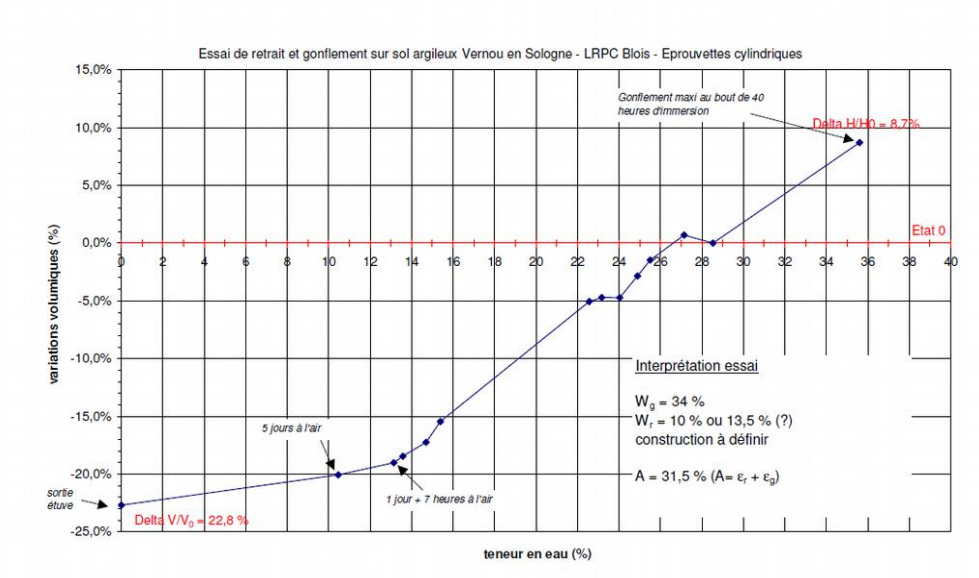



*Illustration 16: Volume variations of a sample as a function of the moisture*

Two intrinsic notions are defined for each clayey soil: the shrinkage limit is the water content of a clay soil below which the volume of the sample no longer decreases. The swelling limit is the water content above which the sample stops growing.

At the Cerema of Aix-en-Provence and North Picardy, Serratrice, Burlon and Legrand have carried out numerous tests of this type in order to characterize different kinds of clays and to measure the impact of the initial compactness of the sample in the evaluation of its swelling and shrinkage potential (illustration 17).

Soil compactness has an effect on the shrinkage and swelling potential of a soil. Dense soils tend to swell whereas loose soils tend to shrink. Furthermore, shrinkage range seems to be linked with initial void ratio of the sample (illustration 18).

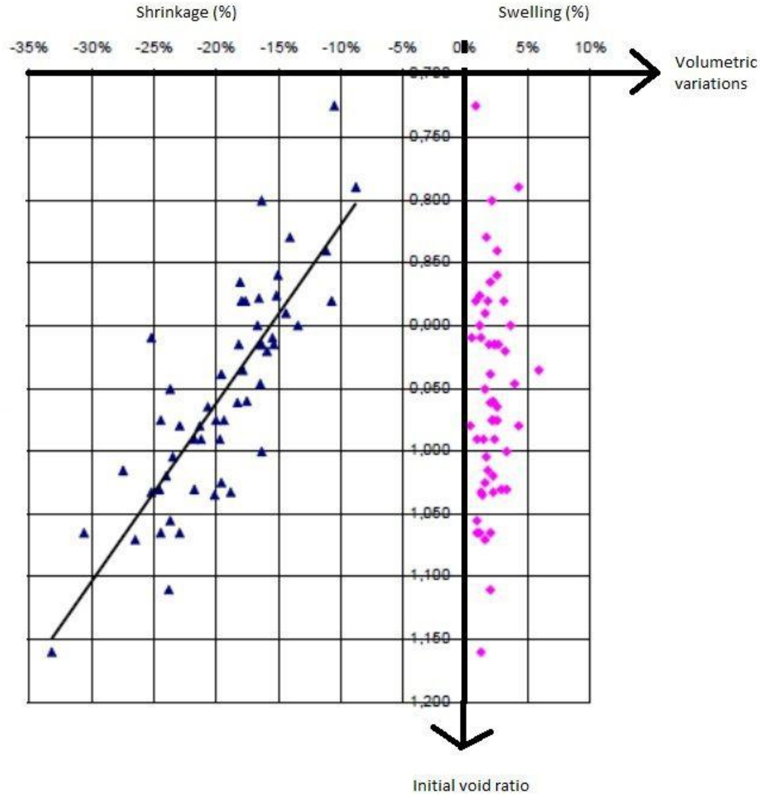



*Illustration 17: Correlations between void ratio and shrinkage potential (Cerema Lille)*

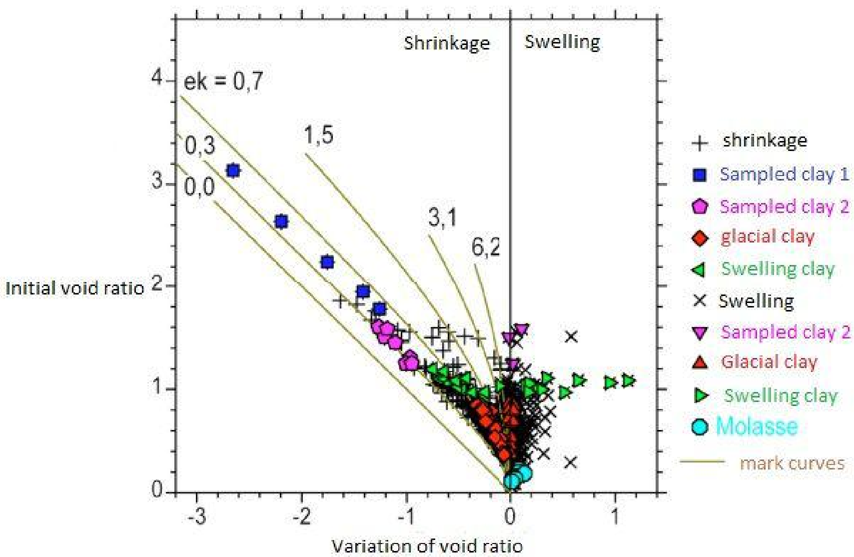



*Illustration 18: Effects of initial void ratio on shrinkage and swelling of a sample (Cerema Aix-en-Provence)*

# Shrinkage and swelling non-direct measurement

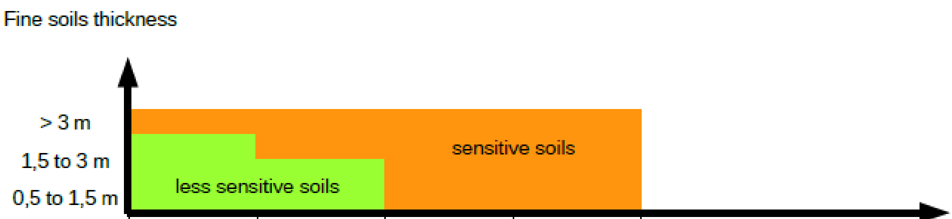
Many methods of non-direct characterization exist about shrinkage and swelling phenomenon.

