HAL open science

Understanding the instability mechanisms of chalk mines in presence of water (France)

Vincent Renaud, Auxane Cherkaoui, Jean-Marc Watelet, Philippe Gombert, Charles Kreziak

▶ To cite this version:

Vincent Renaud, Auxane Cherkaoui, Jean-Marc Watelet, Philippe Gombert, Charles Kreziak. Understanding the instability mechanisms of chalk mines in presence of water (France). 14th International Congress on Rock Mechanics and Rock Engineering (ISRM 2019), Sep 2019, Foz do Iguassu, Brazil. pp.2532-2539. ineris-03237767

HAL Id: ineris-03237767
https://ineris.hal.science/ineris-03237767

Submitted on 26 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Understanding the instability mechanisms of chalk mines in presence of water (France)

V. Renaud, A. Cherkaoui, J.-M. Watelet & P. Gombert
Ineris, Verneuil-en-Halatte, France

C. Kreziak
CEREMA, Trappes-en-Yvelines, France

ABSTRACT: In January 1910, the 100-year flood of the Loing River caused the tragic collapse of an underground chalk mine at Château-Landon (France), which resulted in the death of 7 people. In this valley, three other underground chalk mines had already collapsed. The hydrogeological analysis of the site and the geomechanical studies carried out on the chalk enabled to elaborate a 3-stage collapse scenario: (1) exceptional rainfall generating intense flooding of the Loing, which plays the role of a hydraulic dam and causes (2) a rise of the chalk aquifer, which invades (3) the lower parts of the mine and weakens the pillars until they collapse. To evaluate this scenario, the Royer mine, the last underground mine still intact in this sector, was thoroughly studied. This study included a complete 3D scan of the mine, modelling of its geomechanical behavior and geomechanical and hydrogeological monitoring that will last several years.

1 INTRODUCTION

The 100-year flood of January 1910 caused enormous human and material damage in the Paris region. In particular, it may have caused the collapse of a hillside in Château-Landon (Seine-et-Marne) undermined by the Beaulieu underground chalk mine, leading to the death of 7 people. This collapse occurred after exceptional rainfall (in quantity and intensity) causing the 100-year flood of the Loing, a tributary of the Seine. Therefore, it is likely that a cause-and-effect relationship between these phenomena exist, especially given that three other underground mines had already collapsed in this sector more than 13 years before, leaving only one mine intact (the Royer mine: Fig. 1).

The town of Château-Landon is located on the edge of the Loing, around 80 km south of Paris. The entrances to the chalk mines are located on a hillside at around 70-80 m altitude FOD (French Ordnance Datum), at the foot of the Gâtinais plateau culminating about 30 m higher. The average inter-annual flow of the Loing is approximately 15 m^3/s, with an average water depth of 2.80 m and a water surface at 58.80 m FOD. During a 100-year flood, the flow can reach 300 m^3/s with a water level close to 4 m. The Gâtinais plateau is formed by tertiary sediments (Chert pudding stone and Château-Landon limestone), locally covered with quaternary loess, all resting on Campanian chalk (Fig. 1). The Loing valley is covered with alluviums consisting of 5 to 8 m of silt, sand and gravel. The main aquifer is the chalk aquifer, above which is the limestone aquifer on the plateau and below which is the alluvial aquifer at the bottom of the Loing valley. The latter is 1 m to 2 m below the surface and is in hydraulic continuity with the chalk aquifer.

In this article, the stability conditions of the Royer mine will be studied by (1) back-analyzing the hydrological context of the 1910 flood, (2) scanning the mine with a 3D laser and (3) modelling its geomechanical behavior on the basis of several flooding scenarios. Finally, a geotechnical and hydrogeological instrumentation project will be proposed based on the most probable scenario.

