Impact of climate change on the stability of underground shallow cavities. The case of a tragedy in France in relation with the Seine flooding in 1910

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IMPACT OF CLIMATE CHANGE ON THE STABILITY OF SHALLOW MINES

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SYNOPSIS

The present paper deals with climate change impact on stability of underground cavities due to its indirect effect on ground water levels. In France, several back-analyses have confirmed that variations of underground water tables play a key role in the genesis of surface disorders above shallow mine workings. The paper presents the forecast impacts of climate change on the behaviour of underground water tables as well as the consequences of those variations on the stability of disused underground cavities. A particular collapse that affected the Paris Basin during a major flood of the Seine River, one century ago (January 1910), with dramatic consequences, illustrates the importance of water variation impacts on the rock mass behaviour. The high sensitivity of the extracted material (very pure chalk) to water as well as the dynamics of the mine flooding process are described. The most realistic mechanisms and scenario enabling to explain massive failure of the underground workings are then discussed.

Keywords: climate change, mining, cavity, collapse, water table, chalk, flood.

1. INTRODUCTION

The existence of a global warming process of the global climate is now well admitted by the scientific community. The rise of the average temperatures of air and oceans, as well as the observation of the de-icing of ice caps and the rise of mean sea level constitute some clear indicators. The various studied prospective scenarios, depending on the efficiency of prevention policies engaged by governments show that, up to 2100, the average rise in temperature on the surface of the Earth could vary between 1,5 and 6 °C [1]. Such a temperature increase would be likely to generate serious disturbances on climatic parameters (e.g. modification of rainfalls, disturbances of water tables). Numerous international studies are being performed in order to make progress in the understanding and prediction of the consequences of the presumed climate change. Among these studies, very few relate to the matter of underground cavities.

The paper deals with the impact of climate change on stability of underground cavities. This topic may become a serious problem in France due to the existence of very numerous (hundred of thousands) shallow underground cavities, natural or manmade, well known or totally unlocated, undermining French territory. A large majority of those shallow workings appears to be very sensitive to the variations of their environmental parameters. Several recent examples have confirmed that, among those, the level and variations of underground water tables have a key role in the genesis of surface disturbances. Major trends concerning the forecast impacts of climate change on underground water tables as well as the consequences of those variations on the mechanical behaviour of shallow underground workings (impacts on strata and discontinuities) are thus briefly presented.

Among others, the specific case of a ground collapse (with dramatic human consequences: 7 deaths and 7 severe injured persons) that affected the Paris Basin during a major flood of the Seine River, one century ago is then described, as a perfect illustration of the importance of water variation impacts on rock mass behaviour. The chalk mine of Lorroy (city of Château-Landon), collapsed in January 1910, in direct connection with the flood of the Seine River. The course of events described by the witnesses clearly highlights the role of water table rising on the collapse triggering. As a matter of fact, sudden and massive water outflows are described inside the galleries (hitherto dry) during the morning of the catastrophe.

In addition to a brief description of the chalk mine context, the high sensitivity of the extracted material (a very pure chalk) to water as well as the dynamics of the mine flooding process are described further. The most realistic scenario enabling to explain massive failure of the underground workings is then discussed, according to some hypothesis due to the lack of data.

2. FORECAST IMPACT OF CLIMATE CHANGE ON UNDERGROUND CAVITIES

2.1 Impact of climate change on water table behaviour

A recent report of the International Panel on Climate Change (IPCC) points out that the level of many aquifers in the world tends to decrease during these last years [2]. This usually appears however as a consequence of overexploitation of the resource much more than of climate change. Because of the lack of available data and of the high inertia of the water tables' behaviour, significant modification of the refill of the aquifers related to climate is not yet documented. However, the IPCC insists on the lack of research carried out on the subject and thus on the necessity to develop urgently scientific knowledge on this topic.

The complexity of the subject has strongly contributed to the very limited number of reference papers available. Gradually however, taking advantage of the improvement of predictive models, a convergence of experts' opinion seems to emerge. According to it, an increase of the magnitude of water level variations should be observed in a close future as a consequence of the predictable modification of rainfall regime. As a matter of fact, in European countries, climate experts forecast an increase of rainfall amount during winter time (more important refill of water tables inducing water level rising) and, on the contrary, a severe reduction during summer periods (lack of refill inducing water level lowering).

