Subsidence kinetics above room and pillar mines & development of kinetic criterion based on retro-analysis of subsidence cases

A. Hosni, Rafik Hadadou, Jean-Pierre Josien, Jack-Pierre Piguet, Hafid Baroudi

SUBSIDENCE KINETICS ABOVE ROOM AND PILLAR MINES & DEVELOPMENT OF KINETIC CRITERION BASED ON RETRO-ANALYSIS OF SUBSIDENCE CASES

* A. Hosni, and R. Hadadou
GEODERIS
1 rue Claude Chappe, CS 25198
57075 Metz Cedex 3, France
(*Corresponding author: ahmed.hosni@geoderis.fr)

J. P. Josien
Rovconsult
25 rue du Gruenewald
L-1646 Senningerberg
GD du Luxembourg

J. P. Piguet
Ecole des Mines de Nancy- Université Lorraine- Georessources
Campus Artem, CS 14234
54042, Nancy Cedex, France

H. Baroudi
INERIS
Parc Technologique ALATA, B.P. 2
60550 Verneuil-en-Halatte, France

ANALYSES OF SUBSIDENCE KINETICS ABOVE ROOM AND PILLAR MINES & DEVELOPMENT OF KINETIC CRITERION BASED ON BACK-ANALYSES SUBSIDENCE CASES

ABSTRACT

The iron ore mines in the Lorraine region of north-eastern France cover a surface area of approximately 3,900 km^2 and involve more than 150 cities. A total extraction method was usually used during exploitation, but this technique was sometimes replaced by the room and abandoned pillar technique when it was necessary to protect surface buildings and infrastructure. Rooms and abandoned pillars were initially designed to ensure long-term mine stability. However, this aim was not always reached and numerous collapses occurred in the Lorraine iron basin, either during production or several years after closure. Several subsidence events were identified during a period of one century; the most recent event occurred in 2012. Two groups of events were identified. The first group represents events characterized by sudden surface movement, and the second group includes event characterized by progressive subsidence.

Numerous studies conducted during the last decade helped improve our understanding the origin mechanism of spontaneous or progressive (slow) events. These studies led to identifying long-term potentially unstable underground zones (hazard zones), particularly deep zones located under buildings and infrastructure. The latest are currently monitored by microseismic networks. A similar high requirement level is needed for unstable zones without taking into account the kinetics of the subsidence, which is very important for safety. Thus, GEODERIS initiated this study, primarily to acquire a better understanding of the kinetics of the progressive events group and identify the main parameters that could explain why some pillars zones developed a maximum amplitude subsidence on surface within a few hours or days, while it took several weeks to months for others. In practice, the results of this study will facilitate adapting the requirement level of microseismic monitoring system to the kinetics of pillar collapse.

To retrieve the real kinetics for each event, historical and sparse documentation was used. Firstly, archives research was conducted, especially testimonies and newspaper articles published during the events. This work helped to gather useful information that sometimes contained a precise description of subsidence duration. The archives research helped to classify some progressive events according to the subsidence kinetics. Secondly, a diagnostic of geotechnical and geomechanical parameters of historic events was realized, combined with a cross analysis of the data. The analysis took into account dimensions of underground workings (e.g., pillar lengths, widths, heights, introduction of a "pillar shape factor", and stress amount). An original expression was highlighted to connect the pillar geometry to the stress state. The kinetics expression was calibrated to classify the historic events taken into account according to the kinetics of movements. The kinetic criterion was applied to predict subsidence kinetics for the potential unstable zones currently monitored by a microseismic system.

KEYWORDS

Iron ore deposit basin, Lorraine region, France, subsidence, kinetic, Roncourt, Auboué, stability, pillars, rooms, stresses.

CONTEXT AND AIM OF RESEARCH

The main iron deposit exploited in Lorraine is from the Aalenian era. This Lorraine oolitic deposit spreads across an area 120 km long and 30 km wide. It surfaces on the hillsides of the Moselle in the east and plunges southwesterly towards the Paris basin, following a slope of 2 to 3°. In the exploited areas, the depth does not exceed 250 m.

