MODELING AND ASSESSMENT FOR SUBSIDENCE HAZARD IN INCLINED IRON MINING.

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ABSTRACT: The old iron mines of the North-West of France have geometrical and exploitation configurations appreciably similar, with dips varying between 30° and 90°. Within the framework of the establishment of risk maps related to these exploitations, the observation of subsidence in certain basins leds us to try to better know the conditions of occurrence and the consequences on the surface of these phenomena, and in particular the influence of the dip on their relevance. A modeling was thus undertaken, consisting initially of back-analysis of a subsidence trough observed and studied, in order to seek the initiating mechanism within mining work and to appreciate the influence and the degree of reliability of the parameters, and in the second time the parameterised analysis of the zones of potential failure according to the dip, the opening of the mine seam, the extraction ratio and the thickness of the overburden. The contribution of this modeling and the experience feedback of other mining basins allowed to fix the principles of evaluation of the subsidence alea, in terms of intensity and occurrence, of these deposits.

KEYWORDS: hazard, subsidence, inclined seams, iron mine, modeling.

RESUME : Les anciennes mines de fer du Nord-Ouest de la France présentent des configurations géométriques et d'exploitation sensiblement similaires et des pendages variant de 30° à 90°. Dans le cadre de l'établissement de cartes d'aléas liées à ces exploitations, l'observation de cuvettes d'affaissement dans certains bassins a incité à mieux apprécier les conditions d'apparition et les conséquences en surface de ces phénomènes et notamment l'influence du pendage sur leur pertinence. Une modélisation a ainsi été entreprise, consistant d'abord en la rétro-analyse d'une cuvette d'affaissement observée et étudiée, afin de rechercher le mécanisme initiateur au sein des travaux miniers et apprécier l'influence et le degré de fiabilité des paramètres et, dans un second temps, l'analyse paramétrée des zones de rupture potentielle en fonction du pendage, de l'ouverture de la couche exploitée, du taux de défruitement et du recouvrement. L'apport de cette modélisation et le retour d'expérience d'autres bassins miniers ont permis de fixer les principes d'évaluation de l'aléa affaissement, en termes d'intensité et d'occurrence, de ces gisements.

MOTS-CLEFS : aléa, affaissement, gisement penté, mine de fer, modélisation.

1. Introduction

In the framework of the assessment and the prevention of mining hazards, the establishment of risk maps related to the movements above the iron deposits exploited in the North-West of France (figure 1) highlighted their relative homogeneity and singularity.

These basins indeed have geological and exploitation characteristics of formation relatively homogeneous. In addition, and mainly because these exploitations have an important dip (between 30° and 90°), it quickly appeared during the information collection and the first observations of disorders on the surface that the risk evaluation of ground movement, and especially of subsidence occurrence, had to take into account the singularity of these deposits and could not be completed with the analyses made for horizontal mining works.

This article initially describes the characteristics specific to these exploitations. Then, the objectives are presented, steps and results of the modeling made on the basis of back-analysis of an observed subsidence phenomenon. Finally the transcription of these results and the evaluation of the subsidence risk are discussed.

2. Characteristics of North Western iron mining exploitations

The risk analysis is developed for studies at the scale of a whole basin of risk, even several risk basins, if they present strong analogies. It is the case of the iron deposits of the synclinals of Soumont, May/Orne, La Ferrière-aux-Etangs (Normandy) and Segré (Pays-de-Loire).

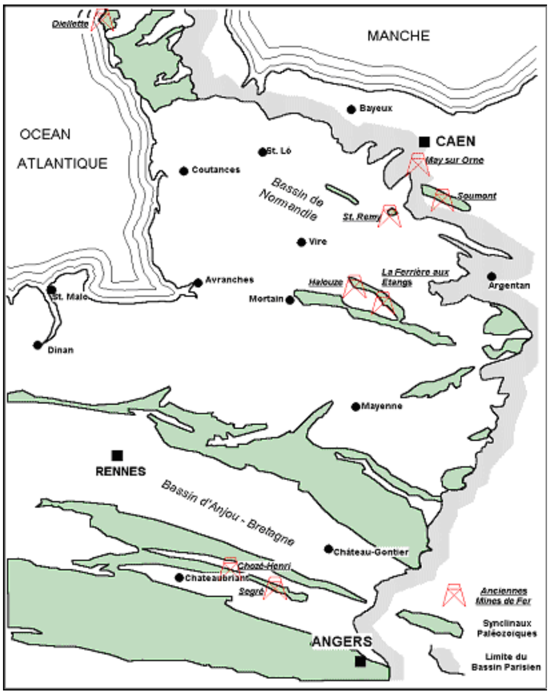

Figure 1. Localisation of the iron-bearing basins of the North-West of France (Varoquaux and Gerard, 1980).

