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An underground research laboratory at Château-Landon (France) to study the impact of climate change on the stability of abandoned mines

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Abstract

In January 1910, a chalk mine at Château-Landon in the Paris basin brutally collapsed, causing 7 fatalities. This dramatic event was related to the centennial flood of the Seine River and one of its tributaries, the Loing River, which invaded the lower parts of the mine and eventually weakened the entire structure. To understand the conditions that triggered the disaster and anticipate other catastrophic event of this kind elsewhere, the Royer mine, located in the same area, was chosen to host an underground scientific observatory. Its goal is to study water-rock interactions and in particular water circulation and unusual ground saturation conditions on the behaviour of chalk. The Royer chalk mine is shallow, above the water-table, easily accessible and globally stable. It has been equipped with a high resolution multiparameter monitoring network in 2019; all the sensors are connected to The French National Monitoring Centre for Ground and Underground risks (Cenaris). Besides from in situ observations and monitoring, series of laboratory tests are carried out on samples to study the impact of hydraulic cycles on the short-and long-term behaviors of chalk. A hydromechanical model is also under development to analyze the results and better assess the overall stability of the mine in the context of climate of change. In this paper, we provide a brief summary on the challenges to assess geohazards from abandoned chalk mines, and then present in details the observatory, its objectives and perspectives, as well as the first results after two years of activity.

Keywords: mine, chalk, collapse, underground cavities, groundwater, long-term stability, multi-parameter monitoring, climate change

Introduction

Because of its geology and industrial history, France has numerous underground natural and man-made cavities. They are estimated around 500,000, the majority of which are not precisely located. These underground cavities may deteriorate over the time and various ground movements such as subsidence, sinkhole and large collapse are to be feared due to climatic conditions. These phenomena, which constitute a major risk for the urban infrastructures in inhabited areas, may sometimes cause victims. The sudden collapse involving large surface of mine, is the more dangerous one since several pillars may collapse simultaneously thereby creating a crater of several hectares (example: the Clamart collapse of 1961, in France, 3 ha, 21 victims, see Al Heib et al. (2014)).

Additionally, climate change is leading to an increasing frequency of exceptional events (summer droughts, winter precipitation or flooding), that consequently can increase the amplitude of the fluctuation of the water table, the flow range of streams (especially during floods) and the modes of water infiltration from the surface (Didier et al. 2010). All of these phenomena likely increase the risk of instability or even collapse of underground mines by acting on the water content and resistance of the most sensitive rocks, such as chalk (Lafrance, 2016). In this way, the exceptional bad weather of spring 2016, in the Paris Basin, confirmed the strong correlation between extreme climatic situation and underground cavities collapses, with 20 to 40 events identified on this occasion (war tunnels in Pas-de-Calais, mines in Loiret, marnières [chalk mines, mostly in Normandy] in Eure, Somme, Marne, Haute-Marne, Nièvre, etc.) (Noury et al. 2016).

In an evolving climatic context, an increase in this type of collapse is very likely, particularly in geological context sensitive to water, such as limestone, chalk, and gypsum. This was the case with the catastrophic flooding of the Seine and its tributaries, which occurred in January 1910 causing significant damage and 7 victims. The latter were buried during the collapse of a hill excavated by the Beaulieu mine near the hamlet of Lorroy, in the municipality of Château-Landon (France) (**Figure 1**). The Château-Landon municipality is located about 100 km southeast of Paris, on the banks of the Loing river, a tributary on the left bank of the Seine. This collapse occurred after an episode of heavy rainfall which triggered a 100-year flooding of the Loing, at the edge of which the mine was located. In addition, three other mines (Rathier, Bourdin, and Charluchet) had previously collapsed in the same municipality in 1897, 1878, and at an earlier unknown date.

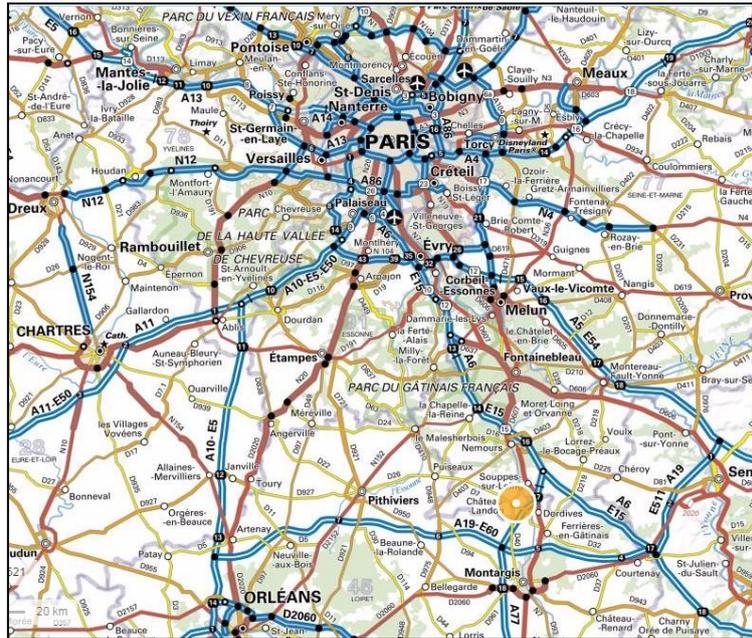


Figure 1. Location of the municipality of Château Landon (circle) in the south of Paris (France)

The analysis done on certain collapses that occurred over decennia has allowed the establishment of a typology of disorders preceding or accompanying the failure (Berenger et al., 2014). The authors divide the factors governing the stability of the mine into two main groups: the factors intrinsic to the cavity (type of entry, extraction method, terrain lithology, geometry of voids, etc.) and external factors (water, plant cover, load variations, natural and/or man-made vibrations, etc.). Although the role of water seems undeniable in this type of collapse, the mechanisms at the origin of it are not fully understood (Didier et al., 2010) and need to be investigated in order to be able to anticipate such catastrophic events.

Many mines, most of which are abandoned today, can in fact be temporarily flooded depending on the groundwater fluctuations or/and on the surface flooding, while in others the level of rock saturation can vary, especially in the event of surface installations modifying the percolation conditions (storm basins, infiltration ditches, etc.). The saturation/desaturation cycles may alter the behaviour of the rock and affect the stability of certain water-sensitive rocks, such as chalk (Homand & Shao, 2000).

The effect of water on the chalk behaviour has already been studied at small scale on intact chalk samples. In this way, the tests carried out early after the collapse of Château-Landon chalk mine (in 1910), confirmed then by Muñoz-Castelblanco et al. (2010), Gombert et al. (2013) and Souley et al. (2019), show that this chalk has a low mechanical resistance in a fully saturated state. At the scale of a mine, studies of the influence of water are less numerous, but essential because they make it possible to take into account the heterogeneous character of chalk, linked to its double or triple porosity (fractures and matrix, and sometimes karstic conduits), and to its spatially variable degree of alteration. The deterioration process depends on a complex coupling between the variations of temperature, hygrometry, pore pressure, and hydrochemistry in the cavity on the one hand, and the deformation of rock on the other hand, the latter itself being a function of the state of deterioration of the underground structure (damage and induced fracturing). Thus, in the first centimetres of the pillars where the rock is partially saturated and occasionally exposed to water and air flows, the flows in the pores and the fractures will induce stress variations at the origin of often irreversible deformations (Homand & Shao, 2000). Moreover, in the chalk mine at Vendôme (Loiret - France), Fargier et al. (2017) have shown significant variations in electrical resistivity within the pillars which are linked to water saturation and which can be correlated with mechanical parameters. Two other chalk mines at Estreux (Nord - France) and Saint-Martin-le-Nœud (Oise - France) have also been studied in various flooding/draining contexts, but without being able to trace back to the phenomena being investigated with sufficient precision, though the role of water has been demonstrated by fluctuations in the rate of extension of the pillars and convergence of galleries (Gombert and Damart, 2012; Gombert et al., 2018).

The action of water can be expressed in various ways (interstitial pressure, physic-chemical action, dissolution, etc.) as a function of geometric, hydromechanical, petrographic, etc. conditions. Based on the feedback and the previous events, and to improve the prediction of this type of collapse, it is necessary to implement synchronous and continuous measurements of the water pressure-strain-temperature parameters in order to study the hydromechanical (HM) coupling process in the underground structure. The creation of an observatory integrating continuous geomechanical and hydrogeological measurements would therefore permit a better characterisation of

the role of water in interaction with the structure thanks to the monitoring of the deformations of the rock mass in the long and short-term periods. At Château-Landon, in fact, there remains a single non-collapsed mine, the Royer Mine (**Figure 2**), which was chosen as a national underground observatory as part of a programme supported by the French Ministry in charge of the Ecological Transition and in collaboration between public organisation (Ineris, Cerema), and the department of Seine-et-Marne. This observatory has multiple objectives: to understand the hydrogeological behaviour of the rock mass; to quantify the effects of inflows and circulation of water on the geomechanical stability of the underground cavity and ultimately detect early signs of rock mass instability. The local real-time multiparameter monitoring system is connected to The National Monitoring Centre for Ground and Underground risks (Cenaris) which enables to centralize and share the data through a dedicated web-monitoring page on the e.cenaris (<https://cenaris.ineris.fr>) web portal. The collected and the deep data analysis will serve to develop and validate a collapse prediction model for comparable underground chalk mine.