In this region, the iron ore was exploited by one or more overlapping layers and several extraction methods were employed. The total extraction method of iron ore was used in areas where there were no buildings, or infrastructure at risk. The almost complete exploitation of the ore was carried out along with the blasting of the mine roof during the works and the surfacing of the subsidence when the area of extraction became wide enough. Hence, subsidence is therefore controlled by this « total » method. Within urban areas the most common method was the abandoned room and pillar extraction method (or partial extraction), therefore preserving housing and infrastructure. This method leaves the pillars in position to maintain the overburden roof. These pillars play an essential role in the long-term stability of the mining structure (Chambon, 1983; Tincelin, 1982). In 1997, industrial extraction of the deposit came to an end, leaving almost 40,000 km of tunnels in the Lorraine underground, and a void volume of 1 billion cubic meters.

On numerous occasions during exploitation, the Lorraine Iron Basin (LIB) was at the centre of uncontrolled subsidence having important effects on the surface. The oldest recorded event was the collapse of Audun-le-Tiche in 1902. The most recent one event occurred in 2012 in Neufchef. The history of well-known subsidence phenomena across this basin has brought about the distinction of two subsidence types (Didier, 2003; El Shayeb, 2001; Tincelin, 1962): those that happen with abrupt surface movement (in a matter of seconds), such as the event in Audun-le-Tiche, and progressive events that happen over a few days, or even months, like the one in Roncourt in 1999 described below. Some of these events (e.g., Auboué in 1996, Moutiers in 1997, and Roncourt in 1999) have been to such a scale that houses have had to have been expropriated because of the extent of the damage.

Over the last decade and in response to the French administration, GEODERIS has carried out many studies to understand the mechanisms for these brutal collapses. A method has been developed and applied to examine the long-term stability of all the former partial-extraction sites in the LIB (Fairhrust, 2003). A retroactive analysis has been carried out on sixteen of the historical events recorded on the LIB to date, half of which are categorized as abrupt, and half as progressive. Geological and geotechnical criteria have been established for the two main types of collapse. For abrupt risk types lying closely to areas with housing and infrastructure on the surface, the risk has been reduced by expropriation. Areas of progressive subsidence are observed by microseismic monitoring systems when the potential damage is substantial. The monitoring program does not consider the kinetics of the phenomena: all the zones are monitored at the same intensity.

SUBSIDENCE KINETICS

Kinetics of Surface Subsidence

Ground subsidence occurs in three main phases (Figure 1). After the initial phase at a slight slow speed, a second phase of acceleration occurs and is followed by a final phase of compaction, during which the speed decreases until it reaches stability. The first effects on the surface, small cracks appearing on the buildings and infrastructure, usually happens just before phase 2; this is the moment where the evolving phenomena can be detected at the surface and hereafter will be referred to as t_0. All other time parameters will be in reference to t_0. Thus, $t_{1.5}$ corresponds to the time to reach the critical slope of 1.5%, and $t_{Amax/2}$ corresponds to the time to reach the amplitude of collapse equal to half of the maximum amplitude expected (or measured). Considering the uncertainty of t_0, we defined $\nu = t_{Amax/2} - t_0$ as the time needed to reach $A_{max/2}$, and $T_c = t_{1.5} - t_0$ as the time needed to reach a slope of 1.5%.

