Impact of climate change on the collapse of shallow mines – feedback from France

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ABSTRACT: For many years, Ineris has been conducting research on the impact of climate change on the stability of abandoned mines. In this context, work has been initiated to reference cases of shallow mine collapses. So far, 480 cases have been identified and described. Preliminary analysis of the information gathered shows that 50% of the cases correspond relate to chalk mines, 32% to limestone mines, and 16% to gypsum mines. Two case studies presented in the paper were also analyzed in more detail. Complexity of the water-rock interaction and the importance of studying more precisely the various parameters impacted and their relationships are highlighted. Therefore, a chalk mine located in Seine-et-Marne (France) was instrumented to monitor the evolution of the structure over time and analyze the different causes of degradation. The objectives are to better understand the behavior of these structures to be able to detect precursor signs to these collapses.

Keywords: shallow abandoned mines, aging, collapse, climate change, water-rock interaction.

1 INTRODUCTION

The collapse of underground shallow cavities may represent an important geohazard for people and infrastructures. The number of cavities is estimated at more than 500,000 in the French subsoil, many of which are abandoned shallow mines. Some are excavated in rocks that are particularly sensitive to water (gypsum, chalk, limestone). With ongoing climate change, we expect an increased frequency of exceptional hydroclimatic events (intense droughts, heavy rains, or floods) that can create high amplitudes in groundwater tables or stream levels or cause important water infiltrations. All these phenomena are likely to increase the risk of instability of water-sensitive mines. The challenges related to this risk are generally high, particularly in human and socio-economic terms. Josien (1995) discusses the possible role of water as an initiating mechanism (loading of the overlying water tables in roof ruptures, modification of the properties of the rock floor rupture) or as an aggravating factor (variations in the rock water content, in the water table or hygrometry, circulation or condensation of water in the case of marly clay interlayers). Vincent & Mathon (1999) cite several collapses that occurred in 1897 in St-Emilion (Gironde), after an extremely rainy winter. Léotot (2016) highlights to the role of the rise of water table or roof infiltration in several collapses near Châtellerault

(Vienne). Noury et al. (2019) analyze the impact of the unusually rainy periods of 1994-1995 and 2000-2001 on the breaking of "marnières[1]" pits in Normandy. The case of Château-Landon, southeast of Paris, illustrates the complexity of the process of interaction between the meteorological factor and the predisposition to mine instability. Over only 1 km, 3 of the 4 chalk mines collapsed between 1878 and 1910 in connection with heavy rains and floods (Kreziak & Watelet 2016).

For several years, Ineris has conducted research on the stability of abandoned mines related to climate change. A catalog of water-sensitive mine collapses was compiled to analyze the link between climate and the degradation of underground structures. A study of the hydroclimatic conditions was conducted for two historic French collapses (Château-Landon in 1910, Clamart in 1961). Finally, a mine was instrumented by Ineris in 2019 in Château-Landon, in collaboration with Cerema (Centre for Studies on Risks, the Environment, Mobility and, Urban Planning), to study its evolution and identify potential precursor signs of instability (Conil et al. 2022).

2 INVENTORY OF COLLAPSES IN FRANCE

Within the framework of this study, a catalog of large-scale collapses (>10 m in diameter) of mines was compiled. These collapses have been selected from the Internet (newspaper articles, reports, etc.) as well as from scientific articles. The catalog includes data on:

- mine environment: department, municipality, locality, geographical coordinates, geological and hydrogeological context;
- mine features: surface area, mining depth, the average height of galleries, mining mode, mine closure date, extraction rate, and material mined;
- collapses: geographical coordinates, date of occurrence, the area concerned, depth, description, bibliographical reference, distance to the nearest river, geomorphological location (valley, slope, plateau, etc.), possibly the climatic conditions in the period preceding the collapse, known damage and casualties.

At this stage of the study, the catalog includes 480 collapses, 50% of which correspond to chalk mines, 32% limestone, and 16% gypsum. Preliminary analyses show an average extraction rate of more than 50%, which means the pillars are very stressed (Figure 1).

