HANDBOOK

Ineris-200986-2197647

Gypsum natural dissolution processes

Assessment and management of subsidence and collapse hazards

Cerema

INERIS
controlling risks
for sustainable development

This methodological handbook was developed at the request of the General Directorate for Risk Prevention (DGPR), a division of the Ministry for the Ecological and Inclusive Transition.

It was created under the direction of the French National Institute for Industrial Environment and Risks (Ineris) and in collaboration with the Centre for studies and expertise on Risks, Environment, Mobility and Urban and Country planning (Cerema), as part of its missions in support of the Ministry.

This handbook is based on the respective experience of Ineris and Cerema and both entities available data (scientific and technical). It has been reviewed by administrations, professionals and local authorities, first users and sources of dissemination of this document.

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1 INTRODUCTION

French territory is exposed to risks of "ground movements", some of which are linked to gypsum dissolution. Dissolution phenomena, developing in the subsoil, lead to an alteration of rock mass properties. These changes can eventually lead to the formation of cavities and ultimately to collapses of the land surface. These phenomena are difficult to predict and potentially dangerous to people and property.

This handbook is intended for stakeholders who must manage the risks linked to the presence of gypsum on their territory. It provides the key aspects for understanding the hydraulic, chemical and mechanical mechanisms involved, and offers methodological tools adapted to management of this problem. This document also explains the specifics inherent to gypsum dissolution, from the process of void creation to their development into ground movement on the surface.

This handbook is mainly based on expert research carried out by Ineris and Cerema over several years, in various regions of France. It also benefits from the progress of several ongoing research projects which have made it possible to better appreciate the contexts, kinetics and geotechnical mechanisms of ground movements.

Authors underline that this document deals exclusively with ground collapse and subsidence hazards related to the dissolution of gypsum. Landslides phenomena which may occur in areas with slopes and which are the consequence of mechanisms do not fall within the scope of this handbook.

2 PRESENTATION OF GYPSUM DISSOLUTION CONTEXT

2.1 Gypsum: definition and formation process

2.1.1 Mineralogy and characteristics

Part of the *evaporite* family, gypsum is the most common sulphated mineral. This mineral has a hardness of 1.5 to 2 on a scale of 10, which makes it a soft mineral: it can be scratched with a fingernail. It is composed of sulphate and calcium ions combined with two water molecules giving the chemical formula $CaSO_4$, 2 (H_2O). It has a density of 2.3. It is also found in its dehydrated form, anhydrite, with the formula $CaSO_4$. It is not uncommon for sulphated rocks to be composed of a combination of gypsum and anhydrite in varying proportions.

2.1.2 Formation and sedimentation conditions

Gypsum minerals are formed by crystallisation, a chemical mechanism. This process occurs in marine environments in climates where there is significant evaporation. It can exist in continental environmnts but periodic connection with the sea is necessary. The precipitation reaction takes place in large, shallow pools that are well connected to the sea (Figure 1).

Strong evaporation of water in this type of medium causes precipitation of the ions present in solution in the water. Gypsum ($CaSO_4$, $2H_2O$) appears second (after the carbonates), then when the volume of seawater is no more than 35% (Boulvain, 2011) to 20% (Charola, 2007) of the initial volume, the anhydrite ($CaSO_4$) precipitates. It is followed by salt (NaCl) when the volume of water reaches no more than 10% of the starting volume (Boulvain, 2011). The sedimentation by evaporation typical with a low "section of water" (if the climatic conditions remain constant for long enough) is therefore, in theory, formed of a layer of limestone, then of gypsum with a layer of anhydrite sitting on top, then possibly salt (Figure 2). This also implies that, during this entire sedimentation process, no new water was supplied by the sea or the continent.

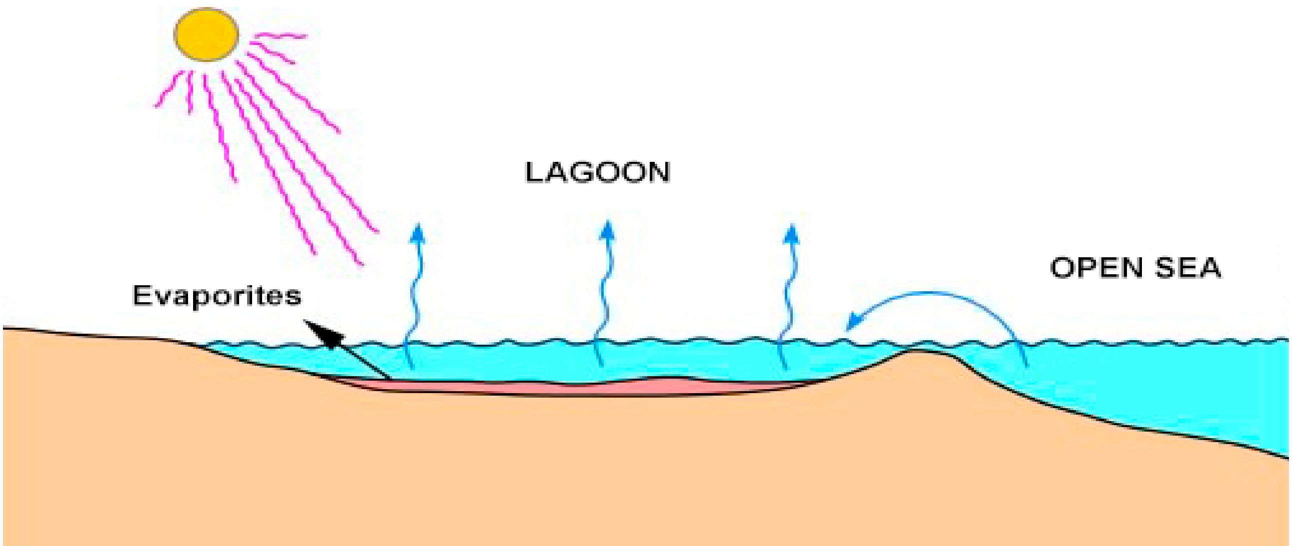

Figure 1: Explanatory diagram of evaporite deposits formation (source: www.ggl.ulaval.ca)

Figure 2: Main minerals of evaporite sequence (source: www.ggl.ulaval.ca)

We rarely see a complete cycle of this process being performed, and it is common to find repetitions or cycles being shortened or reversed by tectonic activity. Sedimentary gypsum layers can then form, either thick or thin, often containing marl or limestone layers in between, which is characteristic of variations in deposit conditions over time and marine or continental water supply.

2.2 Petrology

The classification of gypsum as evaporite rock should not obscure the fact that its formation can also be metamorphic in origin, by hydration of anhydrite. It can also be crystallised as a product of geochemical reactions during diagenetic processes.

Gypsum rocks can be found in various facies. These facies depend on the methods of formation of gypsum minerals and their geological history. The most common forms of gypsum deposition are saccharoid gypsum which are rocks with a sugar-like appearance (Figure 3), and gypsum alabaster, which has a milky white appearance (Figure 4) and broad ranges of *automorphic crystals* and microcrystals. The latter may sometimes be encountered as "spearhead" (Figure 5). It should also be noted that gypsum can be mixed with other sedimentary rocks, such as clays or limestone for example.

Figure 3: At the top, a block of multi-decimetric saccharoid gypsum extracted from the Placoplatre® underground quarry at Baillet-en-France (95). At the bottom, a block of decimetric saccharoid gypsum extracted from the abandoned open pit gypsum quarry at Vizille-en-Isère (38)

Figure 4: Core sample of gypsum alabaster extracted from the horizon of Marnes et Caillasses, from a borehole in Ile-de-France, sample provided by Cerema

Figure 5: Gypsum crystal known as a "spearhead" (Ineris mineralogical collection)

2.3 Gypsum deposits

Gypsum formations may be present in all the sedimentary landscapes around the world, but the biggest deposits are located either around large regional evaporite complexes, or in areas that have remained geologically stable for long periods.

The countries which have vast underground deposits are: The United States, Canada, Australia, Spain, France, Italy, especially in Tuscany and Sicily, Great Britain, especially in England for example in North Yorkshire, Germany, Chile, Mexico, Poland, Russia.

The most widespread gypsum formations in France are those from the Triassic age (around 220 million years). They are found in the following regions:

- in Bourgogne - Franche Comté: Haute-Saône (e.g.: Courbenans), Jura (e.g.: Lons-le-Saunier, Grozon), Saône-et-Loire (e.g.: Berzé-la-Ville/Monts du Maconnais);

- in Provence-Alpes-Côte d'Azur: Alpes Maritimes (e.g.: Sospel), Bouches-du-Rhône (e.g.: Roquevaire), Vaucluse (e.g.: Beaumes-de-Venise), Var (e.g.: Saint-Luc-de-Provence, Bargemon, Draguignan);
- in Grand Est: Vosges (e.g.: Epinal), Lorraine, Alsace;
- in Auvergne – Rhône-Alpes: Savoie (e.g.: Tignes, Bozel), Isère (e.g.: Prunières, Champ-sur-Drac), Haute-Loire (e.g.: Puy-en-Velay);
- in Nouvelle Aquitaine on the fringes of the Aquitaine basin and the foothills of the Pyrenees: Landes (e.g.: Dax, Pouillon), Pyrénées-Atlantiques (e.g.: Sare);
- in Occitanie in the area around the foothills of the Pyrenees: Ariège (e.g.: Prat-Bonrepaux).

These Triassic formations, containing gypsum, served as slaking layers to form large overlaps. They are therefore located mainly in areas with major tectonic activity that have experienced significant deformations (intense folding, chipping, grinding ...).

The other geological formations which contain gypsum mainly come from:

- the Jurassic (around 140 million years), for the deposits in the lagoon formations of Charente (e.g.: Cognac) and small deposits in the Jura Mountains;
- the upper Eocene (around 45 million years ago), which constitutes the large deposit in the Paris Basin (East of Paris, e.g.: Vaujours, Villepinte; west Parisian, e.g.: Baillet-en-France, Montmorency), mainly characterised by Ludien gypsum *masses* and lenticular layers located in the Marnes et Caillasses of upper Lutetian formation;
- the Eocene-Oligocene transition and the Oligocene (around 30 million years) for the lenticular and very thick deposits in Vaucluse (e.g.: Mazan), Bouches-du-Rhône (Saint-Pierre-les-Martigues) and Aude (e.g.: Portel-des-Corbières).

There are also deposits, particularly in the east and south of the country, which are not well known due to their location (significant depth or geographic isolation in mountainous regions). Otherwise, less well-dated deposits are also present, for example in Burgundy, Alsace, Haute-Saône, Var.

When the geological layers have not undergone significant tectonic deformation, as in Lorraine, in the Paris Basin or the Vaucluse, the gypsum deposits are in regular or lenticular horizontal layers. However, these deposits have often been eroded and represent only part of the initial formation.

When the geological layers have undergone strong tectonic deformation, for example in the Triassic deposits, the gypsum formations then have a very complex geometry, in the form of stretched and discontinuous lenses, that lie very close to other types of rocks (limestones, dolomites, shales etc.).

Figure 6 shows the main gypsum deposits extracted in France (according to Marteau, 1993 updated with Placoplatre® data). It does not give an exhaustive representation of the gypsum deposits but allows the areas where the gypsum is present in great amounts to be located.

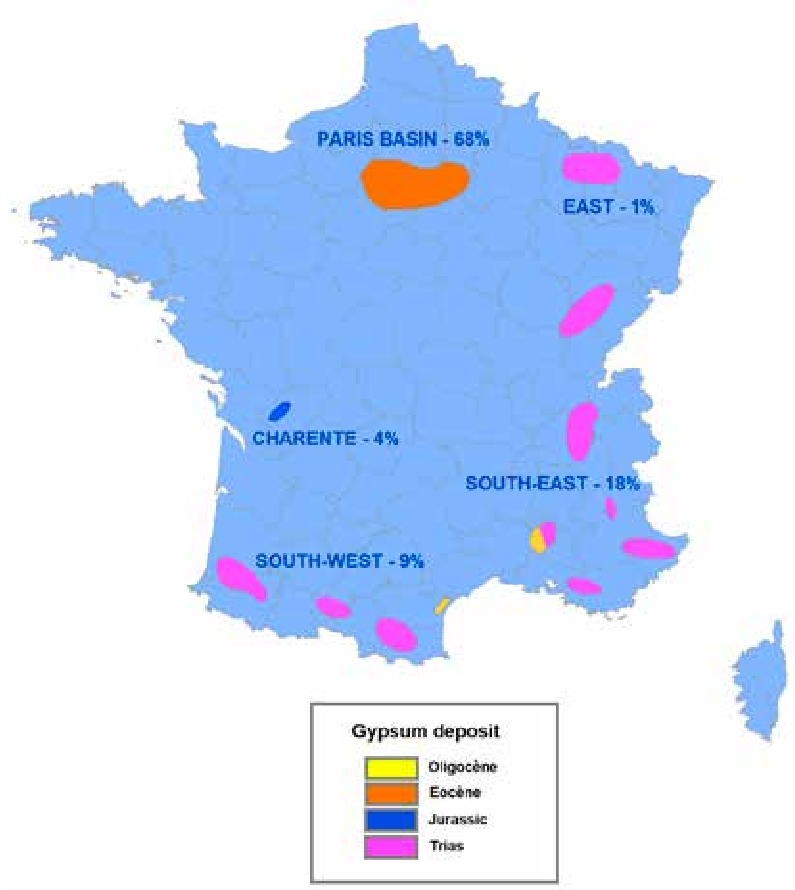

Figure 6: Location of gypsum deposits currently extracted in France and distribution (in %) of annual production according to deposits (according to Marteau, 1993, update: Placoplatre® data)

2.4 Gypsum dissolution

2.4.1 What mechanisms?

Gypsum is a *soluble* rock. Dissolution of the elements that make up the rock is known as the dissolution mechanism.