This general tendency needs to be considered with great care. The regional variability of both climatic conditions and water table behaviour may strongly influence the hydraulic mechanism. For example, a water table subject to a Mediterranean climate can react very differently of another one located north of the Loire River, under an oceanic climate. In addition, Nastev and al. specify that an increase in the frequency of extreme rainfalls would not result automatically in an increase in water tables refill. Such events could rather enhance run-off contribution and thus contribute to catastrophic floods [3].

In a given climate change context, the probable amplification of summer droughts should increase the needs for underground water exploitation, in particular in the areas of intensive irrigation. This may amplify the magnitude of water level variations resulting from natural climatic conditions.

2.2. Impact of water on underground cavities

Water plays a key role in the behaviour and stability of underground mine workings. In addition to the dissolution of some minerals, humidification or drainage of rock mass (and especially successive alternations between these two states) can have important mechanical impacts. Interaction between strata and water appears to be a very complex problem, especially because water impact results from a combination of various effects, some of them resolutely damaging stability and others being, on the contrary, improving it in some specific contexts.

Taking into consideration experience feedback, most rock mechanics experts agree to consider, in a purely observational sense rather than in theory, that modification of the hydraulic context (especially flooding or dewatering of underground cavities) is likely to increase probability of mine workings failure in the short term. The disturbance (whatever its origin) of an "unstable equilibrium" established within disused underground workings often contributes to failure development. As a consequence, mining areas subject to severe "water level variations" constitute a very unfavourable context regarding ground stability.

Many examples described in the international literature confirm this by reporting development of ground instabilities in the weeks (or months) succeeding flooding or dewatering of cavities. One will take care not to conclude that, in the absence of water level variations, these areas would remain stable indefinitely. It is much more appropriate to consider the influence of water variations as a "worsening or triggering factor", likely to initiate a failure process development in a potentially unstable rock mass [4]. Generally, such a ruin is, as a matter of fact, irretrievable in the long term due to mechanical considerations. Water level fluctuations are thus more likely to anticipate failure process than to initiate it by its own.

Those variations will mainly affect, in the short term at least, the shallowest water tables, most rapidly influenced by rainfall regime. It is thus the shallowest cavities that should be seriously affected by climate change. In France, these are mainly the mines having extracted raw building material (e.g. chalk, gypsum, limestone), the underground refuges (notably war saps) as well as the very numerous (and often very old) mine workings that were developed near the outcrops. These kinds of exploitations were generally carried out right above the natural water level. One will exclude on the other hand many mining areas, which were excavated deep enough not to be affected by some minor water level fluctuation in a close future.

2.3. Effect of water on mine workings strength

As mentioned above, impact of water on the rock mass strength results from a combination of several effects. In addition to the dissolution of specific minerals (e.g. salt, gypsum, chalk…), humidification or drainage of rock mass (and even more an alternative succession of both) makes it possible to explain, under certain conditions, some strength reduction of mine workings.

One may consider at first approximation that rocks presenting high values of porosity and permeability are more predisposed than others to be affected by water variations. Thus, except for the most impermeable rocks (e.g. some granites and quarzites) not very sensitive to the hydric variations or, on the contrary, strata presenting an extremely sensitive behaviour to water content (chalk, clays, some marls), most rocks lose between 30% and 50% of their strength when saturated compared to dry (figure 1). It is however important to remember that strata hosting the cavities present already high water content values (often close to 80% according to our experience). This pre-existing high water content value results from water infiltration from surface, capillarity forces which contribute to drain deeper water as well as relatively high ambient hygrometric atmosphere, specially when it is not renewed any more by ventilation after mine closure.