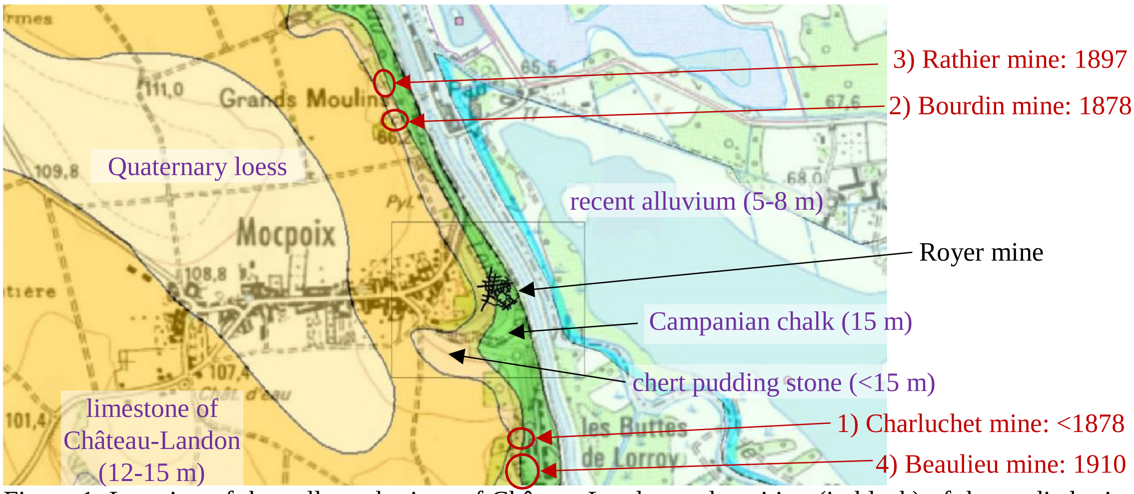

Figure 1. Location of the collapsed mines of Château-Landon and position (in black) of the studied mine (Royer). The dates are those of the collapse of the different mines.

2 LESSONS LEARNED FROM PAST COLLAPSES

The catastrophic collapse of the hillside took place on 21/01/1910 and the subsequent landslide swept away several homes along the Loing causing the death of 7 people. The volume of materials suddenly set in motion was about 100,000 m3. The scarred surface, about 100 m long and 20 m high, was located 40 m behind the initial course of the slope (Fig. 2).

Feedback from this event led us to propose the following scenario (Fig. 3):

1) after 48 mm of rainfall in 10 days, a further 27 mm of rain fell on 19/01/1910; in addition, frosty weather sealed the soil, causing heavy runoff;
2) the Loing and its local tributaries flooded on 20/01/1910 and inundated the flood plain without the water invading the underground mine (Liénard 1910);
3) the aquifer of the Loing rose rapidly and created a hydraulic dam;
4) the flow of the chalk aquifer towards the valley was blocked, leading to a sudden 2 m rise in its piezometric level (Liénard 1910) and the flooding of the old areas of the Beaulieu mine.

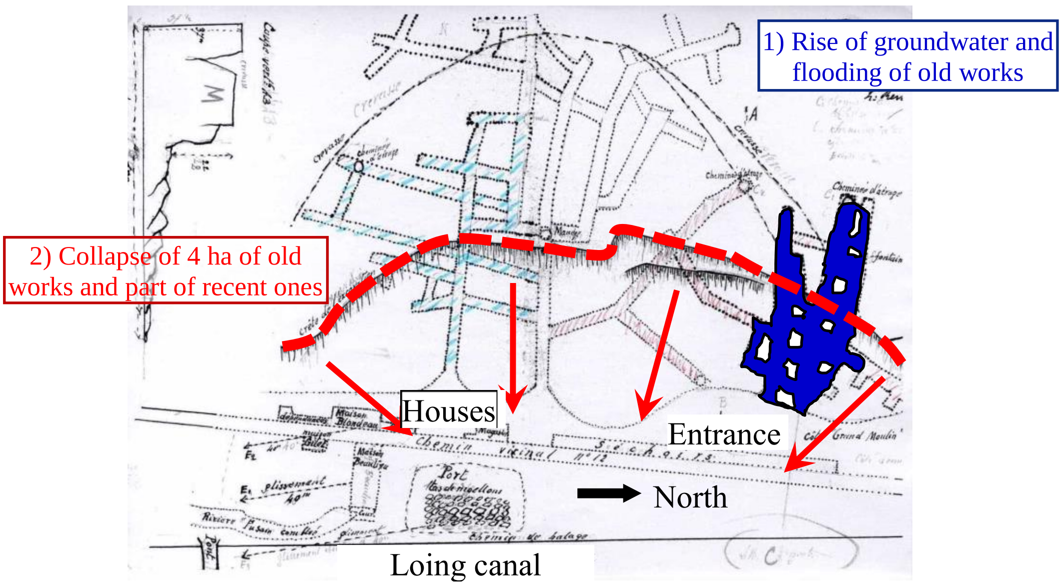

Figure 2. Diagram of the collapse area originally produced by the Mines Service (Liénard 1910).

The origin of the earth movement was attributed to the mass collapse of the northern part of the mine where the flood caused the rupture of the so-called "small pillars" area (in blue Fig. 2). This collapse would have triggered a landslide that buried the homes at the foot of the hill.