The various basins present much analogies on the geological and exploitation aspects. These deposits fit in the dissymmetrical synclinal whose periods of deposit (Ordovician or Silurian) and of crumpling are near on a geological scale. They are fairly to strongly slopes (figure 2), located at very close depths (between 10 and 600 m) and hold one or two veins of low or average thickness (overall 2 to 4 m, locally more).

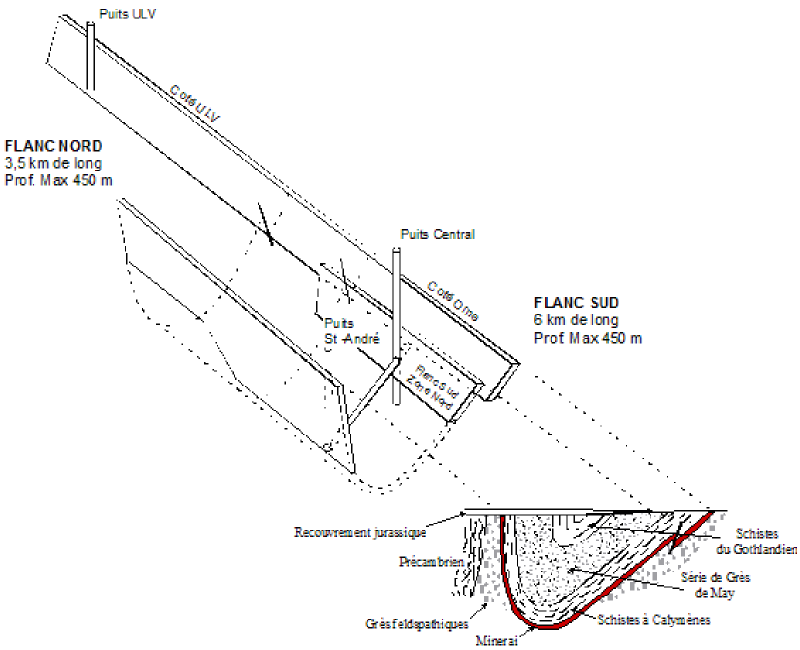

Figure 2. Example of the mine configuration of May-sur-Orne (according to Maury, 1972).

The nature and the strength of the iron ore are relatively variable. The ore is mainly constituted of haematite at May-sur-Orne and at a shallow depth under the calcareous overthrust of Soumont. The ore is carbonated in-depth in others basins, like at Segré and La Ferrière-aux-Etangs. The compressive strength of the ore is about 100 MPa at May-sur-Orne and 200 MPa (perpendicular to the bedding plane) at La Ferrière-aux-Etangs.

The mining methods used in those several basins are appreciably similar (figure 3). The oldest mining sites were exploited by short dip faces also called stops, then by dip strike faces. Thereafter, one systematically applied the method of the rise faces or the mechanised strike faces for the mining sites with low slopes (dip lower than 50°) and the shrinkage method for the mining sites slopes to high slopes (dip higher than 50°). These works are connected by level galleries connected to the works of ore extraction, and spaced of 30 m to 75-80 m in altitude, according to the basins and the methods used.

The observed disorders (table 1) in these various basins are similar (primarily some localized sinkholes by crown section rupture, shaft or raise clearings, or collapses of galleries). One notes however the existence of collapses of important districts at the bottom, in production run, in general without repercussions on the surface, except for Soumont and La Ferrière-aux-Etangs. The observed disorders on surface are traditional depressions with spread out board, with opened cracks but without frank breaks of shearing, which can be connected with subsidence troughs.

On the other hand, the documentary analyses do not identify any accident of huge collapse type: the only events known in the western French basins are exclusively the fact of slate exploitations whose common factors are their complex geometry, very different from iron mining works, and the presence of important residual voids (Tritsch, 2000).

Table 1: Comparative analysis of various Western iron-bearing basins

Basin	**MAY-SUR-ORNE**	**SOUMONT**	**LA FERRIERE-AUX-ETANGS**	**SEGRE**
Dates of exploitation	1896 - 1968	1907 - 1989	1905 - 1970	1907 - 1984
Maximum depth	450 m	650 m	400 m	490 m
Mining methods	stoping, dip faces, shrinkage	Rise faces, shrinkage, strike faces or “stoping”	Stopings, rise faces, retreating workings, shrinkage	shrinkage
Dip	45° to 90°	30° to 60°	25° to 45°	60° to 90°
Number of worked seams	1 (very locally 2)	1	1	2 (intercalated bed of 40 to 50 m thickness)
Dominant nature of the iron ore	Facies haematite	Haematite under calcareous overthrust, Carbonated and siliceous in-depth	Chlorito-carbonated. Little haematite	Carbonated
Content of iron	35-50%	36-50%	35-50%	Average 52%
Compressive strength of the ore	100 MPa	115 MPa	80 MPa parallel to the bedding plane, 200 MPa perpendicular to the bedding plane	???
Thickness	3.5 to 4.0 m (locally: 6 to 7 m)	3 m (locally: 6 m)	3 to 4 m (locally: 5 m)	1 to 2 m
Discordant overburden	0 to 60 m (Jurassic limestone)	0 to 50 m (Jurassic limestone)	missing	missing
Zone of deterioration of the ore	20 to 50 m	20 to 50 m	20 to 80 m	20 to 80 m
Types of observed disorders	Sinkholes (rupture of crown section), shaft collapses or raise clearing	Subsidence (roof failure), sinkholes	Subsidence (roof failure), collapses (rupture of crown section), sinkholes (directly above not very deep galleries)	Sinkholes, collapses (rupture of crown section)