When gypsum ($CaSO_4.2H_2O$) is immersed in water that has never been in contact with this mineral, the chemical elements that constitute it will go into solution in ions' form. A dissolution reaction takes place because the water is in a state of undersaturation of Ca^{2+} and SO_4^{2-} ions compared to the amount of these two ions present in the gypsum (Charmoille and Lecomte, 2011). This step corresponds to phase 1 shown in Figure 7.

Dissolution will then continue until the quantity of Ca^{2+} and SO_4^{2-} ions in solution is in equilibrium with the mineral (phase 2 in Figure 7). The conditions for achieving this balance depend mainly on the existing temperature and pressure. For example, under atmospheric pressure conditions, the solubility varies almost linearly between 0 and 20°C, from 2.15 to 2.53 g/l and has an optimum of 2.67 g/l at 40°C (Daupley *et al.*, 2015).

In comparison, the solubility of salt (NaCl) is around 350 g/l and that of calcite ($CaCO_3$) varies from 0.1 to 0.2 g/l depending on the partial pressure of CO_2.

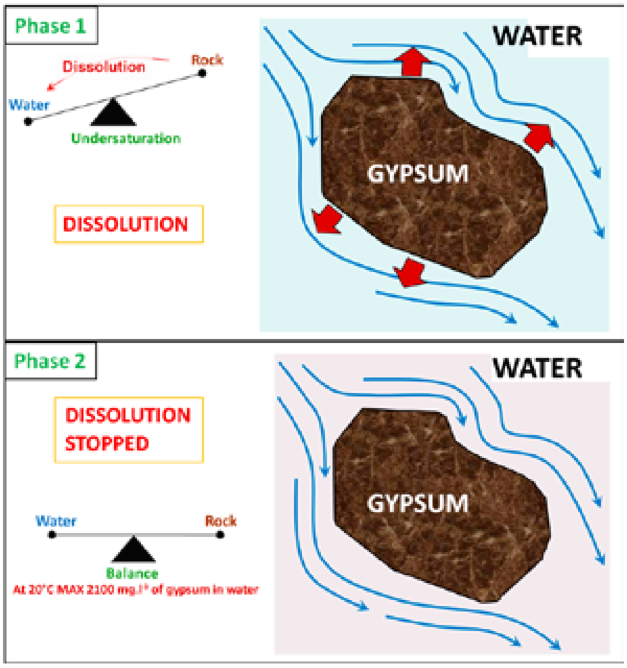

Figure 7: General principle of dissolution mechanism

In order that dissolution process takes place, it is therefore necessary that fluid which is in contact with the soluble mineral (gypsum) be undersaturated. To guarantee the undersaturation of this fluid over time and consequently to maintain the dissolution process, it is necessary for this fluid to have enough flow to regularly renew it in contact with the solid.

2.4.2 What kinetics?

When the conditions for establishing dissolution process are met, the gypsum naturally dissolves. Recent investigations carried out by Ineris, in collaboration with the Mines ParisTech Centre of Geosciences, have made it possible to measure the kinetics of gypsum dissolution for various configurations (Daupley *et al.*, 2015).

Through these results, some interesting orders of magnitude can be seen. In the laboratory, the *dissolution rate* of gypsum from two facies discovered in Ile-de-France (Ludien gypsum deposits from Vaujours and Baillet-en-France) in pure water is between 0.03 and 0.05 $g/m^2/s$. Although gypsum is a soluble evaporite mineral, its rate of dissolution remains low compared to other materials of the same type, such as rock salt. Indeed, laboratory experiments with similar conditions show that the dissolution rate of rock salt is two orders of magnitude higher (» 3 $g/m^2/s^1$). It nevertheless remains higher than that of calcite, the dissolution rate of which is established between 0.3 10^{-4} and 3 10^{-4} $g/m^2/s$ (Cubillas *et al.*, 2005).

By extrapolating the laboratory results and ruling out possible scale effects, it can be kept in mind that, for identical hydrodynamic conditions, a cavity within gypsum will develop a hundred times slower than in rock salt but a hundred to a thousand times faster than in limestone.

The phenomena of gypsum dissolution may cause the appearance or reactivation of old cavities. In fact, over a period of ten years the development of small cavities and/or the growth of pre-existing cavities may be perceptible. However, the development of large dissolution cavities, linked to the presence of gypsum layers of significant thickness, is unlikely over relatively short periods (an annual order of magnitude) from specific and/or anthropized situations. (Daupley *et al.*, 2015).

2.5 Dissolution and ground movement in surface

2.5.1 Why do we talk about ground movements in the presence of gypsum?

In all contexts where soluble rocks are present underground, natural dissolution can develop. This dissolution induces a loss of solid matter which can lead to the creation of voids, with large or small dimensions, within or on the soluble material surface. Changes in the structure of deep underground rocks can also have repercussions on the surface due to slow subsidence of the soil or by the formation of sudden collapses.

For anthropogenic cavities, the destabilisation of the void is largely linked to the configuration and the mechanical resistance of the roof and the overburden.

For dissolution cavities, water plays a very important role and interacts in all phases, from void creation to the occurrence of ground movement disorder on the surface.

2.5.2 Void creation by dissolution

For a void to be created in a gypsum formation, considering dissolution processes, it is necessary for gypsum to be in contact with undersaturated water, that the flow of this water is sufficient for it to be renewed regularly, and that it does not reach chemical equilibrium on contact with gypsum.

Undersaturated water can be brought into contact with gypsum in different geological contexts, from the simplest to the most complex. Considering simplest contexts, two cases can be illustrated:

- the first, when gypsum horizons are located within an *aquifer* (Figure 8a). In fact, the phenomenon of dissolution can take place in the section of land where the gypsum formation is brought into contact with the undersaturated water from the water table flowing in the layer (Figure 8b). This is the case, for example, in the Paris area where the dissolution of Lutetian gypsum layers occurs in the direction of flow of the water table (Toulemont, 1974, 1981 and 1987). It is important to note that, in this context, to lead to the creation and maintenance of voids within rock mass, area overlying dissolution cavity must have sufficient mechanical properties to allow void to grow. Thus, cavity volume can gradually increase without closing due to roof mechanical rupture. It should be noted that mechanically resistant overlay can include beds of soluble rock itself;
- the second, when pre-existing fractures serve as transition points. If structural *discontinuities* exist within the gypsum formation, these can allow undersaturated water to reach it (Figure 9a). If water circulates within these discontinuities, dissolution phenomenon can occur, allowing void development on the periphery (Figure 9b). This is the case, for example, in the Provence-Alpes-Côte d'Azur region and in particular in the municipalities of Draguignan (83) or Prunières (05) where ground movement linked to gypsum dissolution have been caused by water circulation through discontinuities (Rivet *et al.*, 2014 and Paquette, 1991).

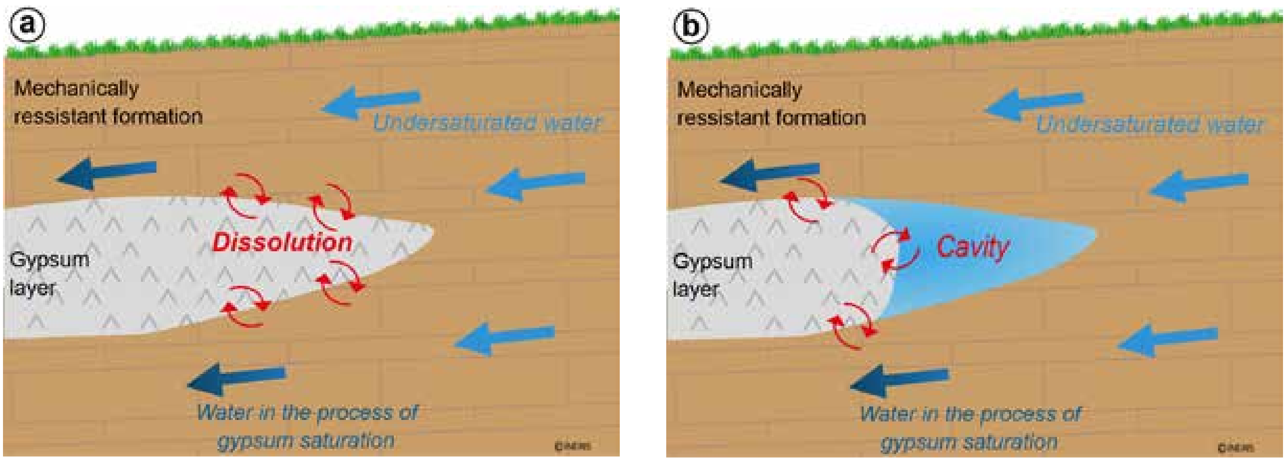

Figure 8: Diagram representing the establishment of dissolution process within an aquifer. The undersaturated water in contact with gypsum (a) causes creation of void by dissolution (b)

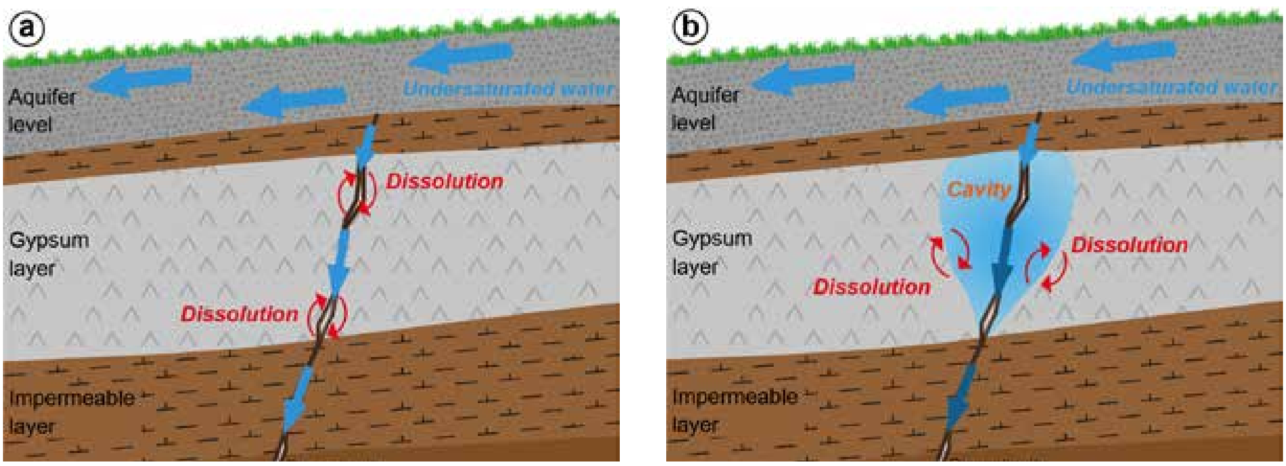

Figure 9: Diagram representing establishment of dissolution process through a pre-existing fracture which cuts through gypsum layer. The undersaturated water circulates within gypsum horizon (here by downward percolation) via the discontinuity (a) and dissolution may then contribute to void creation (b).

2.5.3 Destabilisation mechanism

When the cavity is created by dissolution, destabilisation can occur in two different ways:

- either in combination with an active dissolution. As stated above, the mechanical strength of one or more resistant rock beds present in the overlying layers allows the development of dissolution cavities in the gypsum formation. If the water circulates permanently the dissolution continues, enlarging the cavity until it reaches a critical size with respect to its mechanical stability. The weight of the overburden layers then exceeds the mechanical resistance of the load-bearing elements of the cavity (roof and walls), causing them to rupture.