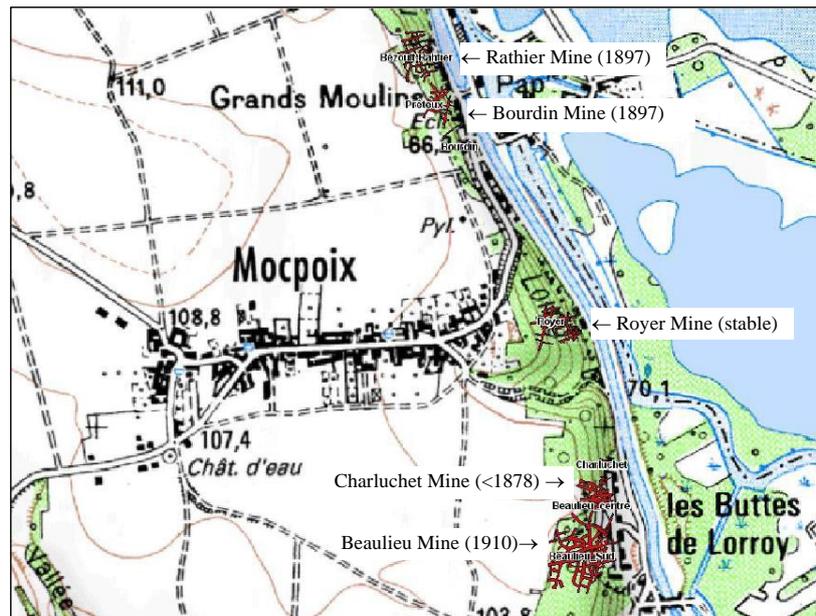


Figure 2. Layout (in red) of the underground mine galleries of Château-Landon with their dates of collapse (Watelet & Kreziak, 2010)

Collapse of the Beaulieu mine at Château-Landon

Chalk mines experienced several large-scale collapses: Château-Landon (Île-de-France) in 1910, Clamart (Île-de-France) and 1961 (Al Heib et al., 2014), Cruzilles (Centre-Val de Loire) in 1990 (Figure 3). More recently, in 2015 (Georgieva et al., 2019), the collapse of chalk mines at La Malogne in Wallonia (Belgium) caused significant damage to the TGV line (Brussels-Paris high-speed train).

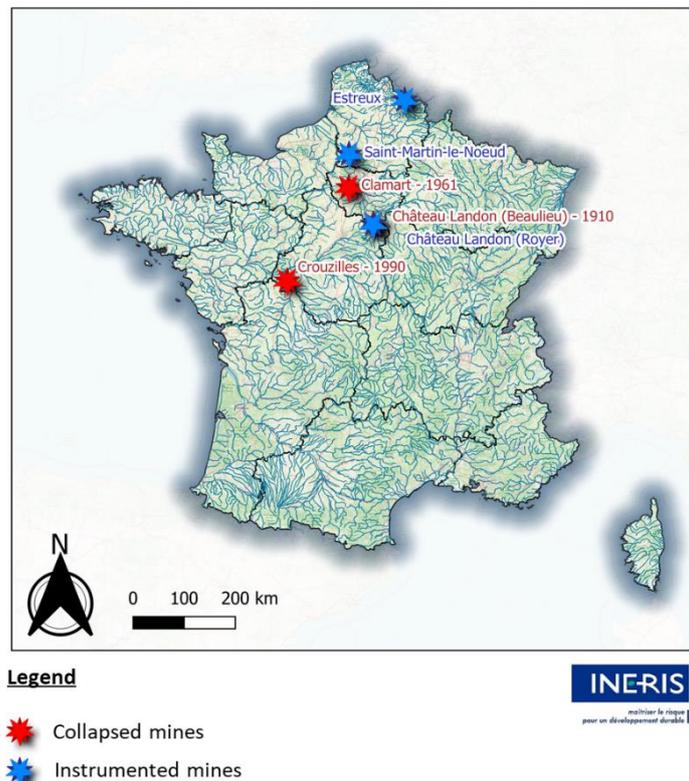


Figure 3. Collapsed mines at Crouzille (1990), Clamart (1961) and Château Landon (1910), and mines instrumented by Ineris at Estreux, Saint Martin le Nœud and Château Landon.

The catastrophic collapse of the Beaulieu mine on 21 January 1910 is the only one that has been documented among the 4 collapses that occurred in the Château-Landon municipality. The sudden collapse of the hillside excavated by the mine and the ensuing landslide (**Figure 4**) took several housings located along the Loing canal and caused the death by burial of 7 people. The volume of material suddenly set in motion is estimated at 100,000 m³. The collapse extended over a line of around one hundred meters and the tear-off surface, around twenty metres high, was located about forty metres back from the original edge of the hill.



Figure 4. View of the area after the collapse (source: DRIEE IdF archives) The tear-off surface can be seen at the far end.

Gombert & Cherkaoui (2011) propose the following stages of the disaster (see **Figure 5** and **Figure 6**):

- 1) After 10 days of important rainfall (48 mm) on ground made impermeable by frost, a new significant rainfall episode (27 mm) occurred on 19 January 1910;
- 2) The Loing was then heavily flooded the next day, with a peak of 3.90 m at the Nemours scale i.e. a rapid rise of water of about 1.8 m. The Fusain and the Betz local tributaries were also flooded, which contributed to the flooding of the alluvial plain located at the foot of Lorroy hamlet; however, witnesses

reported that the flood water stopped at the edge of the road and do not enter the underground galleries of the mine (Liénard, 1910);

- 3) The alluvial aquifer, which was in direct hydraulic connection with the rivers, then rose by a few metres;
- 4) This created a hydraulic dam phenomenon which blocked the flow of the chalk aquifer towards the valley and induced a rise of several metres in its water table, which in turn caused flooding of the lower parts of the old areas of the mine; testimony by the mushroom cultivator who used them indicated that on the day of the disaster, he saw the northern galleries flood under 0.20 to 0.40 m of water which was rising from wells installed in the mine (Liénard, 1910 ; Watelet & Kréziak, 2010); these wells (called “fountains” in **Figure 6**) were 2 m deep, which implies a rise in the water table of the same magnitude;
- 5) At 13:10 on January 21, 1910, the disaster occurred, causing the mass collapse of the northern part of the mine; the flooding caused the failure of the so-called “small pillars” in that northern part, followed by the rest of the cavity; the collapse of that terrain then triggered a concomitant landslide up to a major fracture located 40 m further back.

Recent observations confirmed the previous analysis and explanation. In fact, the monitoring of small floods between 2010 and 2013 in a piezometer installed above the old Beaulieu mine has shown that the chalk aquifer reacts almost synchronously with variations in the level of the Loing, with an amplitude that consistently exceeds that of the Loing flood level by 10 to 85%. This analysis confirms the observations reported during the 1910 collapse.

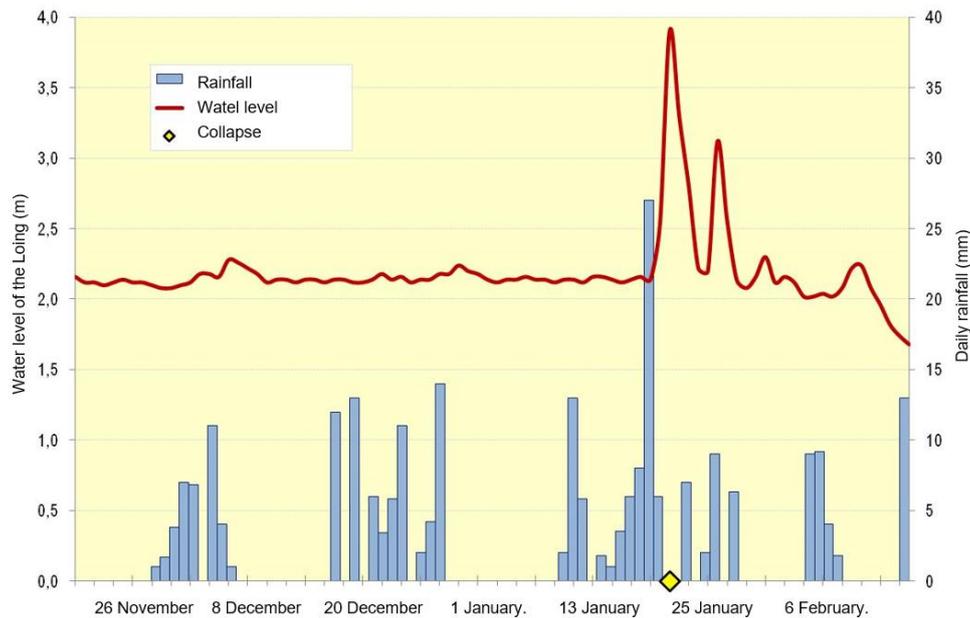


Figure 5. Daily rainfall and hydrology at Nemours during the two months preceding the collapse of 21/01/1910

