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Back analysis on the Lorraine iron ore pillars behaviour.

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ABSTRACT **:** After one hundred years of activity, mining in the Lorraine iron ore basin has ceased. Following several surface instabilities, investigations into methods of evaluating underground stability were initiated few years ago. This paper concerns the latest developments in the field of stability evaluation as input into the risk assessment procedures. The methodology is based on the empirical back analysis philosophy developed by Salamon in South African coalfields. A strength formula resulting in the best possible separation of data bases of safety factors of failed and intact pillar cases was identified. Work is ongoing into the kinematics of failure, distinction between different zones of the basin and the development of a Failure Potential Index.

1. Introduction and context

The Lorraine iron ore basin in north-east France extends over 120 km from north to south, and over 30 km from east to west. The basin was mined throughout the 20th century, but activity declined progressively as of the 1980s. The end of extraction led to cessation of the pumping works and therefore to the progressive flooding of mine workings. In the months that followed the onset of this flooding, several subsidence events occurred with a major impact on the population. On 4 October 1996, approximately 70 buildings had to be demolished in the city of Auboué and 150 families relocated. In the following months, other instabilities developed in vicinity (Moutiers, Moyeuvre-Grande, Roncourt). The Administration sought to implement a procedure to identify rapidly the sectors most susceptible to the risk of subsidence (Didier, 2009). For each sector identified, a risk management procedure was developed (monitoring, treatment, evacuation). Development and implementation of the procedure, entrusted to Geoderis, were centred on a committee of national experts.

The risk management policy was applied to the entire basin. The later flooding of the northern sub-basin of Briey-Longwy area was not started until all the ground stability studies had been completed and measures to mitigate risk were implemented above the sectors considered likely to instabilities. Given the chronology of events in the other sub-basins, it was reasonable to fear new ground movements, or at least triggering of seismic events in the monitoring networks implemented in the critical areas (Couffin, 2003), in the months following the onset of flooding. However, disturbances turned out to be few,.

In order to take advantage of the available information on workings flooding over a vast geographical sector where precise geological and mining data were available, analytic work was undertaken between INERIS and the University of the Witwatersrand, in collaboration with Geoderis. The objective was to seek to better understand the behaviour of the pillars and their *a priori* different response to flooding according to mining sectors. To do this, the approach focussed on the long-term stability of the pillars. The present paper reports on the current work and outlines the prospects for continuation of research.

2. Objectives of the analysis, choice of approach and constitution of the database

The approach developed focuses exclusively on the concept of "potential for pillar failure". It thus does not incorporate the concept of the predictable kinetics of the various disruptions and gives priority to a "back analysis" approach, seeking to better understand the onset (or absence) of instabilities in various areas. To do this, the empirical approach proposed by Salamon and Munro (1967) was used. This model, a standard in the English-speaking mining world, relies on an empirical determination of pillar strength, contrary to the more "deterministic" approach of the procedure usually used in France (laboratory tests, then extrapolation to the *in situ* scale).

Salamon's approach is as follows: having available a database of pillars, some of which have failed and the others remaining stable, how do we determine a relation for pillar strength that, based on the available characteristics, allows the category of failed pillars to be best differentiated from that of intact pillars? The main hypothesis inherent to the Salamon approach is the following: on the scale of a consistent "geographical risk basin", the strength of a pillar depends less on the variations in properties of the rock masses than on its dimensions, and especially its shape. This shape is mainly defined by two magnitudes: the width *w* and the height *h*. Thus we have:

$$\sigma_s = k \frac{w^{\alpha}}{h^{\beta}} \qquad [1]$$

With σ_S: Strength of the pillars in MPa
w and *h*, respectively the width and height of the pillars
k, α and β, parameters to be specified according to the environment considered.

To adapt the formula to the environment considered, it is of primary importance to use a reliable and accurate database describing a sufficient number of pillars, some failed and others stable. In this case, with mining extraction having ceased and access to most of the former areas now impossible, it was not possible to sample various pillars considered representative in several mining areas.

An experience-based approach was thus developed. A database specifically intended to establish the "Lorraine iron basin" empirical relation was built up. The failed pillars are cases known to have affected the mines in the basin in the past (Didier & Josien, 2003). Sixteen cases were found, the oldest dating from 1902 (Audun-le Tiche) and the most recent from 2009 (Angevillers). For each of these sectors, a "representative mesh" was defined to characterise as well as possible the mining layout corresponding to the failed area.

