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A time dependency prediction of the number of mining subsidence events over a large mining field with uncertainties considerations

O. Deck[a,*], H. Baroudi[b], A. Hosni[c], Y. Gueniffey[a]

[a] Université de Lorraine, CNRS, CREGU, GeoRessources Laboratory, Ecole des Mines de Nancy, Campus Artem, CS14234, 54042 Nancy Cedex, France
[b] INERIS, Parc Technologique Alata - BP 2, 60550 Verneuil en Halatte, France
[c] BRGM, 3 avenue Claude Guillemin, 45060 Orléans cedex 2, France

1. Introduction

Ore and mineral extraction via underground mining may induce ground subsidence. Depending on the technique used for excavation, subsidence may be intentional and occur during the extraction or accidental and occur long after the end of mining. This latter case holds for room and pillar mines that were assumed stable at the end of mining but then develop instabilities over the long term. Many regions exists where a large number of mines were excavated and are now abandoned. This is the case in France with the iron-ore field that displays more than 500 abandoned mines over a surface of 140 km^2. Mining subsidence can be considered a hazard that leads to ground movement and may damage buildings and the time prediction of subsidence is a key point for risk analysis studies. Prediction may concern a specific mine: What is the probability of collapse of a given mine in the next decade?, or a whole region: What is the probability of observing a given number of subsidences in the next decade? This second question is investigated in this study.

Stability of underground excavations is mostly studied by considering a safety factor defined as the ratio of the compressive strength of pillars by their loading. At the pillar scale, pillar stability may be investigated with probabilistic analysis based on analytical models[1–5] in order to take into account both uncertainties of stress state or strength heterogeneity in a pillar. This leads to prove that a safety factor significantly greater than one is required to avoid any pillar collapse, when a deterministic analysis considers that a safety factor greater than one is enough. At a larger scale, subsidence occurrence is rather investigated with purely empirical models and statistical analysis as fuzzy methods[6] or artificial neural network.[7] Whatever the considered scale, it is obvious that the time is an important parameter. A stable pillar or mine at a given time may become instable next, whenever all conditions seems remaining constant. This evolution is well known when short term is investigated (a few months[8]) but involves many difficulties for long term (several decades) because of the lack of test monitoring. However, the question of the long term time dependency of rock behaviour is investigated for other hazards like slope stability, rock fall or radioactive waste deposits.[9–14]

Investigation of mining subsidence and influence over buildings and infrastructures was mostly investigated during the last decade. Whittaker and Reddish[15] summarized many approaches to assess ground movements and a large amount of recent research have developed these methods.[16–22] Building damage and soil-structure interaction phenomena are also mostly investigated with analytical models,[23–26] numerical models[27,28] or physical models.[29–31]

Objective of this study is to develop a methodology, based on analytical and empirical models, to assess the number of subsidence that may occur in the next decades and centuries over a large area of several ten kilometres square. Influence of uncertainties about parameters and models are investigated with Monte Carlo simulations in order to assess a confident interval of the prediction. This methodology is first described with an objective of generalization and a case study is then investigated to calibrate or validate different parameters of the models.

In the following sections, general considerations about characteristics of the investigated room and pillar mines and mining subsidence hazard are first summarized. The question of the stability of room and pillar mines is then investigated in order to define a safety factor that take into account both pillars dimensions and mechanical properties, influence of neighboured mines, existence of superimposed excavated layers and dimensions of the mine. The methodology to assess the number of subsidence is then described by introducing Monte Carlo simulations and a time-dependent parameter. Finally the case study is described and the methodology is tested.

This study focuses on room and pillar mines characterised by a GSI greater than 50 with uniaxial compressive strength greater than 25 MPa with depth greater than 100 m. All mines may differ by a large number of parameters (pillars dimension, mine dimension, existence of superimposed layers, depth…). Geological context, as well as initial stress state in the ground is assumed homogeneous, while heterogeneous conditions could be also considered but would require specific data.

2. Stability of room and pillar mines

The room and pillar method is a traditional extraction method that consists of the partial extraction of materials when the dip is small. The

* Corresponding author.
E-mail address: olivier.deck@univ-lorraine.fr (O. Deck).

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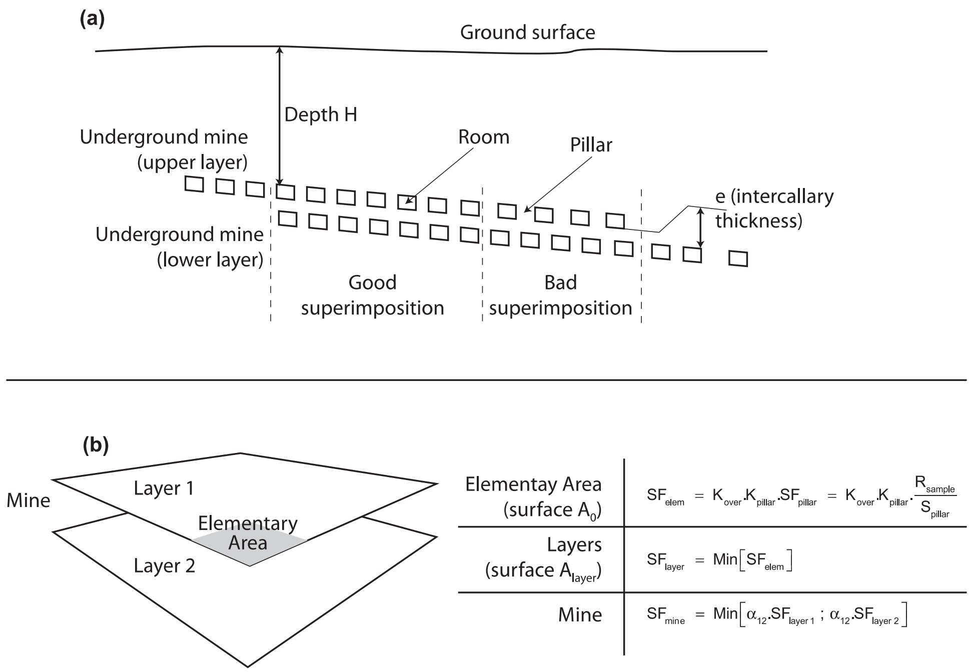