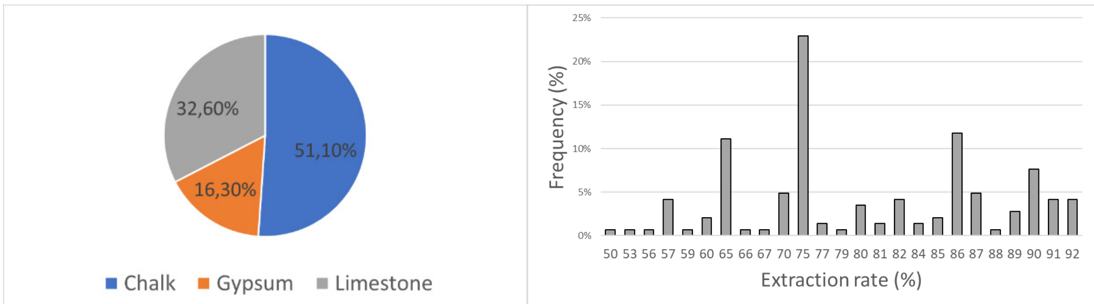

Figure 1. (a) Distribution of mined materials for 473 mines (b) Extraction ratio for 145 mines.

2.1 IMPACT OF CLIMATIC CONDITIONS – PRELIMINARY STUDY

Preliminary analysis of the data shows that several collapses were preceded by heavy rain events some days or weeks earlier. A correlation was investigated between the occurrence of the 139 collapses dated with daily precision and the 447 main rainy events recorded by Météo France (the French national meteorological service) since 1766. Only 3 collapses could be unambiguously linked to the occurrence of one of these extreme events:

[1] Chalk mines generally comprise a vertical access shaft and one or more horizontal chamber(s).

- The collapse of the chalk mine of Château-Landon, which occurred during the historic flood of the Seine and its tributaries which lasted from January 18 to February 26, 1910;
- The opening of a sinkhole on September 1st, 2010 on the surface of a chalk mine in Châlons-en-Champagne (Marne), in connection with heavy rainfalls that occurred two weeks earlier with local intensities of more than 100 mm of water in 48 hours;
- The collapse of a limestone mine in Gidy (Loiret) in 2016 during a heavy rainfall period.

Based on these, the probability that an extreme climatic event could be the direct cause of a mine collapse would be in the order of percent. Although the precise date of most collapses in the list is unknown, the analysis shows that it is difficult to invoke the role of extreme precipitation in collapses: if water plays a role, it must be analyzed over a longer period.

A complementary approach was therefore undertaken. Among the collapses dated to the nearest day, this approach consisted of identifying observations related to degraded weather conditions, such as heavy but not exceptional rains. Out of 86 observations, 13 referred to such. This means that 15% of the collapses occurred in abnormally rainy climatic conditions. Next, the possible impact of long periods of drought will also be examined.

3 RETRO-ANALYSES OF TWO COLLAPSES

Figure 2. Ineris instrumented sites (in blue) - collapsed mines selected as case studies (in red).

To verify the correlation between rainfall events and the collapse of underground cavities, 2 case studies were selected: Château-Landon in Seine et Marne and Clamart in Hauts de Seine. Their location is shown in Figure 2.

3.1 CLAMART (1961)

On June 1st, 1961, a chalk mine suddenly collapsed in Clamart (Hauts-de-Seine) and led to the destruction of an urban district, killing 21 people and injuring more than fifty. The mine, which was mined until 1880, is located on the edge of a chalk hillside topped with tertiary land and overlooking the Seine valley (Al Heib et al. 2014). It comprises an upper level of around 37 m NGF, mined to the south and north according to a very regular pattern and with an extraction rate of 55% to 68%, and a lower level of around 29 m NGF, mined in the southern part with very irregular pillars and an extraction rate of 36% to 51%. There are three aquifers here: the alluvial aquifer of the Seine with a water table around 30-33 m asl, the chalk aquifer, which is in hydraulic continuity about 5 m above, and the layer of Lutetian limestone, separated from the previous ones by about fifteen meters of impermeable formations.

Having been studied extensively, the causes of this mine collapse have never been established with certainty, but experience-based feedback on the possible role of water has been considered. For several years, the lower level of the mine had been flooded by the chalk water table, but its level did not vary before the collapse, just as with the level of the Seine, which was low. However, precipitation was contrasted during the 8 years preceding the collapse with the driest year (400 mm in 1953) and the wettest year (812 mm in 1958) for the entire period 1941-1960. In the month preceding the collapse, significant precipitation concentrated in a small number of days was recorded: there was more precipitation during the week preceding the collapse than in a normal month, in particular with 48 mm on May 25. Although no exceptional hydroclimatic event occurred, this elevated rainfall a week before the collapse could have played a role, as well as the two water system leaks reported to the right of the mine during the days leading up to it (Figure 3).