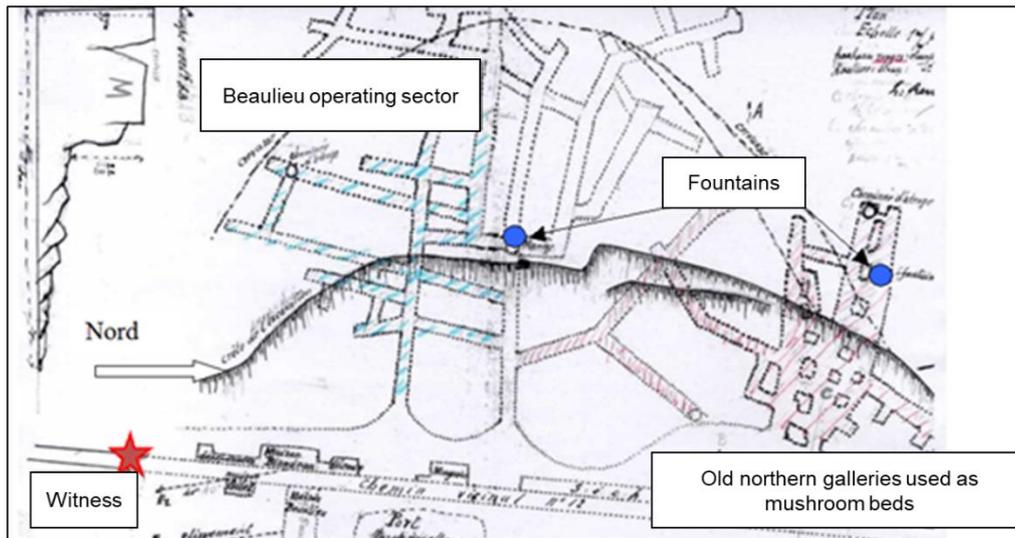


Figure 6. Diagram of the collapse zone established in 1910 by the Mine authorities (in Watelet et al. 2016)

In this context, it seems that the two major factors leading to the collapse of the Beaulieu mine in 1910 were the rise of the water table, causing the saturation of the pillars, and a sudden deterioration of their mechanical properties. However, while the analysis has demonstrated the rapid rise of the water table prior to the collapse, several questions remain unanswered. If the collapse of the most mined area of the northern part of the Beaulieu mine seems logical, the propagation of the upheavals towards the more massive pillars in the south is difficult to explain. In fact the complete collapse fact infers that the destruction of one part of the mine could spread to the entire underground structure and cause a sliding of the entire hillside. The analysis of the aggravating factors, which are the modification of the stress field at the edge of the hillside and the effect of the over-stress linked to the collapse of the northern area, remains incomplete, for lack of information on the exact geotechnical state of the galleries of the Beaulieu mine at this time.

To examine the potential collapse of Royer mine, a comparison of the Beaulieu (already collapsed) and Royer (not yet collapsed) mines was made by Gombert and Cherkaoui (2017); they realised in situ observations of the geology and the geotechnical – hydrogeological conditions. This comparison turned out to be relevant as it highlights various similarities:

- in terms of geometry, both mines have an entry at the foot of a hill that is between 25 and 40 m high. Their geometry (rooms and pillars) is irregular with one or more heavily mined zones, while the mine is only partly mined;
- in terms of geology and geomechanics, it is the same chalk that is known to suffer a sharp decrease in its resistance when it is fully saturated;
- in terms of deterioration, it is possible that the fracturing corridor located 40 m back from the face of the slope is identical on the two mines; it would correspond to the tear-off zone visible on the **Figure 4** on the site of the Beaulieu mine and the large fractures spotted at the same distance from the slope in the Royer mine.

Given the similarities between the two mines (collapsed and non-collapsed) and the recent observations in the Royer mine (some damage was indeed noted) following the 2016 hydroclimatic event which caused the same type of flooding as in 1910, these observations show that a large collapse of the Royer mine can be considered. Thus, it was decided to instrument the Royer mine in order to monitor the evolution of the site in the long-term, particularly during the occurrence of new extreme hydroclimatic phenomena (heavy rainfall and/or major flooding). The aim is to better understand the hydromechanical phenomena underpinning the instabilities of abandoned mines. It is important to study the prevailing hydroclimatic conditions during the occurrence of these events, but also to try to identify potential aggravating factors such as the geometry of the mine, the nature and height of the overburden, the resistance of the mined rock, the state of fracturing or the possibility of water infiltration at the mine surface.

Feedback from sites previously instrumented

Aware of the fragility of these mines and the importance of large-scale collapse, Ineris has since 2004 instrumented chalk mines subjected to water table fluctuations (Gombert et al. 2013). The first one, located at Estreux, (Nord - France) (**Figure 3**) was temporarily flooded after each episode of heavy rainfall, due to the rise in the water table (Gombert et al. 2018). One pillar was instrumented using two extensometers anchored at 0.10 m and 0.70 m depth,

a convergence rod, and 3 pore pressure sensors. Additionally, the water table was monitored by a piezometer installed near the access shaft. The monitoring, which lasted 8 years from 2004 to 2012, mainly showed seasonal water table fluctuations marked by a lateral extension of the pillar that were related to piezometric cycles. The amplitude of these fluctuations reached 14% at 0.10 m depth and 5% at 0.70 m depth (Figure 7). In addition, the deformation due to the total extension of the pillar, which is greater in its peripheral zone ($1.34 \text{ mm}\cdot\text{m}^{-1}$) than in its central zone ($0.3 \text{ mm}\cdot\text{m}^{-1}$), shows that the geomechanical behaviour depends significantly on the differences in water content within the pillar, induced by water table fluctuations. However, during the observation period, the pillar deformation remained small in magnitude compared to a state of potential destruction.

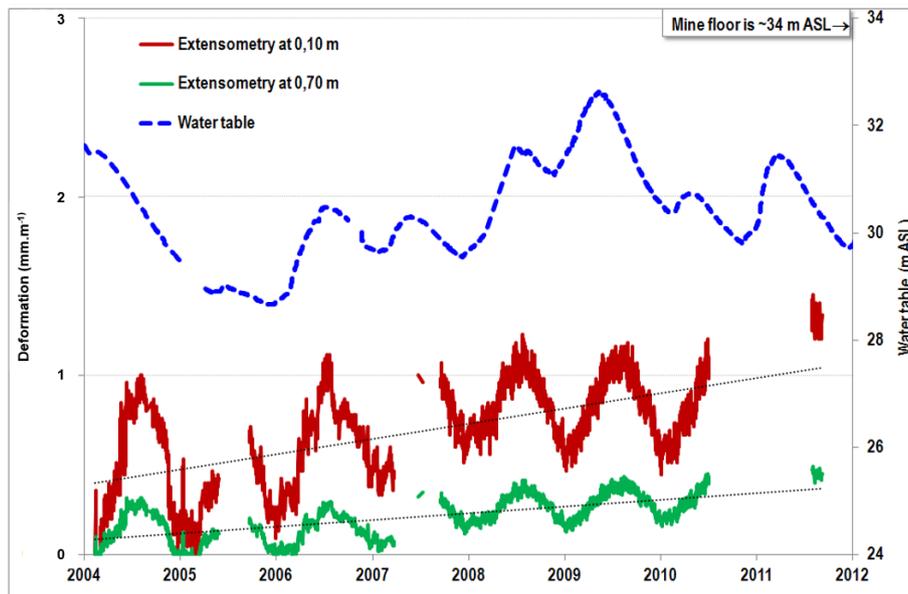


Figure 7. Evolution of the deformation ($\text{mm}\cdot\text{m}^{-1}$) of the pillar at two different depths as a function of the piezometric fluctuations at Estreux chalk mine (Gombert et al., 2013)

The second chalk mine is at Saint-Martin-le-Nœud (**Figure 3**). It has been partially submerged for over a century with water level fluctuations that may reach a metric amplitude (Gombert et al. 2013). Here, also one pillar was instrumented using 2 convergence rods, 2 double-anchored extensometers (0.50 m and 1.0 m), 1 suction sensor and 3 TDR probes to measure the water content of the pillar. In addition, 1 piezometric sensor measured the water level of the lake and its physic-chemical characteristics (temperature, conductivity, pH). Monitoring period was shorter than that of the Estreux mine as it lasted only 3 years from 2009 to 2012. The Saint-Martin-le-Nœud chalk turned out to be more resistant mechanically than expected and relatively less sensitive to water. These findings were consistent with the results obtained on core samples by Lafrance (2016). Besides, the monitoring period ended with a drop in the flooding level, interspersed with a period of slight rise (0.40 m maximum). The recorded deformations were consequently of little significance, but the data revealed the penetration of a moisture front within the pillar to at least 0.20 m depth, associated with hydrological cycles (**Figure 8**).