Atterberg plasticity index (IP), methylene blue value (VBS) or oedometric swelling measurements are the most common ways to evaluate shrinkage and swelling potential of a soil. ARGIC partners demonstrate that combined parameters are also significant. For example, the “activity of a clay” defined as the ratio of VBS (or IP) to its 2 µm sieve passing provide relevant information.

Previous classifications are compiled into a new handbook (written by ARGIC’s partners – illustration 19) called “shrinkage and swelling of clayey soils – characterize a soil before building”. Illustration 20 summarizes the French technical proposal to characterize swelling soil before building. Two parameters are taking into account: shrinkage and swelling potential and soil layer thickness. Special calculations rules are proposed in the handbook according to the presence (or not) of sensitive soils.

At last, the handbook “shrinkage and swelling of clayey soils – characterize a soil before building” suggests a special approach to realize a geotechnical survey with correct scale and calculations rules according to the nature of the soil.


*Illustration 19: French handbook “shrinkage and swelling of clayey soils – characterize a soil before building” - IFSTTAR Editions*




| | | | | |
|---|---|---|---|---|
| <35 | 35 to 45 | 45 to 70 | >70 | Liquidity limit (Wl) |
| <10 | 10 to 20 | 20 to 40 | >40 | Plasticity Index (IP) |
| <1,5 | 1,5 to 4 | 4 to 12 | >12 | Methylen blue value (VBS) |
| <20 | 20 to 50 | 50 to 100 | >100 | Clay Activity (with IP) |
| <35 | 3 to 8 | 8 to 13 | >13 | Clay Activity (with VBS) |

*Illustration 20: extract from the handbook : proposed classification*

# Mapping shrinkage and swelling hazard

A mapping method related to the shrinkage-swelling hazards in France has been developed by the BRGM between 1990 and 2010. It is a large scale mapping based on geological mapping which are available on a scale 1/50 000.

However, this mapping is not enough accurate to be used as planning document (building permission) or as construction's requirements.

During the ARGIC project, it has been tried (Cerema Nice) to improve the existing mapping method (illustration 21 and 22) but, it appears that these improvements induced additional costs and mapping with this new method was not worthwhile (Maurin and al., 2015).

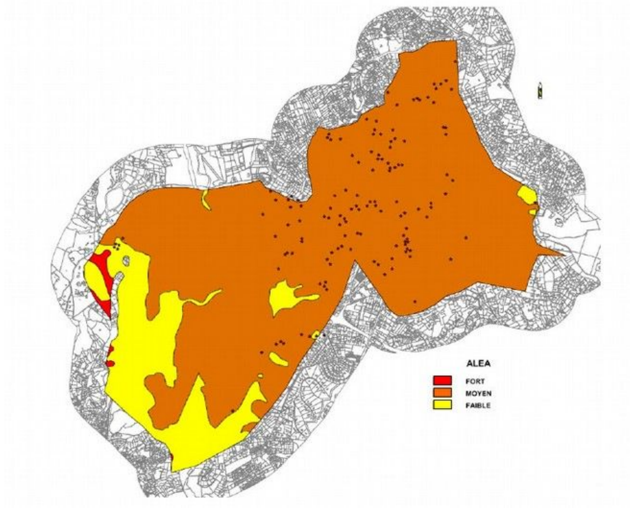



*Illustration 21: hazard mapping with national method*

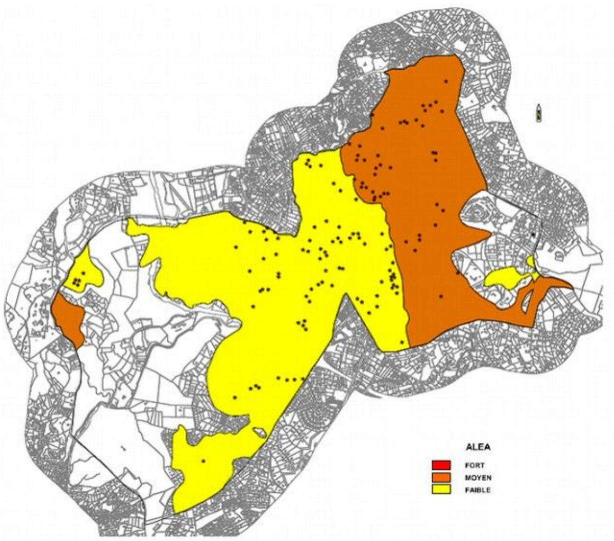



*Illustration 22: hazard mapping with local method*

At last, the handbook "shrinkage and swelling of clayey soils – characterize a soil before building" suggests a special approach to realize a geotechnical survey with correct scale and calculations rules according to the nature of the soil.

# Study the impact of shrinkage-swelling movements on French buildings

Last topic of ARGIC is to Study the impact of shrinkage-swelling movements on French buildings. With this purpose two significant operations were undertaken:

## MISS Operation (Maison Instrumentée sous sollicitations)

(Vinceslas and al.)
The most built type French house since the 1970s is a rectangular house, on two levels (with attic). It is built with elements of masonry (bricks or blocks). Its foundation is a footing. Generally, for economic reasons, the pavement of the lower level (made with concrete) rests directly on the ground after laying a layer of granular materials.

The principle of MISS is to build a real house (illustration 23), in full scale in a totally controlled environment and to apply strains corresponding to those of the shrinkage-swelling of a clayey soil.

