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Vulnerability Assessment of Mining Subsidence Hazards

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Between 1996 and 1999, five mining subsidence events occurred in the iron-ore field in Lorraine, France, and damaged several hundred buildings. Because of the thousand hectares of undermined areas, an assessment of the vulnerability of buildings and land is necessary for risk management. Risk assessment methods changed from initial risk management decisions that took place immediately after the mining subsidence to the risk assessment studies that are currently under consideration. These changes reveal much about the complexity of the vulnerability concept and about difficulties in developing simple and relevant methods for its assessment. The objective of this article is to present this process, suggest improvements on the basis of theoretical definitions of the vulnerability, and give an operational example of vulnerability assessment in the seismic field. The vulnerability is divided into three components: weakness, stakes value, and resilience. Final improvements take into account these three components and constitute an original method of assessing the vulnerability of a city to subsidence.

KEY WORDS: Assessment methods; stakes; subsidence; vulnerability

1. INTRODUCTION

"La Lorraine" is a region of France that has important underground natural resources of iron, coal, and salt. The industrial need for large quantities of raw materials at acceptable costs has led to the establishment of large underground mines, especially between 1900 and 1990. The extraction methods used in the mining created underground voids that may cause mining subsidence phenomena, that is, significant movements at the surface. These may result in serious damage to structures built in the area of influence of such movements. Subsidence is planned in total extraction mining (e.g., the "caving-in" method in coal mines). These methods are profitable and were used in iron-ore fields when no buildings or structures existed on the surface. However, mining subsidence is very unpredictable over mines that use the abandoned rooms and pillars method, even though this should provide permanent ground stability. In the latter case, the operator deliberately leaves natural or artificial pillars in place that are designed to withstand the overburden weight. This method is less profitable and is used under urbanized areas in order to avoid subsidence and damage to surface structures. Recent cases of mining subsidence (1996, 1997, and 1999) in the Lorraine iron-mining area demonstrate the hazard of such mining works when left abandoned.

The subsidence incidents in Lorraine led public authorities to investigate the entire Lorraine iron-mining field to assess the hazard, vulnerability, and risk of the entire region. The first investigations highlighted the existence of about 20 km^2 of urbanized

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areas concerned by abandoned works consisting of rooms and pillars.

The first part of this article is a presentation of recent subsidence phenomena and the identification of damage. The second part deals with different aspects of the vulnerability concept through a bibliographic study, while the third part provides a description and a discussion of the development of methods used in the iron-ore field for vulnerability assessment. The last part deals with possible vulnerability and risk assessment methods for mining subsidence hazards. Some improvements are possible by explicitly dividing the vulnerability components or with careful considerations to the influence attached to the different vulnerability and risk components.

2. MINING SUBSIDENCE IN THE IRON-ORE FIELD

Mining subsidence often produces significant horizontal and vertical movements at the ground surface (Table I). The maximum value "S_m" of the vertical subsidence is usually considered to be characteristic of the subsidence. However, the horizontal strain of the ground "ε," its curvature "R," and its slope "T" are the three main causes of structural damage. The maximum values observed for these parameters (ε_m, R_m, and T_m) can be disastrous for a structure if the movements are fully imparted. The prediction of these parameters entails significant difficulties. Comparison of predicted values with real measures of movement reveal that the vertical subsidence is the only parameter that may be predicted with accuracy. The slope and the horizontal strain deviate slightly from measures and the curvature deviates by an even greater amount.

Prediction of building damage may be performed on the basis of threshold values for ground movements (especially horizontal ground strain) and the building characteristics (especially length and structural strength). However, an accurate prediction of building damage is difficult in light of uncertainties about the real behavior of the ground and structures.

The consequences of subsidence vary, and include (Table I, Fig. 1):

- physical damage to buildings, roads, pavement, and networks;
- economic cost of physical reparations and compensations;
- economic cost of business and workforce interruption;
- social and psychological impacts to both disaster victims and other people in the area who suffer from the lack of public support and a lack of response to their fears; and
- political and media-related impacts because the entire region becomes a key point of political debate and media reports for many months.

Table I. Description of the Five Last Subsidence Events in the Iron-Ore Field and the Associated Damage

	Subsidence Characteristics[a]	Physical Damage	Cost	Others Consequences
Auboué (Metz Street) 1996	$S_m = 1.7$ m $\varepsilon_m \approx 15 \times 10^{-3}$ $T_m = 2.5\%$	130 buildings,[a] pavements, roads, sewerage system[b]	€13.9 million[a]	150 families evacuated,[b] 300 people permanently displaced from their village,[b] nursery school closed[b]
Auboué (Coinville City) 1996	$S_m = 1$ m $\varepsilon_m \approx 8.5 \times 10^{-3}$ $T_m = 3.5\%$	100 buildings,[a] roads, pavements[b]		
Moutiers (high quarter) 1997	$S_m = 1.4$ m $\varepsilon_m \approx 18 \times 10^{-3}$ $T_m = 1.2\%$	70 buildings[a]		Pub closed[b]
Moutiers (near the stadium) 1997	$S_m > 0.5$ m $\varepsilon_m > 6 \times 10^{-3}$ $T_m =$	60 buildings[a]		
Roncourt 1999	$S_m = 0.65$ m $\varepsilon_m \approx 6.5 \times 10^{-3}$ $T_m = 1\%$	18 buildings[a]		

[a]Deck (2002).
[b]Zihri (2004).

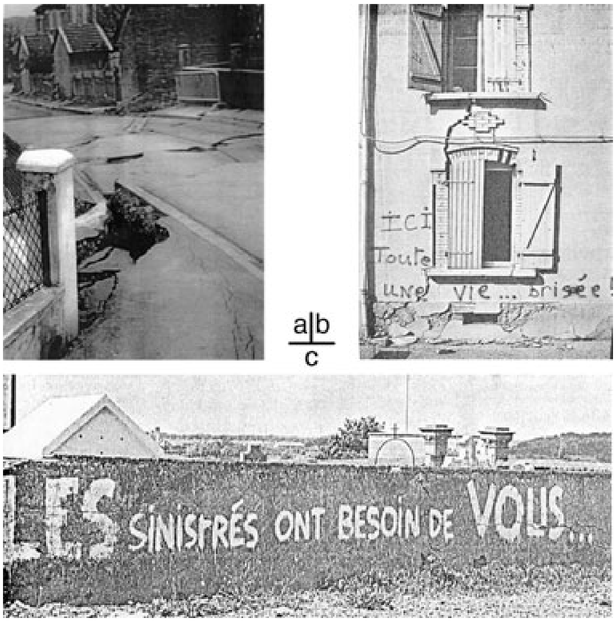

Fig. 1. Example of mining damage in the iron-ore field. (a) Road damage in Auboué, 1954; (b) building damage in Auboué, 1996, "Here, all a life is broken!"; (c) damage in the iron-ore field, "Disaster victims need you . . . "

3. THE VULNERABILITY CONCEPT IN THE SCIENTIFIC LITERATURE

3.1. Definitions

The concept of vulnerability is used in several definitions of risk. The United Nations, through the International Strategy for Disaster Reduction, defines risk as "the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between natural or human-induced hazards and vulnerable conditions" (UN/ISDR, 2004). It has adopted the classical convention expressed by the notation: risk = hazard × vulnerability.