The results of the uniaxial compression (R_c) tests conducted following the collapse (Liénard 1910), confirmed by recent tests conducted by Lafrance (2016), indicate that the mined chalk has low resistance values, especially after saturation ($R_c/R_c^{sat} = 2.5$). This weakening of R_c can explain the collapse of the areas where the pillars were very slender (Lafrance et al. 2014). However, the spread of the disorder following the collapse of the most heavily mined sector (to the north of the Beaulieu mine) towards more bulky pillars is difficult to explain. One reason is that the stress field before and after the collapse of the northern area is not well known due to a lack of precise information on the exact condition of the mine galleries in 1910.

Fortunately, this mine is close to the Royer mine (distance < 500 m) which is still accessible, and similar on several points to the Beaulieu mine. It thus offers a good analog site for studying f the possible mechanisms of the Beaulieu mine collapse. This study includes:

- a field geotechnical and hydrogeological inspection phase;
- numerical modelling to simulate several collapse scenarios;
- deployment of an in situ geotechnical and hydrogeological instrumentation to monitor the evolution of the site.

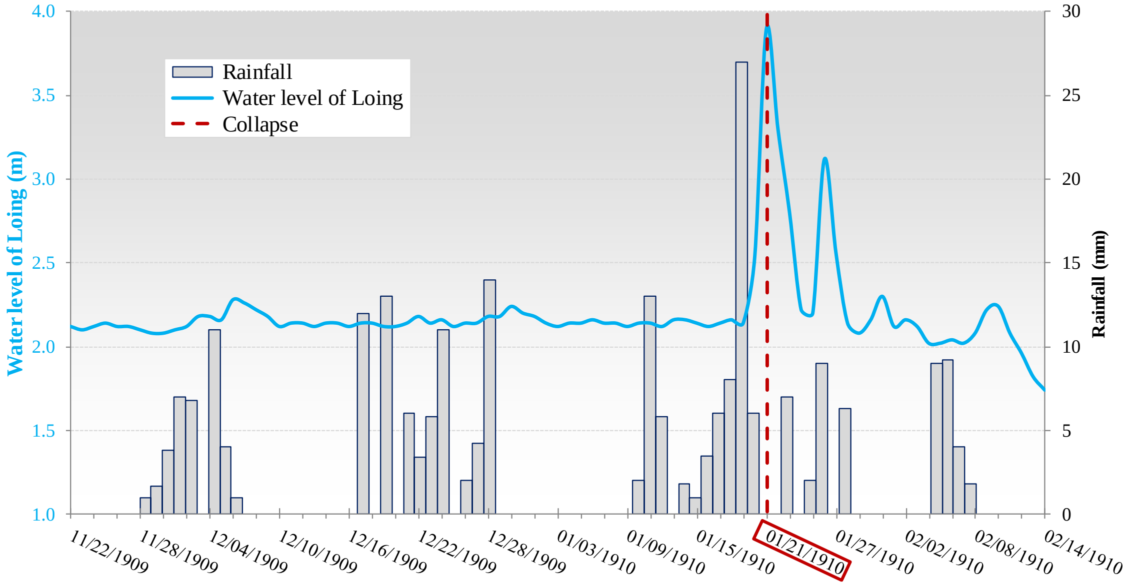

Figure 3. Pluviometry and daily hydrology near Château-Landon (20/11/1909 - 15/02/1910).

3 STUDY OF THE ROYER MINE

3.1 *Current situation*

To obtain a better understanding of the condition of the Royer mine and its evolution, visual inspections and surveys of damage have been carried out from time to time since 2015. In addition to several findings of disorders related to the ageing of the underground structure (mechanical cracks, falls of blocks, fracturing of pillar facing and edges), these surveys enabled to detect the presence of karstic fillings and major discontinuities (fractures) attesting for the tectonic stresses to which the chalk mass was subjected. A full digitalization of the mine using a 3D scanner (Fig. 4) highlighted the lines of these major faults parallel to the slope. These main discontinuities are located about forty meters behind the front of the hillside, i.e. at a distance comparable to that of the scarred surface during the collapse of the Beaulieu mine in 1910 (red line of Fig. 2).

Until 2015, no significant disorder of the structures was found. In 2016, flaking of the facing and caving-in along the F3 fault were observed. This damage was probably due to the new 100-year flood of the Loing, caused by extreme rainfall in June 2016.

