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Sinkhole post-mining risks: the French methodology

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Abstract

Every year, around 20 sinkholes occur in France above former mining galleries or works. Some of those sinkholes significantly impacted buildings and jeopardised public safety.

As part of a risk prevention strategy falling under the responsibility of the French national authorities, the public institution GEODERIS, which is in charge of the post-mining risk expertise, has developed and implemented, for over the past decade, a methodology to assess and map sinkhole hazards and risks. This approach focuses on assessing the building fragility subjected to sinkhole hazards.

The methodology was developed in collaboration with the Scientific and Technical Centre for Building (CSTB), the public institution in charge of research and development in this field and is based on a representative sample of 210 buildings across various French cities. Seven building types and five categories of load-bearing structures were first identified. Owing to analytical simulations of a load-bearing structure behaviour subjected to sinkholes of increasing diameters, a damage curve was derived. The risk level is assessed according to the expected damage building percentage relative to the expected sinkhole's surface area.

Between 2012 and 2015, around 3,000 buildings located in sinkhole hazard zones across French territory were listed. This method made it possible to eliminate the safety risks for half of these buildings. Mining works under buildings rated at medium-risk or high-risk are nowadays either being monitored or have been secured.

The proposed methodology discriminates between situations that could impact buildings from those that could jeopardise public safety. It provides to the authorities in charge of post-mining risks prevention a coherent approach for optimal decision-making.

Keywords: *post-mining, sinkhole, localised collapse, hazard, risk, fragility, building*

1 Introduction

Under certain geological and structural conditions, the instability of a natural or man-made underground cavity may result, after failure, in the occurrence at the surface of a localised collapse phenomenon called sinkhole. Drawing inspiration from the limestone domain classification proposed by Gutiérrez (2016), the observed phenomena correspond to a sinkhole with all failure mechanisms falling under the category of collapses, which are sudden in nature. This propriety can be detrimental public and private infrastructure at the surface, as well as to human safety.

Between 2012 and 2015, around 2,500 buildings located across France and situated in sinkhole-prone areas were listed. Given the large volume to be addressed, it became necessary to develop a streamlined operational methodology in order to distinguish risks to public safety from those impacting only property.

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2 Sinkhole: definition and hazard assessment

2.1 Definition

Supported by numerous studies and field experience, in 2019, INERIS synthesised the methodology for assessing hazards related to former mining operations (INERIS 2019). The sinkhole hazard is a frequent and dangerous phenomenon associated with shallow abandoned mines. It is characterised by the sudden formation at the surface of a crater, with a horizontal extent and a depth generally ranging from a few metres to, in some cases, several tens of metres.

The initiating mechanisms for such events are defined by the type of mining cavity encountered. They can be grouped into four categories:

- Progressive roof collapse of a gallery: the phenomenon known as a sinkhole (Figure 1).
- Collapse of isolated pillar/s within an old shallow mining structure.
- Collapse of the head of a vein-type mining chamber, referred to as 'crown collapse'.
- Loss of backfill material and/or collapse of the shaft collar.

Figure 1 Formation of a localised collapse through the upward progression mechanism of a sinkhole cavity

The occurrence of a collapse is most often marked by two distinct phases (Didier & Salmon 2010). The first phase corresponds to the sudden formation of the collapse at the surface. The flanks of the collapse crater then appear vertical or even overhanging, temporarily retaining the shape of the original vault prior to failure. The second phase, which develops progressively, corresponds to the stabilisation of the collapse through the widening or flaring of the crater.

The duration between these two phases depends on the geotechnical properties of the surface soils, particularly their cohesion.

It should be noted that due to the bulking effect of the fallen materials, a collapse can only initially form and later flare during the secondary phase if the volume of accessible underground voids is sufficiently large. For the development of this methodology, aimed at ensuring a streamlined approach, we chose by default to adopt the most unfavourable situation, namely that the available underground void is sufficiently large for the surface collapse to reach its maximum possible opening.

2.2 Hazard assessment

The hazard assessment is based on the intersection between the probability of occurrence of a phenomenon and its expected intensity. Since localised collapse is inherently sudden and difficult, if not impossible, to predict over time, the probability of occurrence is expressed as the site's predisposition to such phenomena.