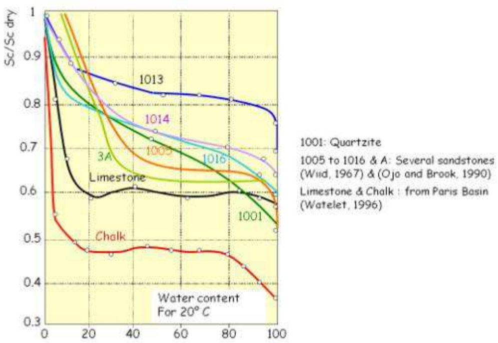

Figure 1: Compressive strength variation depending on water content [5] & [6]

The phenomenology of such a strength reduction is only partially understood, in particular in its quantitative dimension. Among the various mechanisms interacting, few of them are rapidly quoted below:

- Effects of water on discontinuities

  Strata are generally fissured or cracked mediums. Fluids circulate within these discontinuities (faults, fractures, bedding planes). Those flows are determined by complex hydro-mechanical coupled processes, depending in particular on the opening and the surface roughness of discontinuities as well as on the flow and velocity of fluids. The possible effects in terms of opening or closing of discontinuities can have direct impact on the rock mass stability. The relatively frequent context of a fracture or a fault filled with clayish material, for example, may be taken into consideration. The "lubrication effect" due to flooding may be sufficient to initiate failure of a rock structure already close to instability.

- Suction effect

  The "suction effect" describes the effect of the capillarity forces being opposed to the extrusion of the water contained in a rock sample in contact with a medium presenting a lower value of water content than the sample itself (the surrounding mining atmosphere for example). For rocks like partially saturated chalk, this suction effect (generated by desaturation process) can provide to the rock an "apparent cohesion" which contributes, due to the generated containment, to increase the shear strength of the rock (or compressive strength if there is no containment). In case of a progressive flooding of the galleries, this suction effect decreases until being totally cancelled (saturation state) with, in certain circumstances, significant effects on the mine workings behaviour (strength reduction). The consequences are even more important when the rock structure is subject to successive cycles of saturation-desaturation (as a result of seasonal variations of water tables levels). In this case, cumulating suction stress variations can generate "rock fatigue", likely to ease, or even initiate, the propagation of macro- and micro-cracks networks affecting the rock mass.

- Effective stress effect

  The concept of effective stress consists in retracting the fluid pressure within the pores to the total stress value. It can be expressed, into simplified terms, as the stress developed within the "rock skeleton" alone. In a saturated medium (specially in flooded mines), the effective stress is lower than the total stress. At first sight, this "discharge effect" may contribute to decrease the vertical compressive stresses transmitted by the overburden weight and to the rock skeleton. However, in rock mechanics, the concept of failure is more connected to the concept of “stress deviator” (difference between major and minor stresses) that to the only compressive stress. Indeed, the rock strength is strongly dependant of a potential “containment stress” which contributes to reduce the lateral distortion of a rock sample. If the “discharge effect” due to mine flooding contributes to decrease the vertical stress that develops within the rock skeleton, it also reduces the horizontal stress guaranteeing a containment stress of the pillar cores. The combined reduction of these two stresses does not always ensure more stability to the rock mass. On the contrary, in certain contexts it can lead the rock structure closer to its failure threshold.

- Physicochemical effects

Some types of rocks may undergo physicochemical reactions when they are in contact with water or drained. Some of them may expand or shrink with very important magnitude (montmorillonite) or appear sensitive to splitting (illite, kaolinite). In general, clayey minerals present in the marly horizons appear to be the most sensitive to this kind of phenomena, which is mainly due to the structure of clayed minerals in layers of very small dimensions and to the development of electrostatic forces between the surface of those layers and the ions in solution present in underground water. It will not be drawn categorical conclusions concerning these phenomena, certain argillaceous or marly formations being very sensitive to water whereas others not at all.

3. AVAILABLE EXPERIENCE FEEDBACK

Today, the scientific community does not have to its disposal well documented databases enabling to characterise the impact of climate change on water tables behaviour and, even less, on its indirect impact on stability of underground cavities. The available experience feedback of impact of water variations on rock mass stability has thus to be found in circumstances having led, for any other reasons than global climate change, to important variations of water tables levels that have generated disturbances on ground surface. Three French examples are provided below, the last one being described in a more detailed way.