A comparison of the definitions of vulnerability is useful to fully grasp the concepts this term encompasses. Ezell (2007) summarized 14 definitions of vulnerability, and Griots and Ayral (2001) made an inventory of 17 definitions of vulnerability that lead to splitting the vulnerability concept into two elementary ideas: (1) notions of sensibility, susceptibility, weakness, and predisposition and (2) notions of damage, impact, consequences, and level of loss. To study vulnerability, it is then necessary to assess (first idea) damage or consequences (second idea) that may occur for a particular hazard.

The United Nations, through the International Strategy for Disaster Reduction, defined vulnerability as "the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards" (UN/ISDR, 2004). This highlights that the susceptibility (first concept) depends on different factors that are not only physical (e.g., the strength of a building). Schmidtlein *et al.* (2008) used an example of a hurricane that demonstrates that the social characteristics of concern to the community should be considered important. Other definitions lead to the same conclusion. For example, Haimes (2006) defined vulnerability as "the manifestation of the inherent states of the system (e.g., physical, technical, organizational, cultural) that can be exploited to adversely affect (cause harm or damage to) that system," in order to measure risks to critical infrastructures of terrorist attacks and natural disasters.

In France, the Ministry of Environment and Sustainable Development defined vulnerability as the "level of foreseeable consequences of one natural phenomenon upon assets" in which assets are "people, goods, activities, means, heritage . . . likely to be affected by a natural hazard" (MATE, 1997). This highlights that damage and consequences (second idea) may concern a large quantity of different assets.

For human-caused security threats, McGill *et al.* (2007) described five dimensions of the asset-level consequences: (1) fatalities that take into account the number of deaths and injuries; (2) repair costs measured in dollars; (3) value of assets lost (goods, property, information) measured in dollars; (4) time to recuperate the mission measured in units of time; and (5) environmental damage. This emphasizes that there is a diversity of consequences and that it is simplistic to reduce them to a cost. Mining subsidence events in the iron-ore field showed that social damage occurred in addition to the costs associated with damage.

Schmidtlein *et al.* (2008) defined vulnerability as "the likelihood of sustaining losses from some actual or potential hazard event, as well as the ability to recover from those losses." This definition stresses the importance of resilience. Resilience is a concept discussed at length by Klein *et al.* (2003). On the basis of several definitions, they suggested restricting this term to describe the following:

- "the amount of disturbance a system can absorb and still remain within the same state or domain of attraction;
- the degree to which the system is capable of self organization;
- the degree to which the system can build and increase the capacity for learning and adaptation."

On the basis of similar considerations, Bogardi (2004) highlighted uncertainties due to several points:

- The question of "how far should vulnerability be seen as the 'susceptibility' alone or being rather the product of hazard exposure and that very susceptibility?";
- The question of what is the proper scale (national, regional, community, household, or individual) to capture and to quantify vulnerability?";
- The question of "whether (social) vulnerability can adequately be characterized without considering simultaneously the response (coping) capacity of the same social entity."

The first question can be clarified with help of Fig. 2, where the "weakness" is assumed to be quite similar to susceptibility. From a theoretical point of view, weakness of assets may be dependent on the intensity of the hazard. Considering that this intensity may vary according to its probability, the study of vulnerability might lead to as many elementary studies as the number of various potential hazard intensities. Because of the number of studies that this theoretical point of view has led to, engineers used to make a single assessment of vulnerability and thus make the hypothesis that weakness is independent of hazard intensity.

The second question was also considered by Balandier (2004), who suggested that similar risk elements might not have similar importance, depending on the relative importance of the kind of hazard and the surface area (country, city, district).

The third question refers to the resilience concept that has already been discussed.

In conclusion, the term "vulnerability" has many different meanings. It is therefore important to clearly define the held meaning before any study. Fig. 2 shows a possible guideline where the vulnerability is split into three components:

1. The "weakness" term includes physical vulnerability and is linked to the strength of the assets (buildings and facilities in particular). The vulnerability increases as the value of weakness increases.
2. The stakes value includes functional vulnerability and is linked to losses associated with functional damage. The vulnerability increases with increasing stakes value.
3. The "resilience" term is as defined by Klein *et al.* (2003). The vulnerability decreases with the increase of the resilience.

In this synthesis, the assets are used to define elements that may be damaged (e.g., people, buildings, infrastructures, goods, and activities). The stakes value is used to define the importance of these elements because of the cost of repairs or because of the possible other consequences of their damage (e.g., functional damage and social damage).

3.2. Operational Assessment

The above-mentioned theoretical definitions show that a practical assessment of vulnerability is very complicated. Nevertheless, several operational methods have been developed, especially in the seismic field, as described below.

In the United States, the Federal Emergency Management Agency (FEMA) gives the following definition of vulnerability:

> The vulnerability describes how exposed or susceptible to damage an asset is. Vulnerability depends on an asset's construction, contents, and the economic value of its functions. Like indirect damages, the vulnerability of

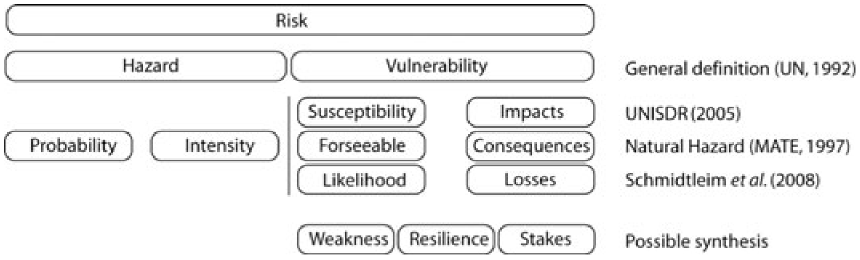

Fig. 2. Guideline of different definitions for the term vulnerability.

> one element of the community is often related to the vulnerability of another. For example, many businesses depend on uninterrupted electrical power—if an electric substation is flooded, it will affect not only the substation itself, but a number of businesses as well. Often, indirect effects can be much more widespread and damaging than direct ones. (FEMA, 2001)

Vulnerability assessment is defined by "the extent of injury and damage that may result from a hazard event of a given intensity in a given area. The vulnerability assessment should address impacts of hazard events on the existing and future built environment" (FEMA, 2001).