  For example, in the case of gypsum from Ile-de-France area, present in the formation of Marnes and Caillasses, the presence of upper layers made of resistant limestone makes it possible for relatively large cavities to develop until the resistance limits of these overburden layers are reached (Toulemont, 1987). We can also consider the case of Ripon in England where the relatively thick gypsum layer (10 to 40 m) itself plays the role of a solid bed[1] (Cooper, 1999). In the latter case, the cavity may collapse, particularly when the thickness of gypsum on its ceiling is no longer sufficient to guarantee its stability;

- or due to particular hydraulic stresses. Sudden changes in hydrodynamic conditions of anthropogenic or natural origin can contribute to the destabilisation of a pre-existing cavity either by reducing the *hydrostatic pressure* (first case, Figure 10) or by unblocking old cavities that have filled in with sedimentary deposits after they were formed (second case, the phenomenon of "karst" collapse, Figure 11).

In the first case, the drop in the *piezometric level* due, for example, to pumping, causes a decrease in the hydrostatic pressure of the water table bathing the cavity. Depending on the stability conditions, this reduction will lead to more stress on the cavity. There may be enough stress that the roof can no longer support the weight of the overburden layers, thus causing the destabilisation of the cavity (Figure 10).

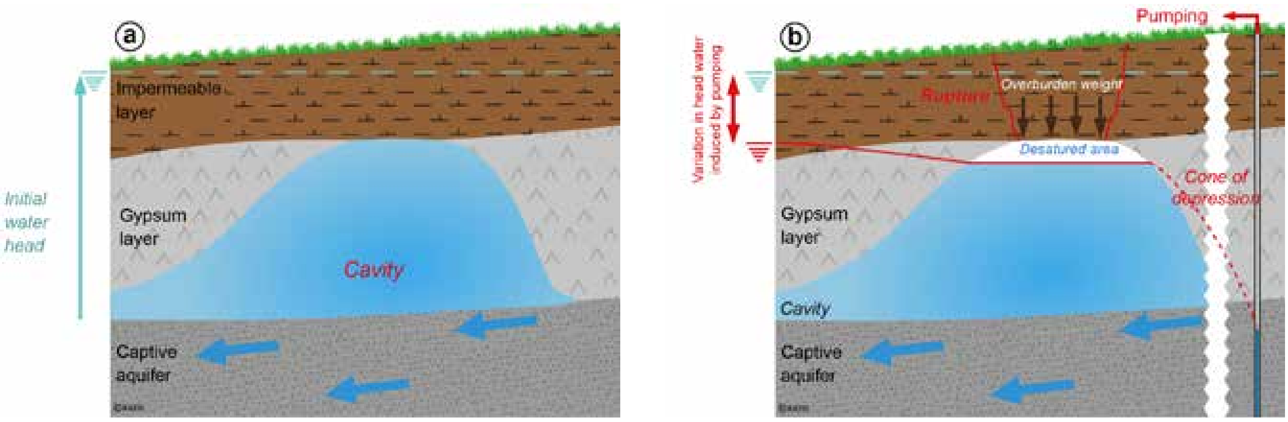

Figure 10: Destabilisation mechanism of a cavity linked to the variation in *hydraulic head* induced by the pumping of a captive water table

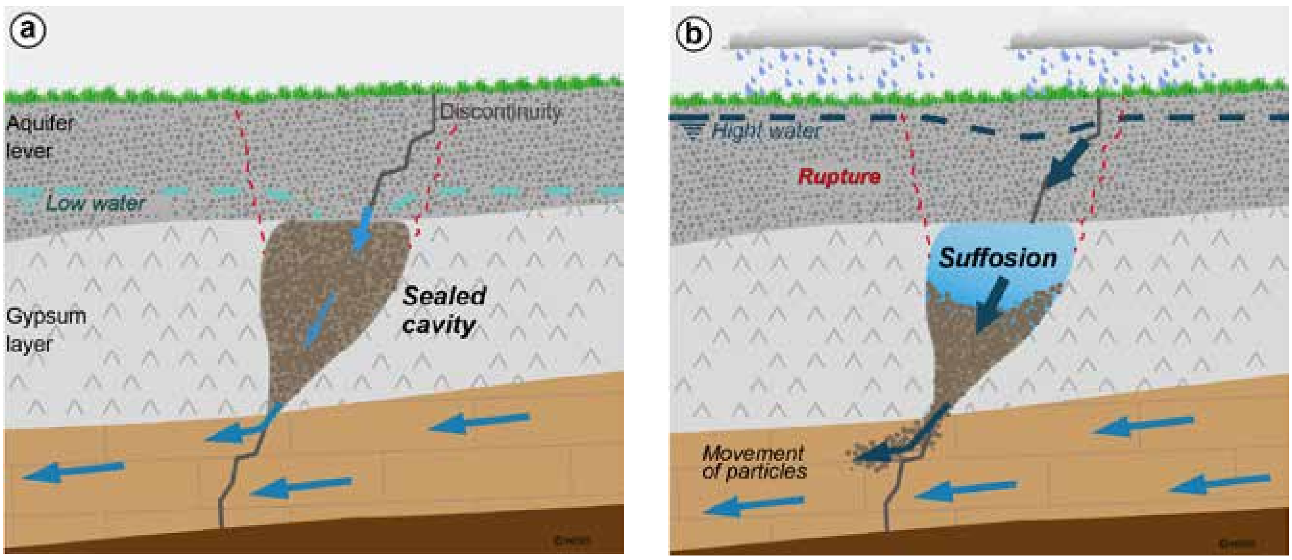

Figure 11: Diagram representing the destabilisation of an old dissolution cavity. The blocked cavity is stable as long as the piezometric level doesn't vary too much (a). In the event of significant hydrodynamic variation, modification of the gradient can induce the forcing out of filling materials, causing the appearance of a clear void and rupture of the land (b).

1 - Strenghtened bridge deck

In the second case, the drop in piezometric levels causes a change in the flow gradients. These hydrodynamic variations lead to the unblocking of filled voids, by hydraulically forcing out the filling materials (Toulemont, 1981). This results in partially or completely empty cavities, the roof of which is no longer supported by the filling materials. These variations have mechanical repercussions, contributing to destabilisation of the cavities by increasing the total stress on the roof of the cavity (Figure 11b).

2.5.4 Propagation of the void to the surface

Once the cavity has been created and the destabilisation mechanism has been initiated, propagation of the void to the surface occurs if the space available is sufficient for the collapsed materials to accumulate there without blocking the collapse by "self-filling". The void then propagates vertically and reaches the surface where it causes a localised collapse (or sinkhole).

In the context of dissolution, the propagation of this void will be accentuated by water. This can have two main impacts:

- modification of the proliferation characteristics. In the context of gypsum dissolution, it is not uncommon for the overburden layers to be impregnated with water due to the presence of underground water tables. Contrary to dry cavities, the presence of water tends to decrease the swelling coefficient of land and therefore increases the potential for more sinkhole on the surface;
- the progression of the void towards the surface is also accentuated when, during its ascent, the cavity's cone causes rupture of the impermeable layer of the overlying water table, thereby connecting two aquifer systems (Toulemont, 1981). Once this horizon is reached by the collapse, *erosion* and *suffosion* processes take place due to the pressure difference between the aquifers.

This hydraulic impact will chronologically lead to (Figure 12):

- the forcing out, by water, of collapsed materials within the "karst" network;
- an increase in the available void volume;
- a vertical progression of the void.

Special case: when overburden layers are not very cohesive (like sand or gravel for example), a sudden variation of the hydrodynamic conditions can, by suffosion, lead these materials to fall into the voids created by dissolution. This loss of material then allows the void to rise more easily to the surface (Benito *et al.*, 1995).

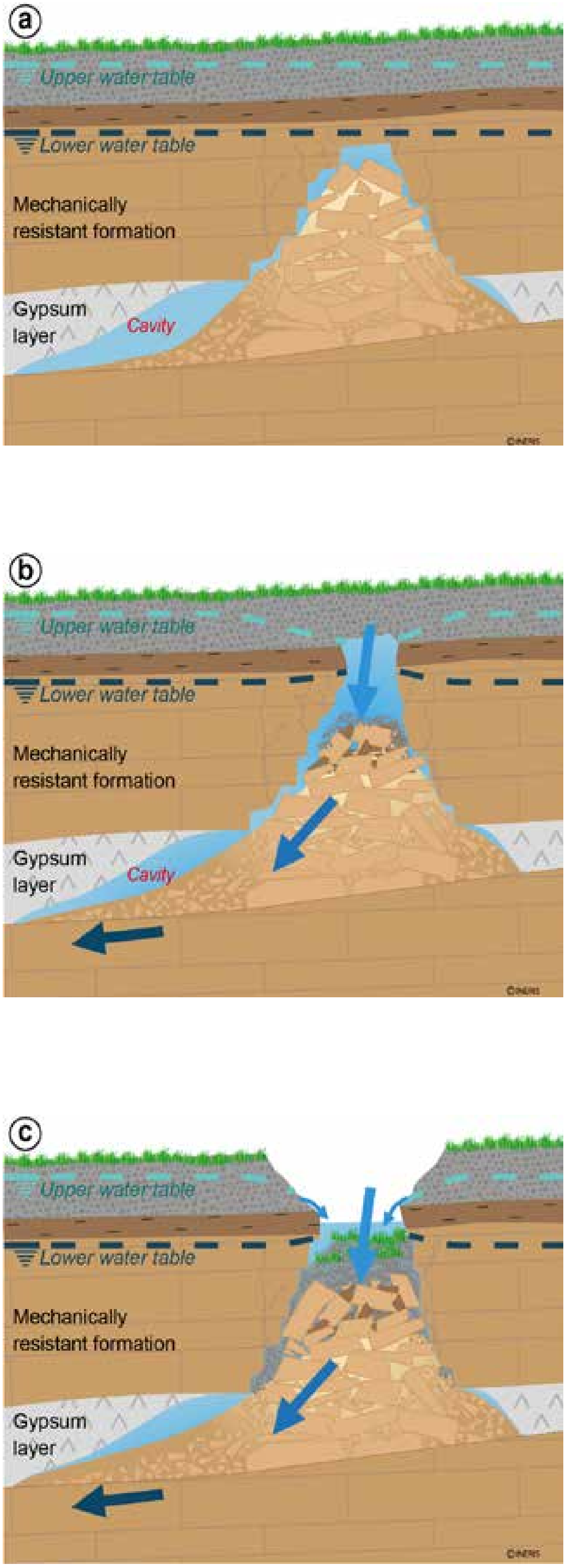

Figure 12: Diagrams representing the propagation of the void up to the surface due to rupture of the impermeable layer of the overlying water table. The void, which is close to self-filling (a), continues its progression towards the surface thanks to erosion and suffosion processes (b and c).

In the case of gypsum, this type of ground movement typically extends horizontally and vertically over several meters (photographs 1 to 4). These dimensions can reach ten or even several tens of meters in certain geological contexts, especially when the overburden layers are not very *cohesive* (photograph 5).

While expansion of an underground vault is a very slow phenomenon which can take several years or decades, the subsequent collapse on the surface happens very suddenly, which makes the phenomenon potentially dangerous for people and property located nearby.

The following photos present some ground movement sinkholes observed in recent years in different contexts of gypsum dissolution.

Photograph 3: Sinkhole of around 6m in diameter and 6.5m deep observed in Draguignan in 2013 (Rivet *et al.*, 2014)

Photograph 1: Sinkhole of 4m in diameter and 2m deep documented in the surroundings of Bois de la Tussion (Seine-Saint-Denis, 93) in 2013 (Ineris)

Photograph 4: Collapse of 13m in diameter observed in 2015 in Sare (Pyrénées-Atlantiques, 64) (BRGM)

Photograph 2: Sinkhole of around 4m in diameter and more than 5m deep observed in Sevran (Seine-Saint-Denis, 93) in 2014 (IGC)

Photograph 5: Collapse of 80m in diameter and 15m deep observed in 1992 in Bargemon (Var, 83) (DDTM 83)

2.5.5 Special case of subsidence

When the dissolution takes place at the interface between the soluble rock and overburden layers and when this overburden has fairly weak mechanical properties (lack of solid bed), conditions for keeping large open cavities are not met. The loss of material resulting from the dissolution is, in this case, directly compensated by the flexion of the overburden layers (Figure 13).

The void created closes gradually. If dissolution mechanisms take place over a sufficiently large surface, regarding to the depth, flexible and continuous movement occur to the surface. This phenomenon is often slow and progressive.

The following photos represent some subsidence linked with gypsum dissolution, observed in Ile-de-France in the last recent years.