For sites with an equal level of predisposition, it is primarily the potential intensity that determines the hazard level. The intensity of a collapse can be defined by its diameter and/or its depth. Field experience from past events ultimately shows that the risk to structures or infrastructures, and thus to people, is primarily determined by the extent of the collapse, namely its diameter or width.

Once the hazard is assessed, the risk is determined by combining it with the vulnerability of surface assets, which, in our case, is represented primarily by those most critical to public safety, namely buildings. In fact, we consider that the risk to the safety of people is greater inside a building because the time needed to evacuate people from danger is longer, especially if people are sleeping. Based on this principle, we developed a methodology relying on an empirical approach to prioritise the risks to building associated with mine-induced sinkholes. The objective is then to assess the sensitivity of buildings exposed to collapse risk.

3 Methodology

The objective of the developed methodology was to provide the French administration in charge of post-mining risk management with a coherent and uniform approach applicable across the national territory, particularly in mine-induced sinkhole-prone areas with large built-up surfaces.

The methodology consists in defining vulnerability thresholds of a given building, through 'percentage of collapse' index as a function of the hazard intensity, chosen as the diameter of the expected crater at the time of the event. This approach allows for distinguishing structural damage posing risks to public safety from damage that would affect only property without endangering public safety. For a risk management strategy focusing on human safety, the key index is the assessment of the dimensions of the collapse formed on the surface. Indeed, it is considered that during the second progressive crater widening phase, signs of instability and damages will appear clearly on the structure before its major failure, giving people sufficient time to evacuate the building and its surroundings.

Therefore, only the diameter at the time of the event of the ground failure was selected as the determining parameter to evaluate the interaction between the building and the collapse. This diameter, which defines the phenomenon's intensity level, determines the potential damages on the building and therefore the level of risks to people and property located within the hazard zone. The severity of these consequences is reflected in the failure of critical structural elements of the building, such as floors, columns, beam and slabs.

3.1 Assessment of the diameter of a sinkhole

The intensity, or diameter, of a sinkhole depends on the geometry, volume, and depth of the subsurface cavities, as well as on the nature and geotechnical properties of the overlying soils. It should be noted that the thickness and characteristics of the overlying soils play a crucial role, as their failure, particularly in the case of unconsolidated soils with low cohesion, greatly contributes to the final dimensions of the collapse.

Starting from an underground void of width (L), the maximum collapse diameter (Dm) likely to occur at the end of Phase 2 (stabilised collapse) is defined according to the following relationship (Figure 2):

$$Dm = L + 2H\cot\alpha \tag{1}$$

where:

Dm = maximum diameter of the collapse (m)

L = width of the underground void (m)

H = thickness of low-cohesion soils (m)

α = internal friction angle of low-cohesion materials (°).