The initial stable data base consisted of pillars not known to have failed (i.e. stable to the best of our knowledge) in the vicinity of the failed cases, in order to have a contrasting stable data base of approximately the same age, depth, etc as the failed cases. This was reported in van der Merwe et al (2011). Subsequent to that investigation, the stable data base was extended substantially by the inclusion of more randomly selected cases over the entire mined area that were as certain to be stable as could possibly be determined. By doing this, the initial stable data base of 33 cases was extended to 107 cases.

Figure 1: in red, example of failed sector that has caused a surface disruption;
in green, nearby sectors in which the pillar dimensions predict stability.

Finally, in an innovation with regard to the approach developed by Salamon, a third category was instituted: pillars considered “suspect”, that is, those for which no information is available on their present state of failure, but that are subject to a level of vertical stress greater than the long-term strength value specified for the ore (7.5 MPa). This category thus corresponds to an “intermediate” class, *a priori* stronger than the “failed” category but less so than the “stable” one. Eighty-two “suspect” samples were thus identified, taking care here too to ensure a geographic distribution of sampling as satisfactory as possible.

3. Methodology of development of the formula used and application to the case studied

To seek to distinguish stable pillars from unstable pillars, we reasoned on the basis of safety factors that require calculation of the stresses acting on the pillars. These are established on the basis of the simple but proven model of the tributary area, corrected by a factor taking account of the context of mining in the area likely to generate stresses in excess of the Tributary Area stress on the pillars considered (Table 1).

Table 1: values of the corrective factors for various mining configurations

Layout 1	Method and factor (f_L)	Layout 2	Method and factor (f_L)	Layout 3	Method and factor (f_L)
	Room and pillar over a wide area $F_L = 1.0$		Room and pillar bordering on pillar extraction $F_L = 1.2$		Room and pillar within a pillar extraction area $F_L = 1.4$

We then find:

$$\sigma_L = \frac{\rho g f_L H}{1-\tau} \qquad [2] \qquad \text{then} \qquad f_s = \frac{\sigma_S}{\sigma_L} = \frac{k(1-\tau)}{\rho g f_L H}\frac{h^\beta}{w^\alpha} \qquad [3]$$

With: H: depth of the works (in m)
τ: extraction ratio
ρ: density of the cover (assumed equal to 2500 kg/m^3)

For each sample of the database, a series of safety factors is established by a parametric approach, varying the values of α and β in a range from 0 to 2, with increments of 0.2. This allows 100 simulations of safety factors (k initially assumed equal to 7.5 MPa) to be produced for each area studied. For each pair of values (α, β), two distributions of safety factors are thus established: one for intact pillars and one for stable.

The objective in parametrising the model is to look for the pair of values for which the "overlap area" between the distributions of values of safety factors calculated for the failed pillars and for the stable pillars is found to be least. The perfect formula would allow complete separation of the two categories of samples but because of the partial understanding of the mechanisms and the incomplete nature of the data available, a minimisation approach is used.

This "Minimum Overlap" approach is different from the one used by Salamon, who preferred the maximum likelihood approach to find that combination of parameters that would result in a safety factor closest to 1.0 for the failed pillar data base. The reason for preferring the Minimum Overlap approach, first used by van der Merwe (2003), is that the original pillars were not designed with the intention of having the same factor of safety and also that there was more merit in finding the combination of parameters that would result in the greatest separation of failed and stable cases, bearing in mind that the main purpose of the formula is to distinguish between failed and intact cases and not to design pillars.

To calculate the overlap area between the two distributions, the principles described by Harr (1987) were applied. To do this, we introduce the parameter λ defined as:

$$\lambda = \frac{M_s - M_f}{\sqrt{S_s^2 + S_f^2}} \qquad [4]$$

with: M_s = Mean of the population of safety factors for the intact pillars
M_{f} = Mean of the population of safety factors for the failed pillars
S_{s} = Standard deviation of the population of safety factors for the intact pillars
S_{f} = Standard deviation of the population of safety factors for the failed pillars

According to the value of λ, the overlap area (A) can be estimated as (Harr, 1987):