Photograph 6: Subsidence of 8.5m x 9.5m that caused the flexion (in red) of the roadway, observed on the ramp of the A15 motorway at Franconville (Val d´Oise, 95) in 2014 (Cerema)

Photograph 7: Subsidence observed along the lateral path of the Tussion woodland (Seine-Saint-Denis, 93) in 2010. In red, the paroxysmal area presenting a cumulative vertical displacement of several centimetres (Ineris)

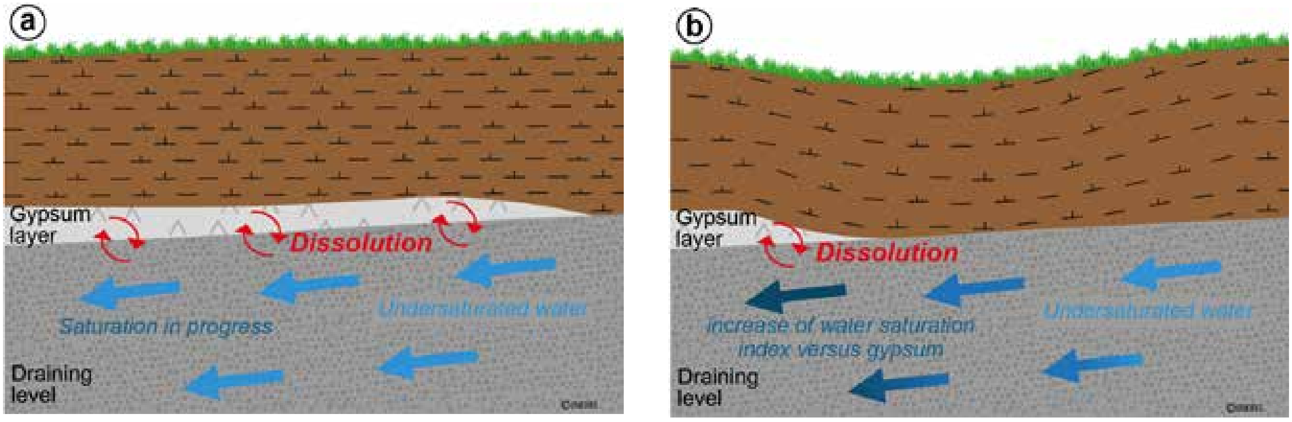

Figure 13: Diagrams representing the phenomenon of subsidence. The loss of material resulting from the dissolution is, in this case, directly compensated by lowering of the overburden layers.

2.5.6 Cohesionless, altered ground

Generally, ground movements observed directly above gypsum layers are associated with a loss of matter which can create underground voids.

However, it is most common to observe, through various surveys or water samples, areas with gypsum deposits that are cohesionless/altered rather than having "real" voids.

These areas are characterised as follows:

- when boring, the drill moves down at high speed but slower than when it passes through a void (Figure 14);
- when pumping, milky white-water containing lots of undissolved granules (with a sandy appearance) is observed.

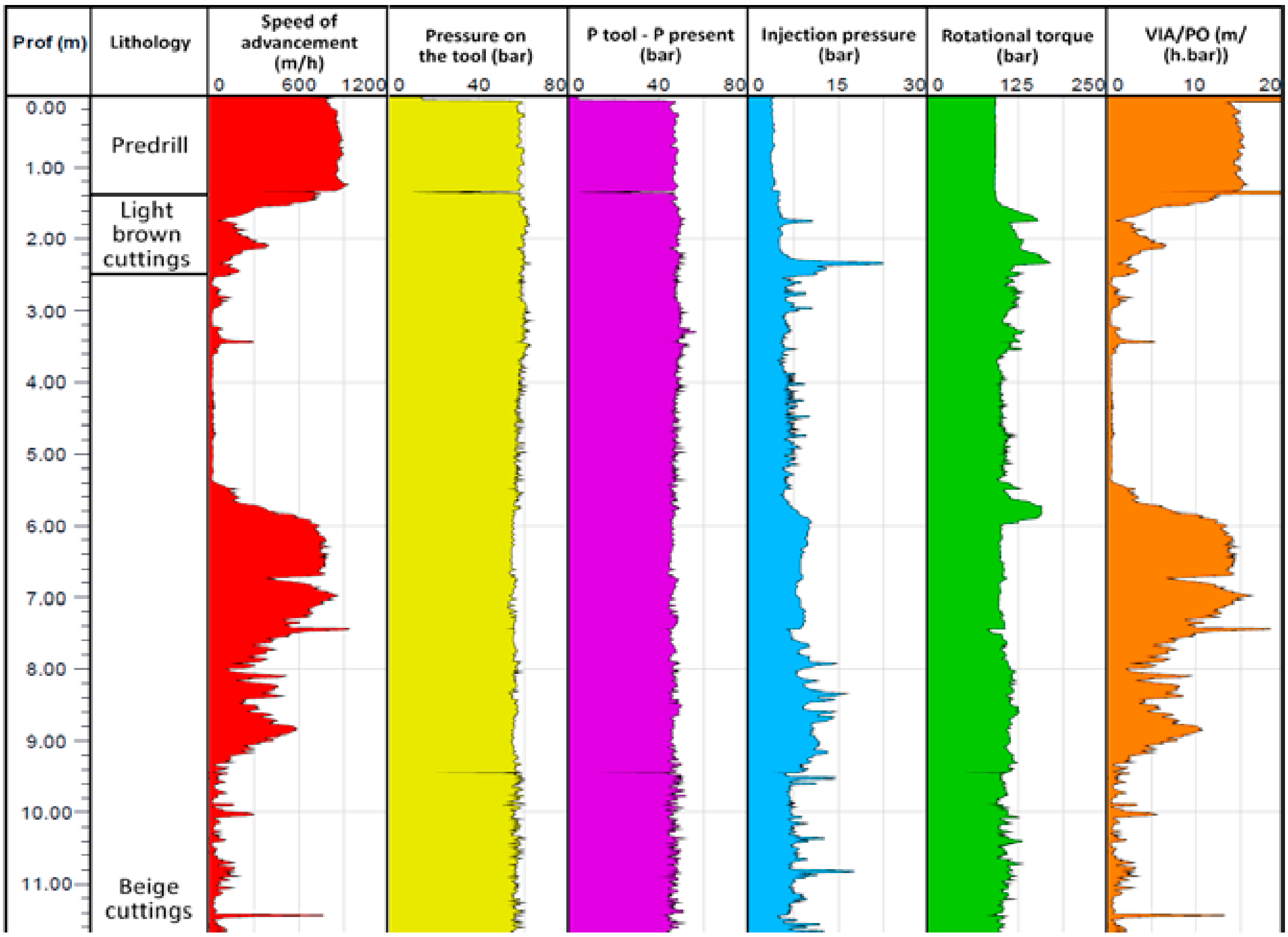

Figure 14: Example of a boring log showing fast progress of the drill between 6 and 8m deep which indicates cohesionless/altered ground

These dissolution mechanisms, which are most often found in saccharoid gypsum facies, can be explained by a partial dissolution of involved layers (Figure 15).

As the saccharoid gypsum is *porous*, the water which circulates through these pores will readily dissolve the gypsum bonds which connect the grains. This dissolution, which occurs in one part of the material, will reduce its mechanical properties without creating a void, but will alter the porosity (Lecomte, 2016).

Ground movement associated with this cohesionless/altered ground is generally caused by a significant modification of the water flow during hydraulic stresses of anthropic (pumping) or hydroclimatic origin.

These altered areas can also result from the mechanical overburden destructuring in the case of a cavity which self-fills as it rises towards the surface. When the volume of void created by dissolution is not sufficient to rise to the surface, the void column is filled with the collapsed materials. In a drilling, these altered areas appear as uncohesive areas.

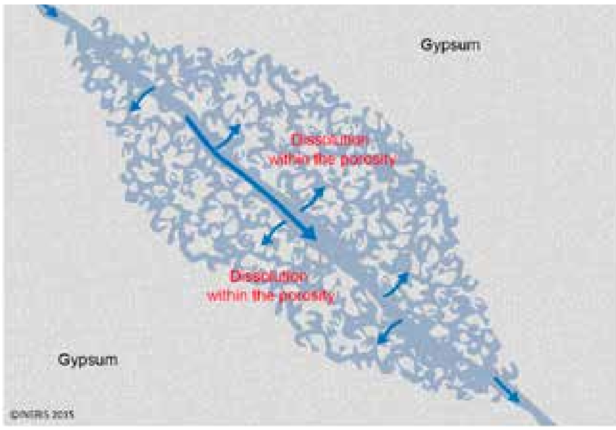

Figure 15: Alteration of gypsum layer by dissolution

3 HAZARD ASSESSMENT

3.1 Hazard: definition and specificities related to the gypsum dissolution

Hazard is generally assessed by combining the expected intensity of a given phenomenon with its probability of occurrence. In the case of natural dissolution processes, the most feared phenomena on surface are localised collapses and/or subsidence (see paragraph 2.5).

The intensity of the surface phenomenon depends on the characteristics of the created void (mainly its depth and volume) and on the geomechanical characteristics of the overburden layers (mainly cohesion and rigidity). There are two methods of intensity assessment:

- by feedback from the ground movement already observed in the study area. The size of the ground movement observed reflects the size of the expected phenomena (according to the overburden layers and the voids that can be created);
- by theoretical calculation according to the available data (overburden layers characteristics, depth and dimensions of the void).

Analysis of the hazard induced by dissolution mechanism faces several difficulties which occur infrequently or never in other contexts, such as hazards linked to anthropogenic cavities. It is a question of:

- the **major role played by water** in the initiation and development of dissolution cavities as well as in triggering the rupture and its propagation to the surface. It will therefore be necessary to take into account the **interactions between water and rock** and variations in the hydrodynamics of aquifers;
- the **evolving nature** of these natural systems;
- the natural component of these systems proves to be highly heterogeneous and anisotropic: which makes its location, and therefore the mapping of the associated hazard, more difficult and inevitably leads to consideration of a **location uncertainty** which can be significant in some cases.

Determining the probability of occurrence of ground movements brings us back to the problem of predicting them over time. If a probabilistic approach is adapted to earthquakes and floods which remain recurrent phenomena comparable to random processes, ground movements are, on the contrary, non-periodic phenomena which develop almost imperceptibly for long periods before suddenly accelerating. They are therefore very difficult to predict. Rather than estimating a probability of occurrence corresponding to a given return period (annual, decennial, centennial etc.), this concept is carried out in terms of the site's predisposition (or susceptibility) to development of a type of phenomenon.

The first step in assessing predisposition to these phenomena is to identify the areas directly above where dissolution mechanisms can occur. For this, an in-depth study of the geological and hydrogeological contexts must be carried out. The next steps have to determine, in these areas, whether the dissolution phenomena are able to destructure gypsum layer and/or to create voids which may rise to the surface.

3.2 General principles of the hazard assessment process

The methodology for evaluating the hazard of ground movements linked to gypsum dissolution[2] considers all the specificities linked to soluble environments and their evolution.

Several situations are considered:

- areas where dissolution mechanisms are active and able to create unstable cavities;
- sectors where pre-existing voids are present (linked to past dissolution processes);
- sectors where active dissolution mechanisms and past voids coexist;
- areas where past collapses have already been observed and where voids may still exist.

The main principles of this methodology bring together these different situations and are based on the acquisition of data to make up a set of criteria which characterise geological, hydrogeological and geomechanical contexts, namely:

- the presence or absence of soluble matter;
- the nature of the fluid in contact with the soluble matter;
- the characteristics of water circulation over time;
- the local geology and the structural and geomorphological context;
- the mechanical properties of the overburden layer;
- the existence of past land movements (subsidence, collapse).

2 - Developed by Ineris in recent years.

These data make it possible to assess, in the first instance, the nature of the expected phenomena (subsidence or collapse). Then, by analysing all of these criteria, predisposition to the appearance of a collapse or subsidence is defined. It is the result of the evaluation of the predisposition to the dissolution mechanism and the predisposition to void presence able to rise to the surface. It is this predisposition, combined with the intensity of the feared phenomenon, which will define the expected hazard on the surface.

Figure 16 schematically presents the procedure for evaluating the hazard of ground movements linked to the dissolution of gypsum. It identifies, by category, the necessary data (on a survey scale) as well as the cross-analysis which makes it possible to successively define the predisposition, the intensity and the hazard as detailed above.

3.3 Data required to evaluate the hazard

3.3.1 Geological data (intensity and predisposition criteria)

Predisposition

To assess the predisposition, it is first necessary to characterise the presence of soluble rock underground. This parameter therefore requires having and/or acquiring a good geological knowledge in the studied areas. The quantity and quality of information available on the presence of soluble materials and their spatial distribution will directly influence the accuracy of the assessment of the surface hazard.

Indeed, beyond the presence or absence of gypsum underground, it is important to be able to determine if this gypsum is present in sufficient quantities and at a depth likely to cause noticeable ground movements on the surface (integrating the mechanical characteristics of the overburden layers). For a given void, the greater its depth, the less the surface consequences of its closure will be significant.