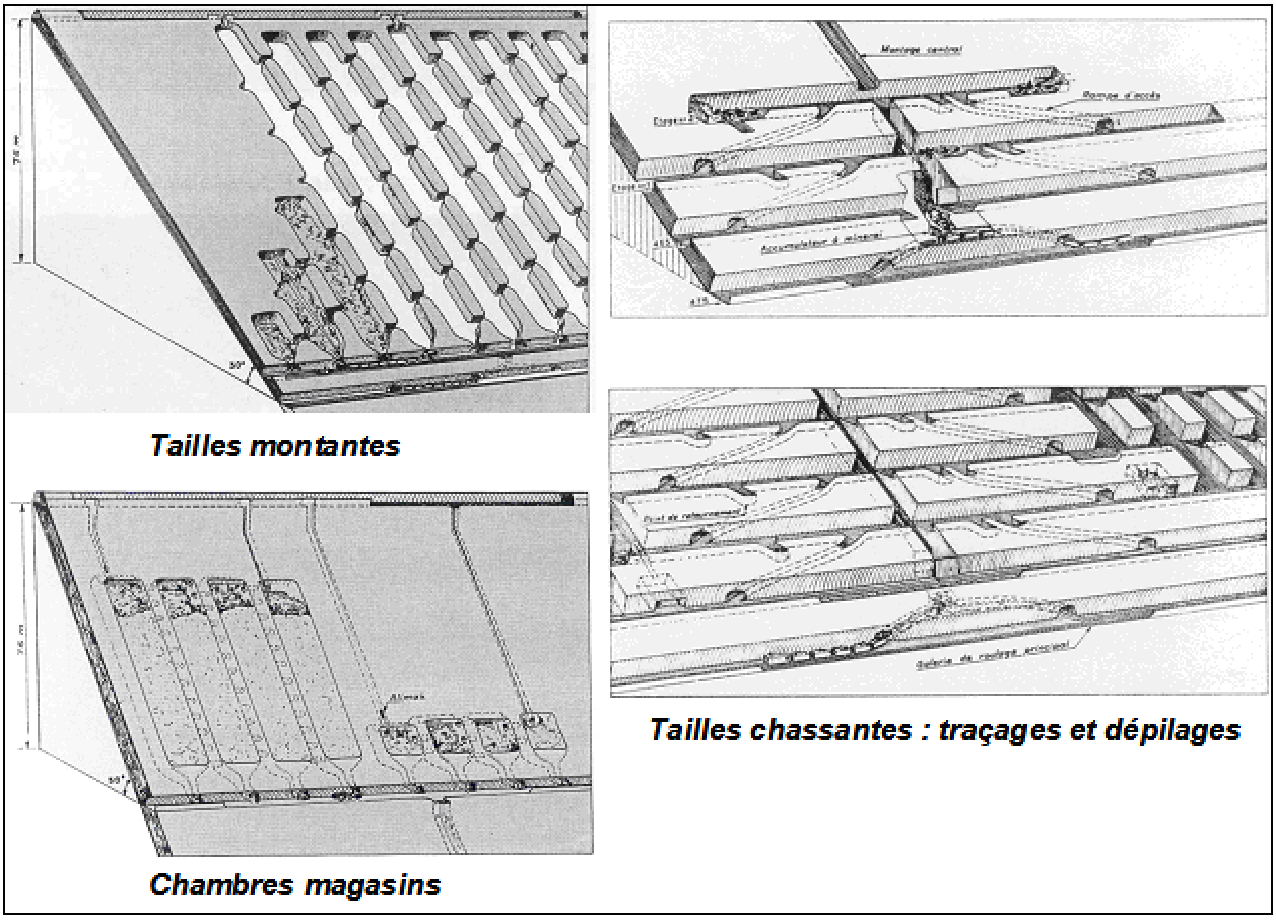

Figure 3. Mining methods of the basin of Soumont (according to Perrotte and Lidou, 1983).