3.1. Flooding of the Lorraine Iron Field

INERIS has been strongly involved in the analysis and the monitoring of the flooding process of disused Lorraine iron mines located North-East of France [7]. Several collapses occurred within the iron field during (or shortly after) the flooding of the “Northern” and “Centre” under-basins (many families living in the towns of Auboué and Moutiers for example had to be evacuated) that followed the stopping of the dewatering system resulting from mine closure. To better understand the phenomena concerned and to be able to predict more accurately the consequences of the future flooding of the third sub-basin, various studies had been carried out by the teams of the Scientific Network on Post Mining [8]. These studies related both to laboratory tests and *in situ* experimentations (artificial flooding of two pillars in the Tressange mine). On this basis, numerical modelling was developed in order to reproduce accurately the observed phenomena and mechanisms. Some of the principal results highlighted are presented here:

- the compressive strength reduction of the iron ore according to its water content is close to 50% for a water content increasing from 80% to 100% (sample becoming totally flooded);
- several creep tests under variable load and controlled hygrometry highlighted significant drops of elastic modulus and an increase of the strain values measured with water content increasing from 90% to 100%. This can be interpreted as an increase of irreversible strains and a stronger tendency to the long term failure of the sample. The use of acoustic sensors during these creep tests clearly highlighted the increase of acoustic emissions (development of microscopic cracks reflecting damage development) as soon as the sample begins to be flooded (figure 2);
- the ambitious *in situ* full scale experiments (flooding of two mine pillars during a few months) enabled to highlight, through tomography tests notably, that the “fringe” of weathered rock at the periphery of the pillars was larger at the end of the experiment than before flooding;
- the weathering effect induced by flooding has not been spatially homogeneous. It appeared to be much higher in sectors where strata were already damaged (important density of cracks) or included minerals very sensitive to water (clay, marls).

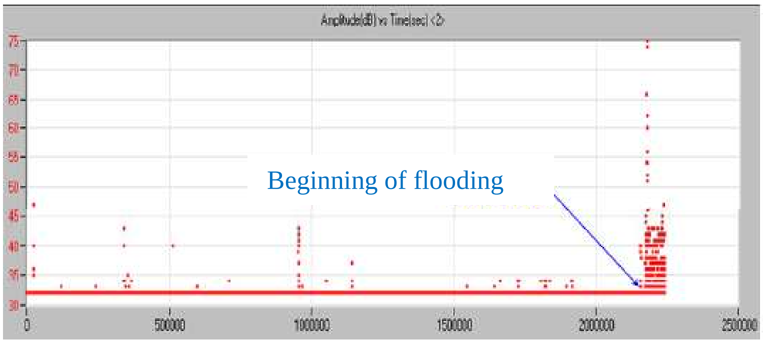

Figure 2: Evolution of the acoustic emissions during creep test with controlled hygrometry [8].

3.2. Impacts of water tables elevation in Picardy during spring 2001

Several towns of the Picardy Plateau (northern part of France) were severely affected during spring 2001 by numerous collapses of buildings undermined by shallow cavities mainly located in chalk (figure 3). These ground disturbances were due to the loss of strength of the rock structures (roof, pillars) that occurred at the time of important rainy events having induced an exceptional elevation of water tables. If, in the long term, the failure of these very ancient cavities, unknown for most of them and badly maintained for the others, was probably inevitable because of the bad condition of the mine workings, degradations and failures were, for sure, accelerated by water intrusion within the cavities.

Year 2000 was characterized by an exceptionally significant rainfall recording (about 950 mm of water, for an annual average of about 600 mm usually). Those rainfalls strongly contributed to supply the water tables and, in particular, the one located in the chalk bed. The average piezometric level, usually located between -15 and -40m below surface, brutally increased during spring 2001 (-5m below surface in average), inducing severe floods in the topographic depressions.

This water table increase generated the outbreak of many surface collapses in numerous regions located North of France (Artois, Picardy, Normandy). One will quote for example:

- sudden flooding (more than 10 m of water table increase within a few days) of cellars making them inaccessible (figure 3.1);
- occurence of numerous sinkholes on surface, some of them under houses built more than 100 years ago (figures 3.2 et 3.3). Some sinkholes were due to backfill run-out (figure 3.4) in old chalk mine shafts abandoned several centuries ago (extraction of chalk by local farmers for fertilizing acid soils).
- the number of rescue interventions performed by the authorities were multiplied by ten to fifteen during the crisis period of spring 2001 compared with a "normal" activity period.