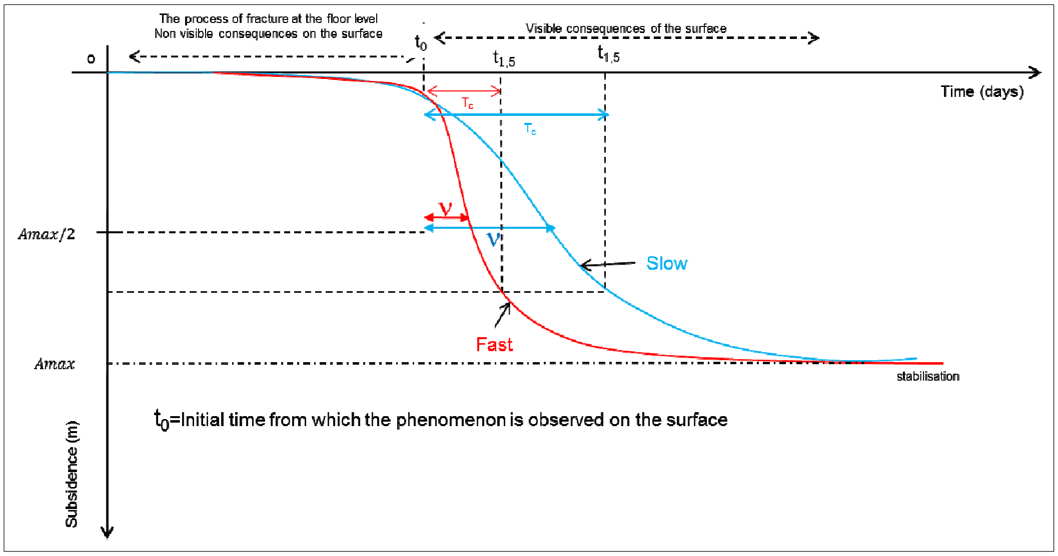

Figure 1. Evolution in function of the time taken to reach the amplitude of collapse at a particular point of the Lorraine Iron Basin (LIB)

An event is a danger to public safety if the subsidence causes structural damage to buildings that could affect the security of people. A subsidence is branded as "rapid" if the time separating the first visible signs on the surface and the critical collapse is too short to initiate evacuation. A rapid subsidence must be anticipated by microseismic surveillance of precursors, such as pillar collapse just before surface subsidence. This critical time (T_c) is highly variable depending on which phenomena are being observed on the LIB as illustrated by the following examples.

Roncourt 1999

In the area of Roncourt, damage was reported as soon as November 1998; an increase in reports brought about the establishment of a land-levelling network in February 1999. In 1991 when the commune decided to renovate the road network, a local levelling network was implanted and reference measurement recorded. The latest helped us to assess the subsidence values obtained in February, 1999. So a collapse of 26 cm had already occurred at a speed of approximately 0.3 cm/day. Movement continued at a maximum speed of 2 cm/day. This very slow subsidence caused structural damage to houses that required the evacuation of buildings during 1999. In this case the critical collapse was 42 cm (with a slope at 1.5%) and the critical time (T_c) was 103 days, the event can therefore be characterized as slow (Table 1, Figure 2).

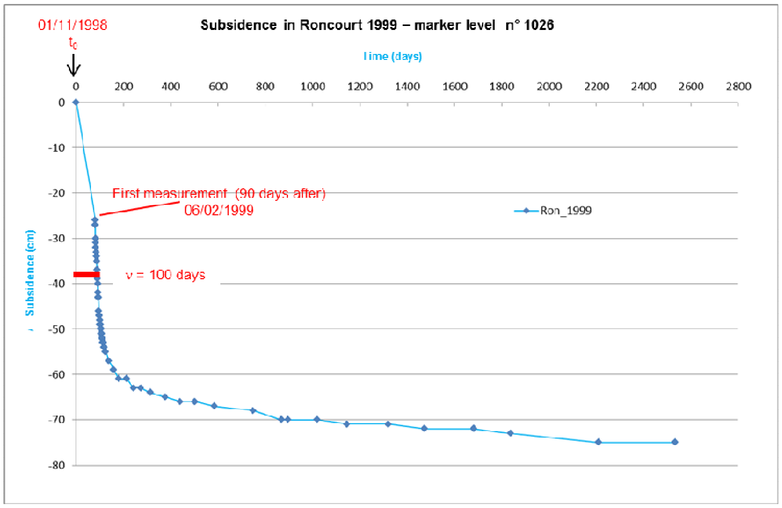

Figure 2. Evolution in function of the time taken to reach the amplitude of collapse measured at the 1026 level in the commune of Roncourt (event Ron_1999)

<u>Auboué 1996 "Cité de Coinville"</u>

In the commune of Auboué, disorder was noticed on the road surface and buildings on 14 October 1996. The levelling network put into place the following day showed a collapse of more than 80 cm in 2 days (i.e., 40 cm/day). Serious damage rapidly affected 57 houses and 70 families, many of whom were evacuated. In this case the collapse was 68 cm, and the T_c was just one day (Table 1, Figure 3).