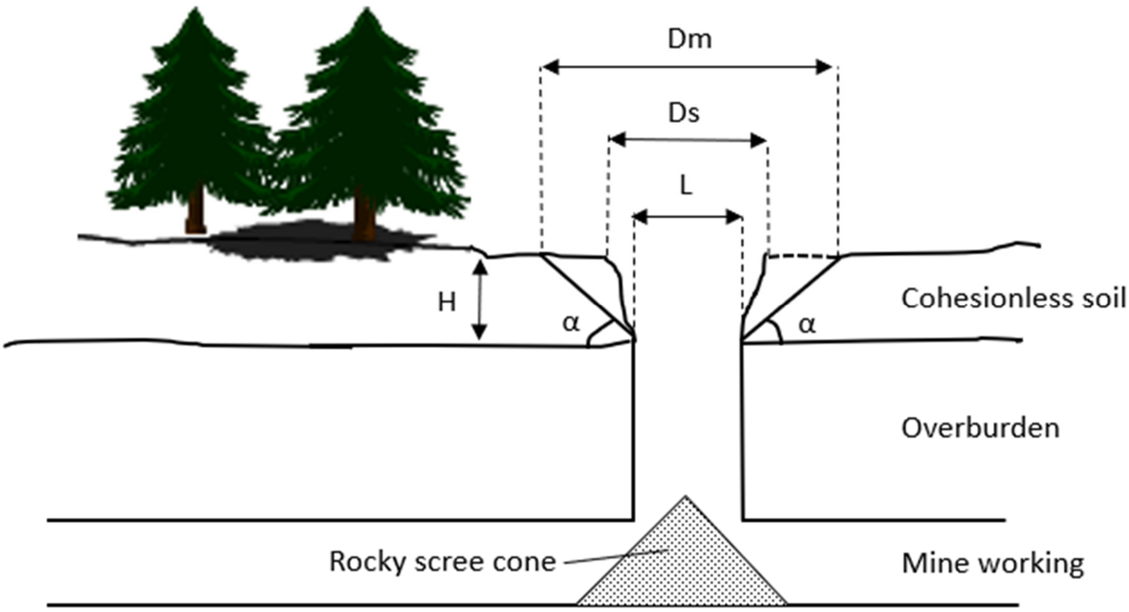

Figure 2 Formation of a localised collapse through the upward progression mechanism of a sinkhole cavity

Mainland France has more than 5,000 former mines. Given this large number, it was not feasible to quickly acquire precise site-by-site data regarding the thickness of low-cohesion soils. Thus, the assessment of the localised collapse diameter is based on available geological archive data and feedback from past incidents at the given site. Throughout France, retro-analysis of 100 historical sinkholes shows, in 83% of cases, the thickness of low-cohesion soils is less than 2 m (GEODERIS 2015). It can reach 5 m on sites with the presence of backfill at surface such as the Nord-Pas-de-Calais coal basin.

For hazard assessment and mapping purposes, this lack of detailed geotechnical information also requires that the internal friction angle (α) be sufficiently conservative to encompass most soil configurations. According to unified soil classification system (Geotechdata 2013), typical values of soil friction angle for backfill or topsoil are between 40 and 45°. For rocks, this value increases beyond 50°. In these conditions, a standard angle (α) of 45° was adopted (GEODERIS, 2012). However, in the presence of sandy or clayey soils, this angle is reduced (30° or less).

When assessing risk to public safety, the crater diameter considered corresponds to the one at the time of the event occurrence (Ds), which is smaller than (Dm). Historical feedback shows when the event occurs, the slope angle is vertical or even inverse before the progressive widening of the crater. For a given site, when the diameter (Ds) cannot be determined based on site-specific data, it is estimated by considering a maximum mobilisable soil width of 0.5 m around the width of the underground void that caused the collapse. The diameter (Ds) is then defined according to the following relationship (Equation 2):

$$Ds = L + 1 \tag{2}$$

where:

Ds = diameter at the time of collapse occurrence (m)

L = width of the underground void (m).

3.2 Assessment of building vulnerability

This part of the methodology was developed in collaboration with the Scientific and Technical Centre for Building (CSTB), the French public institution responsible for research and development in this field.

The development was carried out in two main stages. The first stage analyses a representative sample of 210 buildings of French constructions, included:

- the identification of structural systems
- the identification of damage typologies
- the definition of building vulnerability indicators.

From there, five types of load-bearing construction systems were defined, inspired by standardised classifications for building damage (European Standard 2006). These are buildings with frames and cladding, buildings with frames and filling, buildings with concrete shear walls and reinforced concrete floors, masonry buildings with reinforced concrete floors, and masonry buildings with wooden floors (CSTB 2011).

The vulnerability of a building was defined as the robustness of a construction system, i.e. its ability to ensure occupants safety within a damaged structure. This process requires the determination of the system's capacity to best maintain the condition of floors in the event of partial failure of a load-bearing system, itself caused by partial ground failure. Robustness, or conversely fragility, is characterised by the product of four stability indicators relating to floors, vertical load-bearing systems (walls), type of foundations, and the number of building stories.

These indicators are characterised by the dimensions (lengths and/or surface areas) of unsupported parts of walls, floors, and/or foundations, in order to assess the capacity of the structure to redistribute loads onto the intact load-bearing parts of the structure (CSTB 2011).

In the second stage, these indicators were used through detailed numerical modelling to determine the fragility of different types of buildings subjected to a sinkhole. To this end, several building failure scenarios were modelled based on the sinkhole diameter for each construction system. The approach was to assess the damage sustained by a building's floor following the failure of all or part of the load-bearing structures overlying a static circular void with a radius (Rf). The void simulating the collapse is then displaced throughout the footprint of the building, with numerical simulations run to assess the impact of the collapse at different points within load-bearing systems.