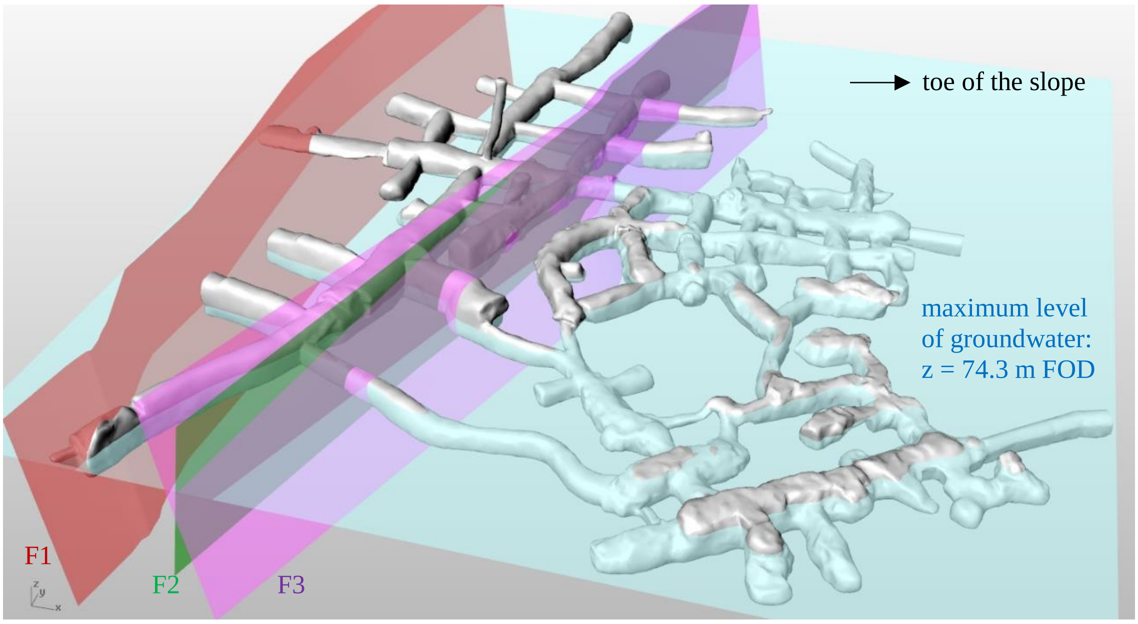

Figure 4. Layout of the galleries and fault planes (F) highlighted by the 3D scan laser survey.

3.2 *Geomechanical modelling of the mine*

The objectives of the numerical modelling are 1) to evaluate and compare scenarios based on the mechanisms involved in the collapse of the Beaulieu mine and 2) to identify, using a probable flooding scenario, the sectors of the Royer mine most prone to displacements in order to localize the instrumentation accordingly. Two main mechanisms likely to cause disorders after exceptionally intense rain were considered:

- the rise of the chalk aquifer (Gombert et al. 2013; Gombert & Cherkaoui 2013) which rapidly reduces the geomechanical properties of the campanian chalk according to the tests of 1910 (Liénard 1910) and 2016 (Lafrance 2016);
- the lubrication of faults located 40-50 m away from the hillside with percolation water.

The current situation of the mine is the benchmark from which different scenarios have been evaluated. The mechanisms associated with this benchmark are: the rise of the chalk aquifer located at 65.5 m FOD and the lubrification of F3 fault crossing the entire model with a steep angle of inclination (77°) facing the Loing valley. The numerical model developed for this study does not consider time-dependent behaviors (creep) nor hydro-mechanical couplings. The rise of the aquifer is performed by increments (+0.5 m) and simulated by a degradation of the chalk mechanical properties (saturated chalk).

Three scenarios were developed to achieve the two objectives mentioned above. The first two scenarios (scenarios 1 and 1 bis) aim to determine which mechanism is most responsible for the collapse of the Beaulieu mine: changes in fault properties or weakening of chalk at the base of pillars due to the rise of the aquifer. The aim of scenario 2 is not to reproduce the conditions of a mass collapse (an exceptional case), but rather to estimate the impact of a large flood on the stability of the Royer mine.