3. Modeling of the inclined deposits of the West of France

3.1. Modeling approach

The study of modeling, using code UDEC (2D calculations in discontinuous medium), was organised in two stages:

- the back-analysis of a subsidence trough in Soumont developed in 1966 above a well delimited underground collapse;
- parametric analysis of the zones of potential failure (extension, amplitude) according to the dip (30 to 65°), the extraction ratio (70 to 90 %), the layer thickness (1.5 to 5 m), and thickness of the formations of overburden in discordance (0 to 50 m).

3.2. Back-analysis of the subsidence phenomenon of Soumont appeared in 1966

Several collapses occurred in the mine of Soumont between 1929 and 1966. They mainly induced subsidence troughs on the surface (figure 4). The latest one is the most documented for underground visits and analyses of the causes were carried out in close connexion with this collapse. Thus this event has been selected for the back-analysis. Collapse occurred between the levels -120 and -250 m, 40 years after the exploitation of this sector of mining works. The dip of the layer is 30° and the extraction ratio is high (80-85 %).The maximum subsidence measured at that time was 65 cm.

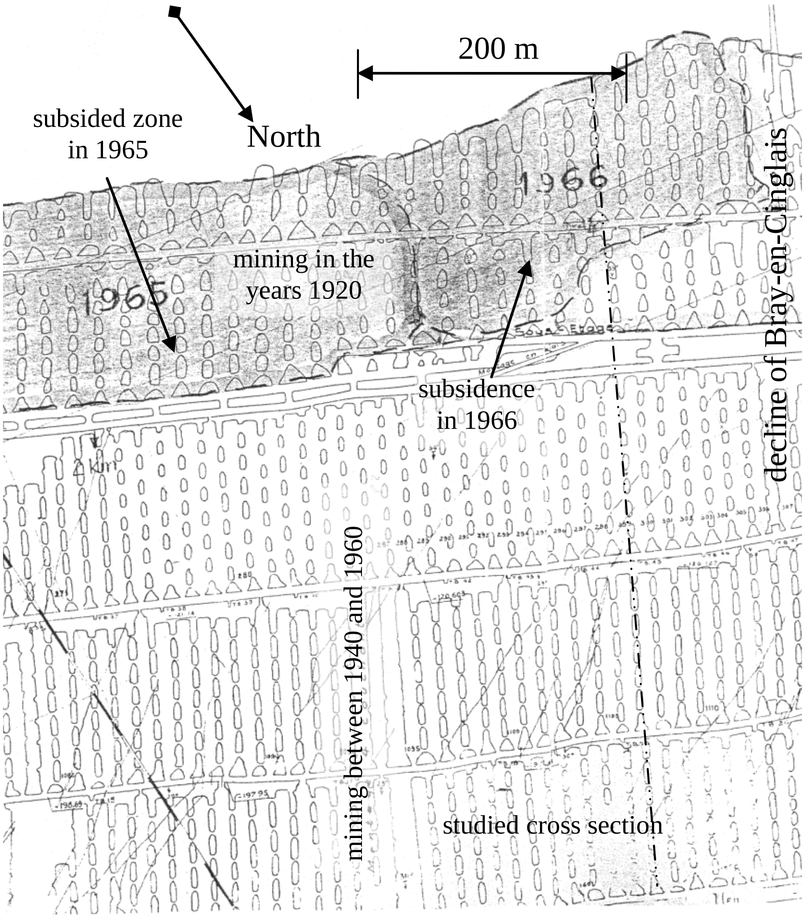

Figure 4. *Plane view of the seam worked by rooms and pillars at Soumont in the collapse zone of 1966*.

The back-analysis was based on a modeling on the collapsed district scale. The objective was to specify the conditions which were at the origin of collapse and the most relevant mechanisms. This work was carried out by respecting the three following checking points:

- A subsidence amplitude of 0.65 m was measured on surface;
- The absence of collapse in work of depth higher than 220 m;
- The stability of the mining works exploited with the same depth by shrinkage, to the west of the collapsed districts.

3.2.1 Description of the mining conditions

The extraction ratio of the lower stages decreases with depth. The section of the way is trapezoidal and the opening of these levels is 4.5 m. The pillar width of the lower stages varies between 4.5 m and 6 m. Above the ore layer, one meets massive and resistant schist beds for a total thickness of 120 m, then sandstone beds over 95 m, then a schist alternation and sandstone of weak thickness (10 m) and finally again sandstone. In lower part of the ore layer, there is a 10 m thick schist bed then a series of sandstones. The whole of these formations is covered by a calcareous slab whose thickness can be evaluated to 30 m at the location of the concerned sector (Tincelin & Vouille, 1992).