More than 90% of single-family houses in France are built with load-bearing masonry or concrete walls, with a ground floor made of concrete and a wooden roof frame, sometimes supporting an upper floor made of either wood or concrete. A simulation was conducted using a typical residential building, rectangular in shape, with a surface area of 112 m², i.e. a width of 8 m and a length of 14 m. Variable mechanical properties of construction materials were introduced into the simulations in order to calculate lower and upper limit damage curves. Finally, an average damage curve was interpolated to allow comparison between the different structural systems.

For the different parametrisations of the typical house, the simulations show that the minimum and maximum damage curves are stepped (Figure 3). These steps mark the limit between partial and total collapses of the floor when a load-bearing wall overturns. This occurs when the intersection between the simulated wall collapse exceeds half the length of the wall. When an overturning begins, it is reflected in the curve by a sudden increase in the percentage of the floor failure indicator (CSTB 2011).

As a conservative risk assessment approach, the interpretation was carried out by considering the maximum damage curves. For collapse diameters less than 4 m, the damage to the different types of floors does not show any overturning of load-bearing walls. Moreover, they exhibit almost the same damage levels, suggesting that the construction material of the walls has little influence.

In the case of a construction with masonry walls and a concrete floor, floor failure begins at around 20% of failure of load-bearing system, corresponding to a minimum collapse diameter of 6 m. The simulation with concrete walls does not change this result. For a wooden floor, failure also initiates at around 20% damage but for a collapse diameter of 4 m. The acceleration phase of the failure, considered from 30% damage, appears faster for wooden floors than for concrete floors. Total failure in both cases corresponds to a collapse diameter of 11 m.

Thus, it can be observed that the shape of the damage distribution curves, governed by the boundary conditions of the floors, is then determined by the floor type, i.e. ground floor upper slab made of wood or reinforced concrete.