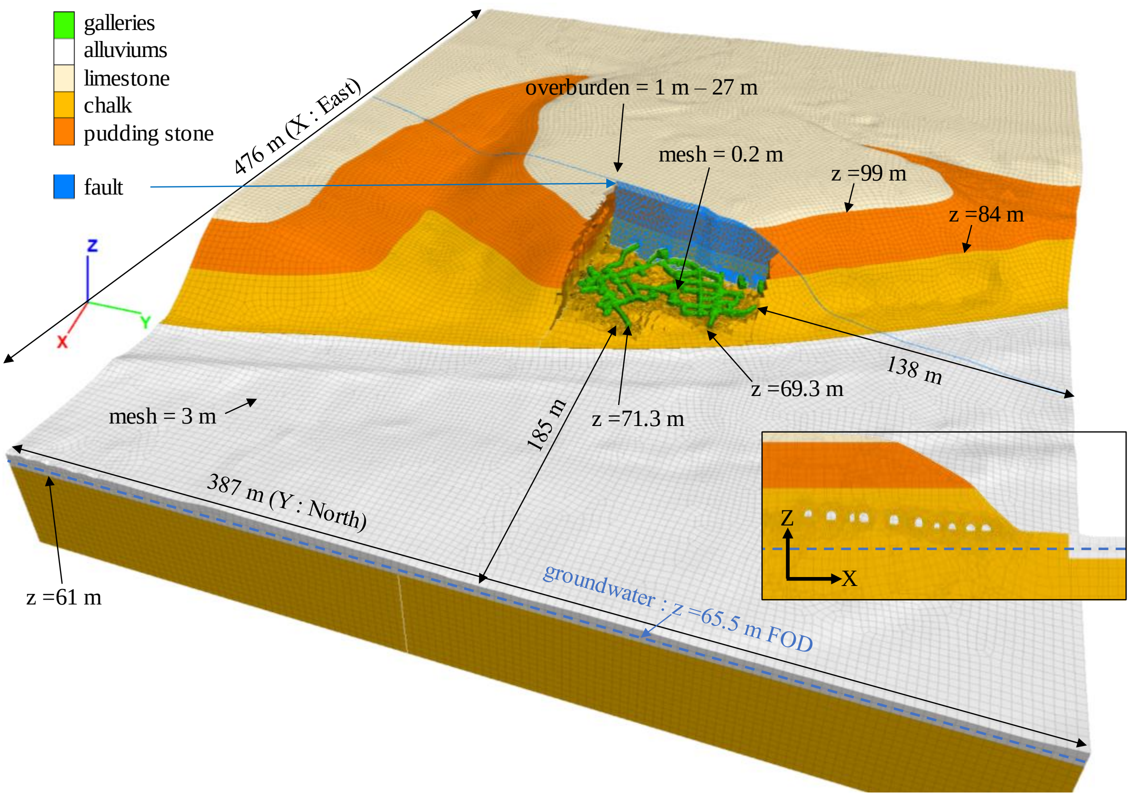

Figure 5: Meshing of the numerical model centered on the Royer mine.

The geometry of the Royer mine galleries is complex since they are not parallel and form various bends. Moreover, their sections are irregular (no symmetry). In addition, the (sub-horizontal) mine floor is not a perfect plane: its dip angle varies locally (Fig. 4). This geometrical complexity plays a key role in determining the areas that are most affected by the properties of the saturated chalk. For these reasons, it was not appropriate to model the geometry of these galleries with a conventional approach based on the juxtaposition of idealized geometries generated by control lines. Instead the geometry of voids was acquired using a 3D laser scanner. A volumetric mesh of approximately 3,500,000 predominantly hexahedral zones was then generated from the global surface mesh (Fig. 5).

The list of geomechanical parameters associated with constitutive models (elastoplastic for chalk and elastic for other materials) used in numerical modelling is presented in Table 1.

Table 1: Mechanical characteristics of geomaterials (Royer mine).

Parameter	E	v	φ	σ_t	c	ρ	k_n	k_s
Unit	MPa	-	°	MPa	MPa	kg.m^{-3}	MPa/m	MPa/m
Chalk	500	0.22	16	*0.1*–0.2	*0.38*–0.75	2000		
Saturated chalk	100	0.23	12.6	*0.04*–0.08	*0.16*-0.32	2000		
Limestone	4000	0.3	-	-	-	2580		
Pudding stone	3000	0.3	-	-	-	2000		
Recent alluvium	200	0.3	-	-	-	1800		
Fault	-	-	0-10	0	0-20	-	1200	100

E = Young's modulus, v = Poisson's coefficient, φ = friction angle, σ_t = tensile strength, c = cohesion, ρ = density, k_n, k_s = normal and tangential stiffnesses

Some values have been inferred from laboratory measurements (Lafrance 2016), others (elastic properties of pudding stone and recent alluviums) were estimated based on the bibliography relating to the Paris Basin (Filliat 1981). These parameters consider an alteration of chalk properties (values of σ_t and c in italics) over a horizontal distance of 20 m from the edge of the hillside, which corresponds to a gradual change from soft chalk to rock chalk. The model is subject to gravity loading. The usual hypothesis of the stress ratio $\sigma_h/\sigma_v = 0.5$ was adopted, due to a lack of data on the initial anisotropy of stresses.