If $\lambda > 2.2$: $A = \frac{1}{f}(2\pi)^{-0.5}\exp\left(\frac{-f^2}{2}\right)$ [5] if $\lambda \leq 2.2$: $A = 0.5 - \psi(f)$ [6]

where $\psi(f)$ can be taken from the statistical tables of Harr (1987) or estimated making use of a less rigorous but nevertheless accurate approach based on the following polynomial equation:

$$\psi(f) = .0006f^6 - .0096f^5 + .0563f^4 - .1379f^3 + .0423f^2 + .3893f + .0004 \quad [7]$$

The approach then consists of calculating the value of the area of overlap between the normal distributions of the safety factors for the intact and failed pillars for each of the 100 simulations obtained for the various values of the pair α and β. The pair of values to be selected is that which minimises the overlap area. Figure 2 summarises the results of the simulations conducted to optimise the values of α and β in the case of the Lorraine iron ore basin.

It shows a map of the overlap area value between the distributions of stable and failed safety coefficients. The centre of gravity of the minimum class (less than 8%) corresponds to the combination $\alpha = 0.4$ and $\beta = 0.5$. At this exact point, the overlap area is 7.9%.

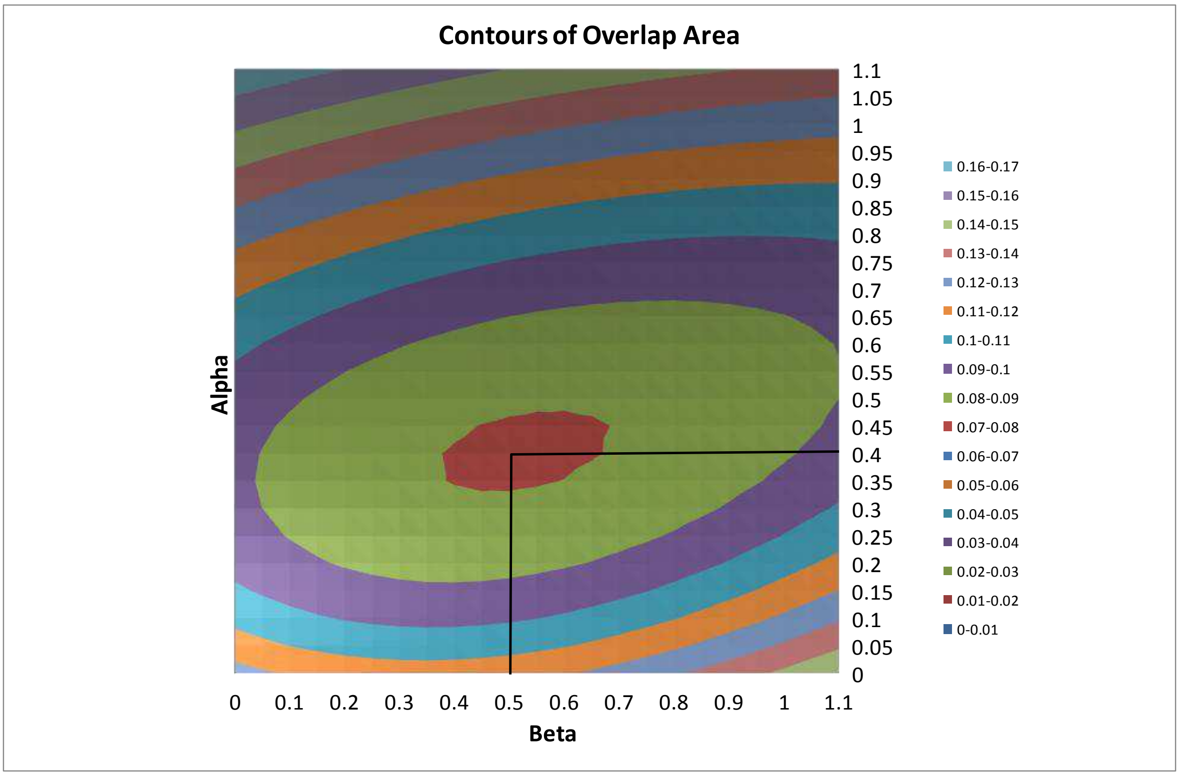

Figure 2: Values of the "overlap areas" of the distributions of safety coefficients for intact and failed pillars according to the values of α and β.