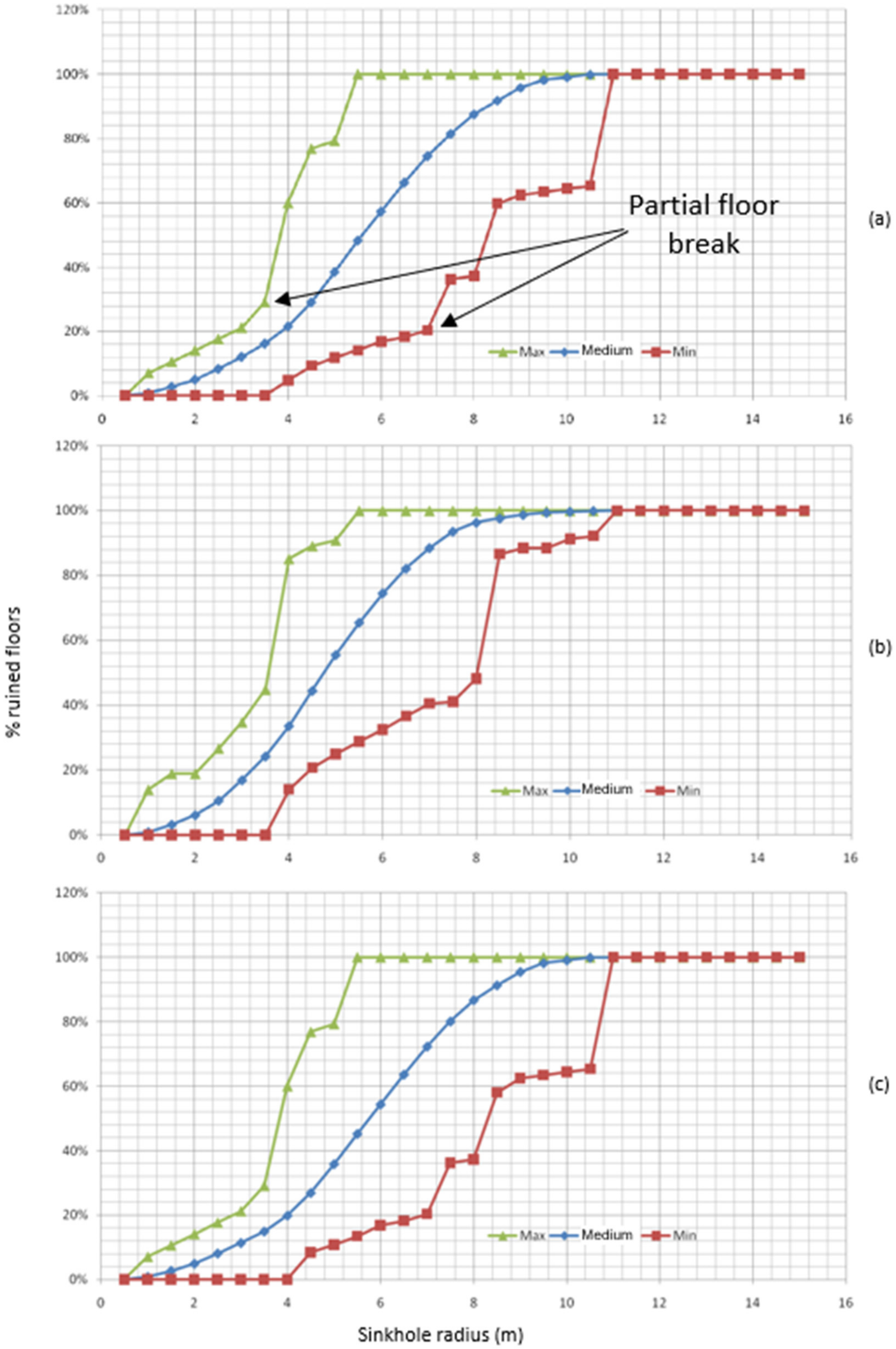

Figure 3 Minimum, average, and maximum damage levels of a building subjected to a sinkhole. (a) Case of a masonry building with a reinforced concrete floor; (b) Case of a masonry building with a wooden floor; (c) Case of a concrete wall building with a reinforced concrete floor

In order to facilitate the comparison between construction systems and to provide an easily manageable model for initial risks prioritisation, the curves of average values are used and then approximated by a mathematical regression relationship (CSTB 2011):

$$F = 1 - e^{-\left(\frac{x}{\lambda}\right)^k} \tag{3}$$

with

$$x = \frac{Rf}{\sqrt{Sb}} \tag{4}$$

where:

K = shape parameter depending on the construction system, obtained through regression

λ = scale parameter depending on the construction system, obtained through regression

Rf = collapse radius (m)

Sb = building surface area (m).

Since it is more intuitive to work with the ratio of the building surface to the collapse surface (y=Sf/Sb), an arithmetic reformulation provides the relationship between the identified parameters as follows:

$$k_x = 2\,k_y \tag{5}$$

$$\lambda_x = \sqrt{\frac{\lambda_y}{\pi}} \tag{6}$$

When (y) reaches the value π, corresponding to the case where (x=1), the damage effectively reaches 100%.

A relationship was thus established between the relative impact surface of the collapse (Sf) and the total surface area of the building (Sb), expressed as Sf/Sb ratio. The same numerical calculations were carried out for structural systems made of a metal or concrete frame with cladding or infill between columns and beams. Figure 4 shows the relationship between the surface area ratio and the percentage of floor collapse for the five structural systems.