3.2.2 Geomechanical characteristics

The geomechanical characterisation of various materials of the southern side of the mine of Soumont is not complete. Only the iron ore and its immediate roof and floor have been tested in laboratory. Hence we estimated the data according to various sources:

- values obtained in laboratory: bibliographical study carried out at the time of the preliminary phase (Delaunay & Renaud, 2003);
- data resulting from a study on the slate mine of Misengrain (Tritsch, 2000);
- data from the database by Fine (1993);
- data (for the sandstone) resulting from the synthesis of the mechanical characterisations for the HBL (Mery & Thoraval, 1998);
- data from the geological map of Mézidon (BRGM);

The values of strengths (tensile and compressive) were then degraded while taking into account:

- the scale effect being estimated at 0.47: according to Bieniawski & Van Heerden (1979), referring to a curve obtained on unconfined iron ore samples;
- the 2D aspect of modeling by preserving the strength/stress ratio for the pillar in 2D and 3D by decreasing the compressive strength of the seam (equation 1):

$$\sigma_{pillar} = \frac{\rho g z}{1-\tau_{3D}} = \frac{1}{\alpha}\frac{\rho g z}{1-\tau_{2D}} \text{ that is to say } \frac{1}{\alpha} = \frac{1-\tau_{2D}}{1-\tau_{3D}}, \ \alpha\text{: coefficient of correction.}$$

$$\tau_{2D} = \frac{L_{room}}{L_{room}+L_{pillar}} \text{ and } \tau_{3D} = 1 - \frac{L_{pillar}^{2}}{\left(L_{room}+L_{pillar}\right)^{2}} \text{ thus } \alpha = \sqrt{1-\tau_{3D}} \quad (1)$$

Let us recall that for square rooms and pillars:

- the time influence on the material (by estimating that the coefficient of reduction of strengths is founded on a ratio elastic strength/ peak strength).

Table 2 shows a synthesis of all strengths values obtained according to the various effects taken into account. The behaviour law retained takes into account a hardening then softening post-failure behaviour.

Table 2. Synthesis of the compressive strengths for various materials of the study.

instantaneous strength (arrow pointing to the row "taking into account of the scale effect (MPa)")

1966 (brace covering the rows "effect 2D/3D (MPa)" and "long-term strength (MPa)")

	Iron ore			
Extraction ratio	85% (upper stage)	82% (stage between z = -202 and z = -302 m)	76% (stages lower than z = -302 m)	Other materials
initial strength of the sample in laboratory (MPa)	Rc^0 (= 115 MPa)			
taking into account of the scale effect (MPa)	0.47 Rc^0			
effect 2D/3D (MPa)	0.182 Rc^0	0.199 Rc^0	0.230 Rc^0	0.47 Rc^0
long-term strength (MPa)	0.084 Rc^0	0.092 Rc^0	0.106 Rc^0	0.216 Rc^0

3.2.3 Initial state of stresses

The assessment of the series of stress measurements carried out in situ in 1979 (TINCELIN & Vouille, 1981) showed that $\sigma_h/\sigma_v = 0.5$. However, many stress measurements carried out in the West of France, within synclinal structures, show that the horizontal stress is always higher or equal to the vertical stress. For the sites of Grais (May/Orne) and St-Sigismond (Maine-et-Loire), the ratio σ_h/σ_v varies between 1 and 1.5 (Burlet, 1991). The stress tensor being of doubtful validity, we considered three values for the ratio σ_h/σ_v: 0.5, 1 and 2.

3.2.4 Results

The solutions being able to explain the collapse of 1966 being plural, some certain data input were regarded sure (extraction ratio, dimensions of the various stages, width of the stage pillars, exploitation thickness, geology, geomechanical characterisation of materials other than the iron ore) and others were regarded as variables of the study.

Each method of calculation of this study was analysed in terms of subsidence on surface, distribution of plasticity, displacements, principal stresses and plastic deformation in five tested pillars (figure 5). To sum up, the different methods of calculation carried out made it possible to study the influence of the:

- stress field with the ratio σ_h/σ_v (3 values: 0.5, 1 and 2);
- density of the roof stratification;
- friction angle of the bedding planes;
- effects of faults on the collapse mechanism;
- joint behaviour law;
- strength of the pillars;
- panel width;
- opening effect.

The various calculations allow to reproduce a mechanism and explain the subsidence observed on surface in 1966. It is due initially to the relative compressions of pillars and then to the deflection of the roof. These two zones are the place of strong shear mechanisms which imply a potential failure by shearing up to surface.

The three checking points (collapse of 1966 in the upper stage, stability of the lower stages and shrinkage stability) were checked.