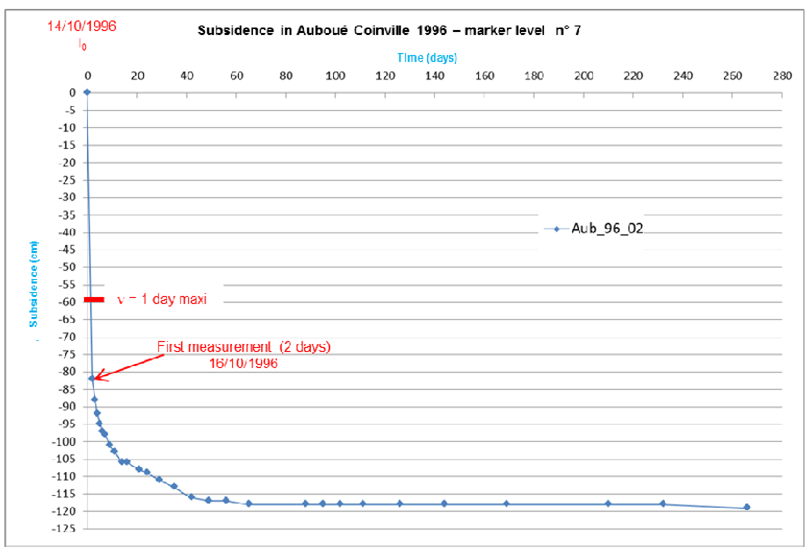

Figure 3. Evolution in function to the time taken to reach the amplitude of collapse measured at marker n 7 in the commune of Auboué (event Aub_96_02)

Other Events

Subsidence measurements for the seven other events included in this study showed that T_c ranged from 1 to 470 days (Table 1). For two events (Doma_01 and Roc_2008), the collapses were sufficiently weak that the damage did not exceed cracks, not impose any danger to people (e.g., Figure 4).

Figure 4. Example of limited damage incurred following the subsidence in Rochonvillers (Roc_2008)

Subsidence kinetics is an important element that has an effect on T_c. The subsidence curves can be characterized by a curve-stiffness parameter independent of the final state of collapse. The time ν was chosen as the stiffness characteristic, the advantage being that T_c is less sensitive to the collapse measurements at the beginning of the event. In actuality, after detecting surface movement (damage to buildings), the frequency of measuring levelling markers was increased (generally by 1 measurement per day). This is the date that was chosen as the date of origin from the information gained from witnesses. It is also the origin of the T_c calculation (Figure 1).

The time ν varies from one event to another, similarly to T_c, except for events where the final collapse was too weak (whether it has slow or rapid kinetics). The values of ν enable us to classify the events as either rapid (ν ranges from 1 to 3 days) or slow (ν ranges from 45 to 100 days; Table 1).

Table 1. Characteristic of parameters of selected events

Event	Date	A_{max} (m)	v (days)	$At_{1,5}$ (m)	T_c (days)	Kinetics
Mou_1997	15/05/1997	1.3	1	0.36	1	rapid
Aub_96_02	14/10/1996	1.2	2	0.51	1	rapid
Affl_01	30/04/1974	1.35	2	0.77	64	slow
Doma_01	1976	0.65	3	0.74	N/A	rapid
Cru_1977	18/11/1977	0.8	2	0.54	26	rapid
Rue Danté	1972	0.9	45	0.51	41	slow
Roc_2008	01/01/2009	0.21	170	0.57	N/A	slow
Ron_1999	01/01/1999	0.75	100	0.42	103	slow
Ang_2009	4/10/2009	0.68	36	0.53	460	slow

Kinetic of Pillars Collapses—Underground Process

The fracture process within mining-works, made up of a group of adjacent pillars, will commence at a point where the security factor is at its weakest, either due to a higher level of stress with the presence of a stacking edge or by a lower level of pillar resistance (brittle pillar fractures). The floor kinetics is the progression of the rupture from one pillar to the next.

The studies conducted in LIB, especially laboratory trials of mechanical resistance to compression, describe the ductile behaviour for this material (Figure 5). Brittle pillar fractures have been dismissed; the rapid kinetics observed for some events is unlikely linked to the mechanism of a brittle fracture (Dagallier, 2002; Grgic, 2003). Instead, the collapse process is maintained by the overstress that the adjacent pillars gain; this overstress is proportional to the mesh cutting and the weight of the overlying ground. The level of stress on the panel is therefore an element that is likely to favour the speed of the phenomena. A higher additional solicitation could be behind the quicker propagation speed, enabling the slight local variations of the safety factor to be overcome.