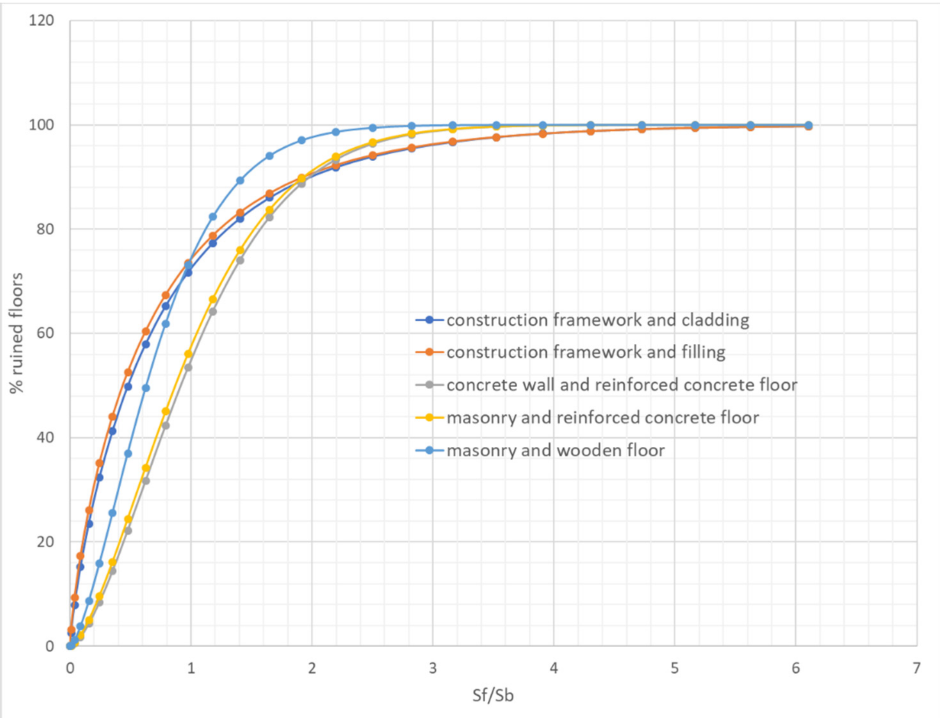

Figure 4 Comparison of the percentages of collapsed floors associated with the five construction systems examined

The curves highlight that wall-bearing structures redistribute loads located directly above the collapse more effectively, but over a shorter distance, than frame (column-beam) structures. As a result, wall-bearing structures exhibit better performance for small-sized collapses. Conversely, frame structures perform slightly better in the case of relatively large collapses.

3.3 Risk assessment

3.3.1 Process

To assess the vulnerability of a building, the previous results show that it is necessary to have structural information. Such information is often difficult to obtain without accessing the interior of the dwellings or conducting building-by-building investigations.

Several thousand buildings located in sinkhole-hazard-prone areas have been recorded across French territory. Facing such a large-scale issue, the initial objective was to prioritise the sites in order to investigate the top critical cases first.

The risk assessment process was carried out in two phases, each aimed at distinguishing risk to public safety from those affecting only buildings (Figure 5).

The first phase consists of assessing the potential risk for a given building based on readily available data to estimate the collapse diameter, without distinguishing between building types and considering only the building's footprint (surface area). When a potential risk to public safety is identified, the second phase aims to deeply analyse the risk by refining the estimation of the collapse diameter and/or specifying the type of building.

These refinements are obtained, in the first case, through geotechnical drilling, offering a better definition of the characteristics and volume of the voids as well as the mechanical properties of the overburden and surface soils. If necessary, an inspection of the building and a parameterised analysis of its construction system by building experts can also be carried out to better assess its vulnerability.