The value of k then remains to be determined.. We note in this connection that the overlap area is independent of the value of k, as k increases or decreases the safety coefficients of the two populations in the same proportion. The value of k was then that value which resulted in the mean safety factor of the failed pillars being 1.0. In the context that interests us, for the combination $\alpha = 0.4$ and $\beta = 0.5$, the value of k is 8.3 MPa. This value inspirers confidence in the strength formula as it is derived by a different route, yet is in good agreement with the strength value of the ore of 7.5 MPa that was derived analytically.

The resulting optimal formula is thus:

$$\sigma_s = 8.3 \frac{w^{0.4}}{h^{0.5}} \quad \text{in MPa} \qquad [8]$$

4. Initial results and prospects for continuation of the work

Initial evaluations of the database and the strength formula for the pillars

Figure 3 shows various distributions for categories of pillars, based on equation [8]. At this stage, safety factors for the sub set of data in the "Suspect" category were also calculated with Equation 8 and compared to the data sets for failed and intact cases. The three main categories used in constituting the (failed, suspect, stable) database are shown. We note that the area of overlap between the "failed" and "stable" categories is in fact relatively low.

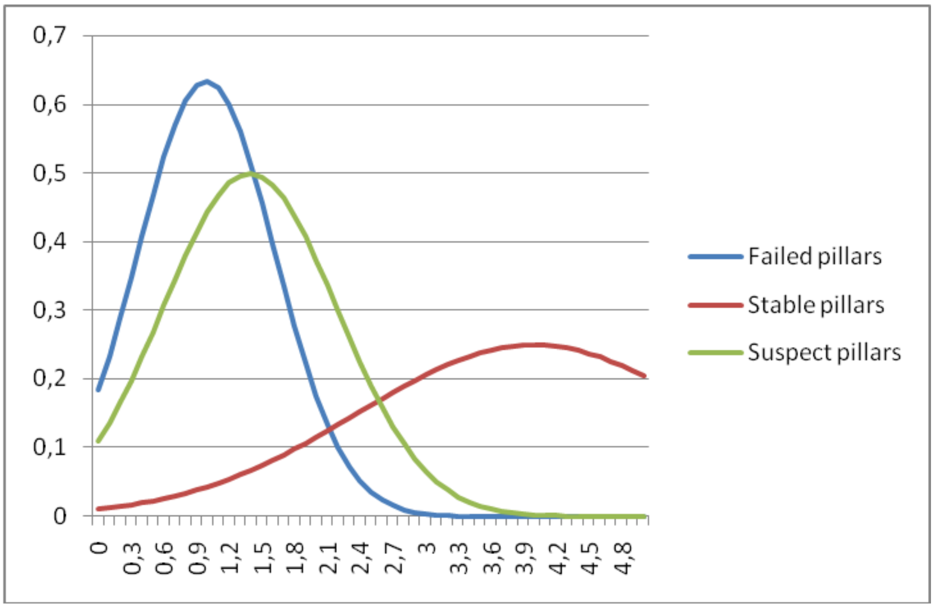

Figure 3: Probability density distributions of safety factors for the stable, suspect and failed pillars.

Logically enough, the distribution for the pillars considered “suspect” shows a profile intermediate between the other two, although very appreciably closer to the “failed” category than the “stable” category. This confirms that the suspect pillars show characteristics that differentiate them very clearly from the long-term stable pillars. Moreover, although of concern, their stability characteristics turn out to be on the average slightly more favourable than those of the already failed pillars (mean safety factor of 1 for the failed and 1.4 for the suspect). This assessment is however only valid at a given time. Everything in fact leads one to expect that several “suspect” sectors will fail in the years to come, thus modifying the present distributions. It will then be particularly interesting to analyse the increase, according to time, in the mean safety factor of the failed pillars.

Figure 4 shows the distribution of the failed and suspect pillars for the south and north basins. An initial analysis reveals that the category of failed pillars in the southern sub-basin shows a noticeably less favourable stability configuration than the others. This may provide an initial factor in explaining the large number of failures that occurred during flooding of this part of the basin (presence of very fragile sectors).