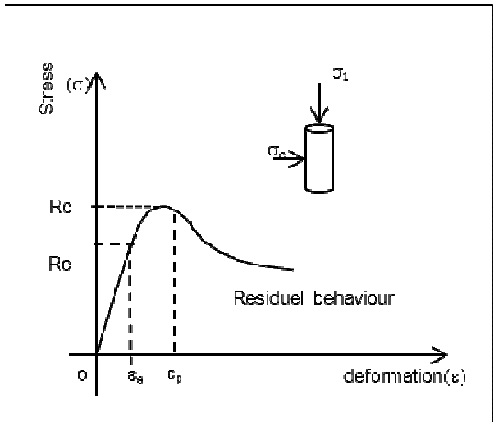

Figure 5. Schema of the elasto-plastic ductile mechanical behaviour of Lorraine iron ore

The capacity of the pillar to withstand this added stress is linked to its geometry. A more massive and flatter pillar would have a higher compressive strength, expressed by the ratio between the opening of the layer (or the height of pillar) and the width (El1) or length (El2) of the pillar. According to the progression of the collapse, the surface of the pillar can also play a role as much as the latest ratio (El1 or El2) in the opposite direction

Transmission Between the Mine Floor and Surface—Role of Mineworks Overburden

The overburden plays a major role in the transmission of movements between the underground failures and the surface. A theoretical subsidence curve established for the LIB from measurements obtained during exploitation shows surface subsidence in accordance with the collapsed width (D) on the floor (Figure 6). For as long as this width is less than approximately 60% of the depth (H), the effects on the surface are barely noticeable. The shifting will not become serious until the D is more than 80% of H. Hence T_c corresponds to the development of the mine floor fractures between these two lengths.

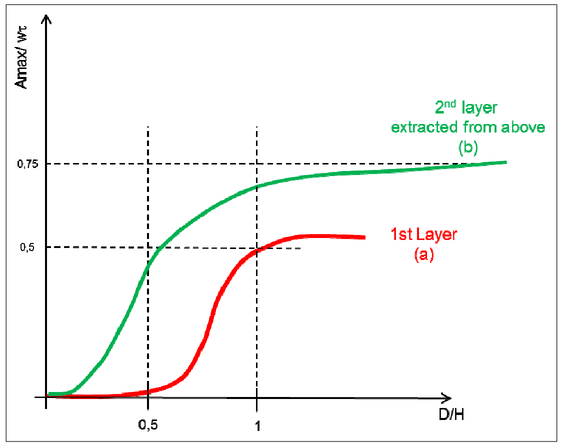

Figure 6. Curve schematics of the subsidence evolution according to the collapsed width below LIB: (a) example without extraction underlying the collapsed stratum (b) example with extraction

This behaviour is linked to the fairly resistant nature of the overburden of the LIB mines, which contains stiff limestone layers. This phenomenon would be different with a more distortable roof such as the b curve in Figure 6 shows, relating to roofing that has been deformed by the block-caving during a previous extraction of an overlaying stratum (Proust, 1964). The speed of the progression at the front of the pillars collapses will depend on the geometry of the pillars.

RETRO-ANALYSIS OF THE NINE COLLAPSES

The main geotechnical parameters of the nine events are presented in Table 2. Recall from Table 1 that the first five events exhibited "rapid kinetics" and the final four exhibited "slow kinetics". On average, the rapid events were deeper and had wider openings than the slow events. The rapid events are also associated with a regular cutting of identical pillars even if at Crusnes one can see panels with slightly different sizes of pillars leading to different extraction rates (42–53%). However the slow events are more irregular with an irregular mine plan (Roncourt) or a mixture of pillars with different dimensions for the other 3 cases. This result is backed up by the fact that a zone where the pillar dimensions are larger with a lower rate of extraction, yet insufficient to completely stop the progression of the collapse, is capable of stopping for the duration of one month (example of Danté event), 9 months (extension of Angevillers 2009) or even many years as in between Affl_01 and Doma_01, these last two being geographically bordering.