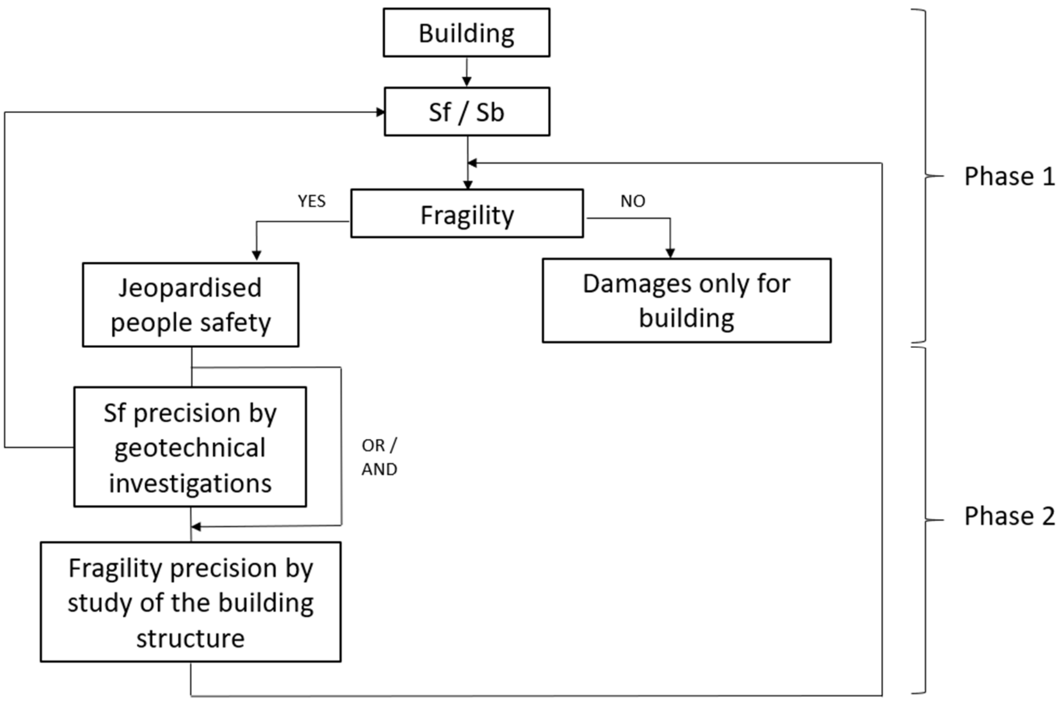

Figure 5 Risk prioritisation process related to the phenomenon of localised collapse

3.3.2 Levels of building vulnerability

Five levels of damage have been established to define the levels of building vulnerability (Ministère de l'Écologie, de l'Énergie, du Développement Durable et de la Mer [MEEDDM] 2012) (Table 1). Starting from the fourth level (high and very high), the structural elements are affected, which can lead to the failure of one or more floors, thereby creating clearly a risk for the occupants.

Table 1 Hierarchy of damage levels and risk based on predictable damage to a building

Damage Levels	Predictable Damage	Risk
Very Low	Minor localised damage (example: hairline cracks)	
Low	Localised damage	Damages only for building
Medium	Failure of part of the structure. Total or partial collapse of the structure is unlikely (example: jammed doors and broken pipelines)	
High	Failure of one or more parts of the structure with a high-risk of partial collapse (example: dislodged beams and bulging walls)	Threat to public safety
Very high	Sudden collapse of the structure (example: detached and unstable floors and walls)	

3.3.3 Risk prioritisation

It has been shown that floor failure in traditional French houses begins at around 20% damage and becomes active from 30% onward. This latter value was chosen as the threshold between medium and high vulnerability levels. According to the damage distribution curves calculated for the various types of building, this threshold corresponds to a minimum surface area ratio Sf/Sb of less than 0.2. On either side of this threshold, two risk levels have been defined (Table 2).

Table 2 Risk level prioritisation based on the Sf/Sb ratio and the percentage of floor collapse in a building

Sf/Sb	% floor collapse	Risk level	Risk
0–0.05	0–5	Very low	Damages only for building
0.05–0.2	5–30	Low	
0.2–0.35	30–40	Medium	Threat to public safety
0.35–1	40–100	High	

Since the floor appears to be the most vulnerable part of a building, the risk level is increased by one category if the building has more than two stories. This adjustment accounts for the population density, distinguishing so-called 'individual' buildings from 'collective' ones. Thus, a building whose risk level is initially assessed as low based on the Sf/Sb ratio will be reassessed as medium (indicating a threat to public safety) if it has more than two stories.

4 Results

Between 2012 and 2015, around 3,000 buildings located in localised collapse hazard zones (excluding issues related to mining shafts) across French territory were inventoried. After the Phase 1 examination of the risk prioritisation process, the risk to public safety could be ruled out for 70% of the buildings (33% classified as very low to no risk and 37% as low risk). For the remaining 30% of buildings, approximately 1,000, 21% were classified as having a potential medium-level risk and 9% as having a potential high-level risk (Figure 6).