In the chalk, which is the only elastoplastic material, the distance to the rupture criterion guarantees the stability of the concerned area. The standardized distance to the Mohr-Coulomb criterion (F) was therefore used to analyze the stability of the chalk pillars (Equation 1):

$$F = \frac{\sigma_1^f - \sigma_3}{\sigma_1 - \sigma_3} \text{ with } \sigma_1^f = tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right)\sigma_3 - 2c\, tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \quad (1)$$

It should be noted that the irregular geometry of the galleries makes it difficult to define the volumes of the different pillars of chalk. Hence only one group of pillars was considered: its extension is delimited by all the meshes between the mean planes of the roof and the wall of the mine (with a polygonal external border: see Fig. 6).

To evaluate the influence of the two mechanisms (fault versus rising aquifer) on the overall stability of the pillars, the mean value of factors F ($\bar{F}$) is calculated for all pillars and for each stage of the different scenarios (including the benchmark). Figure 6 is constructed from these values. Scenario 1 corresponds only to a degradation of the properties of the fault, without a rise of the aquifer. This weakening is related to the lubrication of F3 fault after its loading following the saturation of the surface lands.

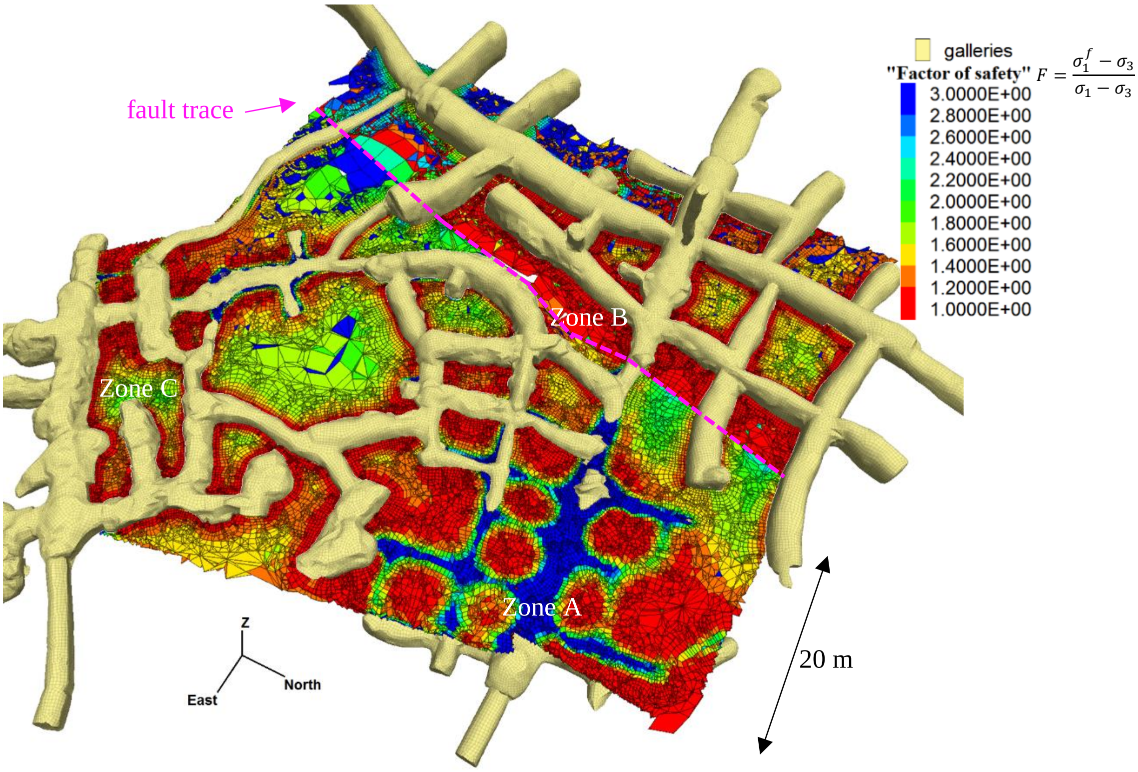

Figure 6. Distribution of F in the chalk pillars: scenario 1 bis (aquifer at 74.8 m FOD).