Table 2. Geotechnical characteristics of the studied events

Name of the event	Opening w (m)	Gallery width (m)	Pillar width (m)	Pillar length (m)	ratio (El1/El2)	Extraction rate	H (m)	Total stress (MPa)
Mou_1997	3.5	6	12	12	0.29/0.29	0.55	120	8
Aub_96_02	5	6	12	14	0.42/0.36	0.53	170	10.9
Affl_01	7	6	24	24	0.29/0.29	0.36	255	12
Doma_01	5	6	27	27	0.19/0.19	0.33	245	11
Cru_1977	3.8	6	11	25	0.35/0.15	0.50	148	10.9
Rue Danté	5	8	12	49	0.42/0.10	0.48	170	9.9
Roc_2008	3	3	10	37	0.30/0.08	0.29	190	8
Ron_1999	2.5	6	6	85	0.42/0.03	0.53	140	9
Ang_2009	5	6	11	40	0.45/0.13	0.44	175	9.4

The stress within the pillars was usually stronger for rapid collapse (mean 11 MPa) than slow events (mean 9 MPa), which confirms the procedure of weight reporting that is shown above. However, a very rapid event (Mou_1997) had a very low stress level (8 MPa).

Pillar geometry is expressed as the width and length of pillars compared with their height. All pillars had a rectangular shape except for Aub_96_02, where the pillars were diamond shaped. As with the stress, it is not the resistance of the pillar (linked with the ratio El) that plays the leading role in the pillar failure process—given that all the pillars in the area are unstable—but their capacity to take on extra weight during the progression. The ratio El1 calculated on the pillar width does not affect the speed of the phenomenon (see Table 2). However the El2 calculated on the pillar length clearly distinguished the slow events that all had a ratio El2 less than 0,15. Indeed the kinetics of rectangular pillars is slower than that of square ones.

As an attempt to explain the previous observation, we draw in the figure 7 two examples of underground exploitations, one was carried out with square pillars and the other with rectangular pillars; both had the same surface and galleries of equal length. Assuming that a similar procedure had resulted in the fracturing of the first line of pillars and then a second, etc., we can observe that the width of square pillars (D1) at the end of a collapse with the same number of rows of pillars, is greater than the width for long narrower pillars (D2). Assuming that the collapse movements are governed by D, they would require a lower collapsed pillars number with the use of the square.

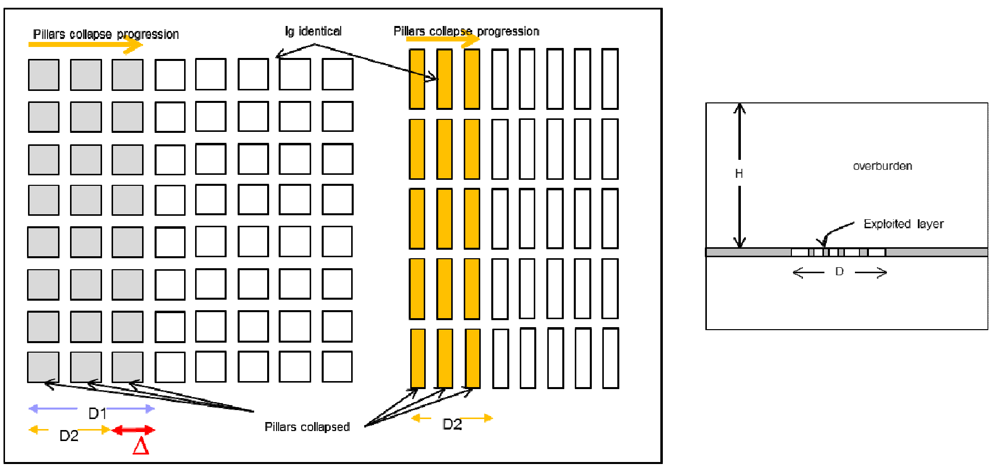

Figure 7. Evolution of the width (D) collapsed at the bottom in the presence of square or rectangular pillars