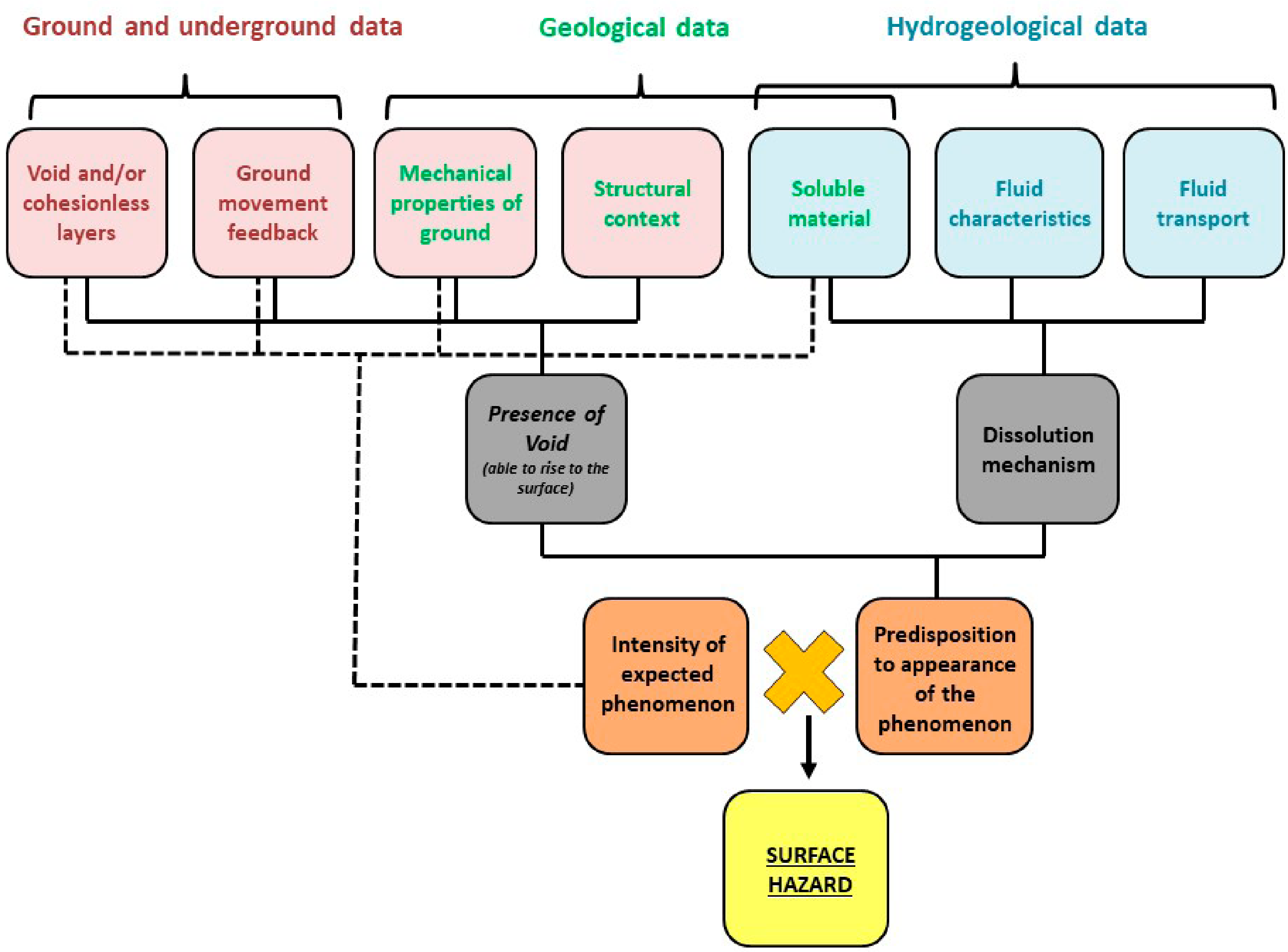

Figure 16: Presentation of ground movement hazard assessment process linked to gypsum dissolution

Intensity

The information concerning the overburden layers (geological characteristics, geomechanical properties) are contextual elements to be considered, in order to define the nature and the intensity of the phenomena expected on the surface. Knowledge or evaluation of the geomechanical properties of the overburden layers allow to assess the possibility of void creation and their progression to the surface.

Questions to assess the geological context:

- Is gypsum present?
- How thick is it?
- How deep is it located?
- What are the geomechanical properties of the overburden layers?

3.3.2 Characteristics of ground and underground movements data (intensity and predisposition criteria)

Predisposition

The existence of surface ground movement as well as the presence of cavities and/or cohesionless/altered areas provide information on the existence of the dissolution process, even if it may no longer be active. An analysis of the ground movement observed on the surface and its "history", coupled with acquisition of new information on the presence of voids underground (as drilling campaign) allows for better evaluation of the predisposition to the appearance of the feared phenomenon.

Intensity

To assess the intensity of the expected ground movement on the surface, the characteristics of past ground movement are generally used. For subsidence, the slope generated at the surface by compensation from the underground void is used. For localised collapses, it is mainly the diameter of the surface sinkhole that is used.

However, this geometrical characterisation is not always possible or is incomplete, especially in an urban environment when surface development has "erased" the ground movement as and when it occurred.

In this case, the size of the ground movement must be evaluated based on other data such as the quantity of materials which can be dissolved and the mechanical properties of the overburden and sub-surface soils (see next chapter on geological data).

Questions to assess underground status and expected phenomena:

- Is there knowledge of the presence of voids or unstructured underground?
- What is the size of the expected voids?
- Is there surface damage in the area of study?
- What are the characteristics of the damage observed?

3.3.3 Hydrogeological data (predisposition criterion)

For a dissolution mechanism to exist, the volume of soluble materials must be temporarily or permanently in contact with a fluid able of dissolving it. It is then necessary to understand how the dissolution system behaves and the parameters which influence this dissolution: characteristics and features of the soluble material considered, chemistry and temperature of the fluid in contact, speed of water circulation on the surface of the mineral, and hydrogeological context.

Knowledge of *groundwater* tables present is therefore necessary. It can be acquired either through sources that naturally drain aquifers, or through piezometers that give access to various water tables.

To quantify the dissolution developments in space and assess the overall area of the dissolution system, it is necessary to have or acquire data on the chemistry of the groundwaters. Taking in situ measurements of the electrical conductivity of water makes it possible to assess whether the various underground water systems have already been in contact with gypsum. These measurements will initially be systematically coupled with chemical analyses in order to identify the origin of the mineralisation, as other chemical elements may be the origin of high electrical conductivities. The calculation of the saturation indices will also be used to characterise the gypsum dissolution potential by the various water systems.

Figure 17 illustrates the importance of knowing of water systems and their chemistry to characterise the potentially sectors affected by ground movements.

In addition to or in the absence of hydrochemical data, it is possible to use other criteria which have indirect effects on the dissolution process. In this way, the *hydraulic gradient* of the water table, which is representative of the speed of groundwater circulation, can be used. This speed circulation has a direct influence on the renewal rate of the fluid in contact with gypsum, which then has an impact on the saturation degree of the solution and therefore on its dissolution potential.

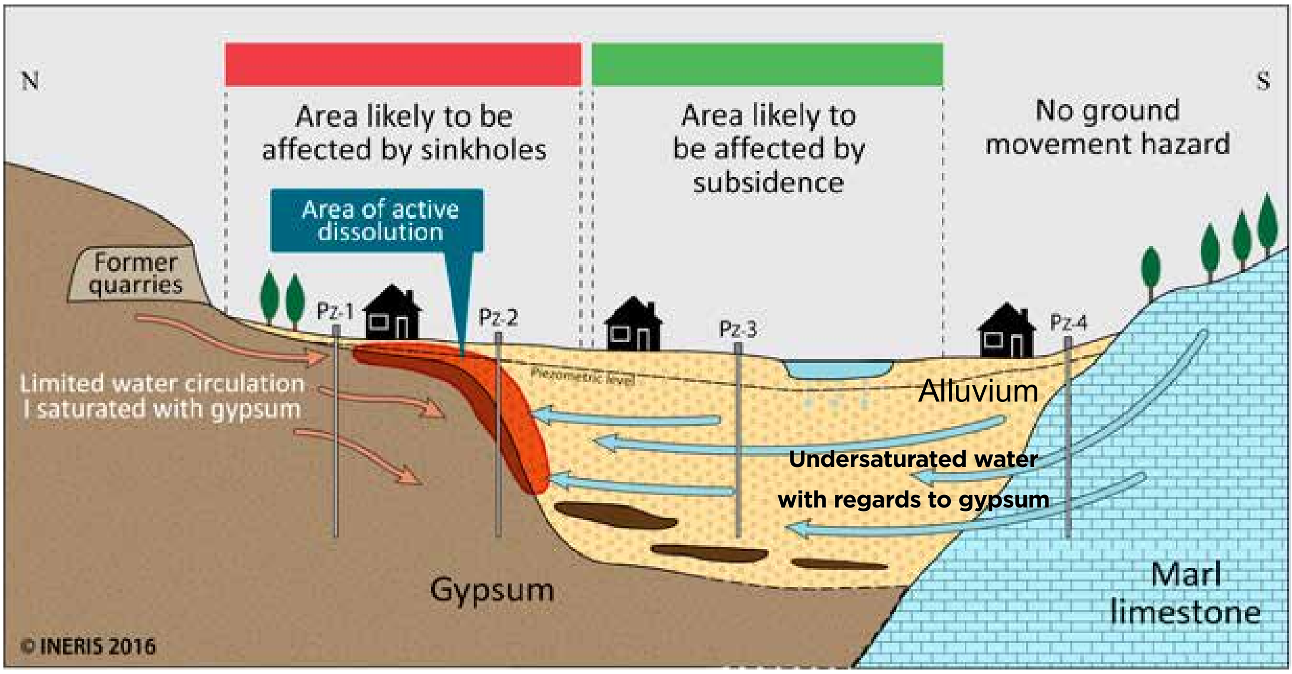

Figure 17: Representative diagram of hydrogeological behaviour - Example of the underground area of the hamlet of La Combe (Isère) and its repercussions on the surface in terms of ground movements. Groundwater flow and its aggressive action on gypsum have been defined by acquisition of hydrochemical data.

A detailed analysis of the hydrogeological context can also make it possible to identify sensitive areas from the point of view of dissolution, by locating the areas where gypsum may be in contact with undersaturated water (Figure 17).

Surface waters (characterisation of surface flows - inventory of shafts and sources) should also be considered when using this approach.

Questions to assess the hydrogeological context:

- What water tables are present underground?
- What is their gypsum saturation level?
- What is their hydraulic gradient?
- Is there a specific context (nearby pumping, injection, loss, etc.)?

3.3.4 Specific comments relating to the data acquisition stage

The methodology for evaluating the hazard of ground movements linked to the dissolution of gypsum must be adapted to each site according to the contexts and especially to the available data. Indeed, the different stages of hazard evaluation and mapping will depend mainly on the data collected during the study.

Several elements must therefore be taken into consideration:

- the quantity and distribution of geological and hydrogeological data. Depending on the location of the study site, its surface area and the means used, the amount of data can vary greatly from one site to another. It will mainly depend on the number of investigations carried out in the past and on the data acquired during the study (when additional investigations are planned). The lack of data, both geological and hydrogeological ones, introduces uncertainty into hazard evaluation. However, even if data is available in large quantities, it is important to examine its distribution over the entire area studied. A dense and homogeneous distribution of data will guarantee better interpolation / evaluation and therefore better mapping of the hazard.

- the quality of geological and hydrogeological data. Even if the data is available in large quantities and its distribution over the site is relatively homogeneous, it is important to examine its quality. The quality of the same type of data, acquired at different periods and for different objectives, can vary significantly and have an impact on the hazard evaluation and mapping. Therefore, for geological data, the quality of the data can vary according to drilling method used (core or destructive drilling) but also according to detail of lithology description. It can therefore be difficult to identify or interpret the gypsum levels precisely (thickness and depth).

- The quality of data relating to local historic ground movements. Generally, old or recent ground movement are used to assess the expected intensity and to justify the existence of dissolution processes. It can also be used to validate mapping resulting from assessment of the hazard. However, it is important to note that the ground movement is often poorly referenced and if information is available (dimensions, description of the event, etc.), there are generally not enough detailed. This may result in misinterpretations as to the real nature of the ground movement or its intensity.

To conclude, hazard mapping precision is linked to the available data (quantity, distribution and quality) and all their uncertainties.

3.4 Cross-referencing tables used to assess hazard

3.4.1 Predisposition assessment

Even if the available data vary from one site to another, it is possible to use it to define the main criteria to consider an initial level of predisposition, these being:

- the "deposit", i.e. the presence or not of gypsum underground in sufficient quantities to generate a perceptible ground movement on the surface (geological data);
- the "hydrodynamic and hydrochemical water potential ", i.e. the presence or not of aggressive water circulation around gypsum (hydrogeological data).