Figure 3: (1) Flooded cellar; (2 & 3) Collapses of buildings due to undermining cavity failure;
(4) Backfill run out of an old chalk mine.

3.3. Collapse of the Lorroy chalk mine

Context

Sometimes, interactions between climatic phenomena and underground instability are occulted by repercussions of those exceptional weather phenomena and their consequences on a region or a even whole country. As an example, at the time of the 1910 catastrophic floods which affected severely Paris and its region, the chalk mine Lorroy (city of Château-Landon) (77) collapsed as a direct consequence of the flood of the Loing River (affluent of the Seine River). In spite of the dramatic consequences of the event (7 people killed and 7 were severely injured), this catastrophe is very poorly known because it occurred during the flood of the Seine River which severely affected Paris and its surroundings and monopolised at length the interest of the media.

The Lorroy site is located about 50 km south of Paris, along the Loing River that notches a limestone plateau causing a steep hillside of about 40m high. Extraction activity began in the area around 1850 with galleries dug in the slope. The very pure and white chalk was initially extracted by peak, then by explosive. The mines were exploited by “arched form galleries” of 3 to 5 m of opening (figure 4). The pillars sections were globally increased with deepening of the mine workings but their fitting and their geometry were designed at random. Overburden thickness varies between a few meters near the outcrop to about thirty meters in the deepest sectors.

Figure 4: Some views of a remaining chalk mines in Lorroy, close to the one collapsed in 1910.

In 1910, 6 underground chalk mines were registered over the city territory. Several were already collapsed, one of them, in 1897, already during a previous flood of the Loing River. Part of the still existing mine was not any more object of active extraction, most of those galleries being then reconverted for mushroom cultivation. Thus, on the 1910 collapse site, the active extraction galleries (called “Beaulieu”) were located south (figure 6), next to northern galleries used for mushroom (called “Guillon”).

The disaster and the investigation

The catastrophe occurred on Friday January 21th, about lunch time. It was characterised by the sudden collapse of the slope combined with an associate major slide of the ground located at the slope base (figure 5). The landslide destroyed 3 houses built along the Loing channel and caused death by burial of 7 people. It is difficult to evaluate precisely the volume of material moved (probably over 100.000 m^3). The collapse of the rock mass extends on about one hundred metres long and 40 metres wide. The debris accumulation filled the channel and broke the closest lock as well as a dam. Several months were necessary to clear the site.

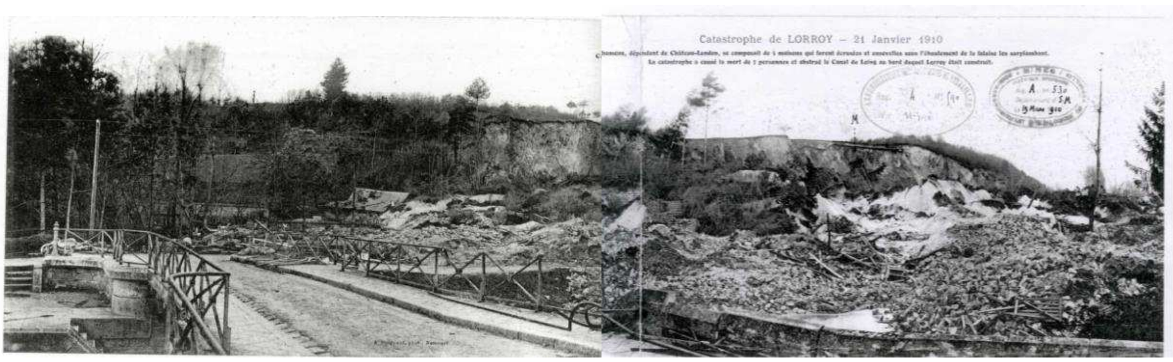

Figure 5: View of the Lorroy site after the disaster of the chalk mine collapse.