CHOOSING THE KINETIC CRITERIA AND DISCUSSION

The pillar geometry plays a key-role in the process of fracture kinetics. Therefore we tried to establish an empirical relationship that could account for pillar shape and pillar length. To this end, we introduced two ratio parameters (El1 and El2); the combination of the two was a way to account for the massiveness of the pillars in this case. We recognize that, all other factors being equal, the square-shaped pillars are strongly conductive to rapid kinetics development. An a-dimensional parameter was therefore introduced enabling us to evaluate the variation of any pillar shape with regards to a square shape that its surface would keep. This shape indicator parameter (IF) is between 1 (square pillar) and 2 (an indefinitely long pillar). For any pillar, this ratio is defined as the relationship between the hydraulic diameter (D_h) of the pillar and the length of the pillar (l_p).

$$IF = D_h / l_p \quad (1)$$

To characterise the massive pillar, we introduced an a-dimensional number made up of the relationship between the pillar surface (Sp) and the exploited opening (w). For this number to be a-dimensional, we considered the square root of the pillar surface area, which enabled us to obtain the following relationship:

$$Ic = IF * \frac{\sqrt{Sp}}{w} \quad (2)$$

The formula $\frac{\sqrt{Sp}}{w}$ is no more than the square root of twice the ratio El of the pillar, namely $\sqrt{lp/w * Lp/w}$, and $Sp = lp * Lp$.

The implementation of the kinetic indicator (I_c) expressed in equation 2 allowed us to distinguish between the two groups of events. In fact, all rapid events (with a small value of ν) have an I_c less than 6.1 (Figure 8) and slow event have an I_c greater than 6.6 (Table 3).

Table 3. Characteristics of the nine events chosen for kinetic analysis

Event	IF	I_c	Kinetics (with time ν)
Mou_1997	1	3.43	Rapid
Aub_96_02	1.08	2.79	Rapid
Affl_01	1	3.43	Rapid
Doma_01	1	5.4	Rapid
Cru_1977	1.39	6.06	Rapid
Rue Danté	1.58	7.79	Slow
Roc_2008	1.57	10.1	Slow
Ron_1999	1.87	16.88	Slow
Ang_2009	1.57	6.58	Slow

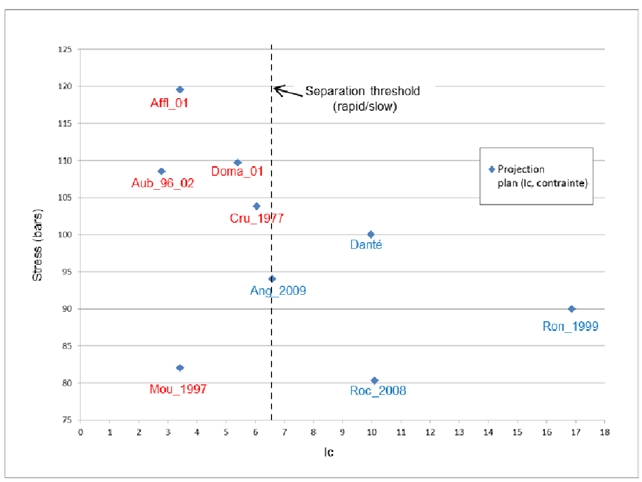

Figure 8. Projection of the 9 events on the plan (Ic, stress) (red: rapid; blue: slow)

CONCLUSIONS

Former room and pillar underground exploitations can manifest as subsidence at the surface. When the effects are serious, these events can produce structural damage on buildings. The kinetics of the collapse must then be taken into account. When there is insufficient time between the first signs on the surface (cracks) and structural damage for protective measures to be put into place, surveillance techniques like microseismic recording can be used to predict surface subsidence.

A retro-analysis of nine progressive subsidence collapse events in the last 40 years in the LIB showed that the available reaction time was highly variable, from one day to several months. The stiffness of the collapse evolution curve in relationship to the time was characterized by the time (v) from the beginning of the acceleration of the collapse until half of the maximum subsidence ($A_{max/2}$). This length of time is short for the rapid kinetic events and long for the slow kinetic events.

Among the nine events, five were categorized as rapid, with v less than 1 week and four events were categorized as slow. The retro-analysis shows that the kinetic is distinguished by the progression of the pillar fracture in the exploited panel. This progression is rapid when the level of stress is high, the panel cutting is regular, and pillars are shaped as close to a square as possible and are short and slim. To quantify the influence of pillar geometry, a shape indicator enabled the separation of the slow and rapid events by a threshold value.

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