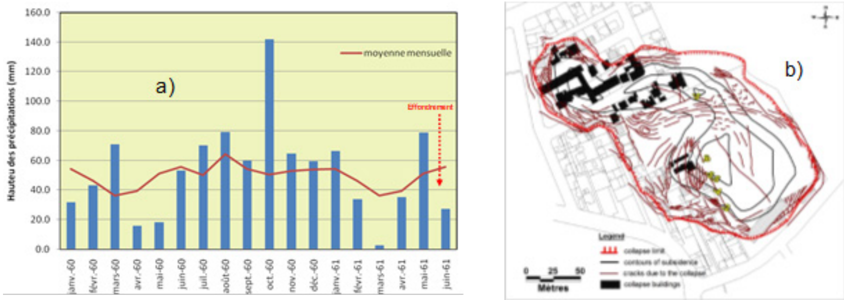

Figure 3. (a) Monthly rainfall from 1960 to June 1961 and (b) Clamart collapse on June 1st, 1961.

3.2 CHATEAU LANDON (1910)

The collapse of the Beaulieu chalk mine in Château-Landon in 1910 followed 3 other collapses of the same type, which occurred in 1878 and 1897 over a section approximately 1 km long. This abnormal succession of disorders shows a particular sensitivity of this sector where the chalk is known to be very sensitive to moisture conditions (Lafrance 2016). These collapses probably result in part from the hydrogeological context of the mines that were excavated at the base of the slope, only a few meters above the water table and the alluvial plain. They occurred during a succession of comparable hydroclimatic events (Figure 4): a very rainy month (94 mm in 1876, 48 mm in 1897, 122 mm in 1910) which saturated the ground and recharged the aquifers, then heavy flooding of the Loing (river passing nearby the mines) the day before each collapse with respective maximum heights of 1.4 m, 3.3 m, and 3.9 m.

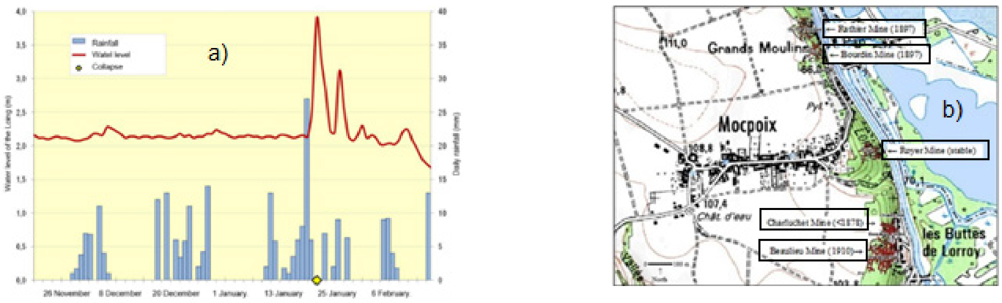

Figure 4. a) Rainfall and height of the Loing before the collapse of Château Landon in 1910, b) Location of the underground mines.

The disaster scenario proposed by Gombert & Cherkaoui (2011) is as follows: (i) the Loing flood creates a hydraulic dam which (ii) prevents the chalk water table from flowing horizontally and (iii) forces its level to rise, until (iv) it overflows at the lower parts of the mine. The soaking of the base of the pillars completely saturated the chalk (v), reducing its compressive strength and causing the collapse of this area (vi). The rest of the slope, more stable but undermined, then lost its eastern abutment and suffered a landslide (vii) which buried a hamlet.

3.3 Conclusions of the case study

These results show that collapses can be controlled by an accumulation of parameters that are not always well-identified. Thus, the case of Clamart shows that a period of drought followed by heavy rainfall could have accelerated the process of degradation of the structure, without being the main cause of the disaster, but a likely triggering factor (Al Heib et al. 2014). The cases of Château-Landon and Clamart collapses show that the geometry of the exploitation is a predisposing factor, as well as the initial and modified mechanical properties of the massif and the overburden. Nguyen (2009) showed that variations in atmospheric relative humidity in the chalk mine of Estreux (59) could modify the saturation level of the massif. As for the heavy rains and associated flooding, they are the cause of the collapses of Château-Landon.