*Illustration 23: view of the MISS*

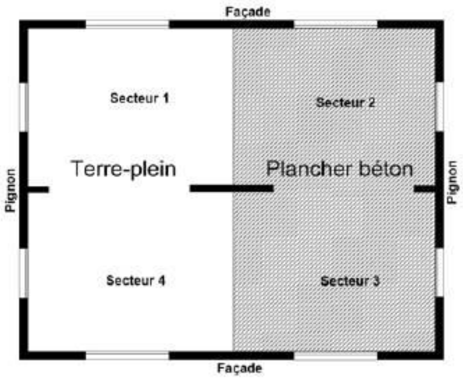



*Illustration 24: map of the MISS*

The MISS is therefore a French standard house. A floor on crawl-space was added for half of it (illustration 24).

Settlements are simulated by substituting pistons for metal supports. The first tests were carried out on the corner with no crawlspace. It appears at first that the house is deformed without breaking or cracking on "fast" daily cycles.

In a second time, it was decided to remove all the supports on half of the house to cause the breakage of it. It occurs 4 days later in the corner initially tested. Looking in detail, it is shown that the post which broke, had a construction anomaly (the steels did not have enough overlap between them).

The conclusion of this MISS operation is that if a house is built in accordance with French standards, it is resistant to shrinkage swelling of clayey soils.

However, it appears that many French houses are broken by this type of phenomenon. The Cerema Ile de France even indicates that this type of construction is the one that is the most affected!

It thus appears that the majority of the losses noted thus comes from the fact that the houses are not correctly built!

Following these experiments, the French State wanted to modify the law of compensation of the natural disasters so that the constructors are responsible for 10 years (the time of the traditional guarantee of a construction).

## Damages on roads

Drought induces shrinkage of clayey soils and differentials settlements which cause disorders on roads in France. These disorders have two kinds of appearance: a long longitudinal cracking with a significant lateral settlement (illustration 25). Most of the time, these disorders appear when vegetation is close to the road (hedges, forest edge…).

*Illustration 25: typical disorders on roads due to drought*

Three road sections have been monitored for several years in Central Region of France by the Cerema Blois. This monitoring highlight a drying of the clayey soils from the edges of the road (aisles or even ditch) towards the center of this one causing differential settlements between the center of the road and the aisles (illustration 26).

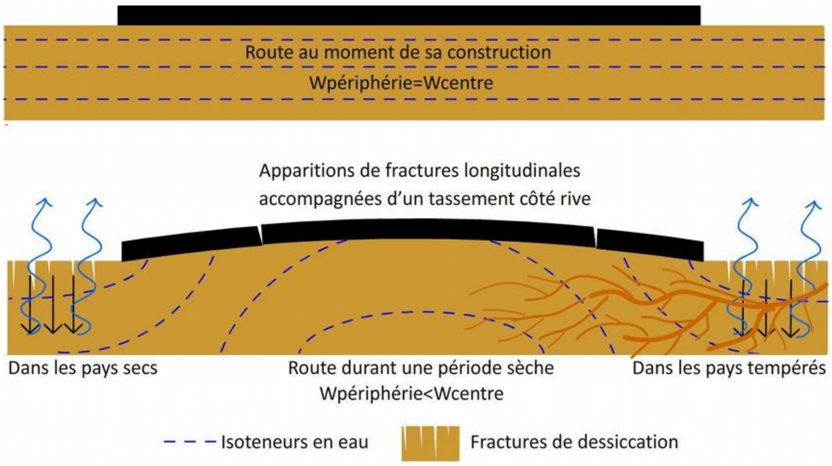



*Illustration 26: explanatory diagram of the shrinkage / swelling phenomenon of clayey soils on roads*

Several repair methods have been tested by the road managers. Some have been monitored by Cerema and gave encouraging results that were published in SEC 2015. I will describe one of them in the line bellow.

The principle of the test site (October 2011) consisted in making vertical concrete sails on both sides of the road.

*Site location and environmental context*

The test site is located north of the Indre department, on the departmental road n°25 going from Chabris to Vatan. Road is in a forest context (oak forest with heights close to 20 meters). Geologically, the road is built (according to the BRGM map) on silts, which cover a Turonian formation (white chalk with flints showing clayey alteration). This Turonian formation covers a marly Cenomanian layer. BRGM associates a low hazard to these silts and a medium hazard to the underneath geological formations.

*Damages observations*

The site diagnosis was made in November 2010 at the request of the road manager. The road already repaired in 2007 was showing numerous pathologies: alligator cracking, bleeding, important edge settlements (illustration 27) and longitudinal cracking out of the wheel track.

*Illustration 27: longitudinal cracking (adaptation cracking)*

The nature of soils, the fact that damages are recurrent, the season of appearance (end of summer – fall), their location (across a forest) and the presence of other similar sites led the CEREMA to diagnose a shrinkage and swelling of road subgrade soils (except for the alligator cracking and the bleeding which are linked to traffic and the coated material laying.)

*Shovel survey and laboratory tests*

In order to know the nature of on-site soils a shovel survey was done on the shoulder of the road (illustration 28) at point n°5 (PR 5). Here, an important longitudinal cracking affects the road.

*Illustration 28: white clayey layer*

The drilling reached 2,50 meter depth. It allowed sampling of two geological formations, establishing a log of the soils on the site and visualizing the pavement (made of a coated layer on a limestone untreated graded aggregate – total thickness 15 cm). From the surface to the depth we can find:

- A 30 cm layer of dark brown vegetal earth containing a lot of small roots ;
- A silty formation brown beige till 80 cm depth;
- A multi-coloured (grey, rust, brown...) very plastic formation becoming white on the bottom of the drilling, around 2,30 m (illustration 28).

Identification laboratory tests were conducted on the clayey layer (-1,2 and -2,00 m). They confirm its high plasticity (A3 clay according to NFP 11-300) with plasticity indexes (PI) > 29%. The white clayey layer at the bottom of the borehole is less plastic (plasticity index = 20).

*Works*

Following those investigations, the following experimental works principle was defined:

- Setting up 1, 1.5 and 2 m deep lateral trenches on 3 different sections. The aim is to cut the materials horizontal capillarity by setting a waterproof membrane. Because of the shoulder trafficability, a trench concrete filling is made;
- Reconstruction of the pavement with supple materials accepting subgrade soil deformations;
- Setting up instrumentation in order to record soils water content variations over the seasons.

The works took place the first two weeks of October 2011 and needed a total traffic interruption.