It is noted (Fig. 7) that $\bar{F}$ is not really affected by the lubrication of the fault (decrease of 1.2%: scenario 1 / reference case). Then, the rise of the chalk aquifer is simulated in 11 successive steps from 65.5 m FOD to 74.3 m FOD. The first stages of aquifer rising have limited influence $\bar{F}$ (-2%) because only 2.2% of the pillars are affected by the properties of saturated chalk up to the spot height of 71.8 m FOD. This is because the mine floor descends to the valley (Figs 4-5). On the other hand, as soon as the aquifer level exceeds the 72 m FOD spot height, more and more pillars are saturated up to a maximum of 54 % in the final stage (74.3 m FOD, Fig. 4). The analysis of the Figure 7 leads to the following conclusions on the respective influences of the rise of the aquifer and lubrication of the fault:

- the discrepancy between scenario 1 and the benchmark is the result of the alteration of the properties of the fault in the upper part, above the aquifer; the change is from c = 20 kPa and φ = 10° for the benchmark to c = 5 kPa and φ = 5° for scenario 1;
- the discrepancy between scenario 2 (c = 0 kPa and φ = 0°) and scenario 1 (c = 5 kPa and φ = 5°), where $\bar{F}$ only decreases by 1.9 %, is due to the aquifer rising to 68 m FOD and the alteration of the plastic properties of the fault surface up to 89 m FOD. However, it was verified that this rise did not involve a change of properties in the areas of the pillars: it can therefore be inferred that only the fault is involved in scenario 2;
- the discrepancies due to the influence of the fault alone are insignificant with respect to the overall behavior of the chalk pillars. However, for areas close to both the fault and the gallery walls, this influence may be locally important;
- the influence of the rise in the aquifer can be seen by comparing the discrepancy between scenario 1 bis and scenario 1. This discrepancy (on $\bar{F}$) may reach -28 %. The influence of this mechanism on $\bar{F}$ (linear based on the volume of the saturated pillars) is therefore more important than that of the fault as this mechanism applies to all the areas under the spot height for the level of the aquifer, whereas the fault has a limited distance of influence.

The conclusion of these comparative analyses is that the predominant factor for the stability of the Royer mine is the rise of the chalk aquifer. However, the presence of the fault may aggravate its effects locally.

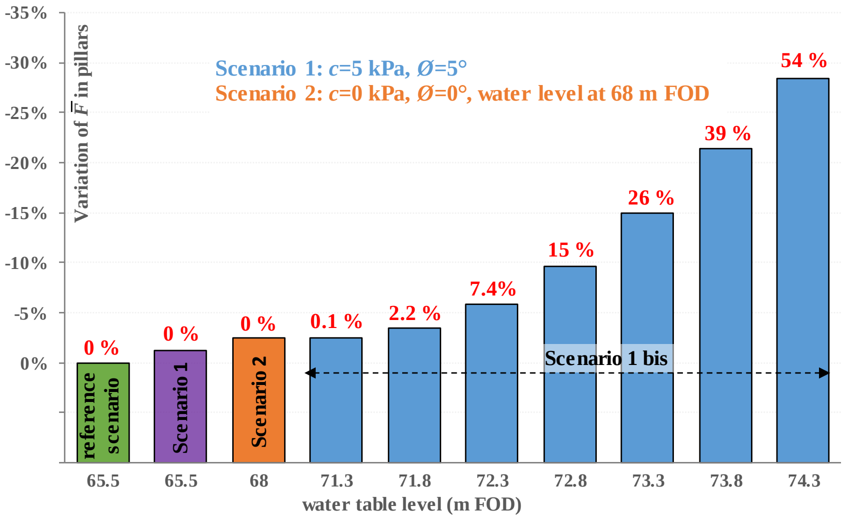

Figure 7. Evolution of $\bar{F}$ based on the rising aquifer scenarios.

3.3 *Mine instrumentation project*

Modelling of a flood scenario at the Royer mine enabled to identify two potentially unstable zones that were chosen for instrumentation (area of small pillars: area A, F3 fault plane: zone B) plus a control area (area C, Fig. 8). Wall strains and movements and the evolution of the existing instabilities were monitored by 3 extensometers with double anchoring (in the pillars), 2 convergence rods and 1 extensometry device in the gallery, 2 microphones (to detect any cracking), 1 horizontal radar and 1 crackmeter at the F3 fault plane.

The important role of water is also monitored. The objective is to understand the evolution of the water content of the chalk, the humidity rate of the ambient air and the aquifer level upstream and downstream of the mine. Several devices were therefore set up: 4 humidity and temperature sensors, 3 water content sensors (evolution of the moisture front), 2 piezometers (hydrologically downstream and upstream), 1 water collector and a pore pressure probe placed on fault F3. Figure 8 summarizes the hydrogeological and geotechnical monitoring devices installed in 2019.