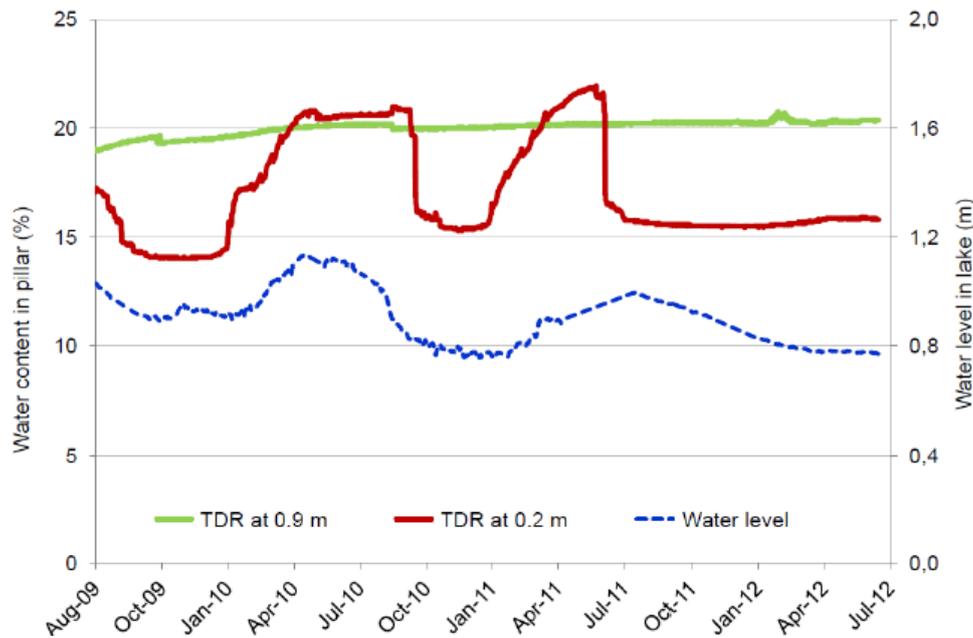


Figure 8. Evolution of the pillar water content at two different depths as a function of piezometric fluctuations at Saint-Martin-le-Nœud chalk mine (Gombert et al. 2013)

Presentation of the Château-Landon observatory

These two previous projects provided useful experience for selecting a new test site and designing the protocol of instrumentation to be able to study the role of water in the stability of chalk cavities. The major criteria that were considered when searching for a new test site were: its geomorphological position in a valley, similarities with and proximity to the Beaulieu mine that collapsed in 1910, and chalk of a particularly water-sensitive nature (Lafrance, 2016), which renders it potentially more susceptible to hydroclimatic phenomena.

The selected site was the Royer mine, located in Château-Landon (Figure 3). This selection is motivated by the proximity of the previous catastrophic collapses (from 1876 to 1910) and the similarity to Beaulieu and Royer mines (Figure 2).

Topographic and hydrological contexts

The studied zone is at an altitude of 70-80 m ASL at the base of the hills, on the left bank of the Loing river, at the foot of the Gâtinais plateaus which peak here at around 100-110 m ASL. In the zone to study, the Loing is joined by the Fusain on the left bank and thus locally forms a large alluvial plain with a flat bottom and a slight inclination. The Loing flows here at around 67 m ASL. Its average inter-annual flow rate is of 15 m³/s, against a maximum flow rate during flooding of about 300 m³/s, with a flood water level that then exceeds 3 m.

Geology and hydrogeology

The Gâtinais plateau is made of sedimentary rocks from the Tertiary era resting on Campanian chalk (c₆) and locally covered with quaternary loess (LP) (Figure 10). The chalk outcrops on the valley edges and bottoms, in a sometimes massive form with flint, sometimes loose and crumbly: it was under this latest facies that it was formerly exploited in mines under the name of "Blanc de Meudon". This formation is overlaid with a few metres of flint clay (RS) then by Tertiary layers which are from bottom to top (cf. Figure 9 and Figure 10):

- the Chailles or Nemours puddingstones (e_{7p}) from the Priabonian, with a maximum thickness of 15 m, made up of a conglomerate of pebbles of various sizes and origins (chalk flint and Jurassic "chailles") with a non-plastic lean clay matrix; this formation is found in the filling of karstic chalk channels, particularly in the Royer mine;
- the upper Ludian Château-Landon limestone (g₁), 12 to 15 m thick, formed of large banks of whitish to locally grey marly limestone, separated by greenish marly to clay beds;
- a layer of sands from the Middle Stampian (g_{2b}) [also called Rupelian] present at reduced thickness north of Château-Landon;
- the upper Stampian Gâtinais limestone (g_{2c}), 12 to 15 m thick, which forms the backbone of the plateaus on the left bank of the Loing; it is a lacustrine limestone interspersed with marly levels.

The Loing and Fusain valleys are, moreover, recovered by recent alluvium (Fz) made up of 1 to 2 m of silt over 4 to 6 m of sand and gravel.

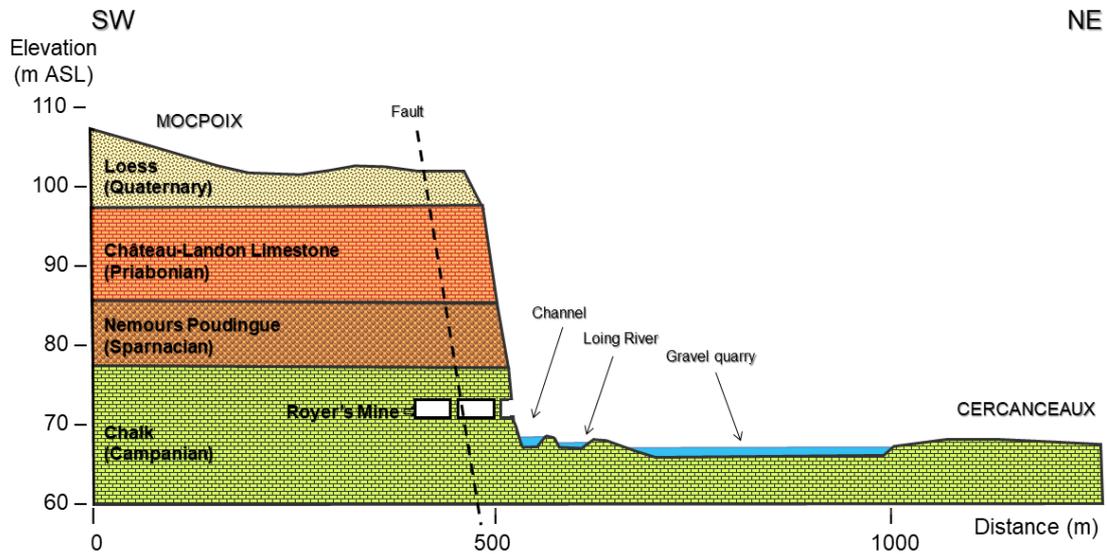


Figure 9. Geological section of the Château Landon site

Hydrogeologically, the main aquifer is the chalk aquifer, which is sometimes overlaid by the limestone aquifer under the plateaus, and sometimes by the alluvial aquifer in the valleys. In the Loing valley, the water table of the alluvial aquifer is very close to the surface (between 1 and 2 m deep) and is hydraulically connected with the underlying chalk aquifer. The limestones form a multi-layer aquifer corresponding to the eastern end of the vast aquifer known as the "Beauce limestones" aquifer, mainly fed by rain falling on the surface of the plateau.

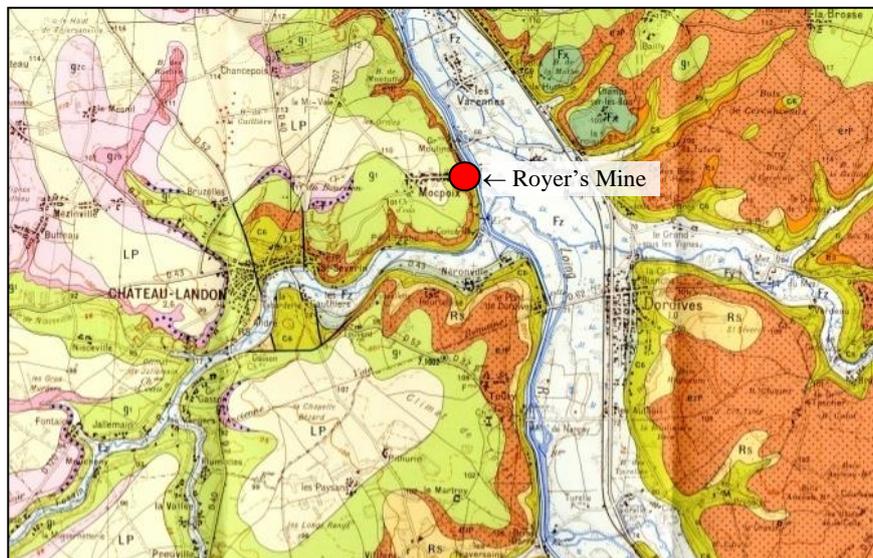


Figure 10. Geological map of the surroundings of Château-Landon (see captions in the text) (after Infoterre)

The Royer mine

Mine geometry

The mine was exploited for making a powder used as a base for paints: it was called “Blanc de Meudon” [“Meudon White”]. The Royer mine was exploited in the 19th century according to the room and pillar mining method. The mine has two entrances, 35 m apart, located at the foot of a 25 m high hill. It is made up of two main galleries of about 10 m² cross-section, which penetrate perpendicular to the cliff for 80 m from entrance A (zone A) and 60 m from entrance C (zone C) (Figure 11). These two galleries then branch out and are notably linked to each other towards the end of the mine, by two transverse galleries with a total length of about 100 m. Small pillars have been left at the edge of the hillside (2.5 to 3.5 m side) and wide galleries deeper inside (4 to 5 m wide) (Figure 11). In general, it has a low extraction rate (less than 45%) except for an area to the north which has an extraction rate of around 75%. Without considering mechanical deterioration, the critical point of the mine in geometrical terms is located at the level of this area with a high extraction rate, corresponding to the most used zone.