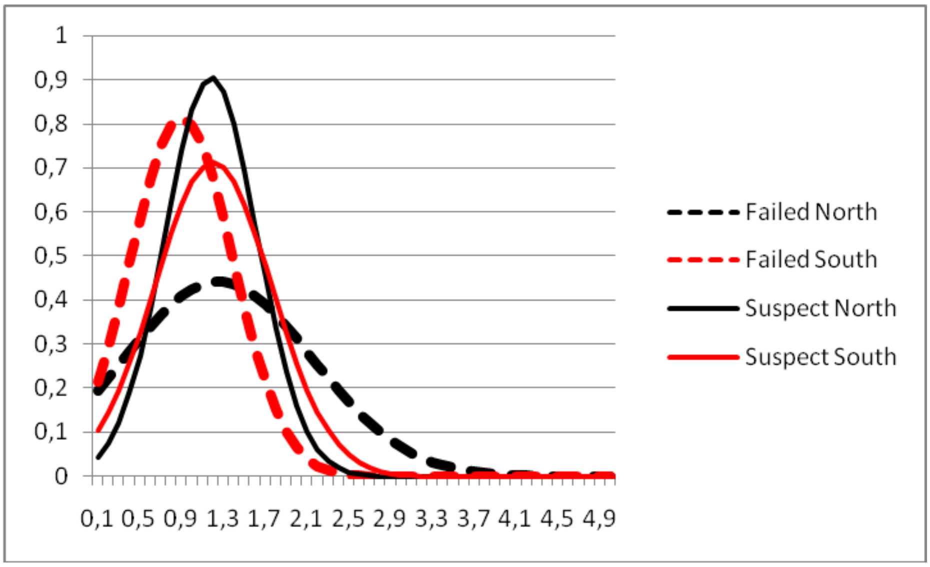

Figure 4: Distributions of the safety factors for the pillars of the northern and southern basins.

Moreover, the “stability potential” of the suspect pillars seems very low (both for north and south), as they show a safety factor profile very similar to that of the failed sectors of the north basin. Everything thus leads one to believe that, given the ageing of the rock in addition, several sectors now considered suspect will fail in the years or decades to come.

A more thorough analysis of various parameters likely to play a key role in creating instabilities (before or after mining, before or after flooding, nature of the iron layer, nature of the mining operations in the vicinity of the collapsed area) should be conducted in the months to come to extract the maximum information from the database. But monitoring and interpretation of the development of the profile of the failed areas over time presents in particular the most interesting prospects for scientific advances.

Possible considerations on the kinetics of progressive subsidence

Among the instabilities that have affected the Lorraine iron ore basin, some have appeared as “progressive subsidence” developing over periods on the order of a day to several months, damaging to structures but with little danger for people when sectors are subject to monitoring. Conversely, others have given rise to “sudden collapses” that occur with the failure of the overburden as a whole in several seconds, often accompanied by a strong seismic tremor. Due to their suddenness, these potentially disastrous events are especially hazardous and should be identified with the greatest care before taking the safety measures best adapted to the context (reinforcement of the workings, moving surface features).

A specific methodology has been established by the group of experts led by Géoderis to identify the sectors at risk of sudden collapse, based on cross-analysis of the weakness of the underground works and the “rigidity” of the soil cover (Josien et al., 2010). Figure 5 gives rise to interesting prospects in terms of use of the approach described in the present paper to identify areas at risk of subsidence and those susceptible to collapse. It shows the location on the normal distribution of the failed pillars, the cases of sudden collapses (in red) and those of progressive subsidence (in green).