The worksite is 420 meters long and 6 meters wide. It was divided into three sections of 140 m each. Each section has a concrete walls lateral protection. Walls depth are -1m, -1.5m and -1.65m. Works were conducted as follows:

- Making a 30 centimetres wide excavation on the side of the road using a trench excavator (illustration 29). The maximum depth reached by the trench excavator is 1,65 m (this depth limit was announced only during works, even though requirements were to reach 2 meters);
- Filling the trench with fluid concrete, directly poured by concrete mixers (illustration 30);
- Carrying out a milling of the pavement on the whole site and setting up a double surface dressing before re-establishing traffic (illustration 31).

*Illustration 29: excavation using a trench excavator*

*Illustration 30: Pouring concrete by concrete mixers*

*Illustration 31: view of the double surface dressing*

The tensiometry monitoring system set up was made by the CEREMA after the milling of the pavement. Instrumentation was carried out as follows:

- Creating a 50 cm depth trench across the road (illustration 32);
- Making starter holes in the soil, with a diameter inferior or equal to the probes;
- Thrusting the probes with the drill (illustration 33);
- Weaving electrical wires connecting the probes and the recording box “Watermark Monitor”. The box is placed in a manhole (telephone-type) under the shoulder beyond the concrete wall (illustration 34).

Note that a pipe was placed through the trenches before pouring the concrete in order to pass connection wires between the probes and the monitor.

*Illustration 32: transversal trench*

*Illustration 33: The probes are installed by the drill*

*Illustration 34: Recording box in a manhole under the shoulder*

Relative positions of the probes are shown on illustration 35. One probe was purposely moved in the shoulder in order to compare suctions evolution in the area protected by the concrete wall and in an unprotected zone near the ditch.

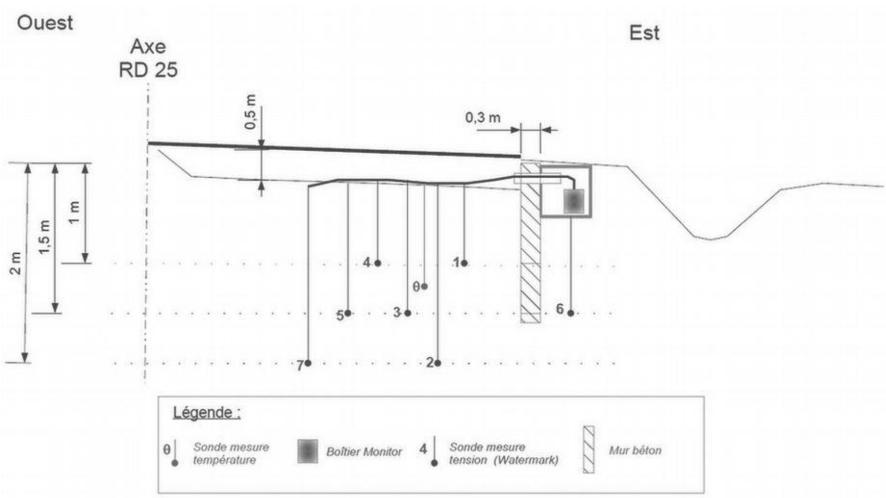



*Illustration 35: Diagram of probes implantation (depth of concrete wall varies according to the sections between 1 and 1.65 m)*

Recordings are collected every two months during a checking visit. The operator checks existing visible disorders on the pavement, empties collected data thanks to a RS232 (or Jack) connection (liaison RS232) and performs maintenance operations (change of batteries, …).

On site Watermark-type tensiometric probes measure the electric resistance of a porous solid placed inside the probe (a piece of gypsum) in hydric equilibrium with the surrounding environment (i.e. the soil). The measured electrical resistance is calibrated and matches a “soil tension”, expressed in cbars or kPa. The soil tension is assimilated to suction or internal negative pressure. Soil tension is correlated to its hydric state (increasing tension means increasing soil dryness). The on-site equipment range of measurement goes from 0 to 250 kPa. It allows to measure with great accuracy the water content range between plasticity limit and shrinkage limit of clayey soils.

*Results*

The measurements results are commented for only two road sections on three summer periods: end of summer 2011, summer 2012 and summer 2013. Technical problems prevented data exploitation on the protected road section at -1m depth.

About the section protected by -1.5 m walls, we can see (illustration 36) the following elements:

- A high suction starts in November 2011 in unprotected soils (probe 6). It rises till February, then the recording is stopped (probably because of the strong frost in this area at that time). The recording starts again in late August. The data collected after this date are very irregular and show probable probe deterioration;
- The probe 2, at -2 m near the wall, shows a very strong suction (superior to 200 kPa) between the end of February and the beginning of September 2012. Suction rises again in July 2013;
- Every other probe under the pavement (1, 3, 4, 5, 7) has values inferior to 5 kPa, meaning an overall stable and rather damp humidity state.

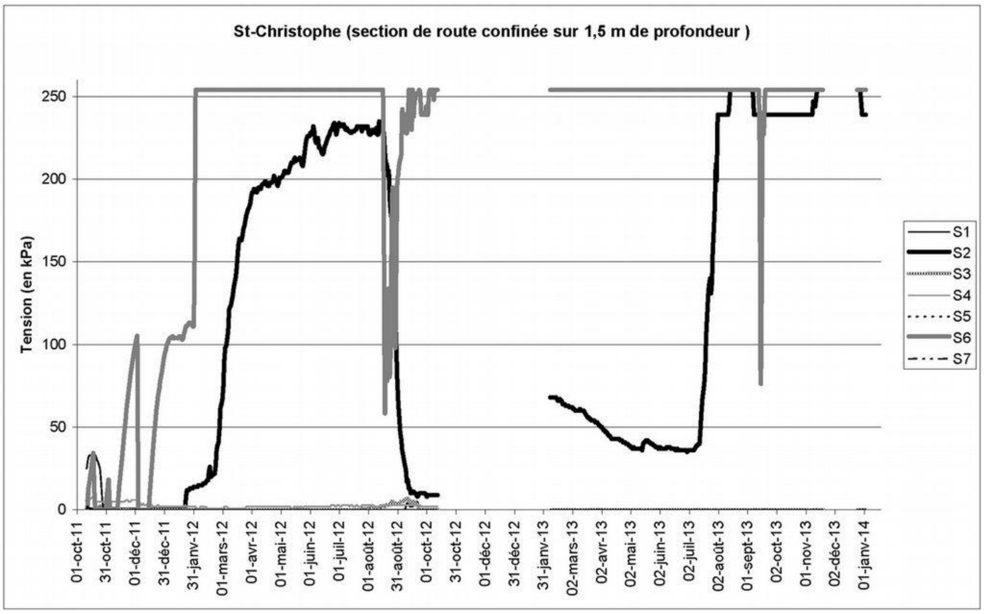



*Illustration 36: Suctions evolution on section (-1.50 m)*

About the section protected by walls at -1,65 m, we can observe (illustration 37) the following points:

- In unprotected soils, the first significant measurements occur in October 2011, in August and September 2012 and from July to September 2013. The low (< 50 kPa) and irregular values show a rainy end of summer and the proximity between the probe and the ditch;
- The probe 2, located at -2m near the wall shows a very strong suction (more than 200 kPa) at the end of year 2011. It falls end of December and starts again at the beginning of July 2012. The suction increases again in July 2013;
- All other probes under the pavement (1, 3, 4, 5, 7) have values equal to zero, meaning an overall stable and rather damp humidity state.