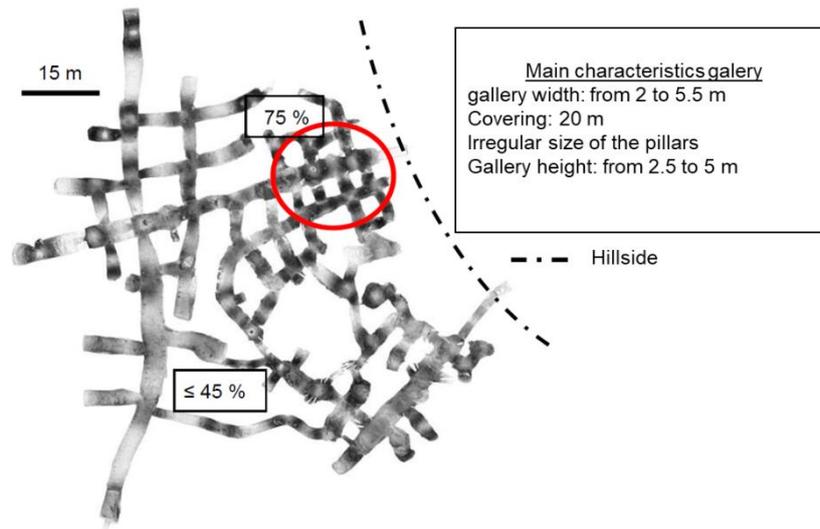


Figure 11. Plan of the Royer mine showing the different extraction rates (45% and 75%) and the main geometric characteristics of the galleries

Visual observations of the mine

In order to better assess the state of the Royer mine and its evolution, visual inspections and degradation readings have occasionally been carried out there since 2015 (Figure 12). In addition to several observations of disorders linked to the ageing of the underground structure (mechanical cracks, falling rocks, fracturing of the facing and pillar edges), these investigations revealed the presence of a large sub-vertical fault which is representative of the stresses that the chalky rock mass was probably subject to. We also noted the presence of paleokarstic channels of variable diameter (0.5 to 3 m), filled with Nemours puddingstone elements, which may indicate weak points in the rock mass as well as possible water inlets.

The characterisation of about fifty fractures (Figure 12) has revealed dominant directions between N010 and N120, corresponding to the orientation of the Loing valley upstream (N015) and to that of its main tributary, la Cléry (N100). According to the observations made in other chalk mines (Moiriat et al., 2005), this direction reflects the influence of decompression phenomena linked to river digging. However, other families of fractures are present and may have been under-sampled during the surveys.

In general, the entire gallery is heavily fractured, as is shown by the photos taken from the roof of the gallery (Figure 13), and it is currently difficult to account for this fracturing density using the cartographic surveys, which are not exhaustive. This intense fracturing affects the pillars as well as the roofs of the galleries, with the embankments on the ground hiding the fracturing at the base of the walls. More than three quarters of fractures are without displacement (diaclasses), the majority being closed. Split-level fractures are normal, radial or stepped flaws, showing openings and level differences of a few mm to a few cm. Apart from a few fractures enlarged by karst dissolution processes, the others are open and either dry or filled with brown or ochre clays or a siliceous vein. This latter observation indicates the existence of a fracturing prior to the diagenetic precipitation of silica which may be of tectonic origin. The dip of the fractures is essentially large (> 65 °) to subvertical, which could favour large masses of chalk remaining intact during pillar failure events, without spalling or shearing.



Figure 12. Cartographic survey of the most important fractures of the Royer mine (Cerema, 2020)



Figure 13. Photos of the roof of one of the galleries. The multiple conjugate fractures (arrows) testify to the intense fracturing of the galleries (Cerema, 2020).

In addition, the full 3D scan of the mine (**Figure 14**) has clearly revealed the profile of the large fault parallel to the slope and located about forty metres behind.

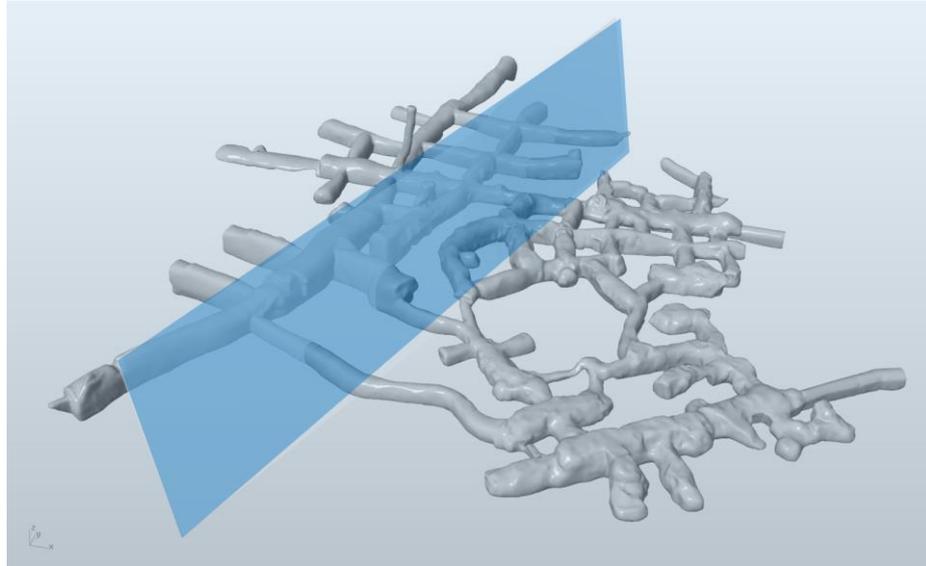


Figure 14. Layout of the galleries and main fault planes highlighted by the 3D scanner survey

Following the extreme hydroclimatic event of June 2016, although no significant disorder of the structure had been seen previously, spalling on the facings and a collapse along the large identified fault had been observed, as well as movements of the embankment near the entrance (**Figure 15**). This attests to the active character of the deterioration, under the influence of heavy rainfalls which caused more than a once-in-a-century flooding of the Loing.



Figure 15. View of the disorders observed after the extreme hydroclimatic event of June 2016, affecting a fault (on the left) and packing down the brickwork through the remobilisation of the embankments at the base of the galleries (on the right)

Behaviour of Château-Landon chalk

As mentioned before, generally chalk is a porous rock, sensitive to water. Its mechanical behaviour depends on its physico-chemical properties. In 1910, chalk samples were taken from the Royer mine to determine the properties of the rock (Munos-Castelblanco et al., 2011) and more recently by Lafrance (2016). A summary of the principal characterization results is presented here-after.

The Château-Landon chalk is composed of 84% micrite and 13% sparite. It has a porosity of about 45% and its water content in the natural state is around 30% (Lafrance, 2016). Its gas and water permeabilities are respectively 10^{-14} m^2 and $2 \cdot 10^{-16} \text{ m}^2$ in laboratory conditions (Munos-Castelblanco et al., 2011, Souley & Lafrance, 2017).

Regarding its mechanical characteristics: under dry laboratory conditions, its average uniaxial compressive strength (UCS) is 4.5 MPa. Saturation of this chalk sample makes this compressive strength suddenly drop to 0.8 MPa i.e. practically 17% of its dry strength. This is therefore a chalk that is highly sensitive to water. In the dry state, the chalk breaks mainly through shear action even if it tends to collapse under a confining pressure greater than 3 MPa. When the material is fully saturated, the shape of the break is not as sharp, the chalk crumbles as it rapidly becomes plastic regardless of its confining pressure (Munos-Castelblanco et al., 2011, Souley & Lafrance, 2017). The Château-Landon chalk is extremely sensitive to water in comparison with other types of chalk, for example the chalk from the mines of St. Martin-le-Nœuds or even of Extreux (Lafrance, 2016).

Regarding the long term and creep behaviour of this chalk: though few tests were carried out, Lafrance (2016) shows that the creep behaviour of the chalk is influenced by:

- the mineralogy/microstructure of the chalk;
- hygrometry which hugely increases the amplitude of viscoplastic deformations and drives an increase in the deferred deformation speed;
- the deviator which also increases viscoplastic deformations;

The mechanisms believed to be at the origin of deferred deformations are of a physico-mechanical nature.

3D hydro-mechanical numerical model

A 3D preliminary numerical model was built using the terrain model including the underground mine (**Figure 14**) to build the 3D numerical model of the Royer mine. In addition to geology, the model incorporates the fault that is believed to play a role in the formation and occurrence of a potential collapse. The main objective of the numerical modelling was, additionally to the in situ investigations, to identify the most critical areas in terms of stress and strain concentration (**Figure 16**).

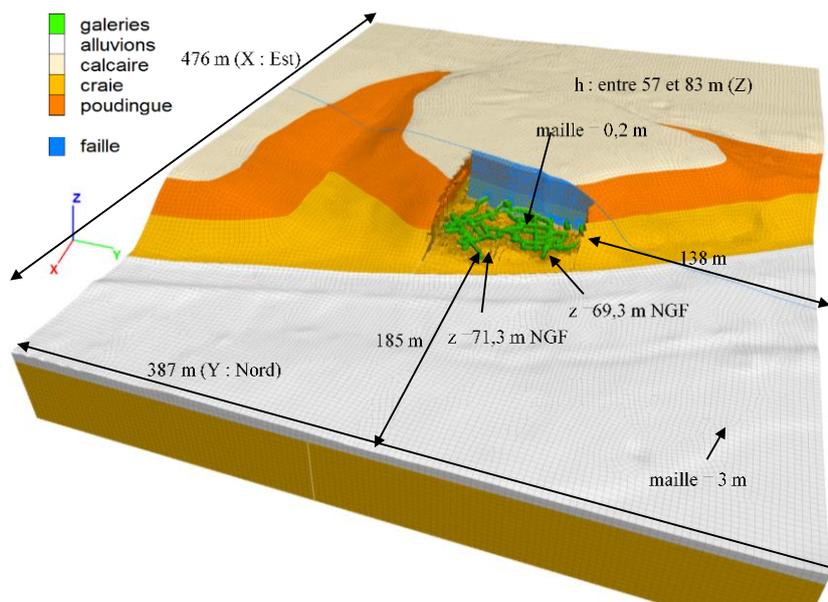


Figure 16. 3D model of the Royer mine taking into account the geology and the presence of the observed fault (Renaud et al., 2019).