This definition emphasizes the economic dimension of vulnerability over the social dimension. HAZUS-MH (Hazards U.S. Multi-Hazard) gives many detailed explanations to identify hazards and assets and to assess the vulnerability for a large number of different hazards (e.g., earthquake, flood, landslide, tsunami, tornado, wildfire, and coastal storm). Examples written in technical guides (FEMA, 2001) show that the vulnerability assessment results in the economic estimation of losses. This estimation takes into account both structural and functional damages, but does not include damages that are difficult to quantify.

In the seismic field, the European Macroseismic Scale (EMS 98) used vulnerability in the strict sense of building strength:

> [It] incorporates a compromise, in which a simple differentiation of the resistance of buildings to earthquake generated shaking (vulnerability) has been employed in order to give a robust way of differentiating the way in which buildings may respond to earthquake shaking. The Vulnerability Table is an attempt to categorise in a manageable way the strength of structures, taking both building type and other factors into account. This is a development from previous scales, which used only construction type as an analogue of vulnerability. (EMS 98)

Nevertheless, the seismic field has a strong foothold in the development of the term vulnerability. Recent studies have shown an increase in assessment of both social and material vulnerabilities. Balandier (2004) listed different types of elements at risk (e.g., urbanized areas, roads, networks, power plants, and community facilities) that are relevant for social vulnerability.

Also in the seismic field, Teramo *et al.* (2005) introduced a methodology of urban and territorial seismic vulnerability assessments related to both engineering studies and social priority levels. They first highlighted the impossibility of administrations being able to plan suitable prevention interventions through usual approaches on the basis of the building weakness and the earthquake loss estimates (as in the EMS 98 case). They identified different vulnerabilities related to three kinds of elements:

1. the vulnerability related to the "morpho-typological characters of buildings" (as the EMS 98 vulnerability);
2. the vulnerability related to "the collective or public system" (distribution of services, productive assets, and public buildings); and
3. the vulnerability related to "the critical spatial elements" (streets, safety routes, and strategic structures).

Each type of vulnerability is assessed with two functions that model the seismic weakness/reliability and the social or strategic priority levels within the system.

It is important to note that vulnerability is always a subjective concept due to the number of different stakeholders, administrations, or insurance companies who have to support the consequences of hazard occurrences. The results of vulnerability studies are dependent on the end user.

The following section describes the example of the risk assessment methods used in the iron-ore field in Lorraine and focus on the evolution of the vulnerability assessment. The final objective of this article is to suggest some improvements on the basis of theoretical definitions of vulnerability and practical methods that are actually used in other contexts.

4. EVOLUTION OF THE VULNERABILITY CONCEPT AND ITS METHOD OF ASSESSMENT IN THE IRON-ORE FIELD BETWEEN 1996 AND 2005

4.1. The First Ranking System

In reaction to recent subsidence events in Lorraine in 1996 (Auboué), 1997 (Moutiers), and 1999 (Roncourt), and sinkholes in 1998 (Moyeuvre), public authorities ordered investigations to understand the extent of the problem.

Because of the lack of knowledge regarding subsidence phenomena, a first ranking system was based on two main considerations:

1. the subsidence probability, through the value of the extraction ratio; and
2. the subsidence intensity, through the value of the maximum expected vertical subsidence.

Table II. First Ranking System of Risk in the Iron-Ore Field and the Associated Recommendations

Maximum subsidence < 1 m	Surface of building < 400 m^2, maximum length < 25 m, number of floors $\leq$ ground floor $+ 3$
Maximum subsidence < 2.5 m	Surface of building < 150 m^2, maximum length < 15 m, number of floors $\leq$ ground floor $+ 1$
Maximum subsidence > 2.5 m	Forbidden

This first ranking system was in agreement with the regulations of the French urban code (Articles R111-2 and R111-3). It defines three kinds of areas, depending on the maximum possible subsidence and associated recommendations for building projects (Table II; Kouniali, 2001).

This first ranking system is called step 1 (Fig. 3). It deals mainly with the urban side of vulnerability and is unsuitable for other aspects of vulnerability, especially human, social, and economic.

4.2. The Multicriteria Ranking System

Supplementary investigations were necessary to perform a more detailed hazard assessment and for the human vulnerability assessment. Merad *et al.* (2004) developed a method on the basis of a multicriteria analysis. The mathematical functions included in the method allow management of a "complex decision-making problem where the available information is uncertain and imprecise and where knowledge is incomplete" (Merad *et al.*, 2004). This method uses weighted factors for all criteria and stresses their relative importance in the risk assessment.

In this method, each area is described by a set of criteria that characterizes the hazard (probability and intensity of the subsidence) and the vulnerability. Each criterion is then compared with threshold values in order to decide if the given criterion corresponds to a slight, medium, high, or very high risk area. These elementary results are then counterbalanced by a weighting factor and aggregated to determine the final risk level. For example, if the values of three criteria A, B, and C with respective weight factors of 2, 1, and 5 are characteristic of a medium risk for A and B and a high risk for C, then the final risk level will be high. This example is simplistic. The many nuances of this method are not detailed in this article, but are provided by Merad *et al.* (2004).

This methodology has been applied to constructed areas (civil security objectives). One of the main goals of the multicriteria ranking system was to identify areas requiring specific surveillance because of their high risk level. This leads to the second and third steps of Fig. 3, which concern asset identification, hazard intensity, and the final risk level (Table III). An extension of the methodology has been applied to nonurbanized areas in a land-use planning perspective.

Two kinds of assets were studied: buildings and infrastructure assets. Fig. 4 shows the methodology used to determine the vulnerability of each kind of asset and the values of the selected weight factors. In the case of buildings, no other asset is taken into account. Buildings' assets are then assessed with one criterion that may have five values, from "business park," which corresponds to a small vulnerability level because of its single daily activity, to "city," which corresponds to the highest vulnerability level because of its daily and nightly activities and the number of affected people. This typology is mainly devoted to population safety and to a lesser degree to economic or structural vulnerability, although those kinds of vulnerabilities are indirectly taken into account since they increase with population. The associated recommendations are listed in Table III. The cost of real-time monitoring may be estimated at about €120 per habitant per year. The decision to consider only one of the two asset types—buildings assets and infrastructure assets—shows that this methodology and the associated recommendations are geared toward human vulnerability. It will not be an effective assessment of other vulnerabilities connected to physical damages and their consequences (e.g., damage to buildings and economic losses).