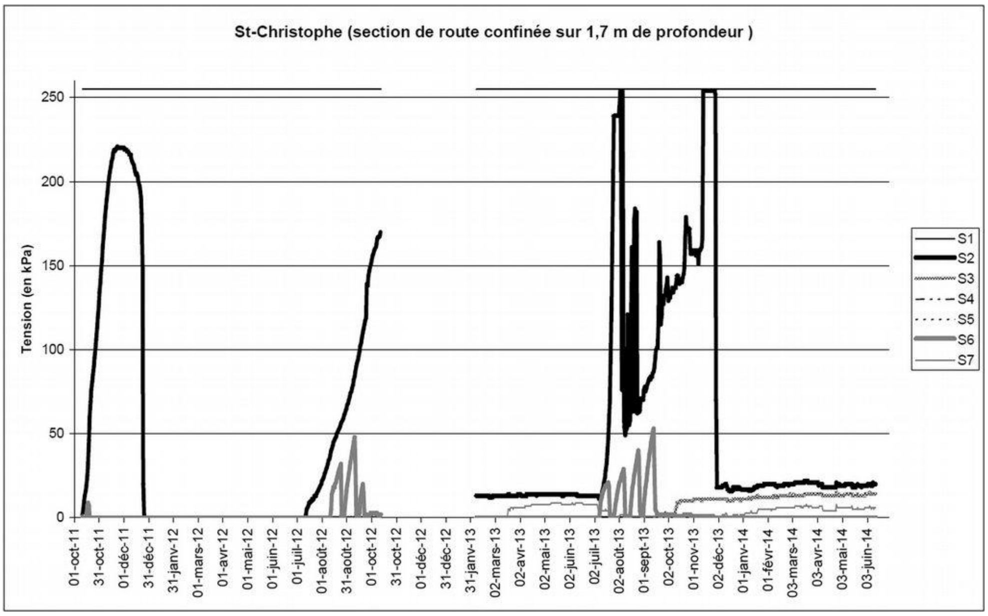



*Illustration 37: Suctions evolution on section (-1.65 m)*

Until August 2012, no significant damage was observed on the pavement. In September 2012, we saw:

- Some light longitudinal cracks on the side of the pavement (illustration 38). They are related to the proximity of the concrete wall, which acts like a rigid beam;
- A slightly more significant longitudinal crack located on the road axis (longer, less straight and showing a small slope towards the west side). This crack is at the exact same place than the one seen in November 2010 near the PR 5 (illustration 39) in an area protected by a wall. The wall depth is between 1,5 and 1 m (transition).

*Illustration 38: crack on the side ("beam" effect of the concrete wall)*

*Illustration 39: longitudinal cracking with edge settlement (same place as illustration 27)*

A (rainy) month later, in November 2012, the cracking evolution is small: no increase of its length or of the slope. During year 2013, the manager conducted crack bridging on the longitudinal cracks near PR5. Since this intervention, cracking lengths did not change (illustration 40).

Illustration 40: state of the location at PR5 in January 2015 (3 years after confinement works)

*Illustration 41: PR 5 - September 2016*

Unfortunately, summer and fall 2015 and 2016 were dryer and hotter and longitudinal cracking re-appeared (illustration 41). This crack will grow to become too large and the road manager was forced to repar it in May 2017.

*Findings*

Suction recordings made by tensiometry show a good steadiness of soils water contents under the road up to 1,50 meter depth. Soil encapsulation with moisture barriers is therefore effective (GODEFROY A et al, 2015).

The 1,65 m limit of veil depth is prejudicial, because it does not allow an actual analysis of behaviour difference between protected area at -1.50 m and -1.65 m. However, it shows the difficulty of getting a powerful enough and designed equipment to reach such trench depth according to the small size of the works.

The re-appearance of the longitudinal crack right to PR 5 indicates that the road confinement on -1.50 m seems insufficient in this context. Suction measurements recorded by the S2 probe at -2 meters depth corroborates this observation. There is a drying at greater depths.

The operation cost is evaluated at 315 Euros per road linear meter. The price includes setting up the pavement confinement with two “concrete walls” and re-building it with double surface dressing.

# Ongoing research projects in Cerema

## ORSS Project (Observatoire des routes sinistrées par la sécheresse)

Could be translate in “Observatory of drought-stricken roads”.

As a continuation of ARGIC operation, Cerema Blois has entered into a partnership with local communities in the Center region to test road repair techniques over time (similar to what has been done by UTSA in Texas over the years. 2000).

It involves undertaking test sites in several departments and monitoring their aging over several years as well as meteorological changes. The proposed test sites are:
- lime treatment of arase
- treatment with a product comprising enzymes of the arase
- reprocessing in place with bituminous binders
- encapsulation with membranes over 2.5 m depth
- reinforcement with one or two geogrid (s)
- Resin injections under the roadway.

Operation is going to start at the beginning of the tear 2018.

## MACH Project (Maison Confortée par Humidification)

could be translate in “HOuse repaired by Watering)

Cerema Blois is currently undertaking an experiment on a house that has been affected by drought. You will find below the presentation I prepared for the Pan AM Unsat Symposium 2017 to be held next week in Dallas.

The MACH (illustration 42) is located in Mer (Loir-et-Cher, France). The house (illustration 43) was built in 1968. It is a one storey house with an extension which has been built in 1995 on the East side of the former house. The foundation system is a footing and the floor is a slab-on-ground one. The house is located in a residential area where vegetation is rather small and cared (owner’s gardens and some trees in the streets). The MACH is an inhabited house. It was excluded from the French compensating system for the drought of 2015. Thus, the owners are really involved in the experiment in order to repair their dwelling.