Table 1 summarizes the geomechanical parameters associated with the various laws of behaviour (elastic and elastoplastic) used in the numerical modelling. Certain values come from laboratory measurements resulting from the work of Lafrance (2016), others are estimates based on the following assumptions:

- the elastic properties of puddingstone and recent alluvium are based on a bibliography on the Paris Basin (Filliat, 1981);
- it is assumed that the partially desaturated chalk ($s = 70-80\%$) from Château-Landon has the same properties as that from mines exploited south of Paris (Renaud et al., 2019).

These geomechanical parameters incorporate an alteration of the properties of chalk over a distance of 20 m, starting from the edge of the hill, which corresponds to the gradual transition from soft chalk to a harder chalk. The initial vertical stresses correspond to the weight of the terrain. In the absence of stress anisotropy data, the

classic stress ratio assumption $\frac{\sigma_h}{\sigma_v}=0,5$ was adopted.

Table 1: Mechanical characteristics (elastic and elastoplastic) of the geomaterials of the Royer mine rock mass in Château-Landon)- Legend: the values in bold correspond to weathered chalk

Designation	Symbol	Unit	limestone	puddingstone	recent alluviums	chalk	saturated chalk
Mass density	ρ	kg.m ⁻³	2580	2000	1800	2000	
Young's Modulus	E	MPa	4000	3000	200	500	100
Poisson coefficient	ν	-	0.3	0.3	0.3	0.22	0.23
Cohesion	C	MPa	Elastic			0.38 to 0.75	0.16 to 0.32
Friction angle	φ	°				16	12.6
Tensile strength	TS	MPa				0.1 to 0.2	0.04 to 0.08
Uniaxial compressive strength	UCS	MPa				1.0 to 2.0	0.4 to 0.8

These results of the calculations have shown, above all, that the small-pillar zone is the most critical zone, and that the rise of the groundwater in the mine would be the predominant factor behind the instability of the Royer mine because it is likely to rapidly change the geomechanical properties of this chalk. In addition, the presence of the fault could, to a lesser extent, locally worsen its effects (Renaud et al., 2019) (**Figure 17**). Three zones have been revealed by these preliminary numerical modelling (Renaud et al., 2019):

- two potentially unstable zones (A and B), the so-called “small-pillar” zone (zone A) and the so-called “fault plane” zone (Zone B);
- a control zone which does not appear to be subject to significant ground movements (zone C).

As previously indicated, the water permeability in the chalk is low ($2 \cdot 10^{-16} \text{ m}^2$), so it can prevent the water flow. So although this factor was not taken into account in these purely mechanical calculations, one can imagine that in the case of a strong and violent water inflow, overpressures could then appear in the rock mass thereby aggravating the instabilities already caused by the decrease of the mechanical properties.

In this context of the risk of collapse of this mine and comparable mines, only scientific instrumentation can provide the data necessary to improve the collapse prediction model based on the consequences of climate change characterised by heavy rainfall.

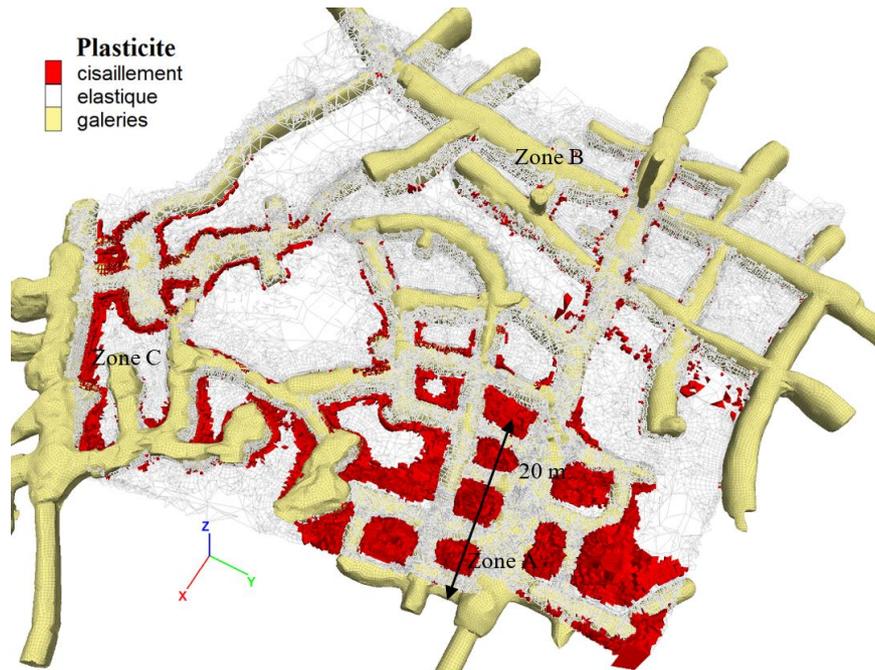


Figure 17. Distribution of plasticity (shear failure) in the chalk pillars as a result of the weakening of the base of the pillars caused by a rising water table (here, the water table is at 72.8 m NGF) (Renaud et al., 2019)

Instrumentation

Based on these numerical results and on-site observations, two types of parallel monitoring were set up: monitoring of the “water” phase and monitoring of deformations of the rock mass. More than 50 sensors have been installed in areas A, B, and C (Table 2, Table 4) as well as outside the mine (Table 3, Figure 18).

All measurements make up a part of the observatory which has been sized in order to correlate water data (variations in water table, water saturation of the chalk, and air humidity level) and acquired geotechnical data (deformation and failure of the pillars, roof, and of the fault). At the same time, regular monitoring of the evolution of the state of fracturing of the structure has been set up to monitor its evolution over time.

Monitoring of the “water” phase

The aim of monitoring the “water” phase is to know the evolution of the water table upstream and downstream from the mine, the water content of the rock mass, the mine’s internal atmosphere humidity level, and any flow of water via the covering land. To do this, an important instrumentation have been set up:

- 2 piezometers: SD1 (upstream of the mine, on the plateau) and SD2 (immediately downstream of the mine, near the entrance) with probes measuring the water table as well as its temperature and conductivity; these piezometers, the location of which is shown in **Figure 18**, make it possible to monitor the evolution of the chalk aquifer characteristics on either side of the mine;
- 4 humidity and temperature sensors in the galleries in order to determine the level of humidity of its internal atmosphere and monitor its evolution in time and its influence on the parameters of the rock mass;
- 10 water content sensors in order to monitor the water content of the chalk, to calculate the water saturation and to observe the evolution of the saturation front in the wall as a function of fluctuations in the chalk’s water table and air humidity;
- 6 suction sensors in order to monitor water movements within the rock mass;
- 1 water level-meter device to monitor the water level in the Loing river near the mine, the level of the canal having already been measured and supplied by Voies Navigables de France (VNF) company.

Monitoring movements in the mine

The aim of this instrumentation is to monitor gallery wall deformations and movements, as well as the evolution of existing instabilities. The instrumentation that has been set up is as follows:

- 5 wire extensometers, in the small pillars zone (zone A) and in the control zone (zone C), in order to monitor the convergences of the gallery;
- 3 extensometers with double anchoring in the boreholes of zones A, B, and C to observe the lateral movements of the pillars and walls of the mine in the horizontal plane;
- 1 horizontal radar to measure the movement of the fracture plane located in front of the collapse of zone B;
- 1 vertical radar on the roof of zone C in order to monitor the movements of the embankment;
- 1 acoustic network of 4 triggered microphones in order to detect any cracking or falling rocks;
- 1 fissurometer on one of the cracks present in the facing located behind the fracture plane.

To analyse the mine's climatic conditions as well as the effect of external conditions, a temperature sensor has also been installed at the entrance to the mine. Atmospheric temperatures and rainfalls are obtained (via the Meteo-France site) from the Nemours meteorological station which is located about fifteen kilometres northwards from the mine.