The weight factors linked with the probability, intensity and vulnerability criteria raise an important question connected with the previous definition of risk. If risk is the product of hazard and vulnerability, does the sum of the weight factors for each component have to be equal? In this case, the sum of the weight factors related to the hazard criteria reaches the value of 46, while the sum of the weight factors related to the vulnerability criteria reaches "only" a value between 2 and 14, depending on the assets in the area. This difference produces results that are more dependent on hazard than on vulnerability. Consequently, this multicriteria ranking system may

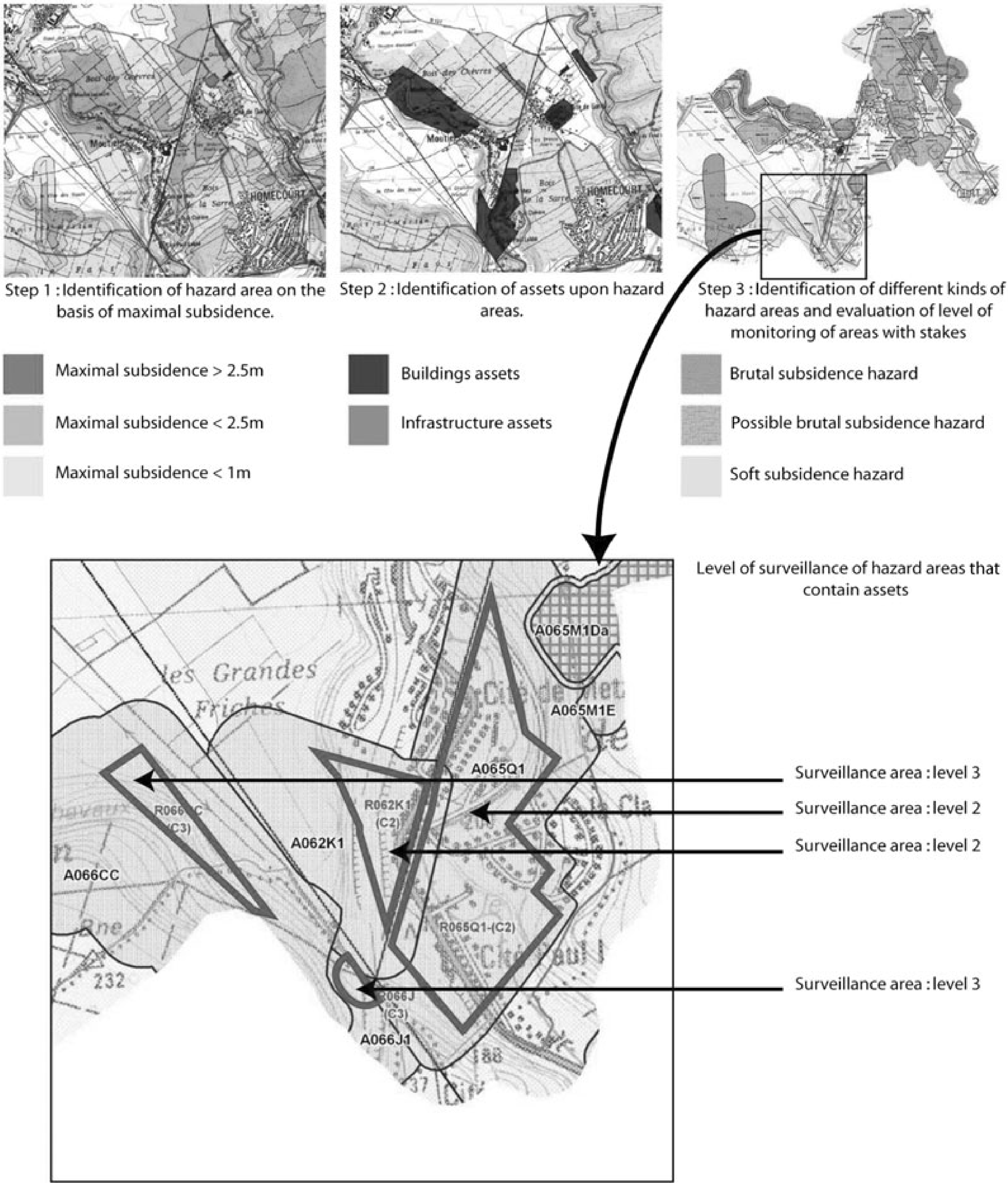

Fig. 3. Development of risk assessment in the Lorraine iron-ore field.

Table III. Second Ranking System of Risk in the Iron-Ore Field and its Associated Recommendations

Level 1 of surveillance area Very high risk	Real-time monitoring
Level 2 of surveillance area High risk	Periodic monitoring, which will become real time at the first forewarning
Level 3 of surveillance area Medium risk	Supplementary investigations are required to assess the need for periodic monitoring
Level 4 of surveillance area Slight risk	No monitoring is required; only leveling measurements are made

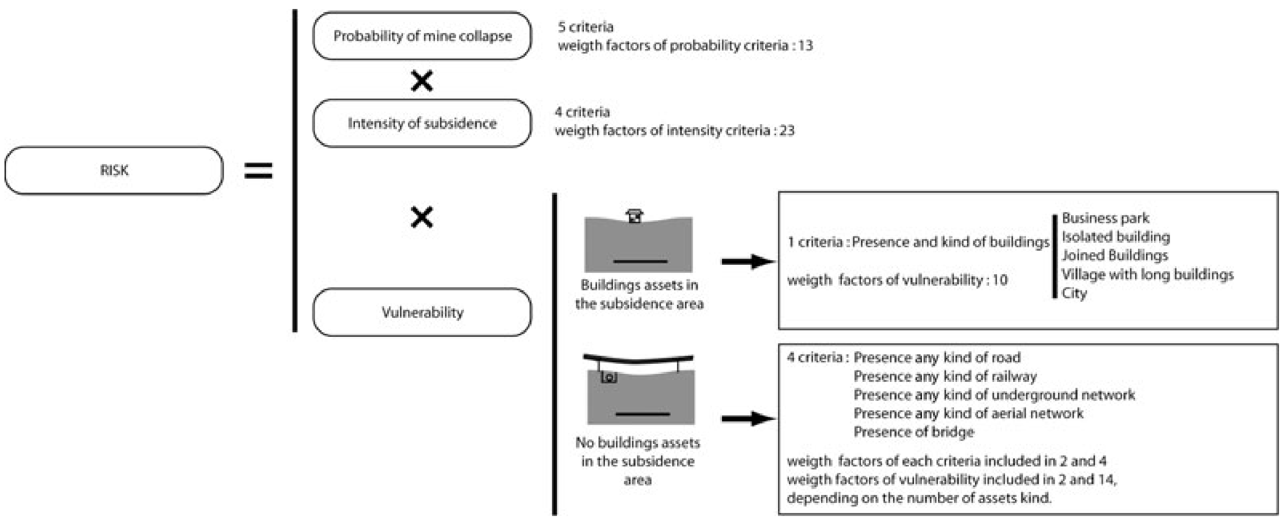

Fig. 4. Description of criteria and weight factors used in the actual assessment of risk, hazard, and vulnerability in the iron-ore field.

be criticized because it focuses on hazard assessment rather than on risk assessment.