An investigation was quickly undertaken by the Mining Authority to identify the reasons of the catastrophe. It made it possible to establish that the collapse occurred right at the peak of the flood of both Seine and Loing

Rivers. On the Thursday, the day before the accident, the flood had reached its local maximum but no water had yet entered the mine. The testimony of the mushroom grower exploiting the northern galleries of the collapsed mine is, concerning this subject, of first interest. He specified formally that no trace of water penetration was yet visible underground on Thursday 20th evening. But, the morning after, day of the accident, about 9:00 (that is to say three hours before the catastrophe), at the time of its visit of underground workings, he declared that "*water was invading the galleries on 20 to 40 centimetres high*". It seems that water entered the mine through old shafts dug for water supply (usually located about 10 metres lower) used for washing the extracted chalk before its conditioning (figure 6).

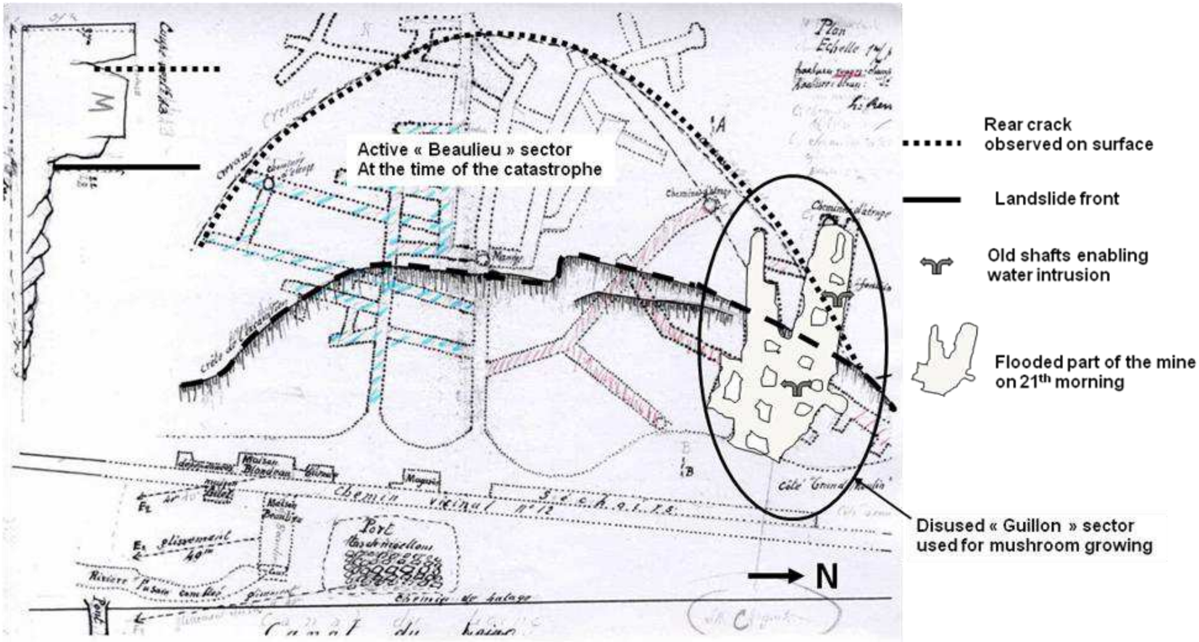

Figure 6: Schematic view of the collapse and associate landslide of the Lorroy hillside on January 21th, 1910.

The main conclusions drawn from the investigation clearly highlighted the origin of the catastrophe to the collapse of the disused mine workings located north of the chalk mine. The initial failure of this "small pillars sector" seems to have been initiated by the flooding of the galleries basis. Then, due to dynamic shock, this triggering collapse would have propagated to the other parts of the exploitation even though, according to the mine operator, the southern galleries were not flooded the morning of the collapse. The global subsidence of the rock mass would have then generated a concomitant slide of the hill towards the channel.

Several compressive strength tests were carried out on cubic samples taken in the nearby mines. They confirmed the very sensitive behaviour of this chalk to water. The values of compressive strength, in totally saturated conditions, appeared to be extremely low with an average of about 0.5 MPa for an average value of 1.5 MPa for usual water content values (80% corresponding to not submerged galleries). The propensity of the chalk "*to lose any consistency when it has been submerged for a few hours*" is clearly underlined in the report.

Some calculations of the apparent stress based on the tributary area method based on the available indicated vertical stresses developing in the pillars varying from 0.9 to 1.3 MPa depending on the size of the pillars as well as the thickness of the overburden. These results consolidated the assumption of a mine collapse due to a sudden drop of rock mass strength generated by the water intrusion within the mine.