Table 2 Instrumentation of the Château-Landon observatory: measurements in the galleries

Type of measurement	Name	Position	Precision	Objective	Location
Volumetric water content	10	5, 20, 50 cm from the wall	$\pm 1\%$	Monitor saturation of the rock mass	Zone A
		5 cm			Zone B (2a)
		5, 30 cm from the wall			Zone B (2b)
		5, 30, 50 cm from the wall			Zone C
		15 cm within the embankment			
Movements in the boreholes	3	65, 130 cm from the wall	± 0.15 mm	Monitor deformation of the rock mass	Zone A
					Zone B (2b)
					Zone C
Convergence	5	1 horizontal	± 0.15 mm	Monitor the gallery wall movements	Zone A
		1 oblique			
		1 horizontal			Zone B (2b)
		1 horizontal			Zone C
		1 oblique			
Opening of fissure	1	NA	± 0.25 mm	Measure a fissure's gap	Zone B (2b)
Humidity	4	In the gallery	$\pm 2\%$	Monitor ambient humidity in the zone	Zone A
					Zone B (2a)
					Zone B (2b)
					Zone C
Temperature	5	In the gallery	± 0.5 °C	Monitor ambient temperature in the zone	Zone A
					Zone B (2a)
					Zone B (2b)
					Zone C

		In front of entrance A, outside the mine		Monitor temperature variations outside the mine	Entrance A
Suction	6	10, 30, 50 cm from the wall		Monitor water pressure in the rock mass	Zone A
		40 cm from the wall			Zone B (2a)
		40 cm from the wall			Zone B (2b)
		40 cm from the wall			Zone C
Radar	2	Horizontal	± 2 mm	Monitor the movement of the fault plane wall	Zone A
		Vertical		Monitor the movement of the embankment	Zone C

Table 3 Instrumentation of the Château-Landon observatory: piezometric measurements

Name	Type of sensor	Measurement	Precision
SD1 - village	Piezometric level sensor	Water level	± 5 mm
		Temperature	± 0.25 °C
SD2 - mine	Piezometric level sensor	Water level	± 10 mm
		Temperature	± 0.25 °C
		Conductivity	± 1.5 $\mu\text{S}\cdot\text{cm}^{-1}$

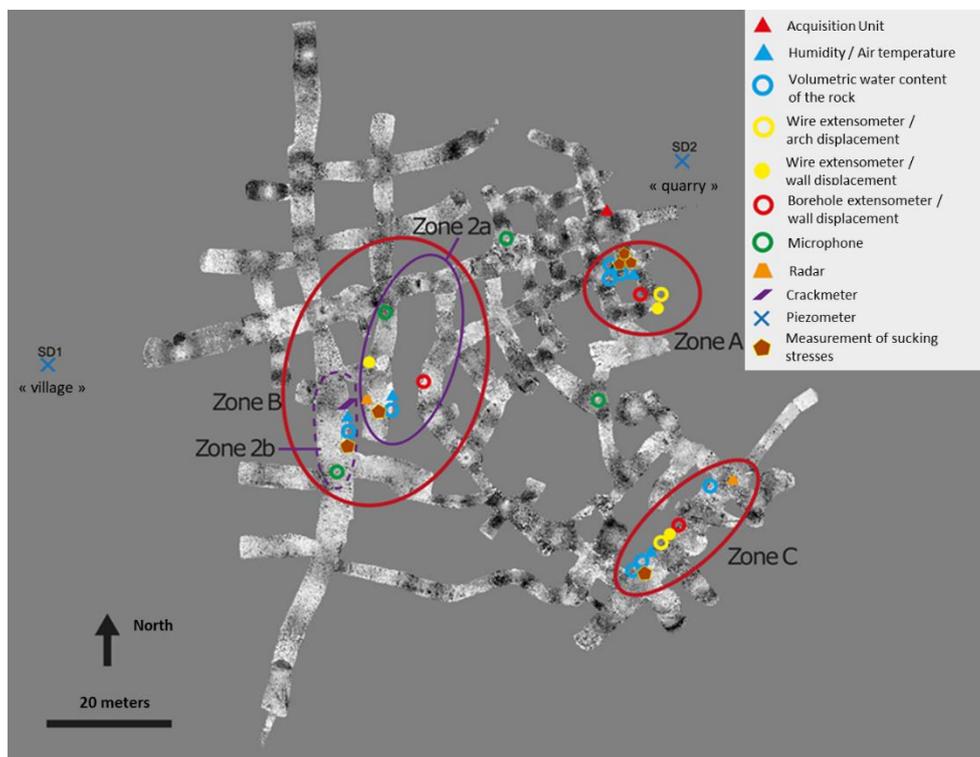


Figure 18. Location of the instrumentation set up in the Royer mine. More than 50 sensors have been installed in the three zones A, B, and C.

The instrumentation has been designed to meet the different objectives. In zone A, one of the pillars was selected in order to study its behaviour, taking into account the seasonal variations of the water table. The choice of this pillar was made taking into account its small diameter and its proximity to the entrance, where the impact of the water table's fluctuation is assumed to be stronger than at the back, under normal climatic conditions. Let us remember that in the Beaulieu mine, it was the destruction of the smallest pillars that led to the complete collapse. Water content sensors were installed to monitor the variation in the saturation of the pillar over time. In order to quantify the flow of water in the pillar, suction sensors were added. Between the pillar and the gallery walls, wire extensometers were placed in order to measure vertical and horizontal convergences. Finally, a multipoint extensometer was installed in the borehole in order to follow the movements of the rock mass (**Figure 19**). In the adjoining gallery, ambient temperatures and humidity are measured and compared to temperatures outside the mine.

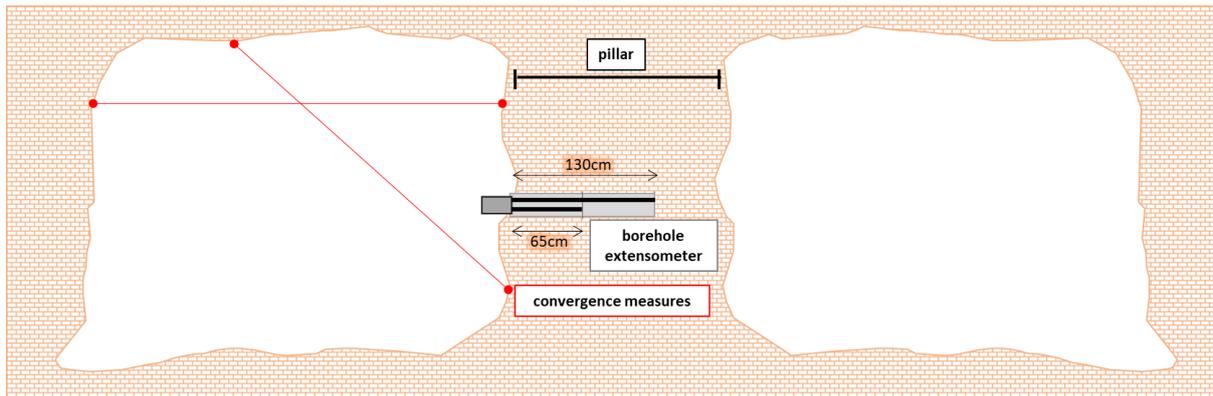


Figure 19. Schematic representation of the location of the extensometers in the small pillar zone - zone A

As mentioned before, the collapse occurred in 2016 at the level of the fault in the Royer mine. A similar fault was also observed in the Beaulieu mine. According to the investigations, the fault probably played either a primary or an aggravating role. In order to study the impact of seasonal variations and especially variations in water in the rock mass, specific instrumentation was put in place at the fault plane. This instrumentation, consisting of a water content sensor and a suction sensor associated with strain gauges and a radar should make it possible to observe the swelling that may arise, in particular through water seeping in from the overlying terrain, given the high density of fracturing that has been noted. In order to verify this point, a rain gauge has been installed at the base of a fracture to measure the potential water inflows. This instrumented zone, denoted zone B, is schematically shown in **Figure 20**.

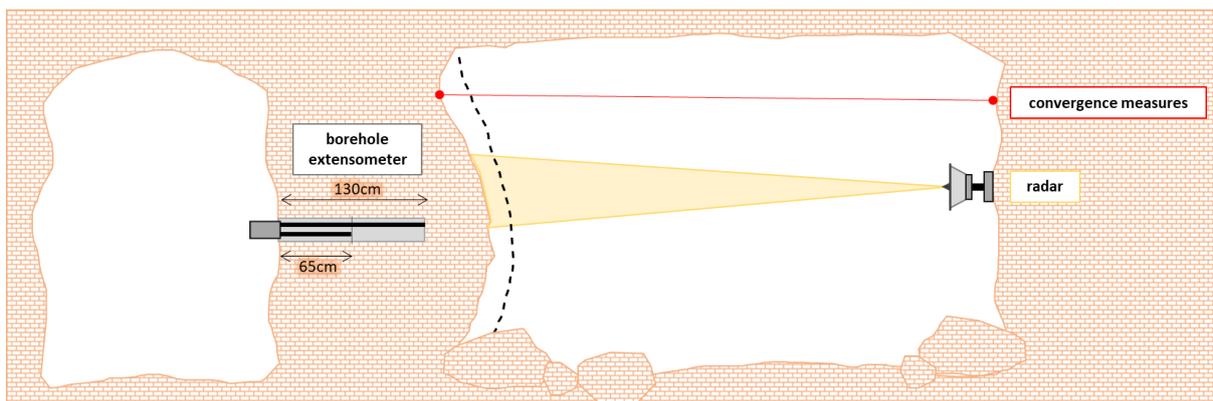


Figure 20. Schematic presentation of the location of the extensometers and the radar measurement in the fault plane zone - zone B - zone 2a

Not very far from the fault plane, a fracture (Zone B - Zone 2b) has been selected in order to monitor its evolution over time, during which readings will be carried out regularly with the aid of a 3D laser scanner, so as to verify the evolution of the mine's general state of fracturing. In this zone, measurements of the water content and suction are carried out at different depths. Temperature and humidity sensors make it possible to monitor the evolution of the zone's climatic conditions.

Zone C, known as the control zone, has been highlighted by simulations (Figure 17), in particular because this part of the mine seems to deform very little in the event of a rise of the water table. Measurements coming from this zone can therefore be compared with zones that are potentially more unstable. Water content sensors have been set up in the embankment in the hope of obtaining an indication of the water table, particularly in the event of an unusual rise. A suction sensor has also been added to the wall. Convergences of the gallery as well as movements of the rock mass are monitored. Finally, a radar has been set up to monitor the movements of the embankment (**Figure 21**). Indeed, let us remember that we assume that the events of 2016 are at the origin of the damage noted in the brickwork which is located nearby (Figure 14).