Illustration 42: Site location

Illustration 43: View of the house

*Damages*

After Summer 2015, the damages were noted only on the extension part of the house. Major cracks were drawn on illustration 44. It was found out that the extension is tilting to the East.


*Illustration 44: Noticed damage survey in 2015 and 2016*

Inside the house, the floor did not settle at all. However, the tilled floor is broken at the junction of the former construction and the extension. The tilting phenomenon induced damages on the interior finishing (cracks on partition and doubling walls, offset of windows panels, doors which doesn't close or open…). These damages reduced during Winter 2015/2016 and increased during Summer and Fall 2016.

*Climate*

Mer climate is a mixed oceanic/continental types: average annual cumulative rainfall is about 600 millimeters and average temperature 11°C (about 52°F). Meteorological station of Blois (which is only 25 km far away from Mer) gives following datas:

- 2014 is “a normal year” with 694 mm cumulative rainfall (uniformly spread out across the year) and average temperature equal to 12.5°C. Swelling and shrinkage phenomenon is not a problem in 2014;
- 2015 is dryer than 2014 with only 594 mm annual rainfall and a short drought period during Spring, June and July. Important rainfalls during August and September avoided a major drought;

- Annual cumulative rainfall in 2016 is over 720 mm but with an exceptional rainy Spring (over 210 mm rainfall during May!). Despite this rainy Spring, 2016 is considered as a dry year, especially after June (illustration 45).

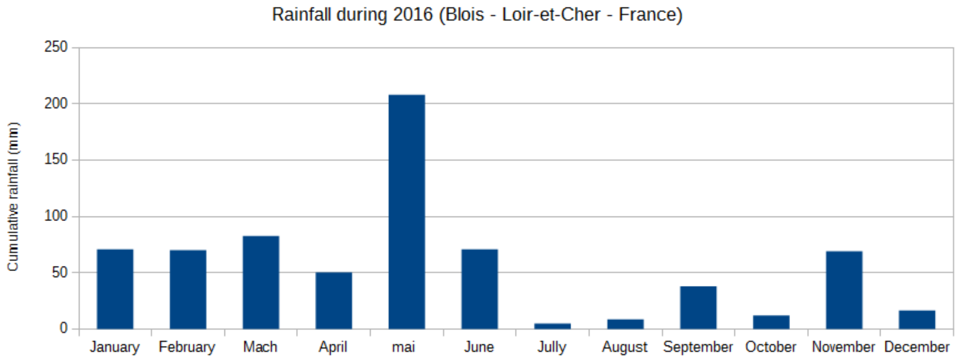



*Illustration 45: Annual rainfall in Blois (2016)*

### *Vegetation*

Every shrubs or trees are transcribed on a plan (illustration 46). A cotoneaster hedge is located just in front of the damaged gable of the MACH. A wisteria is also noted on the south façade.

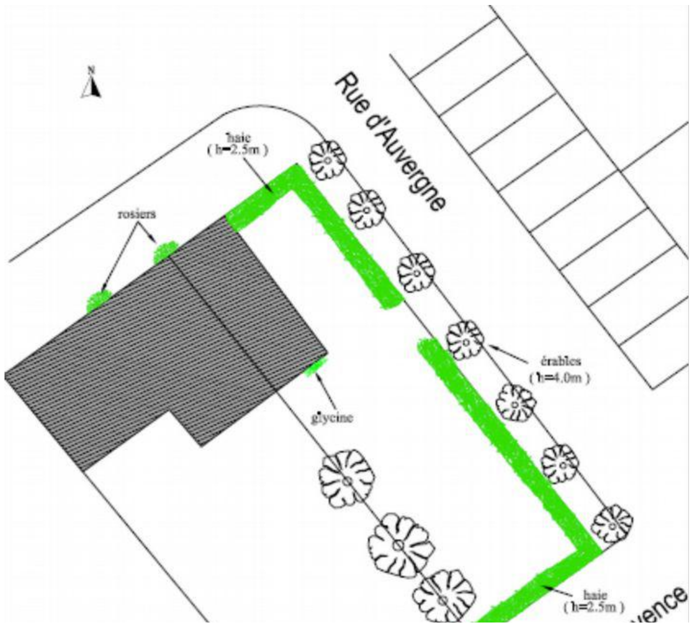



*Illustration 46: vegetation survey*

### *Geology*

Cerema provided a geotechnical survey in order to characterize foundation soil of the house and to determine how it could be fixed. Thus, Cerema realized two drillings including in situ pressumeters tests close to the house. These investigations allowed to set a geotechnical model which can be resumed as follows:

- a dark brown, strong and plastic clay. This layer is about 2.50 meters thick. It is a decalcification clay;
- the Beauce limestone is found deeper.

Mechanical properties of these geological layers are presented in Table 2:

| | Number of values | Limit Pressure pl* (MPa) | Pressumeter modulus $E_M$ (MPa) | Observations |
|---|---|---|---|---|
| Decalcification clay | 4 | 0.22 < pl* < 0.55<br>pl* geom. mean = 0.38 | $3 < E_M < 6.9$<br>$E_M$ geom. Mean. = 4.6 | Soft clays |
| Beauce Limestone | 5 | 1.97 < pl* < 2.82 | $20.8 < E_M < 131.9$ | Altered rock |

Table 2: in situ presiometers tests results

An excavator drilling was realized in front of the most damaged edge of the house. It shows that the foundation system, which is an 85 cm deep footing, is set on the soft and plastic clay. The footing is 35 cm thick. Numerous roots are observed in the excavation (see illustration 47).

*Illustration 47: excavator drilling (with numerous roots)*

Some soil samples were brought to the laboratory. Table 3 shows main results of the characterization tests.

| | localization | Particle size distribution | | | | Plasticity | |
|---|---|---|---|---|---|---|---|
| | | Sieve passing (%) | | | Dmax (mm) | VBS (g/100 g of dry soil) | Plasticity Index PI (%) |
| | | 2 µm | 80 µm | 2 mm | | | |
| Decalcification clay | Excavator drilling | 57 | 97 | 99 | 10 | / | 37 |
| | SP1 (1.5 m) | / | 98 | 99 | 5 | 5.5 | 39 |
| | SP2 (1 m) | / | 98 | 100 | 5 | 6.4 | / |
| | SP2 (2 m) | / | 89 | 98 | 10 | 6.0 | / |
| Beauce limestone | SP1 (5 m) | / | 58 | 84 | 20 | 1.4 | / |

Table 3 : soil properties

The foundation soil is a soft and plastic clay (PI ≈ 37 to 39), sensitive to swelling and shrinkage phenomenon. Beauce limestone lying under the clay layer is not sensitive.