4 CHATEAU-LANDON OBSERVATORY

To better understand mines degradation, monitoring the in-situ behavior of an abandoned mine seemed necessary to supplement the knowledge of aging kinetics.
The selected site is the Royer mine, located in Château-Landon (Conil et al. 2022), close to the historical catastrophic collapses from 1878 to 1910. The chosen site also presents several similarities with the Beaulieu mine, in terms of geomorphology, exploited chalk (it is particularly water-sensitive), and exploitation method.

The mine is heavily fractured. This fracturing affects the pillars as well as the roof of the galleries, with the backfill hiding the fracturing at their base. More than three-quarters of fractures are without displacement (diaclases), the majority being closed. Split-level fractures are normal, radial, or stepped flaws, showing openings and level differences of a few mm to cm. The preliminary risk assessment analysis showed that the mine is susceptible to hydroclimatic phenomena.

Two types of parallel monitoring were set up at the end of 2019 to correlate water data (variations in water table, water content of the chalk, and hygrometry) and acquired geotechnical data (deformation and failure of a pillar, a roof, and a fault). More than 50 sensors are installed in 3 different areas called A, B, and C as well as outside the mine (Figure 5a): A is the small pillars area, B is the fault area, and C is the control area. All the data are shared through a dedicated web-monitoring page on the e.cenaris (https://cenaris.ineris.fr) web portal.

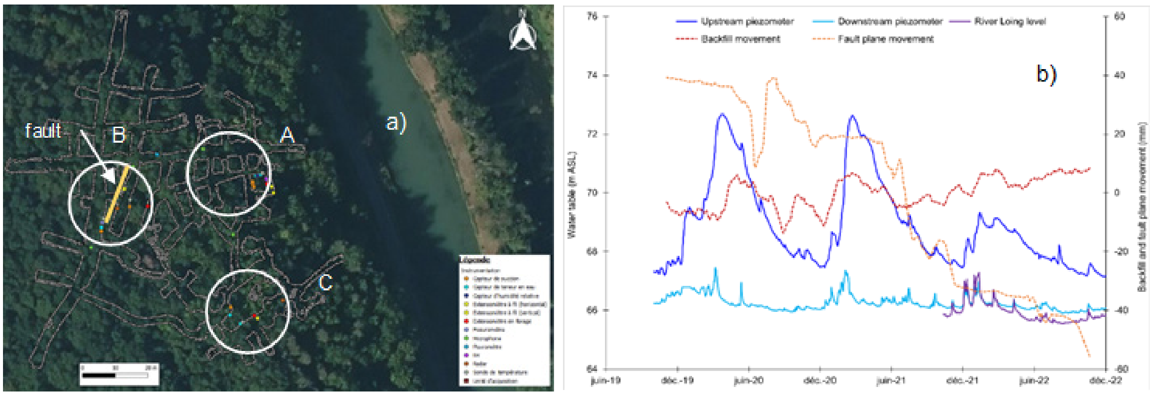

Figure 5. (a) Instrumentation of the Royer mine and (b) comparative evolution of the mean movements of the backfill and the fault plane with the daily heights of the water table and the river.

Fluctuations in the level of the chalk water table, which correspond to the high water / low water cycles, reach ±2.77 m upstream and ±0.78 m downstream where they are buffered by those of the Loing river (±0.87 m) which forms the base level of the aquifer (Figure 5a). The figure also includes the distance variation measurements from the vault of the gallery to the embankment (zone C) and at the level of the fault plane (zone B). A correlation is observed between the piezometric cycles and the level of the embankment as well as the displacements of the fault plane (Figure 5b).

5 CONCLUSION

The impact of climatic events on potentially unstable underground cavities has been widely studied. Nevertheless, important scientific gaps remain, concerning the origins of the collapses of shallow abandoned cavities. To better evaluate this impact, Ineris carried out a dedicated research program that includes referencing large collapse events. To date, 480 cases have been identified. Preliminary analysis shows that collapses concern mainly cavities with a high extraction ratio (> 50%) and particularly the chalk mines. Additionally, even if water has a significant role in the collapse process, exceptional climate event is rarely a triggering factor of the event. It seems that a long period of rainfall has more impact. The analysis of different case studies also shows that the impact of water is not always well understood and is often coupled with many other parameters which are important to better estimate the probability of such disaster. The research program also includes the Chateau Landon observatory which is located near the collapses of old mines that occurred between 1878 and 1910. The measurements show a good correlation between cavity deformation and the water table variation and highlight the necessity to improve our knowledge of the aging of these structures to understand the different phenomena and their coupling which can lead to such events.

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