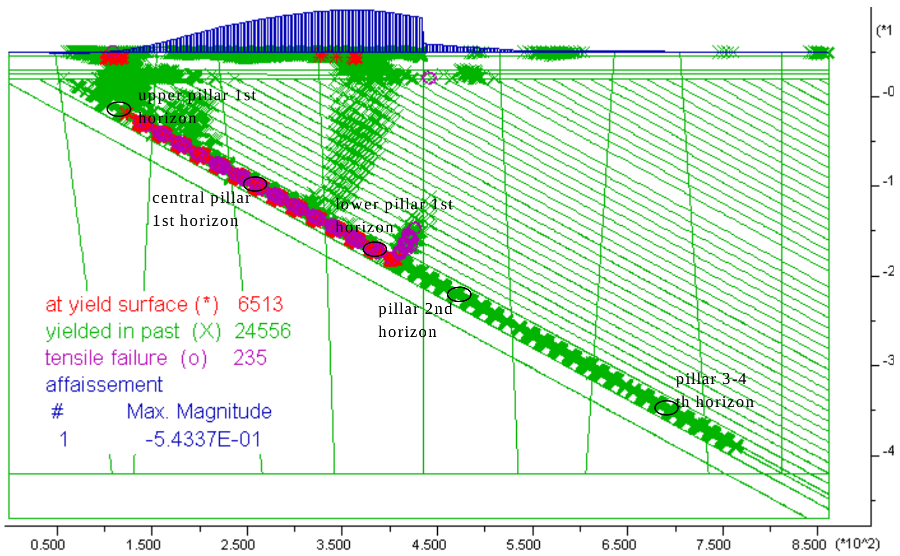

Figure 5: Distribution of plasticity: joint spacing of 10 m + variation of subsidence on the surface

3.2.5 Conclusion

Works completed showed that the height/width ratio and the strength of the pillars and the roof stratification are the essential parameters which allow to carry out this back-analysis. This work let us draw some conclusions and clear tendencies:

- the length of the plastic zone cannot exceed 200 m**.** The mechanism highlighted cannot thus be repeated in the lower stages;
- the verification of the 2nd checking point showed the importance of the strength value of the barrier pillars. The pillar strength must be higher (51 MPa) than that of the pillars of the higher stage (34 MPa) for the mechanism to occur. That is compatible with the fact that the iron ore of the lower stages is more carbonated (so more resistant);
- for σ_h/σ_v = 0.5 and 1, we notice that the value of maximum subsidence on the surface is close to that measured in 1966: 65 cm;
- the state of the initial stresses has a relatively weak influence on the thresholds of pillar strength of the lower stages;
- the characteristics (spacing and friction angle) of the stratification network parallel to the dip are essential parameters in the mechanism which we highlighted: the increase in spacing between the joints inhibits the mechanism of collapse. It is the same for the friction angle;
- the values of strengths which we introduced into our models are compatible with the intervals of variation of the in-situ characteristics [instantaneous value ; value in the long term integrating the effect of time].

3.3. Parametric analysis

The second part of this study consisted in carrying out a numerical modeling on the scale of the mine in order to develop the back-analysis collapse (of Soumont in 1966) and to evaluate the criteria to specify the risk by carrying out a parametric study (allowing a valorization on the whole inclined deposits of the same type). We thus studied the sensitivity of four parameters by carrying out twenty calculations:

- the dip (between 30 and 65°);
- the extraction ratio (between 70 and 90 %);
- the exploitation thickness (between 1.5 and 5 m);
- the height of overburden (between 0 and 50 m).

The analysis of these twenty calculations was focused on the extension of the zones of potential failures (plasticity), on the value of maximum displacement in the pillars and on the value of the maximum subsidence on the surface. This reveals that the mechanism identified at the time of the back-analysis can be reproduced under the geometrical conditions synthesised in table 4. In addition, we noticed that the subvertical faults can inhibit or amplify the mechanism of failure by shearing. Moreover, the reduction of the height/width ratio of the pillars (or thickness reduction) has a very significant positive role on the exploitation stability.

4. Evaluation of the "subsidence" hazard

The hazard assessment is classically made by combining the awaited intensity of the phenomenon with its probability of occurrence, this being the predisposition of the site with respect to the dreaded phenomenon.

4.1. Qualification of the intensity

It is recognised that the characteristics of depression which materialise the most severe damage for the goods located on surface are the horizontal differential strains and movements of ground inclined setting rather than maximum vertical subsidence in itself. Table 3 gives indicative values of the strains and slopes which make it possible to evaluate the phenomenon intensity.

Table 3: Classes of intensity of the risk "subsidence" (purely indicative values)

Classify intensity	**Horizontal differential strains ε (in mm/m)**	**Surface inclination μ (in %)**
Negligible	$\varepsilon < 1$	$\mu < 0.2$
Very low	$1 < \varepsilon < 5$	$0.2 < \mu < 1$
Low	$5 < \varepsilon < 10$	$1 < \mu < 2$
Medium	$10 < \varepsilon < 30$	$2 < \mu < 6$
High	$\varepsilon > 30$	$\mu > 6$

The value of these two parameters can be appreciably influenced by different factors studied before.