The conclusion of the geotechnical survey is that early 2015 hydric deficit induced a severe drying of the clays located under the footing of the house. The hedge of cotoneaster was an aggravating factor for the shrinkage phenomenon. This heavy drying caused settlement of the footing and lead to cracking the east gable of the house.

*MACH's works description*

*Principles*

The MACH project consists in watering foundation soil of the damaged house as soon as it is drying. With this purpose, the clayey soils located under the footing are:

- protected by removing the cotoneaster hedge close to the East gable of the house;
- monitored by tensiometric probes, which measure 4 times a day the moisture content.
- watered by a device with 10 water injection points located 15 cm under the footing.

*Removing vegetation*

Early November 2016, the cotoneaster hedge and the wisteria were removed (see illustration 48). The hedge was substituted by a metallic fence with a green screen.

*Illustration 48: MACH's views before removing the hedge and after*

*Rainwater collecting device*

Obviously, the water provenance is a sustainable one: it comes from a device that recovers rainwater. The gutter located on the north face of the house was modified in order to collect rainwater falling on the North-East part of the extension (about 12 m² roof). A new rainwater down-pipe was set and 3 tanks were installed (see illustration 49). The tanks are hidden behind the green screen.

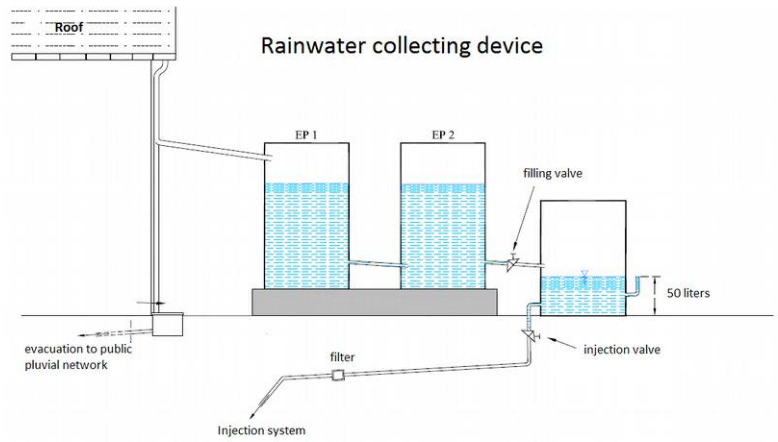



*Illustration 49: Rainwater collecting device*

According to the roof surface and estimate losses of the device, it has been estimated that a cumulative rainwater of 80 mm is required to fill up the three reservoirs.

*Water injection device*

The principle was to set a manual and robust device that injects water under the foundation level. The MACH owner opens the valve, which releases water from the third rainwater reservoir. The third reservoir is calibrated to contain about 140 litres, which is the estimate water volume to moisten sufficiently clayey foundation soils. Injections points are spread out along the gable of the house. They are located 20 centimetres far from the wall and about 1 meter deep. In fact, an injection point is a PVC pipe (diameter 5 centimetres) which has been driven in a manual auger drill. A capillary tube coming from the rainfall reservoir is put in the PVC pipe (see illustration 50) and releases the water in the pipe.

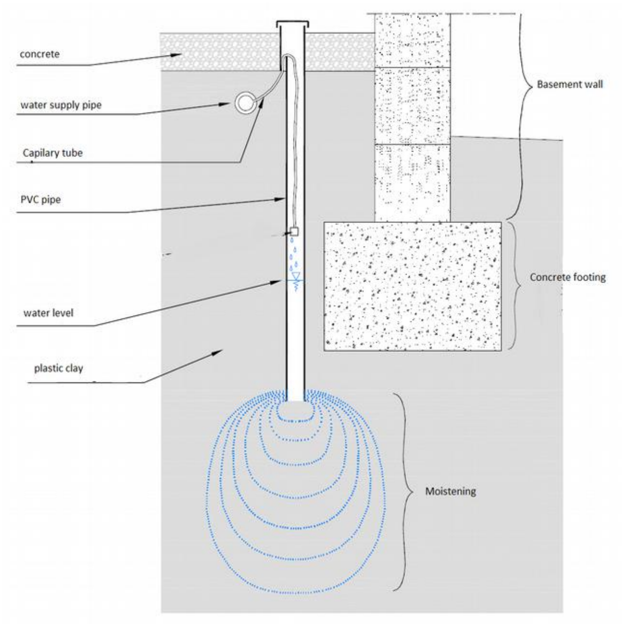



*Illustration 50: Water injection device*

Opening the valve releases the water in each PVC pipe. Thus, water infiltrates the soil only at the bottom end of the pipe.

*Tensiometric monitoring*

Tension is a concept used in the agronomy field. It gives information about direction of hydraulic flows in the soil and on the available water for cultivating. Tension measurement allows to quantify, on a given point, the attraction force applied by solid particles on water. It is given in kilo Pascal (kPa) and is called, in the soil mechanics field, “soil suction”. Suction and moisture content are linked. Previous research works (Mathon and al. 2015) aimed to correlate them based on an experimental approach of drying. Under a given moisture content (which corresponds to the air inlet), the more tension is increasing, the more moisture content is decreasing.

In the MACH project, 20 probes were driven into the soil at the same depth than the water injection points (about 1 meter depth). Each probe is linked to a data-logger unit which is located on the south face of the house (see illustration 51). This data-logger send 4 times a day tensiometric information to the Cerema. Thus, soil drying is monitored and water injection can be decided as soon as the engineer analyzes the tensiometric graphs.

Existing damages on the MACH have been noted in October 2015. Every month, Cerema’s engineers observe carefully the house in order to drawn every new crack that could be occur. Furthermore, the biggest crack located on the north face was equipped with a displacement sensor (see illustration 52) to record opening and closing of the crack according to the water injections and meteorology. This displacement sensor is a fissurometer and it has been set in November 2016.