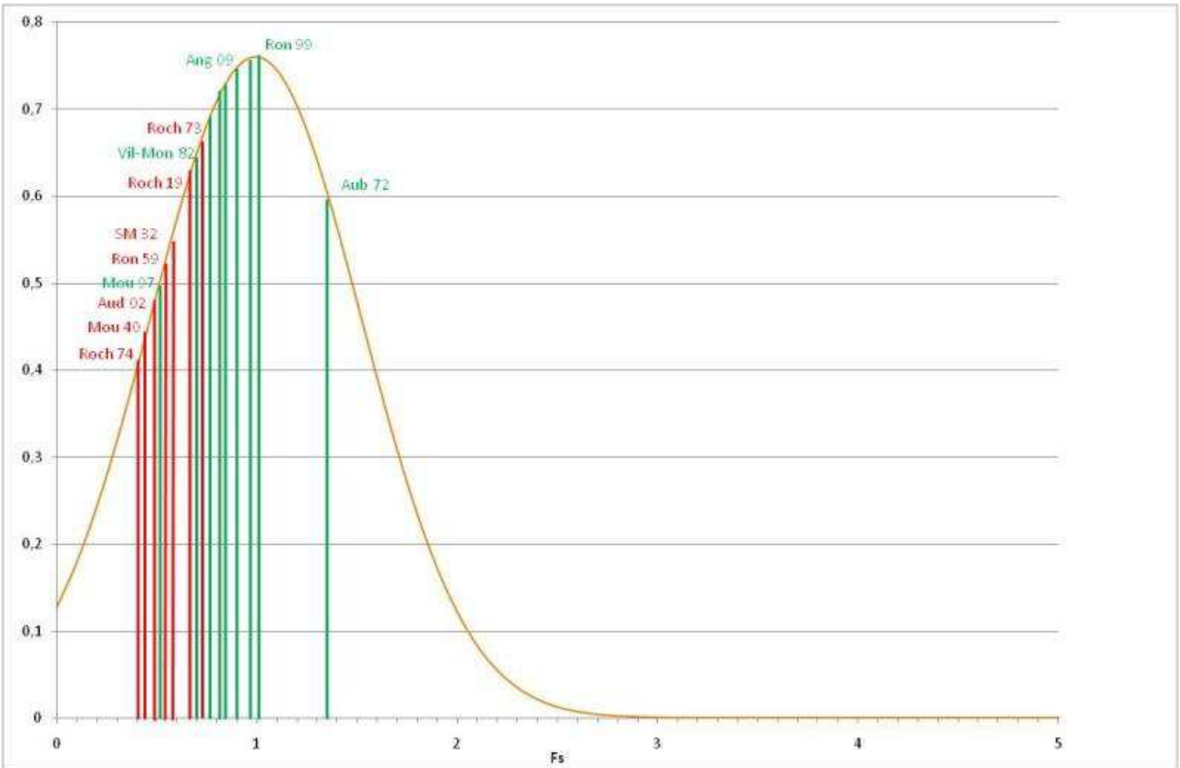

Figure 5: Location of past instabilities (in red collapses, in green subsidences).

From the analysis, it emerges that with one exception (Moutiers 97) the formula allows a very clear distinction: the lowest safety factors correspond to sudden events, the others to progressive subsidence. It appears that, in cases of progressive subsidence, the approach even allows the slowest events, hardly perceptible by the monitoring networks (Auboué 72, Roncourt 99, Angevillers), that correspond to the highest safety factors to be distinguished

Development of Failure Potential Index concept

The concept of a safety factor only has merit in describing relative stability of pillars, but it is not possible to quantify by *how much* pillars with high safety factors will be more stable than pillars with lower safety factors. The concept of a probability of failure is considered to be more useful in this regard.

The historical probability of failure can be determined by comparing the number of failed pillar cases to the stable ones for each category of safety factor, using the total populations of failed and stable cases. That was not practical in this case, due to the magnitude of the total population of stable pillar cases. A pragmatic approach was then followed, by statistically extending the existing sample of the population of failed pillars according to the ratio of the sum of the sample areas to the total area mined. Furthermore, as only the as mined dimensions were known and not the dimensions of the pillars at the time of failure and to avoid confusion, the term "Failure Potential" was preferred over the term "Probability of Failure", but it was derived in the same way.

This work is ongoing and publishing results at this stage is premature, yet we considered it appropriate to mention that this extension and hopefully refinement of the procedures is already being attended to. Preliminary results are very encouraging..

5. Conclusions

The principle implemented by Salamon to determine *in situ* strengths of coal pillars in South African mines has been adapted to the context of the abandoned mines of the Lorraine iron ore basin. A formula relying mainly on the dimensions of the pillars has been established, with the parameters determined using a database of nearly 200 pillars considered representative of the basin. Among these pillars, some have already failed and others are assumed long-term stable, with the remainder considered "suspect", that is, susceptible to eventual failure.

The distributions of the various categories provide a very satisfactory distinction between the failed pillars and the intact pillars, a fundamental parameter in the possibility of using the approach to assess the "potential for failure" of suspect pillars. A probabilistic approach is presently being developed. The initial results show that the failed pillars in the south sub-basin, particularly after inundation, had appreciably less favourable configurations in terms of stability than those encountered in the north sub-basin overall. This can contribute to explaining the difference in terms of occurrence of failures after flooding of both sub-basins. They also indicate the relevance of using the approach developed to assist in distinguishing the kinetics of failure (rapid or progressive) of the various mining configurations encountered.

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