Fig. 1. Cross-section of an underground mine composed of two exploited layers (a) and illustration of the procedure adopted to assess the safety factor for a mine SF_{mine} including two exploited layers (b).

unexploited ground acts as pillars that support the overburden. In some cases, exploited layers may be superimposed with an intercalary between the two (Fig. 1-a).

The main geometrical parameters used to characterise a room and pillar mine are the thickness H_{mine} of the overburden, the height H_{pillar} and width W_{pillar} of pillars and the extraction ratio τ, which corresponds to the proportion of extracted material. An extraction ratio of 0% corresponds to a mine without any extraction, while a 100% extraction ratio corresponds to a fully extracted mine.

Room and pillar mines may be the origin of ground subsidence associated to the collapse of numerous pillars, which is basically investigated by considering a safety factor defined as the ratio of the resistance, by the solicitation of pillars (Eq. (1)). This is also frequently defined as the ratio of the capacity of pillars by the demand.

$$SF_{pillar} = \frac{R_{sample}}{S_{pillar}} \tag{1}$$

where SF_{pillar} is the safety factor of pillars, R_{sample} is the uniaxial compressive strength of pillars rock sample and S_{pillar} the characteristic vertical stress of pillars basically assessed with the tributary area model.[32]

$$S_{pillar} = \frac{\gamma.\, H_{mine}}{1-\tau} \tag{2}$$

where S_{pillar} is an estimation of the average vertical stresses in pillars in [Pa], γ is the unit weight of the overburden in [N/m^3], H_{mine} is the thickness of the overburden in [m], τ is the extraction ratio, between 0 and 1.

A value of SF_{pillar} greater than one indicates a theoretically stable and safe situation, while a ratio less than one indicates unstable pillars and consequently an unstable mine. However, many uncertainties exist about the quantification of parameters because some lack of knowledge and spatial heterogeneity of both mechanical and geometrical parameters. It is then a common way to adopt a probabilistic approach to assess the safety factor. When applied to Eq. (1), a probabilistic approach requires considering all parameters as probabilistic rather than deterministic. As a result, the mean value of the safety factor and its probability to be less than unit may be calculated. Such an approach can be illustrated in the literature.[1,2,4] A similar approach will be considered in this study, where all parameters will be assumed as probabilistic.

However, some phenomena are neglected and Eq. (1) must be discussed and completed to finally define a more relevant safety factors of a mine that will be used in this study. Fig. 1-b synthetizes the procedure adopted to assess a safety factor for a mine SF_{mine} including two exploited layers with a set of parameters described in the following subsections. SF_{mine} is calculated with the safety factor SF_{layer} of each superimposed layer by introducing an α coefficient in order to take into account influence of layers superimposition. Each layer is divided into a number of adjacent elementary areas with a surface A_0 in order to take into account influence of the mine dimensions. SF_{layer} is then calculated with the safety factor SF_{elem} of each elementary area: SF_{layer} is equal to the smallest safety factor of all the adjacent elementary areas included in the layer. Finally, SF_{elem} is calculated with Eq. (1) modified to take into account influence of pillars dimensions and neighboured fully excavated mines. This approach necessitates SF_{elem} to be probabilistic. This is the case in this study by considering probabilistic values for all parameters.

2.1. Influence of pillar dimensions

Pillars dimension is known to have a significant influence over the safety factor and the characteristic compressive strength of pillars may be significantly reduced compare to the value of the sample compressive strength. Martin and Maybee[33] summarized five empirical formula of R_{pillar} as a function of R_{sample}, W_{pillar} and H_{pillar}. The difference between R_{pillar} and R_{sample} is the consequence of different causes as the spatial scale influence, buckling phenomena for slenderness pillars and confinement effect for width pillars. Indeed, the compressive strength of pillars is typically assessed with laboratory compressive tests. The samples are then very small (about 20 cm^2) compared to the dimension of pillars (about 100–1000 m^2).

Influence of pillars dimensions above the safety factor can then be taken into account by mutiplicate Eq. (1) by a coefficient K_{pillar} defined by one of the relations summarized in Table 1, so that K_{pillar} multiplicate by R_{sample} is equal to R_{pillar}. In order to take into account influence of