Table 1 shows the predisposition defined by cross-referencing both criteria, which have been classified considering summary data.

This table should be used as basis reflection and the criteria must be adapted according to the context and the available data. Therefore, when it is available or can be acquired during the study, the following data can be used:

- for the "deposit" criterion (taking into account the characteristics of the overburden layers):
  - the gypsum thickness:
  - the thickness-to-depth ratio of the gypsum layers.
- For the "hydrodynamic and hydrochemical water potentials" criterion:
  - the sulphate water concentration;
  - the water table(s) piezometry.

For ground and underground data, two criteria, called corrective or aggravating, have been considered, one relating to "ground movement", that is to say knowledge of recent or past ground movements associated with the dissolution, the other relating to the presence of underground "voids" (clear voids or cohesionless/altered areas).

These criteria, when they are provided, allow to adjust the predisposition initially qualified. Also, the presence of a void and/or ground movement will tend to increase (by one or two levels) the classification predisposition defined with main criteria. The correction value of the predisposition classification is generally limited to two, considering the limited number of predisposition classes (unlikely, likely, highly likely).

3.4.2 Intensity assessment

In recent years, the intensity classifications for ground movement phenomena, whether they are linked to mining operations, abandoned quarries or even natural cavities, have been standardised.

The limit values for each classification are identical to those given in the PPRN [Natural Risk Prevention Plan] handbook for abandoned underground cavities (Ministry, 2012). There are no objective reasons to re-evaluate these intensity classifications in the case of mechanisms for the creation of natural cavities.

Table 1: Initial qualification of the predisposition

Predisposition to the hazard of ground movements linked to gypsum dissolution		Hydrodynamic and hydrochemical water potentials	
		Unlikely circulation or saturated water	**Aggressive water circulation around gypsum**
Deposit	**Absent**	None	None
	Suspected	Unlikely	Likely
	Proven	Unlikely	Likely to highly likely

Table 2 shows the intensity classifications for localised collapses and subsidence. This table presented in the PPRN handbook for cavities has nevertheless been adjusted here by removing the two extreme intensity classifications (very low and very high). It was a question of having a maximum of three intensity levels in order to simplify the hazard assessment by considering that, in a natural context, the information available may be limited. In this case, it can be difficult to differentiate the extreme values of the intensities.

3.4.3 Hazard matrix

To consider hazard of ground movements linked to gypsum dissolution, a conventional referencing grid, as is usually used in mining risks or in natural risks, was chosen (Table 3). It is homogeneous, so it does not favour the intensity or the predisposition in analysis to determine hazard level.

As previously stated for the intensity classifications, only three hazard levels were considered for hazard. The very high-level hazard was not considered here considering the absence of very high-level intensity.

Table 2: intensity classifications used for localised collapses and subsidence land movement phenomena

Intensity classification	Phenomena	Main judgment criteria (not exhaustive)	Expected consequences
Low	Subsidence	Slope <3%	Light ground movement - isolated cracks that do not affect the functionality of the building
	Localised collapse	Diameter of the collapse <3 m	A potentially deep hole but sufficiently narrow so as not to immediately affect a conventional foundation
Moderate	Subsidence	Slope <6%	Cracks visible on the exterior. Doors and windows become stuck and some pipes break
	Localised collapse	Diameter of the collapse <10 m	Crater +/- deep and wide enough to ruin a recent concrete construction, even in raft foundation
High	Subsidence	Slope >6%	Serious structural ground movement. Buildings uninhabitable
	Localised collapse or widespread collapse of the surface	Diameter of the collapse > 10 m	Large crater with steep sides and a risk of the building collapsing into it or complete and immediate destruction of several constructions.

Table 3: Ground movement hazard matrix

		Predisposition		
		Unlikely	**Likely**	**Highly likely**
Intensity	**Low**	Low	Low	Medium
	Moderate	Low	Medium	High
	High	Medium	High	High

4 RISK MANAGEMENT

4.1 Risks: definition and evaluation

Usually, risk assessment is defined by cross-referencing the hazard (probability that a phenomenon will occur with a given intensity) and the vulnerable elements on the surface.

Risk = hazard x vulnerable elements

The vulnerable elements of a territory are defined as the people, property and activities present in the study area, likely to be affected by a phenomenon and to suffer damage or harm (Ministry, 2012).

Among the vulnerable elements to be identified on a site subject to a hazard, it is necessary to consider non-urbanised areas (parks, green spaces, campsites, viewing areas, sports fields etc.) which could, in the future, regularly or temporarily receive property and/or activities which may expose populations.

Consideration of these elements when defining the risk also integrates the vulnerability of the exposed property (the most sensitive equipment, establishments open to the public, priority traffic lanes, etc.) thereby characterising the sensitivity of an element in the face of a given hazard.

4.2 Prevention measures

Evaluation of the ground movement hazard linked to gypsum dissolution, defined through the methodology presented above, is mainly based on specifics geological and hydrogeological contexts. It does not take into account any modifications to the hydrodynamic or chemical balances existing within aquifers and which would be likely to accelerate the dissolution rate or destabilise previously weakened areas (cohesionless/altered areas or temporarily stable cavities, see paragraph 2.5.3).

Defining suitable prevention measures requires a good knowledge of the geological and hydrogeological conditions. From this point of view, technical studies (geotechnical and hydrogeological) constitute a prevention tool. However, in the following paragraphs we will not return to the content of these studies as they are already the subject of reference documents (Fauchard, 2004; IGC, 2016; Reiffsteck, 2010; Cailleux *et al.*, 1982; Marçot, 2016).

On the other hand, in light of what has been indicated above, it seems important to pay particular attention to water management methods as well as to the monitoring of hydrogeological modifications and induced ground movement.

4.2.1 Water management

External stresses, be they anthropogenic or not, can modify the hydrodynamic or chemical balances existing within aquifers, and consequently worsen the defined predisposition levels. It is therefore important to take them into account.

These stresses can vary in nature: underground constructions, pumping activities, localised heavy *infiltration*, network leaks, extreme rainfall, floods etc. Many publications highlight the appearance of ground movement in connection with hydrogeological modifications.

For example, in Ile-de-France, correlations have been established by many authors (Feugueur, 1964; Diffre, 1969; Mégnien, 1970; Toulemont, 1974, 1981, 1987) between the appearance of collapses and significant changes in the hydrogeological situation. The increase of collapse, that occurred between the 1950s and 1975, is attributed to the stoppage of large industrial pumping operations that had greatly reduced the Lutetian water table. Two phases may have come one after the other: one where, if pumping is active, there was an acceleration of the dissolution processes, and another which occurred after the pumping stopped, inducing changes in the hydrodynamic and mechanical balance and destabilising the existing cavities.

We can also cite, more recently in 2004, the collapse observed in the municipality of Villetaneuse (photograph 8) which was partly associated with the aging sewage network becoming “leaky” (correlation between the void encountered during drilling with an anomaly in the collection pit).

Photograph 8: Collapse observed in Villetaneuse (93) linked to leakage of the sanitation network (source: Cerema, July/October 2004)

In another context and again by way of example, in Spain, near Zaragoza, the intense meteorological phenomena and water infiltration, for example along the uncovered irrigation canals, can lead to significant variations in the level of aquifers (5m during irrigation). The appearance of ground movement is well correlated with these significant changes in the hydrological and hydrogeological context (Benito *et al.*, 1995).

These correlations between intense meteorological phenomena and the appearance of ground movement were also established by some experts in 2014 in the Var (e.g.: Bargemon), following the heavy rain recorded in January and November.

Therefore, in order not to aggravate the natural phenomena of dissolution by significantly modifying the existing hydraulic gradients, water management must not be neglected.

There are some recommendations that can be made, i.e.:

- avoid heavy pumping and heavy infiltration into gypsum areas. Regarding infiltration, it is not about the surface waterproofing but about concentrating the water into one single place.
- avoid chemical and thermal (geothermal) balances disturbing;
- regularly check the potential sources of parasitic water inflows (leaks from networks) which could also have an impact on the existing gypsum deposits;
- pay attention to backfilling boreholes and survey drilling. The filling materials and how they are used must make it possible to restore a seal that is at least equal to that of the pre-existing overburden layers;
- waterproofing water storage structures.

Depending on the context, the above recommendations may be adapted subject to the completion of specific surveys to ensure there will be no impact and to specify the construction methods.

4.2.2 Piezometric monitoring

Depending on the context, gypsum dissolution can lead to the creation of voids, unstructured areas, or the opening of pre-existing fractures. These changes in the underground structure will result in an increase in the permeability of the soil or rock mass and therefore in a modification of the flow speeds of the aquifer and/or its hydraulic gradient.

Consequently, monitoring the piezometry of the water tables bathing the gypsum layers makes it possible to receive indications about the location and evolution of the dissolution phenomenon. In the north-east of Paris, a correlation was noted between the ground movement observed on the surface and the local presence of a secondary drainage basin axis with a stronger gradient than the one more generally existing in the aquifer. These observations require regular monitoring on a close piezometric network.

It should also be noted that the identification of active dissolution zones can be carried out by monitoring the conductivity of the water. However, this monitoring should be supplemented with chemical analyses to ensure that the conductivity measured is due to the gypsum dissolution.

4.2.3 Surface events monitoring

As described in paragraph 3.3, monitoring historic ground movement is a key step to characterise the expected intensity of ground movement as well as identifying active areas and their possible geographic progression.

For this, it is necessary to set up a database to register the events observed on the surface. Their description must be as exhaustive as possible and include, as a minimum, the location (georeferencing), the geometry (diameter, depth, slope etc.), and the date and conditions of appearance (environment, aggravating phenomena etc.).

In the case of urbanised sectors, where ground movement is often masked by frame, reports of the damage to structures can also be a good indicator of ground movement in progress. However, the cause of this damage can be other (e.g. shrinkage/swelling of clays).

Similarly, if specific investigations are performed and safety work carried out, it is important for this to be recorded. Knowledge of the nature of the building work makes it possible to assess the extent of the phenomena causing the damage and can possibly be used in the event of a second-generation disaster or similar event (evolutionary nature of the phenomenon).

4.3 Protective measures

Protective measures refer to the solutions that can be adopted to reduce the vulnerability of an asset or avoid a serious accident that can affect people. They are the result of reconnaissance work which includes the acquisition of data from various sources (archives, surveys, geophysics, etc.) allowing the geometrical and geographic characteristics of the cavity(ies) to be defined in relation to the surface (Pinon, 2016).

4.3.1 Constraints to consider

Treatment methods are varied and depend on:

- the geological context in which the dissolved gypsum layers are found. Treatment methods can vary significantly if the gypsum levels are found in a rocky mass containing temporarily stable voids or in loose or plastic ground, sensitive to decompression phenomena. The identification of an aquifer system and the knowledge of its hydrodynamic characteristics is also an essential point;

- the sensitivity of structures to ground movements. For structures sensitive to ground movement (structure or foundation of a building, for example), the methods used must allow a definitive treatment that is guaranteed not to change over time. In the case of less restrictive use of the surface (low traffic roads, green spaces, etc.), the treatment methods may be more minor and allow for limited surface movements or even deferred building work in time;
- the context of intervention (current ground movement, pathology on or near an existing structure).

4.3.2 Brief description of treatment methods

4.3.2.1 Injections

Different injection techniques can be used to fill or consolidate a dissolution area. In the presence of a water table or water flow, these works absolutely must be accompanied by provisions making it possible to limit the hydraulic impact (modifications of gradients, dam effect etc.) at the risk of causing other ground movement. Surface monitoring and adjusting injection pressures as necessary is therefore required.

Depending on the condition of the gypsum deposits, the injections will aim either to fill the voids (filling injection), or to consolidate altered soil (treatment injection) in order to obtain soil resistance values deemed sufficient for construction of the project or the securing of the site.

For filling voids, it is recommended to gravity fill with a cement mortar (Figure 18 box a) that contains a significant mineral load (sand or even fly ash or fillers for ready-to-use mortars) but that is also fluid, in a network of boreholes arranged according to a grid that is adapted to the vulnerable elements on the surface. Then, after a period of 7 days, a mixture comprising a higher proportion of cement (grout) must be injected under pressure (approximately 5 bars at the rotary head) into the boreholes to fill the residual voids: this is known as grouting.

As an indication, the recommendations of the Paris General Inspectorate of Quarries [IGC] on grid drilling are[3]:

- 7m x 7m under green spaces;
- 5m x 5m under constructions;
- 3.5m x 3.5m perpendicular to sinkholes.