4.3. The Mining Risk Prevention Plan

The last step for the mining risk assessment and management is currently in its completion stage. The mining risk prevention plan (MRPP) will provide a legal framework for all municipalities to identify both hazards and the current or foreseen assets in their region. These plans aim to identify the most sensitive areas with regard to risk development and establish rules for the proper management of regions according to postmining constraints. The MRPP was introduced by Didier and Leloup (2005). It consists of four steps (Fig. 5).

The "assets assessment" step aims to identify all existing assets within the studied region, as well as possible future projects. It enables the identification of threatened populations and the most sensitive infrastructure. This step produces a map of assets. Several maps may be generated to fit the goal of the study (e.g., civil security and land-use planning).

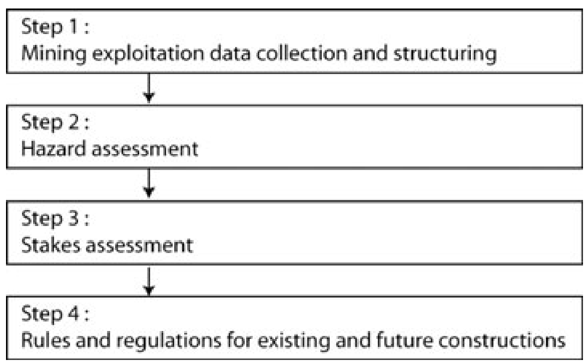

Fig. 5. Description of the four steps of the mining risk prevention plan.

The MRPP framework is intended for application over potentially hazardous mining fields. Its organization is based on the experience of existing prevention plans for other hazards (e.g., floods and fires). The MRPP global methodology is the result of the experience of the former REP (risk exposition plan) that was applied in the 1980s. Within the REP, vulnerability was assessed through an exhaustive study of susceptibilities. At the scale of a town, this task appeared to be too complex and long. This led to the requirement that the MRPP methodology be simple and produce results quickly.

In Lorraine, the MRPP has been implemented in all municipalities affected by the hazard without modifying the global ranking between these municipalities. There is no significant difference in terms of vulnerability assessment compared to previous studies. More generally, the application of the MRPP will not provide methods to assess the vulnerability of the municipality or the framework needed to estimate losses. Thus, it can be concluded that the MRPP is mainly used to define rules in order to avoid any risk increase from unsuitable projects, and not for the accurate assessment of the existing vulnerability and possible losses.

Consequently, the objective of the next section is to identify and suggest possible improvements to the current methods so that they include a better assessment of the vulnerability.

5. IMPROVEMENTS FOR A BETTER VULNERABILITY ASSESSMENT

The suggested improvements are mainly based on methodologies used in the United States with HAZUS-MH, in Europe with EMS 98, and in a report for the Ministry of Environment and Sustainable Development and the Ministry of Industry, Economy and Finance (Deck, 2003) that suggested the need for improved methods of assessing vulnerability in the Lorraine iron-ore field.

5.1. General Objectives of the Improvements

- At present, there are two different geographic scales for the study of vulnerability. The first is the scale of the entire Lorraine iron-ore field, which includes more than 100 cities and villages affected by the mining hazard. This is the scale of the multicriteria analysis that permits a ranking of every urbanized area (small villages or districts) in comparison with one another and guarantees the standardized evaluation of the towns' vulnerabilities. At this scale, the goal is to classify the cities into a small number of risk levels. Thus, any improvement that would lead to a detailed estimation of possible losses would not be very effective. The second scale is the city scale, which is the scale of the MRPP. At this scale, the results could be an accurate evaluation of the possible losses. This article focus on improvements adapted to the larger scale of the entire iron-ore field.
- Analysis of the literature shows that any vulnerability study should take into account both physical damage to buildings and infrastructure that depends on the weakness, and functional damage that depends on the stakes value and the resilience (Fig. 2). The multicriteria analysis uses a very small number of criteria that confuses these three dimensions of vulnerability, underestimates the functional consequences, and does not take into account resilience. Moreover, the weakness assessment is simplistic and, in particular, no distinction is made between the different buildings, whereas physical damages are strictly dependent on the building materials and design. The improvement of this method is a major objective of this article.
- The current rankings (carried out at the large scale) appear to give more importance to the hazard criteria than to the vulnerability criteria, as indicated by a comparison of the sums of their respective weight factors (Fig. 4). This probably reflects the skills of the experts who performed this analysis. It is clear that the risk analysis is made by engineers, who are more familiar with the hazard concept than with the vulnerability concept, which has multiple topics that they are not specialized in, including social, political, and economic factors. Giving exactly the same weight to the vulnerability and hazard criteria comes from a theoretical point of view, but poses difficulties. Increasing the vulnerability weight factors results in direct safety measures for vulnerable areas, although no certainty exists concerning the hazard occurrence. Conversely, a decrease in the vulnerability weight factors causes limits to the safety measures in high-probability hazard areas. The adjustment of both the hazard and the vulnerability with equivalent weight factors is one of the most important objectives of this work.

5.2. Comparison with HAZUS-MH

HAZUS-MH is a standardized methodology and risk assessment software program for analyzing potential losses from floods, tornadoes, tsunamis, landslides, coastal storms, wildfires, and earthquakes. The methodology is explained in a large number of technical manuals edited by the FEMA.

HAZUS-MH gives a methodology for risk assessment with five steps that can be compared to the four steps used in the MRPP (Fig. 6; FEMA, 2004). The first two steps are comparable, but the third and fourth steps of the HAZUS methodology are combined into a single step in the current MRPP. The HAZUS methodology has a more in-depth stakes value assessment with two distinct steps: the asset inventory and the losses estimation. Consequently, the current methodology should be amended to go further in the stakes value assessment. The HAZUS methodology is well adapted to the city scale but is not intended to rank cities Consequently, it is not directly applicable to the improvement of the ranking of hazard areas in the iron-ore field. Nevertheless, it provides important suggestions to improve the multicriteria analysis and the MRPP.