It appears so that value of maximum subsidence is in the form: $A_{max} = 0.3.\ w.\tau$, with:

- A_{max} = maximum subsidence;
- w = exploited thickness (in the districts exploited by shrinkage);
- τ = extraction ratio (or recovery factor).

It can be easily deduced from them the values from the strains (ε_{max}) and slopes (μ_{max}) starting from the following traditional relations:

$$\varepsilon_{max} = \alpha\ .\ A_{max} / P$$

$$\mu_{max} = \beta\ .\ A_{max} / P$$

Where:

- P is the average depth of the panel;
- α and β of the coefficients estimated respectively at 1.5 and 5 in the western iron basin.

The values of the coefficients α and β are deduced from the studies in experience feedback carried out on the Iron Mines of Lorraine and adopted for their drastic security character.

4.2. Qualification of the occurrence probability

In the inclined exploitations of the iron deposits of the West of France, it is mainly the stability of the barrier pillars, the slabs or the pillars left in place to ensure the behaviour of the immediate strata which controls the subsidence predisposition. To evaluate the long-term stability of the under-mined surface, main factors that have to be take into account are:

- dimensions of the panels;
- dip of the layers;
- extraction ratio;
- opening (height exploited between immediate strata);
- strength of pillars.

In a more precise way, the parametric analysis described previously provides fundamental indications on the configurations of layer and exploitation for which the occurrence of a subsidence can be excluded (table 4, below).

Table 4: conditions of exclusion of the process of subsidence (according to Renaud, 2004)

Dip	**Extraction ratio (τ %)**	**Thickness (W)**
> 55°	≤ 90%	≤ 4 m
	≤ 85%	≤ 5 m
45° to 55°	≤ 90%	≤ 3 m
	≤ 80%	≤ 5 m
30° to 45°	≤ 80%	≤ 3 m
	≤ 70%	≤ 5 m

The influence of an increase in the dip appears by a displacement of the zones of failure toward the surface (or of the outcrop): the greater the dip value, the more one affects the grounds close to surface (plastic points).

In addition to these configurations of exploitation, other conditions must be taken into account for a reduction of the hazard level, like:

- condition n° 1: for a subsidence to occur entirely, it is necessary that dimensions of the mining sites (width L) reach or exceed the depth (H) (that is: $L \geq H$), which represents, in the context of these exploitations, a width along the dip from 250 to 290 m (depth lower than 220–250 m). In lower part ($L < H$), subsidence is all the more, the hazard level is lower;
- condition n° 2: it is considered that there are no repercussions on surface (non perceptible subsidence) if the mining site has a width $L < 0.4$ H;
- condition n° 3: if the minimum depth of mine working is higher than 250-300 m (according to the geometry of the mining sites), it is considered that the failure zones are not likely to reach surface.

Table 5: Classes of predisposition of the site for the risk “subsidence”

Site predisposition	**Ratio L/H**	**Depth (H)**
Very sensitive	L/H > 1	< 250 m
sensitive	L/H # 1	< 250 m
Not very sensitive	0.4 < L/H <1	< 250 m
negligible	L/H < 0.4	< 250 m
	L/H ≥ 1	> 250-300 m

4.3. Hazard zoning

The limits materialising on surface the zone influenced by subsidence are established, taking in account an angle called “influence angle”, measured from the vertical, which connects the end of the panel, at the bottom, to the points of surface where subsidence, strains or slopes are regarded as unperceivable or null. Although an single influence angle (γ) value of 30° to 35° is retained for flat veins, three angle limit values are defined for inclined layers (exploitations) These are:

- the limiting angle value (γ), in the direction of drivage which is equal to the limiting angle in flat vein;
- the “upstream” angle value, lower than the angle γ ;
- the “downstream” angle value, always greater than the angle γ ;

Looking at the data obtained in Soumont, it can be noticed (table 6) that the values of failure angles measured upstream and downstream (on average respectively about 7° and 30°), for a dip ranging between 30° and 40°, are very close to the corresponding values of the abacuses of the Lorraine coalfields or the Nord Pas-de-Calais region (Proust, 1964). Hence, it can be deduced that the influence angles must be also very close and take for the layer of Segré some values of influence angle equal to 30° (upstream side) and 45° (downstream side).