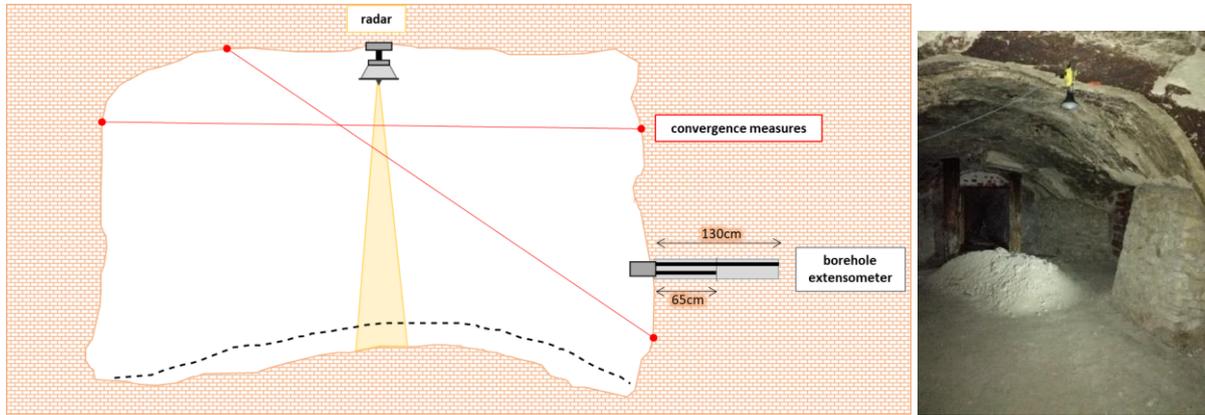


Figure 21. Schematic presentation of the location of the extensometers and radar measurement in the control zone - Zone C' (at left) and photo of the radar (at right)

Along with this instrumentation, an acoustic listening network made up of 4 microphones distributed throughout the mine has been set up. This monitoring method implemented by Ineris for many years in different places makes it possible to detect, record, and characterise the sounds associated with the evolution of the structure and, in particular falling boulders. Other disorders can also be detected: the phenomena of spalling, fracturing, infiltration of water, etc. The reason for choosing this method for the Château Landon observatory is that several boulder falls have already been observed, particularly in 2016. These could potentially be repeated. It is a “volumetric” measurement that complements the more local measurements carried out by the extensometer and convergence measurements. It therefore makes it possible to detect phenomena - over a larger extent of the mine - that are more or less significant, depending on the conditions. This method also makes it possible to locate the source of the event and to characterise it i.e. provide an assessment of the size of fallen boulders without having to enter the mine (Nadim et al., 2013).

Table 4 Instrumentation of the Château Landon observatory: acoustic network

Location	Type of sensor	Name	Precision
Zone A	Microphone probe	Microphone 3	
Zone B: Zone 2a	Microphone probe	Microphone 1	0.025 Pa
Zone B: Zone 2b	Microphone probe	Microphone 2	
Zone A -Zone C	Microphone probe	Microphone 4	

The first results of the continuous monitoring seem to indicate that while the climatic variations recorded over the year 2021 - particularly regarding the amount of rainfall - are not exceptional, they have clearly influenced the water table of the chalk aquifer (**Figure 22**). On the plateau (piezometer SD1), the average piezometric level of the chalk aquifer is 70 m ASL. Low water occurs in November-December with values below 67.4 m ASL. It is quickly followed by a replenishment which exceeds 72.6 m ASL, with a peak in February-March. The annual chalk water table fluctuation here is therefore of the order of 5.2 m. The behaviour differs significantly downstream of the mine (piezometer SD2), where, under the influence of the Loing, we observe a quasi-stabilisation of the

piezometric level at around 66,7 m ASL, from which some peaks emerge corresponding to the more significant rainy or hydrological episodes. High water levels are brief and also occur in February-March with values above 67.3 m ASL. The annual fluctuation of the chalk water table buffered by the alluvial water table is only 1.3 m here. The Loing canal runs along the foot of the landform where the mine is dug and is located between it and the Loing, about 2 m above the latter. The canal, however, does not seem to play any hydrogeological role next to the mine, because it is probably watertight. On the other hand, it forms an obstacle to the chalk aquifer, forcing it to pass underneath the anthropic channel in order to rejoin the Loing's alluvial aquifer. To complete this setup, and understand the impact of variations in the level of the Loing on that of the water table, a water level meter was recently installed directly in the Loing.

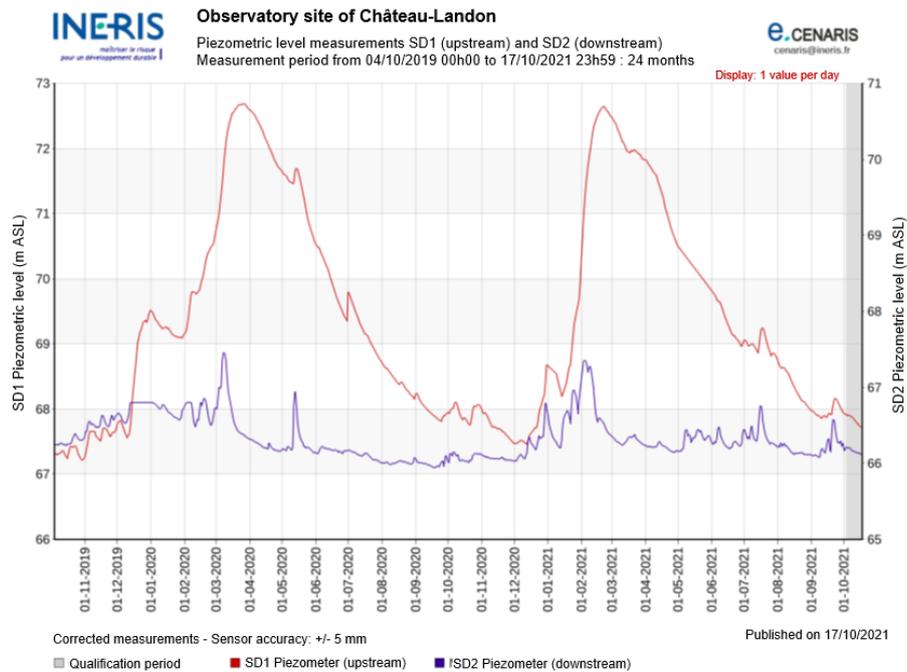


Figure 22. Water table level recorded by the two piezometers SD1 and SD2 since their installation

Conclusions

The 100-year flood of January 1910 led to the catastrophic collapse of the Beaulieu chalk mine at Château-Landon. The feedback analysis of this major event made it possible to suggest a 5-stage scenario to explain the progress and the occurrence: heavy rainfall (1) leads to a strong and sudden flow of the Loing (2) which creates a hydraulic dam (3) and floods the mine by the uplift of the chalk water table (4), which in turn invades the lower parts of the mine and weakens the pillars, leading to the collapse of the mine (5). causing by domino effect the mass collapse of a part of the recent mine works.

This type of collapse could happen again due to climate change characterised by heavy and more frequent rainfalls, and the existence of numerous chalk mines in France. The Royer mine - neighbouring the mine that collapsed in 1910 - has remained intact and has been selected as an underground observatory in order to monitor geomechanical and hydrogeological parameters, to study water-rock interactions, and to understand the hydrogeological behaviour of the site by quantifying the effects of water circulation on its stability. Stable today, while three neighbouring mines collapsed during the floods of the 19th and 20th centuries, this site seems ideal for setting up this observatory which is currently stable, but which exhibits some disorders related to recent heavy rainfall (2016). A multiparameter monitoring network has been recently implemented by Ineris and Cerema. All the sensors are connected to The National Monitoring Centre for Ground and Underground risks (Cenaris) which enables to centralize and share the data through a dedicated web-monitoring page on the e.cenaris (<https://cenaris.ineris.fr>) web portal. This project brings together recognized and complementary research to focus on the issue of underground cavity risks linked to climate change.

Fifty sensors have been installed in the Royer mine in three preselected zones, thanks to the combination of 3D numerical modelling, on site observations, and the lessons learned from the collapse of the Beaulieu mine. These highly accurate sensors which allow continuous acquisition of data using the quasi real-time monitoring from the e.cenaris web site associated to this multidisciplinary approach combining geotechnical, hydrogeological and hydro-chemical measurements - should allow the early detection of phenomena which may be at the origin of a collapse. The analysis of these measurements and their correlation will thus increase our knowledge of the

behaviour of the Château-Landon chalk layer. Today, the mechanisms underlying these phenomena are still poorly understood; however, the first measurements confirm the correlation between the Loing's water level, the fluctuation of the water table, and the heavy rainfall which are the key parameters for predicting a potential collapse.

The observatory is now operational and the first results after one year of measurements show that seasonal variations do not seem to generate significant movements in the mine : the sensors do not measure any variation in strain and water contents in the rock mass do not seem to be influenced by precipitation periods. Some parameters, however, seem more sensitive than the others. New sample tests will be carried out in the laboratory in order to investigate the effect of water cycles on the short and long-term behaviour of this very water-sensitive chalk. A model under development will make it possible to analyse results obtained on site and to study the impact of extreme climatic conditions on the overall stability of the mine.

Acknowledgments:

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