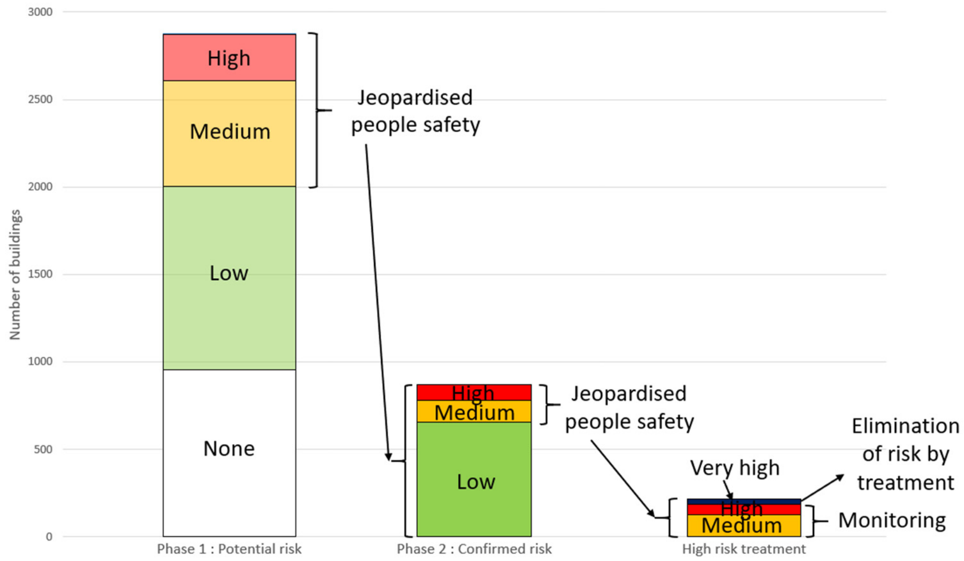

Figure 6 Results of risk prioritisation related to the phenomenon of localised collapse in France (excluding shaft-related issues)

Based on this classification, geotechnical drilling investigations were carried out for the thousand buildings classified as presenting a high or medium potential risk. These investigations made it possible, on the one hand, to verify the dimensions, depth, and condition of the mining works, and on the other hand, to assess the mechanical properties of the overburden and surface soils. It should be noted that, as of today, there remain nearly 150 buildings classified at a potential medium-risk level for which investigations are scheduled between 2025 and 2027.

At the end of Phase 2, in the event of a localised collapse, 90 buildings were classified as high-risk and 125 as medium-risk. For all these buildings, a monitoring system for the evolution of underground mine workings was implemented. Monitoring is carried out through periodic inspections (between once and twice a year) when the mines are accessible, or through laser, videoscopic, or sonar inspections via boreholes from the surface when the cavities are inaccessible and/or flooded.

Among the 90 buildings classified as high-risk, 41 were located directly above underground mining works that were very close to the surface, severely degraded, and exhibiting rapidly evolving instability. The French state authorities therefore decided to address the risk either by filling the cavities (29 cases, including adjacent buildings classified as medium risk) or by expropriating and demolishing the dwellings (12 cases).

In parallel, at the request of the French administration, experts from CSTB produced a constructability guide for localised collapse hazard zones in 2012 (MEEDDM 2012) to enable municipalities affected by these hazards to continue urban development within their territories. This guide defines, for new buildings, the necessary construction measures to protect against any risk in the event of a collapse.

5 Conclusion and outlook

The methodology presented in this study offers a streamlined criterion to discriminate sinkholes likely to have a limited impact on buildings from those that could jeopardise public safety.

This criterion, based on the easy-to-compute ratio between the surface area of the ground failure and that of a building, combines both geotechnical data related to former mining works and the structural vulnerability of buildings based on their typology. It allows for rapid verification of potential risks to people's safety. In this case, the next phase aims to deeply analyse the real risk by refining the estimation of the collapse diameter and/or specifying the type of building. These refinements are obtained by geotechnical reconnaissance of the mining works and the ground and, if necessary, by an analysis of the building's construction systems to better assess their vulnerability.

This methodology has been formalised in a national guidebook (GEODERIS 2013). It provides to all regional authorities in charge of post-mining risk prevention with a coherent management tool for optimal decision-making. The strength of this methodology lies in its capacity to standardise and prioritise risk assessment across a vast number of sites, thereby optimising the prioritisation of the allocation of resources and facilitating preventive or remedial actions.

Since 2024, GEODERIS is extending and adapting this methodology within the very specific context of mining shafts, as very deep vertical structures with poor footprint on surface, which present challenging issues in terms of both hazard localisation and geotechnical as well as structural behaviour.

Acknowledgement

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