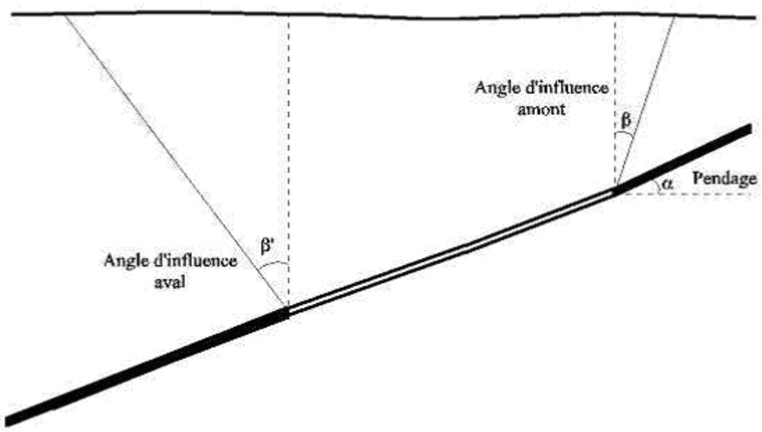

Figure 6: Diagram showing the dissymmetry of the upstream and downstream influence angles in inclined deposit

Table 6: Values given in the subsidence abacuses of Nord/Pas-de-Calais, Saar and Lorraine basins

Dip values		0°	15°	25°	30°	**40°**	50°	60°
Angles of rupture giving the limits of fracturing on the surface	Upstream angle	18	14	12	11	9	7	6
	Downstream angle	18	22	25	27	30	33	36
Angles of influence giving the limits of null subsidence	Upstream angle	35	32	30	30	**30**	28	27
	Downstream angle	35	38	40	43	**45**	47	48

Let us specify that the downstream influence angle is taken at the base of the exploited panels, and the upstream influence angle at the higher part of the panels.

5. References

Bieniawski, Z.T., Van Heerden, W. L. (1979). *The significance of in-situ tests on large rock specimens*. Int. J. Rock Mech. Min. Sci., 12, 101-113.

Burlet D. (1991). *Détermination du champ de contrainte régional à partir de tests hydrauliques en forages, résultats de neuf expérimentations in-situ réalisées en France*. Thèse de doctorat de Géophysique Interne à l'université de Paris VII.

Delaunay T., Renaud V. (2003). *Phase préliminaire à la réalisation d'une modélisation numérique sur les gisements pentés des bassins ferrifères de Soumont, May-sur-Orne et Segré (Calvados et Maine-et-Loire)*. Rapport INERIS DRS-03-49161/R01.

Fine J. (1993). *Le soutènement des galeries minières*. Ed. Armines, Centre de Géotechnique et d'Exploitation du Sous-sol.

Itasca (2000). *UDEC 3.01 User's Guide and Command Reference*. Itasca Consulting Group Inc. Minneapolis, USA.

Maury V. (1972). *Aménagement de la mine de May-sur-Orne en stockage souterrain d'hydrocarbures*. Revue de l'Industrie Minérale. Cahier 4 du Comité Français de Mécanique des Roches, 73-84.

Mery C., Thoraval A. (1998). *Synthèse des caractérisations géomécaniques*. Rapport INERIS SSE-CMe/ATh-98-25EP51.

Perrotte A. et Lidou B. (1983). *Diverses variantes de chambres avec piliers abandonnés dans la mine de fer de Soumont*. Industrie Minérale – Les Techniques, p.74-78, février 1983.

Proust A. (1964). *Etude sur les affaissements miniers dans le Bassin du Nord et du Pas-de-Calais*. Revue de l'Industrie Minérale, juin-juillet 1964, n° 6 et 7, 68.

Renaud V. (2004). *Contribution à l'analyse des conditions d'effondrement des gisements pentés des bassins ferrifères de Soumont, May-sur-Orne et Segré (Calvados, 14 et Maine-et-Loire, 49)*. Rapport INERIS DRS-04-50864/RN01.

Tincelin E., Vouille G. (1981). *Société des mines de Soumont - Projet d'exploitation des Etages 560-475 et 650-560 - Etude de stabilité.* Rapport de l'Ecole Nationale Supérieure des Mines de Paris – Centre de géotechnique et d'exploitation du sous-sol. R81/21.

Tincelin E., Vouille G. (1992). *Mine de Soumont - Mesures à entreprendre pour prévoir l'imminence d'un risque d'effondrement survenant à l'aplomb des routes nationales n°158 ou départementales n°43.* Rapport de l'Ecole Nationale Supérieure des Mines de Paris – Centre de géotechnique et d'exploitation du sous-sol. R92/12.

Tritsch J.-J. (2000). *Assistance technique à l'élaboration d'un dossier de demande d'abandon, carrières de Misengrain – site de Noyant, ardoisières d'Angers*. Rapport INERIS DRS-00-25078/R01.

Varoquaux J.-A., Gérard E. (1980). *Les gisements de minerai de fer français*. Annales des Mines, juillet-août 1980, 135-154.