FEMA (2001) explained that it is necessary to gather building- and hazard-specific information about particular assets or critical facilities. Five categories are identified: (1) essential facilities (e.g., hospitals, police stations, and schools), (2) transportation systems (e.g., airports, highways, railroads, and waterways), (3) lifeline utility systems (e.g., potable water, wastewater, natural gas, electric power, and communication systems), (4) high-potential-loss facilities (e.g., nuclear power plants, dams, and military installations), and (5) hazardous material facilities. The suggested improvements to the multicriteria analysis take these categories into account.

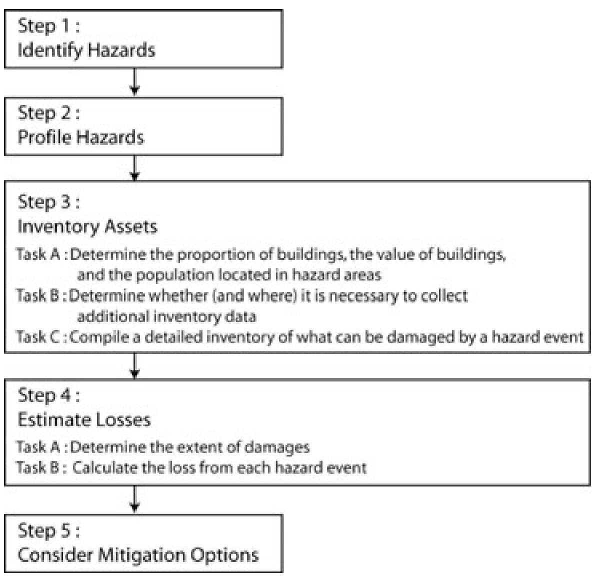

Fig. 6. Methodology for risk assessment with HAZUS-MH (FEMA, 2004).

HAZUS-MH provides a complex methodology that is based on the use of vulnerability and fragility curves and a large number of relevant ratios to assess the building vulnerability and the potential losses. Vulnerability curves show the relationships between the mean damage for a given type of building and the value of the event intensity. The development and validation of such relationships for the mining subsidence hazard is a difficult undertaking that is beyond the scope of this article. In addition, this approach to studying building vulnerability appears to be much too detailed at the large scale, where multicriteria analysis is used, but it is effective for the MRPP scale.

FEMA (2002) also provides a simpler methodology for a rapid assessment of building vulnerability. Each building is characterized by a score on the basis of the type and particular features (e.g., height, irregularities, and soil type). Table IV gives descriptions of six selected building types that are the most comparable with buildings in the Lorraine iron-ore field. Application of this methodology appears to be an effective tool to improve the MRPP but is still much too detailed to improve the actual multicriteria analysis. However, building classification by defining a small number of easy to recognize types for all concerned cities is a possible improvement.

5.3. Comparison with EMS 98

The European Macroseismic Scale (EMS 98) focuses on the "weakness" term of vulnerability. It gives a simpler methodology that is based on the definition of six vulnerability classes. All building types are classified into these six classes (Fig. 7). Building losses are assessed by an empirical relation between the proportion of damage in each vulnerability class and the seismic intensity. Comparison with Table IV shows that the common buildings of the Lorraine iron-ore field are basically classified into three classes (B, C, and D). This methodology appears to be more detailed than that presently used and has the potential to provide effective comparisons of the global vulnerability of a large number of different villages. It should be noted that the EMS does not account for functional damage or resilience.

5.4. Final Propositions

In this section, proposals are adapted to the country scale to improve the multicriteria analysis. They are presented in Fig. 8.

Table IV. Description of Six Building Types and Associated Basic Score Among the 15 Used for a "Rapid Visual Screening of Buildings for Potential Seismic Hazards" (FEMA, 2002)

Building Type	Description	Basic Score (Building Vulnerability Increases with Smaller Values of the Score)
C1	Concrete movement-resisting frame	3.0
C2	Concrete shear wall	3.6
C3	Concrete frame with unreinforced masonry infill	3.2
RM1	Reinforced masonry with flexible floor and roof diaphragms	3.6
RM2	Reinforced masonry with rigid diaphragms	3.4
URM	Unreinforced masonry bearing-wall buildings	3.4

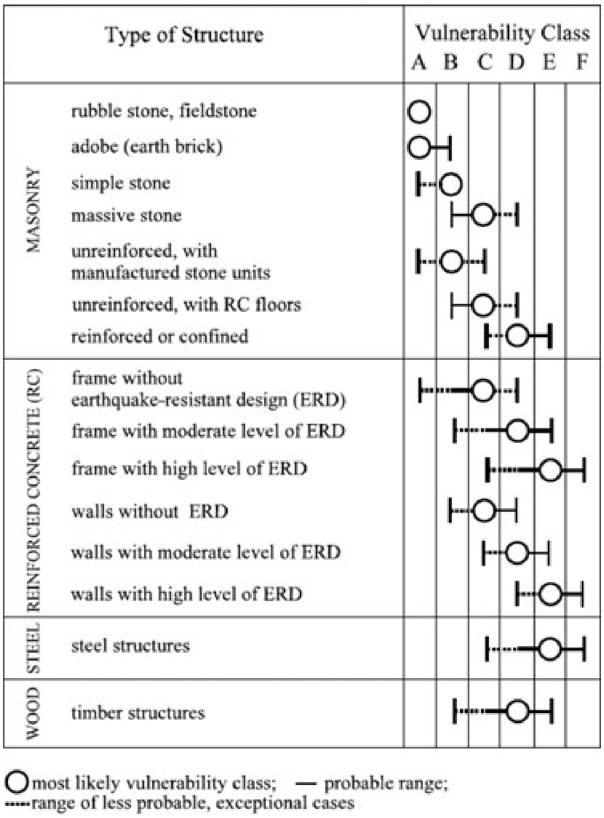

Fig. 7. Distribution of 15 current building types into six vulnerability classes (EMS, 1998).

For a more accurate vulnerability assessment, the very weak elements must be simultaneously considered in the analysis. In accordance with the literature and the methodology defined in HAZUS-MH, it is necessary to split vulnerability into different components.

For buildings, the current method assesses vulnerability through one criterion that characterizes the global nature of the buildings. However, we propose dividing building vulnerability into two components: "weakness" and "stakes value." For networks, we chose to keep a single criterion but it is defined quite differently. These choices address the problem because most urbanized areas are small, and previous subsidence occurrences have shown that buildings were the most critical structures due to their weakness and function. Second, the use of explicit criteria for the weakness allows the consideration of the seismic field results as a model for these criteria.