*Illustration 51: Outside data-logger*

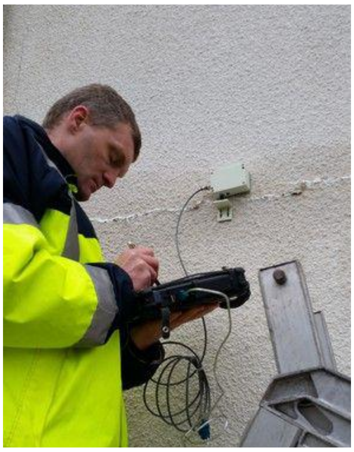


*Illustration 52: Cerema's agent downloading movement sensor datas*

*Monitoring first Findings*

Annual cumulative rainfall in 2016 was over 720 mm with an exceptional rainy Spring. Despite this rainy Spring, 2016 is considered as a dry year especially after June and until December.
This exceptional contrast induced a maximal moistening of shallow and expansive soils during Spring and a gradual and durable drying after Summer until the end of the year.

During Fall, the MACH's owner declared that interior doors and windows were really hard to close and open. In October 2016, a new vertical crack was observed on the North face of the MACH, illustrating the east tilting movement of the extension.

Thus, Cerema decided to open the valve in order to release water in the injection points. The tensiometric probes recorded the quickly moistening of the clayey soils. The MACH's owner noted that doors and windows were easier to use. Furthermore, a clear closing of the monitored crack was recorded in December 2016 (see illustration 53).

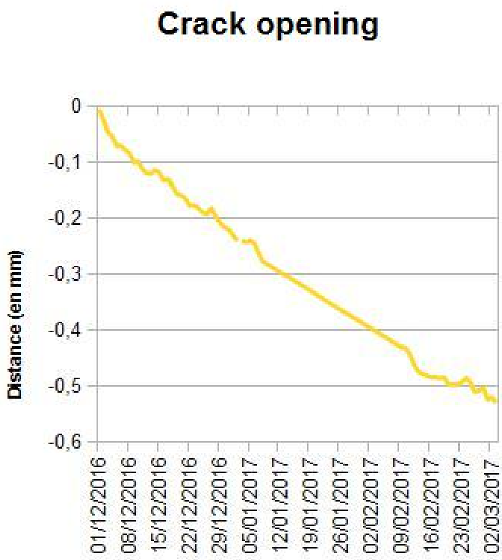



*Illustration 53: Crack monitoring*

*Conclusions*

The MACH Project is a field experiment of an innovative approach to repair houses that have been damaged by geotechnical drought. The principle of the MACH is to water or moister clayey soil to neutralize natural shrinkage due to its desiccation. A damaged and inhabited house was chosen. Experiment works began in October 2016 during a severe drought period (in France). A relationship between damages, geology and meteorology was highlighted by the geotechnical survey carried out by Cerema.

A watering device has been set under the footing of the MACH. First uses of this device showed encouraging results, as it induced closing of the major crack and decreasing of bad effects felt by the owners. The monitoring of the house is planned until 2019, it will be important to confirm these encouraging first results.

# Final conclusions

*I hope that all this interested you. With a few exceptions, this is the case with French research knowledge and advances, as the Cerema covers the majority of the French geotechnical community's efforts.*

*I think you have understood that the problem of expansives soils (and more specifically the shrinkage of these) is very important for us and that research prospects remain.*

*Working with foreign countries with dryer climate is really important for us as we forecast the situation considering climate change and the necessary adaptation of road maintenance policies.*

*Once again, I thank Professor Dessouky for his invitation. I hope that this presentation will allow us to develop technical partnerships between UTSA and Cerema and that we will have a common approach and projects on the subject of expansive soils.*

# Bibliographical references

NEVEU G. (2012). Missions d'ingénierie géotechnique et suivi d'un site expérimental. Mémoire Master Sciences de la Terre et Environnement, Ecologie : spécialité Génie Géologique, Génie Civil et Environnement – 3 GCE. Bordeaux : Université Bordeaux 1, 90 p.

TRON R., Chol P. Isbérie C. (2000). La tensiométrie pour piloter les irrigations. Dijon : Educagri édition, 247 p.

MATHON D. (2013). Bilan de la participation du LR de Blois pour les années 2011 et 2012. CETE Normandie centre.

MATHON D., Godefroy A. (2014). Suivi expérimental d'une maison instrumentée à Langon (33), CEREMA Dter Normandie Centre, Avril 38p.

BOUSSAFIR Y. (2006). Les effets de la sécheresse sur les chaussées à faible trafic dans la région Centre. Journées Nationales de Géotechnique et de Géologie de l'Ingénieur, 2006.

MATHON D. (2008). Les impacts de la sécheresse sur les chaussées.2007-11449.0 D 174. Blois : LRPC, 2008, 22p.

MATHON D. (2010). Impact de la sécheresse sur les chaussées – Installation de 3 sites test en Loir-et-Cher (41).2009-12438.0. Blois : LRPC, 2010, 41p.

MATHON D. (2010). La sécheresse et les routes : suivi de la dessiccation des sols sur trois sites tests en Sologne. Journées Nationales de Géotechnique et de Géologie de l'Ingénieur, 2010.

MATHON D. (2013). Impact de la sécheresse sur les chaussées – contribution du CETE NC – LR Blois pour 2011 et 2012. 13145.0. Blois : LRB, 2013, 34p.

GODEFROY A., MATHON D. (2014). Impact de la sécheresse sur les chaussées – contribution du CEREMA pour 2012, 2013 et 2014.C14IS0005. Blois : CEREMA, 2014, 47p.

Sols : reconnaissance et essais - Méthode d'essai ME 81
Détermination rapide de l'amplitude totale des déformations de retrait et gonflement des sols sur un prélèvement non remanié (essai rapide de retrait-gonflement)

DESSOUKY S., ILIAS M. (2015). LONG-TERM PERFORMANCE OF PAVEMENT REPAIR METHODS IN LOW-VOLUME ROADS BUILT OVER EXPANSIVE SOIL - SEC 2015 International Symposium

MAGNAN JP, BURLON S. (2015). PANORAMA OF FRENCH RESEARCH PROJECTS RELATED TO SOIL SHRINKAGE AND EXPANSION – SEC 2015 International Symposium

MAURIN P., TRIELLI E., PEREZ JL, IMPORTANCE OF MAPPING SCALE FOR CHARACTERIZING SHRINKAGE AND SWELLING (NATURAL) HAZARDS - SEC 2015 International Symposium

VINCESLAS G. (2015) Expérimentation en vraie grandeur d'une maison soumise au retrait-gonflement de sa fondation. Actes, Symposium International SEC2015, Marne-la- Vallée, 18 et 19 juin 2015.