Depending on the extent of the ground movement, these filling injections can be supplemented with treatment injections. This consists of injecting the ground and impregnating the soil or rock mass with a fluid grout that is more heavily loaded with cement. These injections are performed with sleeved tubes (devices sealed in the ground allowing the choice of the area to be injected (Figure 18, box b).

Depending on the objectives of the injection (safety, construction project), minimum mechanical resistance characteristics of the products and of the injected grounds are required. At the end of the process, the characteristics of the land are checked using monitoring probes (characterisation method, preferably like the one implemented before the works began). If the values obtained are lower than those set, injection must be carried out again.

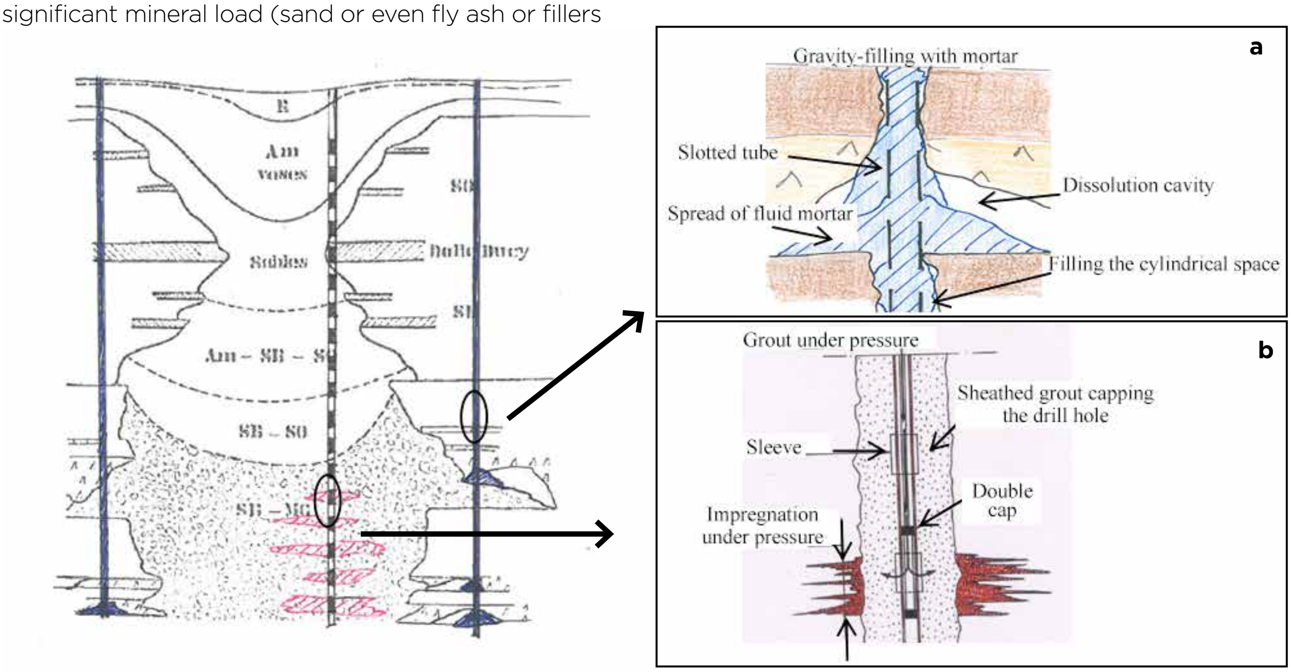

Figure 18: Injection treatment (filling mortar in blue, grout treatment in red) of a dissolving gypsum sinkhole from the Lutetian Paris Basin (Cerema)

3 - Notice IGC : https://api-site.paris.fr/images/78407

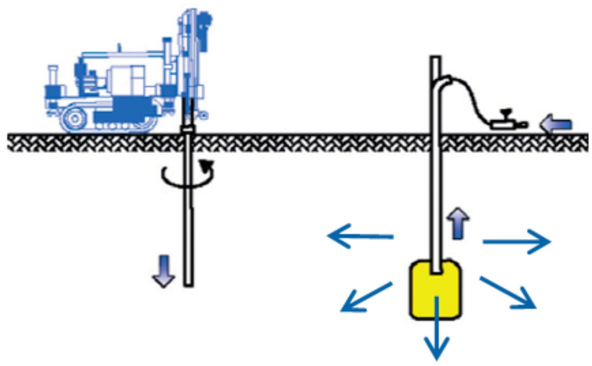

Figure 19: Diagram showing the principle of solid injection and a in situ example (Grand Rapids convention centre – USA – Thome *et al.*, 2006)

In areas where dissolution results of ground decompression, it is possible, considering the nature of the ground, to "redensify" it by injecting a very thick mortar which will hold back the ground around the borehole: this is known as solid injection (Figure 19).

The various injection techniques described in this paragraph act directly on the gypsum layers. They are therefore likely to limit the probability of ground movement and therefore reduce the hazard level. Nevertheless, special attention must be paid to the influence of injection filling works which can influence the flow of groundwater and therefore displace the problems associated with dissolution phenomena.

4.3.2.2 Filling from the surface:

This technique is used when a surface collapse appears (near an existing structure or during an earth-moving phase).

Filling with "hardcore" is generally a losing strategy. In fact, since stability is only ensured in the short term, it is likely that a new subsidence/collapse will appear again in the same place a few years later, in particular following variations in the level of the water table or infiltration of significant amounts of water.

To guarantee stability during filling, including under the effect of water (at least precipitation), two approaches can be proposed:

- either closure of the sinkhole throat, for example, a concrete slab placed at an appropriate level (example Figure 20);
- or filling with frictional granular materials with an appropriate granulometry that fills from the surface (fine particles) to the bottom (coarse particles) (see Figure 21).

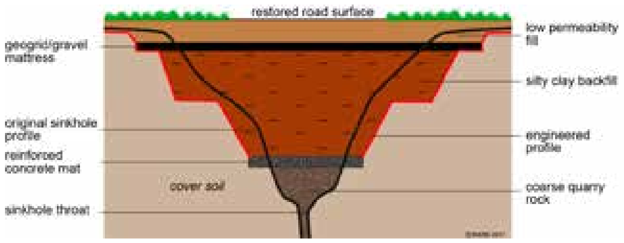

Figure 20: Backfill blocked at its base by a reinforced concrete slab (after Bonaparte and Berg (1987) in Waltham *et al.*, 2005)

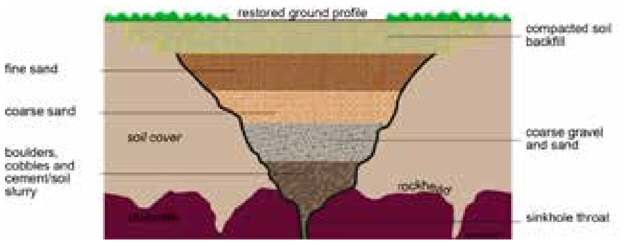

Figure 21: Backfilling a collapse using granular materials with a graded particle size (from Waltham *et al.*, 2005)

Only backfilling with granular materials makes it possible to limit the impact of the work on the underlying aquifer circulation.

This technique essentially aims to secure the ground movement appearing on the surface. It reduces residual risks. However, it does not affect the level of hazard.

4.3.2.3 Reinforcement of structures

Depending on the sensitivity of the constructions to be carried out and on the possibility of treating the ground, the implementation of specific constructive measures may prove necessary to guarantee the stability of the foundations or to limit damage to the structures in the event of ground movement.

Consideration of a localised collapse for superficial foundations

This approach involves sizing the support structures (foundations + load-bearing walls) in order to resist, without serious damage, a collapse of predefined diameter at any point within the limits of the structure's foundations.

The stiffening and the increase in the geometry of the foundation elements (invert section or footing) must make it possible to ensure "bridging" of the collapse, with the remaining contact surface between the ground and the foundation having to be sufficient to pass on the loads.

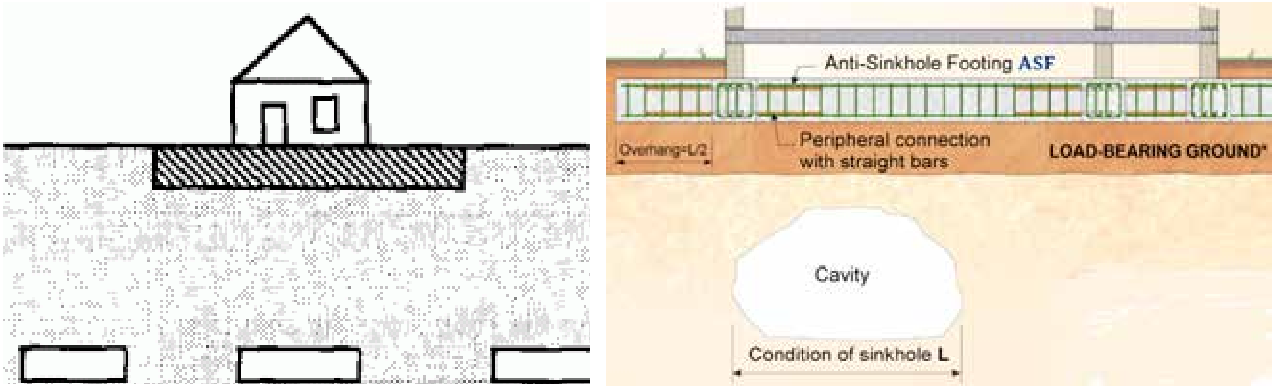

Figure 22: diagram of the principle of stiffening of the foundations (source: IGC Versailles) and example of the principle of sizing an anti-sinkhole footing (source: FIMUREX)

This method results in larger sizing compared to conventional foundations in order to obtain greater rigidity of the foundation. The footings may be lengthened, and the thickness of the rafts increased (Figure 22).

Adjustment for deep foundations

Where the gypsum levels are at a low depth, it is possible to use deep foundations with a base anchored beneath the horizons affected by the dissolution. The sizing considers foundations working principally at a point, as well as parasitic forces (negative friction) acting on the area that is cohesionless/altered or affected by dissolution.

Creating this type of foundation can require a preliminary filling of the voids resulting from dissolution or the implementation of a lining to avoid loss of concrete (Figure 23).

Structure adaptation of work construction

In some cases, the geometry of the feared events can be such that a stiffening of the superstructure is more suitable than reinforcement of the foundations or treatment of the ground.

This is the case for certain linear infrastructure projects, the local failure of supports following the appearance of a localised collapse on the surface. In order to alleviate this problem, the stability of the structures is reinforced by installing "bridges" making it possible to stiffen the structure. Figure 24 presents an example of structural reinforcement (road bridge) by installing concrete beams.

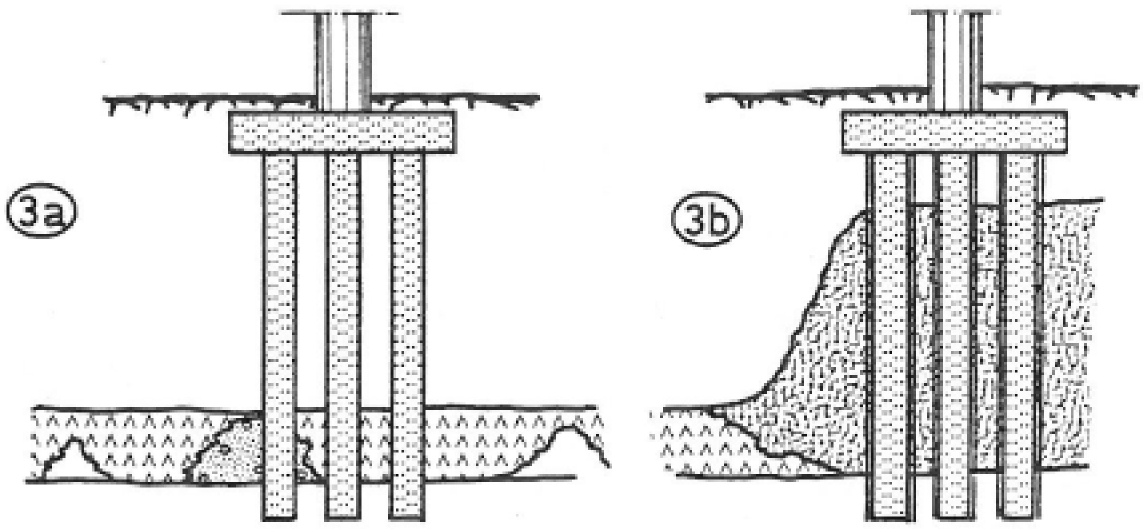

Figure 23: Deep foundations anchored under a dissolution zone: with gravity filling of the cavities (3a) or lining with piles (3b) (Toulemont, 1987)

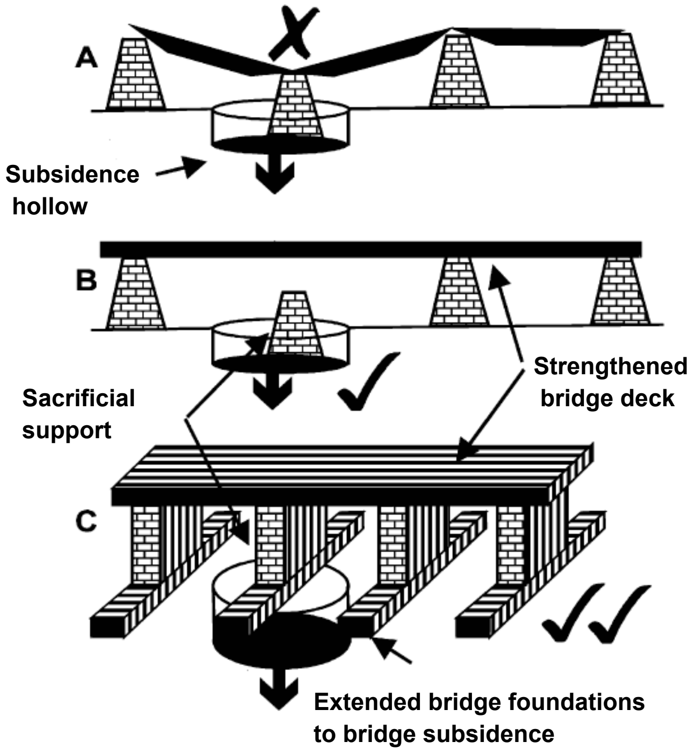

Figure 24: Reinforcement of a bridge deck for a road (Cooper *et al.*, 2002)

The size of the "bridges" able to work on a beam over the failing foundation depends on the geometry of the collapse and possibly its size in relation to the surface materials put in place for building the structure (embankment).