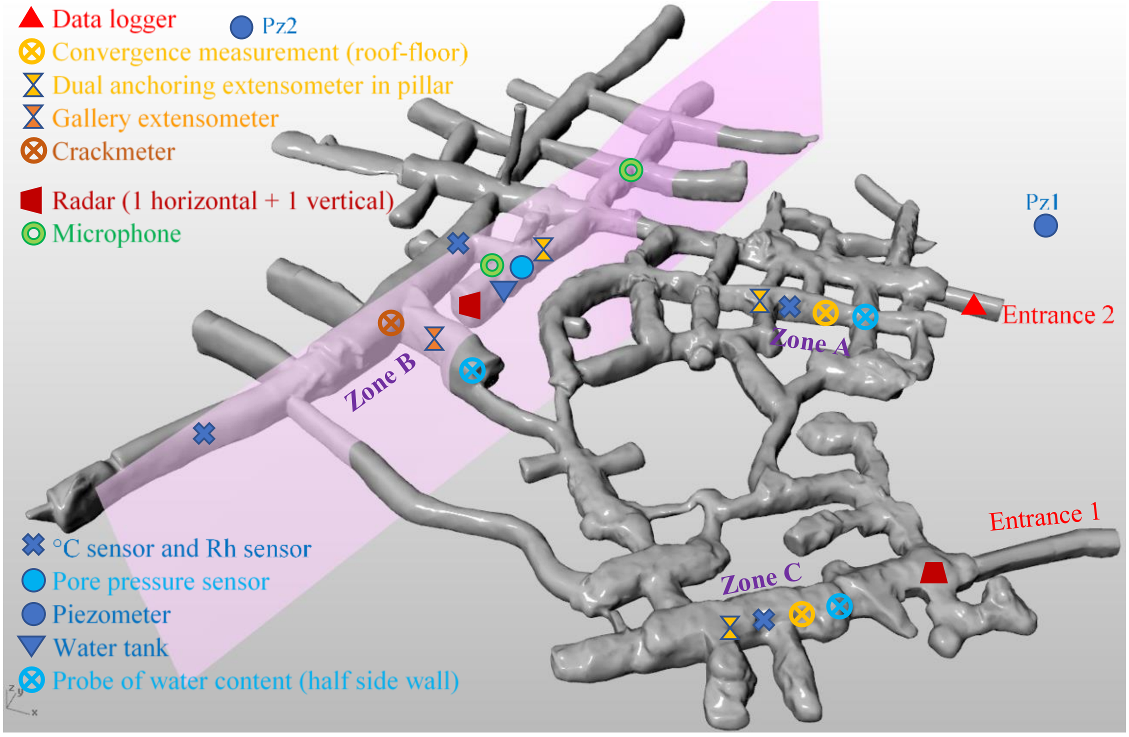

Figure 8. Diagram of the hydrogeological and geotechnical instrumentation of the Royer mine.

4 CONCLUSION

Various scenarios have been proposed and modelled to understand the primary mechanisms that participated in the collapse of the mine Beaulieu. The model takes into account the complex geometry of the Royer mine acquired by 3D scanner. It enabled to identify the zones of maximum variations of displacements, strains and stresses. That information has been used to design an adequate monitoring instrumentation. Its objective is to monitor the displacements and strains of the pillars and galleries, fluctuations in the aquifer level, variations in water content in the chalk and relative humidity in the mine. The ultimate goal is to highlight correlations between these different measures. This innovative multidisciplinary approach, i.e. feedback from the 1910 collapse, 3D digitization, 3D modeling, instrumentation, opens new roads for the understanding and prevention of collapse risks that may concern other chalk mines in Paris Basin and elsewhere.

REFERENCES

Filliat, G. 1981. La pratique des sols et fondations. Paris: Editions du Moniteur.

Gombert, P., Auvray, C. & Al Heib, M. 2013. In-situ and laboratory tests to evaluate the impact of water table fluctuations on stability of underground chalk mines. *Procedia Earth and Planetary Science* 7: 304-308.

Gombert, P. & Cherkaoui, A. 2013. Role of water in the stability of abandoned and partially or temporarily flooded underground quarries and expected impact of climate change. *Tunnels and Underground Areas* 240: 468-482.

Lafrance, N. 2016. Study of the effects of water on the phenomena of rupture and deformation affecting underground chalk quarries. PhD thesis, University of Lorraine.

Lafrance, N., Souley, M., Auvray, C., Favreau, O. & Labiouse, V. 2014. Aging of chalk rocks in an underground quarry. *Rock Engineering and Rock Mechanics: Structures in and on Rock Masses: proceedings of the international symposium EUROCK 2014*: 445-450. Leiden: CRC Press.

Liénard, A.M. 1910. Procès-verbal d'enquête. Effondrement d'une carrière. *Mines*. Arrondissement minéralogique de Versailles: 16 p.