Remaining questions

Despite the seriousness of the investigation performed, several questions remain today unanswered. INERIS who fortuitously discovered this unique case study will undertake in the following months a research program to better understand some of those "shadow zones". First of all, looking carefully at the mining map, if a collapse of the old highly extracted and moreover flooded sectors appears quite easy to understand, it is more difficult to explain the extension of the failure to much larger pillars located southern. The concept of "barrier pillar" needs to be studied in this context, specially considering the width/height ratio of the pillars. Was the dynamic wave generated by the collapse of the northern part sufficient to enable propagation of the instability or was there a more complex mechanism, including for example shearing stress due to the hillside proximity?

It will also be of great interest to analyse precisely the sequence of the catastrophe and particularly the overlapping between cavity failure and landslide triggering. As rock mechanics experts, it does not appear evident to us that the potential failure scenario considered would have be as catastrophic as it really was. Necessary coupling processes between rock mechanics and soil mechanics as well as between geotechnics and hydrogeology will be of first interest. This could be useful to make progress in our ability to determine the way to deal properly with the necessity to predict safely, but reasonably, the concept of "over-accident".

The existence of remaining accessible mine in the surroundings will enable INERIS to carry out some new characterisation tests to precise the constitutive law governing this material. Some monitoring equipment will also be implemented underground to characterise the evolution of the geotechnical and environmental parameters within the mine. According to the results, numerical modelling will be carried out to better understand the sequence of events that lead to the 1910 catastrophe but also to identify if the still existing mines remain sensitive to major hazardous events or no.

4. CONCLUSIONS AND PERSPECTIVES

The various scenarios of climate change for the 21st century envisage, for France, a serious modification of the rainfall regime likely to generate increased fluctuations of water tables. The forecast increase of water tables level variations seems to be the major parameter likely to influence the behaviour of the underground cavities.

Important scientific gaps remain, concerning, for example, the mechanical impact of seasonal water level fluctuations on potentially unstable underground cavities but also the impact on rock mass of potential physicochemical modifications of water seeping from the surface.

In order to better appreciate this impact, INERIS chose to carry out a dedicated research program that will contribute notably to monitor several cavities, located in various geological and climatic contexts, for which water plays a key role. Some of them are located in chalk, others in gypsum and a last one in limestone. The monitoring devices previously developed by INERIS will feed the available database. Today such data concerning impact of climate change on water table behaviour and consequently on underground cavity stability are greatly lacking.

This experimental program, coupled with case studies analysis (like the one of Château-Landon), will have a greater interest if same initiatives are taken in the coming years in other countries to enlarge the available database to numerous contexts. INERIS would be pleased to take part of an international network of organisms interested to develop knowledge and research initiatives concerning interaction between climate change and rock mechanics, not only dealing with underground cavities but also landslides and rock falls.

5. REFERENCES

[1] International Panel on Climate Change. 2007 Synthesis on Climate Change. 114 p.

[2] IPPC Technical Paper VI: Climate Change and Water. 214 p.

[3] IPPC Nastev, M., Rivera, A., Lefevre, R., Savard, M.M. (2002). Hydrogeology and numerical simulation of the regional groundwater flow of the St. Laurence Lowlands of South-Westren Quebec. http://www.nwri.ca/threats2full/ch10-1-f.html

[4] Hawkins, A.B., Mc Connell, B.J., 1992. Sensitivity of sandstone strength and deformability to changes in moisture content. Quarterly Journal of Engineering Geology, 25, pp. 115-130.

[5] Wiid, B.L., 1967. The influence of moisture upon the strength behaviour of rock. Ph.D. Thesis. University of Witwaterstrand. 184 p.

[6] Watelet, J.M., 1996. Méthode d'analyse et diagnostic des conditions de stabilité des carrières souterraines. Mémoire de diplôme d'ingénieur CNAM.

[7] Didier, C., 2009. Post-Mining Management in France: Situation and Perspectives. Risk Analysis, vol 29, n°10, pp. 1347-1354.

[8] GISOS 2005. Synthèse des travaux de recherche sur l'Après-mine. www.gisos.org

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