Fig. 9 shows different kinds of buildings classified into four classes of *weakness*. Class A characterizes buildings with the lowest strength, while Class D characterizes the strongest buildings. This classification is modeled on that used in the EMS 98. We based our proposal on statistical studies performed on damaged buildings in Lorraine (Deck, 2003) and on an architectural study on the typology of buildings for typical villages in Lorraine. Traditional buildings generally fall into Class A. Individual buildings with concrete masonry and basic reinforcement at the floor levels and around openings can be grouped into Class B. Tall buildings with reinforced concrete walls and floors are in Class C. This typology may be compared with the literature. Existing methods of building damage assessment in subsidence areas show that masonry buildings are weaker than concrete buildings and that building reinforcements reduce building damage (Kwiatek, 1998; Yu *et al.*, 1988; Kratzsch, 1983). The final distribution of building types into weakness classes should be adapted with further investigations.

Fig. 9 can be used to determine the number of buildings in each weakness class. This results in the consideration of four criteria to assess the building weakness, which are the numbers of Class A, B, C, and D buildings. These criteria are directly associated with the economic losses of subsidence because

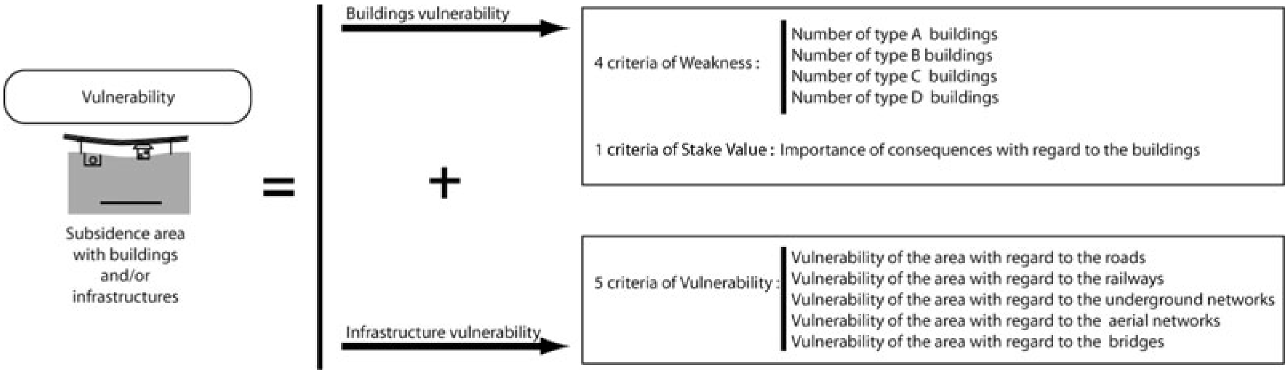

Fig. 8. Propositions to better assess vulnerability in the iron-ore field. The vulnerability is assessed with both building and infrastructure assets.

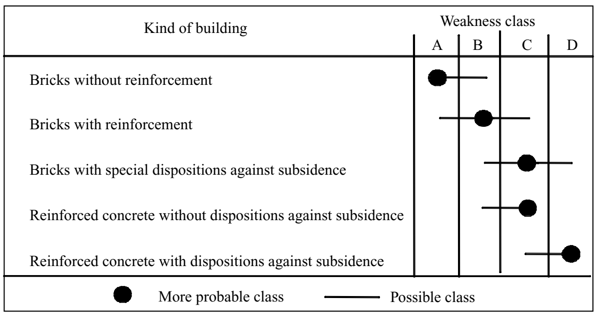

Fig. 9. Distribution of building types into four classes of weakness for the building vulnerability assessment in subsidence hazard areas. "A" indicates the weakest buildings and "D" the strongest.

the Class A buildings will sustain more damage than Class B buildings for similar subsidence phenomena. These four criteria do not relate to social or environmental consequences of building damage, or to the resilience.

For this reason, we define another criterion (stakes value) for the qualitative assessment of stakes value connected with buildings that takes into account the resilience, and is concerned with the degree to which the village is capable of self-organization. Table V describes three possible levels for this criterion. If we compare these levels to the five categories of critical facilities identified in HAZUS (FEMA, 2001), it can be concluded that a slight stakes value means that there are no critical facilities of concern, a medium stakes value means that some critical facilities may be slightly affected, and a strong stakes value means that some critical facilities may be strongly affected.

For the infrastructure vulnerability assessment, we chose to keep the same number of criteria (five) for the current method, but altered the meanings in order to take into account both the weakness and the stakes value. Because of the comparison between the lowest levels of vulnerability importance of infrastructure and buildings, and the necessity of a relevant method for risk assessment, it is necessary to incorporate the weakness into the assessment of a single vulnerability criterion for each of the five kinds of infrastructure: roads, railways, underground networks, aerial networks, and bridges. Table VI describes five possible levels for each of these five criteria. This assessment follows the thesis of Zihri (2004), and

Table V. Indicators of Stakes Value Connected with Buildings

Slight	Medium	Strong
Individual consequences due to a slight value of stakes or a small quantity of possible damaged buildings	Collective consequences due to a high importance of stakes or a large quantity of possible damaged buildings Consequences throughout the society are possible (social and economic equilibrium)	Collective consequences with the possibility of a series of accidents; in addition to the collective consequences previously described, a possibility of a series of accidents exists due to the very high stakes (e.g., hospitals and emergency services) or because problems are identified in the hazard area (e.g., chemical factories and petrol stations)

Table VI. Indicators of Damage Levels Due to the Infrastructure Weakness and Stakes Value

Null	Slight	Medium	Strong	Very Strong
No infrastructure in the area	Combination of weakness, stakes value, and resilience of the infrastructure leads to the assumption that the damage will only affect:			
	A few people (individual consequences)	People and economy at the village scale	People and economy at the administrative region scale	People and economy at the scale of several administrative regions or the national scale

Table VII. Comparison Between the Current and Proposed Methods of Vulnerability Assessment

Current Method		Proposed Method	
One criterion for building vulnerability	The entire area is classified as a village	Four criteria for building weakness	The four criteria of building weakness for the assessment of possible economic losses: 5 buildings in Class A 15 buildings in Class B 22 buildings in Class C 8 buildings in Class D
		One criterion for building stakes value	Medium value of stakes connected with buildings due to the important number of concerned buildings and due to the difficulty in relocating people
Five criteria for infrastructure vulnerability	The five vulnerability criteria of infrastructures—bridge, road, railway, aerial network, and underground network—are not taken into account because of the presence of buildings	Five criteria for infrastructure vulnerability	Medium value for road infrastructure vulnerability Null values for railway and bridge infrastructure vulnerability because it is nonexistent Slight values for aerial and underground network because some damage is possible

integrates the weakness, the stakes value, and the resilience concept, with the understanding that the social, economic, and political response of the community is required and then assessed.