These constructive provisions can be supplemented by monitoring devices that make it possible to see, during the lifetime of the structure, any deformations associated with changes in gypsum levels (decompression or rising cavity) and/or changes in the structures (deformations, stress variations around support) and/or supporting ground (settlement of supporting ground).

They essentially aim to reduce the vulnerability of the property faced with the appearance of ground movement (collapse or subsidence) linked to gypsum dissolution.

4.3.2.4 Reinforcement geogrid

This type of device is used when it is impossible to delimit, to a sufficient degree, the areas likely to be impacted by collapses and/or when the vulnerable elements to be protected can allow significant ground displacement (at least temporarily).

The principle involves limiting the deformations perpendicular to a collapse by installing a system (geogrid) in the ground close to the surface which retains the overlying ground and only has an effect during subsidence/settlement of a limited amplitude.

As the void progresses towards the surface, the geogrid, buried at a variable depth according to the sizing (in particular according to the amplitude of the permissible deformations on the surface), is put under tension from friction in the non-collapsed area (Figure 25). This will then compensate for the weight of the ground resting on the geogrid perpendicular to the collapse.

With the properties of geogrids available on the market, this process can be used to protect against collapses up to 5m in diameter. It is also possible for these geogrids to detect an initial tensioning and prevent subsidence before it is visible.

This type of device is particularly suited to securing roads or protecting spaces open to the public (green spaces, pedestrian walkways, etc.). In terms of more unclear collapse hazards, geogrids present an important economic interest compared to the other techniques presented above.

However, the geogrid system does not constitute definitive protection. Geogrids secure land for a limited period after the collapse, but their mechanical characteristics do not allow tension to be maintained in the long term.

Identification of a collapse (subsidence/settlement in the area protected by the geogrid) requires subsequent consolidation of the ground (see injection paragraph).

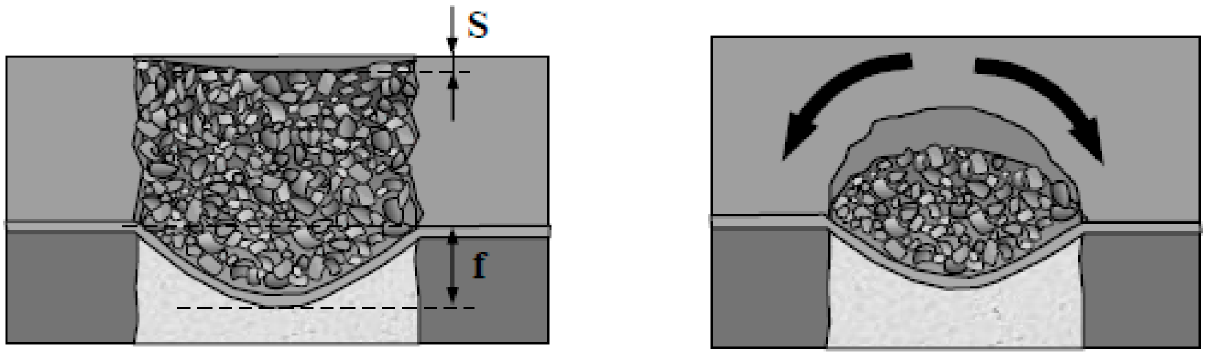

Figure 25: Tensioning of a geogrid over a cavity under the effect of the collapse of the overlying ground (P. Villard, 2006)

4.4 Summary of prevention methods and treatment methods

Table 4 summarises the means of prevention and the methods of treatment defined in the preceding paragraphs. It characterises each of the techniques with regard to the following criteria:

- ease/simplicity of implementation;
- relative cost;
- relevance and effectiveness in terms of hazard ground movement.

Table 4: Main methods of prevention and treatment of gypsum dissolution zones

Risk management methods	Techniques	Cost	Feasibility		Residual hazard	Residual risk	Comments
			For new	For existing			
Prevention measures	Water management	€	Easy	Possible	=	↘	Measure to be sustained over time. Avoid making the phenomenon worse. In some cases, the hazard level is reduced
	Piezometric monitoring	€	Easy	Easy	=	↘	Measure to be sustained over time.
	Monitoring of surface events	€	Easy	Possible	=	↘	Difficulty in urban environment
Protective measures	Injections / Ground treatments	€€€	Easy	Easy	↘	↘ ↘	Possible impact on surrounding areas
	Surface filling	€/€€	Easy	Possible/ Complicated	=	↘ ↘	Securing the collapse Large land takes required
	Stiffening of structures	€€/€€€	Easy	Possible/ Complicated	=	↘ ↘	Requires a good evaluation of the phenomena upstream
	Flexible structure	€€	Easy	Complicated	=	↘	Hardly possible for what currently exists Requires monitoring and possible repeat

€: inexpensive technique to implement
€€: expensive technique to implement
€€€: very expensive technique to implement
=: criterion unchanged
↘: criterion reduced

5 CONCLUSION

Natural gypsum dissolution phenomena can be the cause of ground movements likely to affect vulnerable elements on the surface. To better understand this hazard, Ineris and Cerema have combined their respective experience in order to establish a methodology for its assessment.

This methodology is based on knowledge of the geological and hydrogeological contexts of the site, of ground and underground area conditions and also on the understanding of the mechanisms involved from dissolution phenomena up to the appearance of ground movement in surface.

The intensity of the phenomena is determined according to the size of the expected ground movement. For a subsidence, it is the slope generated on the surface, by compensation of the deep void which is used. For local sinkhole, it is mainly the diameter of the sinkhole expected on the surface which is considered.

The probability of the appearance of ground movement on the surface (more precisely the predisposition of the site to the ground movement appearance), depends mainly on two criteria:

- the "deposit", the presence or absence of gypsum and, more precisely, its thickness and depth which must be sufficient to cause noticeable ground movements on the surface (taking into account recovery properties);
- the "hydrodynamic and hydrochemical water potential" i.e., the presence or absence of aggressive water circulation around gypsum (hydrogeological data). These potentials are assessed by a detailed analysis of the hydrogeological context and if possible, by carrying out chemical analyses and by calculating the saturation indices.

By cross-referencing these two parameters, the predisposition level is obtained. It can be corrected if the presence of underground voids or the knowledge of ground movements are known on considered area.

Cross-referencing the intensity and this predisposition makes it possible to assess the hazard according to three levels (low, medium and high).

This general approach must also include consideration of possible anthropogenic external stresses (infiltration, pumping, extreme rainfall events etc.) which could modify the intensity of the dissolution phenomena and/or destabilise previously dissolved areas.

In order to limit the risks associated with the presence of vulnerable elements on the surface, prevention and protection measures can be adopted. These mainly consist of:

- treatment, if necessary, of voids and cohesionless/altered areas using technically and economically appropriate methods (injection, filling, reinforcement of structures, geogrids, etc.).
- monitoring the piezometry of the water tables "bathing" the gypsum layers in order to collect indications about the location and evolution of the dissolution phenomenon;
- monitoring the appearance in surface of ground movement to characterise the intensity of expected ground movement as well as identifying active areas and their possible geographic progression;
- implementing "good water management practices" in order to not to modify the existing hydraulic gradients, which could accentuate the dissolution phenomena or destabilise dissolved areas.

Throughout this handbook it can be seen that water plays an essential role, from the initiation of dissolution phenomena to the final characteristics of the ground movement on the surface. It is therefore essential to consider it during ground movements hazard assessment linked to gypsum dissolution. The important role of anthropic stresses in cavities development is also highlighted. In order to acquire a more precise understanding of the mechanisms involved, investigation studies and research projects are carried out by Ineris and Cerema on this subject.

6 GLOSSARY

Aquifer: a permeable hydrogeological formation allowing the drainage and the capture of water tables.

Automorphic crystal: a mineral in the form of a perfect crystal or, at least, having flat crystal faces.

Cohesion: a property allowing soil particles to bond with each other.

Cone of depression (or drawdown): an area where the water level of the aquifer around the pumping point is lowered.

Discontinuity (in a soil or rock mass): a surface which interrupts the physical continuity of the ground layers and structures. Discontinuities can vary in nature: joints, faults, cracks or extension fractures, stratigraphic joints...

Dissolution rate: the rate at which a solute dissolve in a solvent.

Erosion: a chemical, mechanical or microbiological process causing rocks alteration.

Evaporite: a deposit rich in alkaline chlorides (rock salt, sylvine, carnallite, etc.) and sulphates (gypsum, anhydrite), soluble in water and resulting from the evaporation of surface water mass.

Groundwater: water contained in the interstices or cracks of underground rock, also called an aquifer.

Hydraulic gradient: the quotient of the difference in hydraulic head between two points of a saturated porous medium, on the same streamline, over the distance separating them on this streamline.

Hydraulic head: difference in piezometric level between two points of a watercourse line, which gives rise to a flow.

Hydrostatic pressure: pressure exerted by a fluid on a surface due to its weight.

Infiltration: penetration of surface water into the ground.

Mass: geological bed measuring several meters or even tens of meters.

Piezometric level: water level recorded within a borehole that characterises the pressure of the aquifer at a given point.

Porous: relating to a medium containing empty spaces.

Soluble: solid body which can dissolve in a liquid, forming a homogeneous mixture.

Suffosion: the phenomenon of fine materials being moved hydraulically.

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Credits: Ineris (1, 10, 12, 12, 13, 14, 15, 16, 17, 18, 19, 22 and 24) • Université Laval (9 and 11) • BRGM (16) • DDTM 83 (16) • IGC (16) • Cerema (17, 18, 27 and 29) • Thome *et al*. (30) • Waltham *et al*. (30) • Fimurex (31) • Toulemont M. (31) • Cooper A.H. & Saunders J.M. (32) • Villard P., Gourc J.-P. & Blivet J. (32)
Conception-réalisation : O'communication – Les Récréateurs

This handbook, produced jointly by Ineris and Cerema, is intended for public authorities and natural risk managers. It is the result of studies and research work carried out over the past decade.

In most contexts where gypsum is present beneath the ground surface, dissolution mechanisms can occur and lead to the creation of underground voids. Whenever the geomechanical conditions are conducive, the destabilisation of such cavities can lead to severe ground movements on land surface.

The objective of this handbook is to manage hazard assessment studies related to collapse and subsidence phenomena induced by dissolution mechanisms. For that purpose, it is important to describe the overall physical process, from the progressive development of voids to their progression through the geological layers up to the land surface. This description relies on disciplines and skills including hydrogeology, geotechnics and risk analysis.

The methodology proposed by the authors is based on the combination of both geological and hydrogeological criteria. The cross-referencing of these criteria makes it possible to define the susceptibility of an area to ground collapses due to subsurface dissolution of gypse. This hazard is then assessed by combining the susceptibility of the land area and the intensity of the feared phenomenon. The latter is assessed by considering the dimensions of the phenomenon, whether observed in situ or based on geotechnical expertise.

The pervasive and sudden nature of such ground collapse mechanisms makes it potentially dangerous for people and property. To deal with such risks, prevention, mitigation and protection measures are proposed in this handbook.

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