Table VII shows a comparison of a theoretical area between the current method of vulnerability assessment and the proposed one. The example assumes an area with 50 buildings, one main road, two shops, without possibility of relocating people within 10 km, with a public debate and a population that is highly informed about the risk of subsidence.

6. CONCLUSION

The study of vulnerability for risk assessment is complex because of the gap between the social expectations and the difficulty in formalizing a coherent and unbiased methodology.

A bibliographic study identified different concepts for possible inclusion in the definition of vulnerability. We chose to consider three elementary components within the vulnerability concept: the weakness, the stakes value, and the resilience. The weakness characterizes the possible structural damage to physical elements such as buildings and infrastructures and is directly connected to the economic loss due to reparations. The stakes value characterizes the importance of other damages to other aspects (e.g., social, economic, and civil) that are affected by the damaged physical elements. The resilience characterizes the ability to recover from damage.

All of these three components are very subjective. Several preliminary considerations are necessary to define the meaning of vulnerability before using it in a risk assessment study, including the following:

- What is the scale of the study (national, regional, or community)?
- What is the balance between the weight factors for the hazard criteria and for vulnerability criteria? An upper weight factor for vulnerability favors civil protection, while an upper weight factor for hazard favors land-use planning.
- What are the components of vulnerability that must be taken into account? Weakness, stakes value, and resilience assessment may be very subjective and require interdisciplinary

studies. Improvements suggested for the vulnerability assessment in the Lorraine iron-ore field show a pragmatic but subjective method of considering these three components.

These questions need to be answered prior to any vulnerability study. They all refer to the question of who is the end user and what will the results be used for? Inappropriate use of a vulnerability assessment study can cause much confusion; some aspects may be relevant for one objective or a specific end user but not for others. In a single hazard area, vulnerability will be very different for one citizen with individual concerns than for the municipality with collective concerns or for insurance companies with business concerns.

The case of the Lorraine iron-ore field illustrates the complexity of vulnerability assessment, which may require several consecutive studies to fully analyze and understand the present hazard. A consequence of these studies is the development of the ranking system and the necessity of explaining it to both citizens and end users. This highlights the necessity of clarifying the study objectives to prevent results from being misinterpreted.

Finally, this study suggests possible improvements to the current multicriteria analysis and the MRPP developed for the iron-ore field on the basis of two important methodologies used in Europe (EMS 98) and in the United States (HAZUS-MH). Suggested improvements mainly concern the prioritization of risk between large numbers of hazard areas on the basis of a more rigorous assessment of the vulnerability. Comparison of the methodology of the MRPP with the HAZUS-MH shows that the first three steps are comparable: identification of hazards, assessing hazards, and identification of assets. However, it appears that the MRPP lacks effective methods of damage assessment and loss estimation. The vulnerability curves that relate the subsidence intensity to the building damage for each building type are a promising direction for further research.

REFERENCES

Balandier P. Urbanisme et Aménagements—Objectifs et problématiques. Collection Conception Parasismique, cahier n 3, Les grands Ateliers de l'Isle d'Abeau, 2004.

Bogardi JJ. Hazards, risks and vulnerabilities in a changing environment: The unexpected onslaught on human security. Global Environmental Change, 2004; 14:361–365.

Deck O. Etude des conséquences des affaissements miniers sur le bâti: Propositions pour une méthodologie d'évaluation de la vulnérabilité du bâti. Thèse de Doctorat de l'INPL Nancy, France, 2002.

Deck O. Réduction de la vulnérabilité par prise en compte du risque dans l'aménagement: Etude des interactions sol-structures. Application au cas des affaissements progressifs. Rapport INERIS DRS-02-45828/RN, 2003.

Didier C, Leloup J. PPRM: A powerful technical and administrative tool to prevent and manage post mining hazards. Colloque Post-Mining—GISOS, 2005; 16–17.

European Macroseismic Scale (EMS) 98. Cahiers du Centre Européen de Géodynamique et de Séismologie, Vol. 15, Grünthal G. (ed).

Ezell BC (eds). Infrastructure Vulnerability Assessment Model (I-VAM). Risk Analysis, 2007; 27(3).

FEMA. Understanding Your Risks—Identifying Hazards and Estimating Losses. Federal Emergency Management Agency, FEMA-386-2, August 2001.

FEMA. Rapid Visual Screening of Buildings for Potential Seismic Hazards. Federal Emergency Management Agency, FEMA-154, March 2002.

FEMA. Using HAZUS-MH for Risk Assessment. Federal Emergency Management Agency, FEMA-433, August 2004.

Griot C, Ayral PA. Terminologie en science du risque, d'après le document de travail du colloque international "Dire le risque: Le risque mis en examen," Mèze, May 18–20, 2001.

Haimes Y. On the definition of vulnerabilities in measuring risks to infrastructures. Risk Analysis, 2006; 26(2):293–296.

Klein RJT, Nicholls RJ, Thomalla F. Resilience to natural hazards: How useful is this concept? Environmental Hazards, 2003; 5:35–45.

Kouniali S. Sécurité des personnes et urbanisme après la fermeture d'un grand bassin minier sédimentaire: Le cas des mines de fer de Lorraine. Les techniques de l'Industrie Minérale, 2001; n 10, June 2001, 91–95.

Kratzsch H. Mining Subsidence Engineering. Springer-Verlag, 1983.

Kwiatek J. Protection of constructions on surface ground mine. (Original title "Ochrona objektow budowlanych na terenach gorniczyych"). GIG, Katowice, Poland, 1998.

MATE. Plans de prévention des risques naturels prévisibles—guide général. La documentation Française, 1997.

McGill WL, Ayyub BM, Kaminskiy M. Risk analysis for critical asset protection. Risk Analysis, 2007; 27(5):1265–1281.

Merad M, Verdel T, Kouniali S. Use of multi-criteria decision-aids for risk zoning and management of large area subjected to mining-induced hazards. Tunnelling and Underground Space Technology, 2004; 19:125–138.

Schmidtlein MC, Deutsch RC, Piegorsch WW, Cutter SL. A sensitivity analysis of the social vulnerability index. Risk Analysis, 2008; 28(4):1099–1114.

Teramo A, Bottari D, Termini D, Bottari C. A methodological approach for the evaluation of urban and territorial vulnerability. Pure and Applied Geophysics, 2005; 162:659–670.

UN/ISDR. Living with risk: A global review of disaster reduction initiatives (2004 version).

Yu Z, Karmis M, Jarosz A, Haycocks C. Development of damage criteria for buildings affected by mining subsidence. 6th annual workshop generic mineral technology centre mine system design and ground control 1988, 1988, 83–92.

Zihri G. 2004. Risques liés aux ouvrages souterrains. Constitution d'une échelle de dommages. Thèse de Doctorat de l'INPL Nancy, France.