afitexinov GEOSYNTHETICS

3SR

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

INERIS
maîtriser le risque pour un développement durable

Recommendations guide

Release date: 2021

Recommendations for the use of geosynthetic reinforcement to reduce the risks associated with a localised collapse

Project sponsored by :

ADEME
Agence de l'Environnement et de la Maîtrise de l'Energie

Work performs from the research & development project **REGIC** (Reinforcement over natural or man-made cavities using smart Geosynthetics)

Authors :

- Marwan AL HEIB (Ineris)
- Philippe DELMAS et Mathilde RIOT (Afitexinov)
- Fabrice EMERIAULT et Pascal VILLARD (3SR)

Expert Committee :

- Marianne CHAHINE (Cerema)
- Hubert GIRAUD (SNCF)
- Yasmina BOUSSAFIR (IFSTTAR)

Table of contents

Abstract

Road and urban developments are sometimes confronted with very local disorders (cave-ins and sinkholes) due to the collapse of natural cavities (karstic) and anthropogenic cavities (former underground mines or quarries) located at shallow depths.

This document first provides an overview of the different types of cavities and the ground movements that can be caused by the deterioration of these cavities followed by their rise to the surface. This is followed by a brief overview of the treatment methods available to reduce the hazard or risk as well as illustrations of uses of geosynthetic reinforcement over cavities.

The geosynthetic reinforcement method is then described for granular and cohesive ground. The "dual-stiffness" geosynthetic developed as part of the REGIC project is presented.

Methodological recommendations for the use of instrumented geosynthetics are made. On the one hand, they make it possible to use geosynthetic as a ground reinforcement system above cavities likely to have a risk of small local collapses, generally less than 4 m. On the other hand, the inclusion of fibre optic instrumentation during geosynthetic production makes it possible to continuously monitor deformations and to issue alerts if the cavity rises.

This document is intended to provide decision-making aids to help secure land impacted by abandoned anthropic origin cavities (mines, underground quarries, marl pits, tunnels-shelters, troglodyte dwellings, war sapping works, etc.) or natural cavities (dissolution cavities, karst, etc.) to players concerned by ground movement risk management, in particular decentralised public services, local elected representatives and managers, developers, engineering offices and geosynthetic manufacturers.

1. Introduction

The French territory is widely exposed to risks related to the presence of anthropic or natural underground cavities. They are of different origins: karstic, former underground mines[1] or former underground quarries located at shallow depths. The presence of these cavities is a major risk for surface structures. Therefore, risk management related to the effects of potential collapses of these cavities, particularly with regards to the assets involved, is a particularly important challenge for the stakeholders. Indeed, a hazard must be dealt with of which is it often impossible to accurately describe both the location and the probability of its occurrence.

Reducing the corresponding hazard and mitigating its potential consequences are one of the objectives of land movement risk management. The choice of risk control method must take into account both short and long term safety along with cost implications. The guide to solutions to secure underground cavities (Ineris, 2016a) presents possible treatment methods. Geosynthetic (GSY) reinforcement is one of the solutions that can be used to protect surface assets. Due to its economic and environmental benefits and its ease of use, it has been in use for many years.

The purpose of this document is to explain the use of geosynthetics in local collapse risk zones. Hence, should provide project managers, design offices and contractors with the highly important information for the design and quantification of this ground reinforced method using instrumented geosynthetics, as well as the related items necessary for the development of their projects:

- whether for geosynthetic reinforcement;
- or to monitor cavities using instrumented geosynthetics.

The document also explains the criteria adopted to select the geosynthetic solutions and its viability versus other available treatment methods.

Subsequently, the document presents:

- the design approach of the geosynthetic solution using detection.
- a summary of the advantages, limits, and conditions for the use of the geosynthetic solution.
- a summary of relevant project cases in France and elsewhere.

The document however, assumes that the contracting authority and project management have previously defined the <u>objectives in terms of the duration of protection</u> of property and people from the effects of surface collapses (service life). At this stage, the characteristics or safety coefficients considered should take into account clearly defined product durability or degradation (particularly during installation), as well as illustration of a comparative lifecycle analysis versus the different solutions being considered.

[1] The regulatory difference between underground mines and quarries is not addressed in this document, only the notion of ground movement hazard is considered.

To do that, it may be useful to base on applicable standards and recommendations as well as on the national or international state of the art outside any reference systems specific to the contracting authority. The document is divided into the following chapters:

- **Chapter 1: Introduction**.
- **Chapter 2: Cavities in the subsoil.**
  This chapter describes the origin of cavities in France and their density.
- **Chapter 3: Cavity development, collapses and associated ground movements.**
  This chapter indicates the different ground movement types and their consequences on the surface. Special attention is given to local collapse risks (cave-ins and sinkholes).
- **Chapter 4: Methods of reducing ground movement risk.**
  This chapter covers the different treatment methods, in particular a methodology adopted to select the most appropriate method.
- **Chapter 5: Geosynthetic reinforcement.**
  This chapter describes the different types of geosynthetics, their mechanical behaviour, physical and mechanical characteristics. It also illustrates their use as an underground cavity reinforcement system, including their application.
- **Chapter 6: Geosynthetic design method.**
  This chapter first describes the reinforcement mechanism, the geosynthetic reinforcement sizing method rules for granular and cohesive embankments and anchoring design. It indicates the required data, especially in terms of admissible settlement.
- **Chapter 7: Implementation.**
  This chapter covers the installation of geosynthetics over cavities. It highlights installation recommendations, including ground compacting over geosynthetics, to ensure the success of the solution application.
- **Chapter 8: Monitoring.**
  This chapter describes the method and objectives of monitoring geosynthetic reinforced solution over cavities using fibre optics instrumentation. It describes two configurations: a local cavity and an area of potential (non-localised) cavities.
- **Chapter 9: Summary - benefits and limitations.**
  This chapter indicates and sums up the design approach. It also outlines the main technical advantages and limitations of geosynthetic reinforcement installations.
- **Chapter 10: Conclusion**

2. Cavities in the subsoil

Anthropogenic underground cavities, caves, abandoned workings, troglodyte dwellings, underground shelters, wartime sapping structures, etc., are widely spread throughout the country and are preoccupying for many local authorities and contracting authorities because of their concentration and their inevitable deterioration.

The **National Cavities Plan**, launched by the French State in 2013[2] for the prevention of underground cavity collapse risks (excluding mines) mentions that there are over 500,000 underground cavities on the French territory. Some areas, such as Normandy, Hauts-de-France and Île-de-France, are particularly concerned by the existence of cavities (Figure 1 and Figure 2).

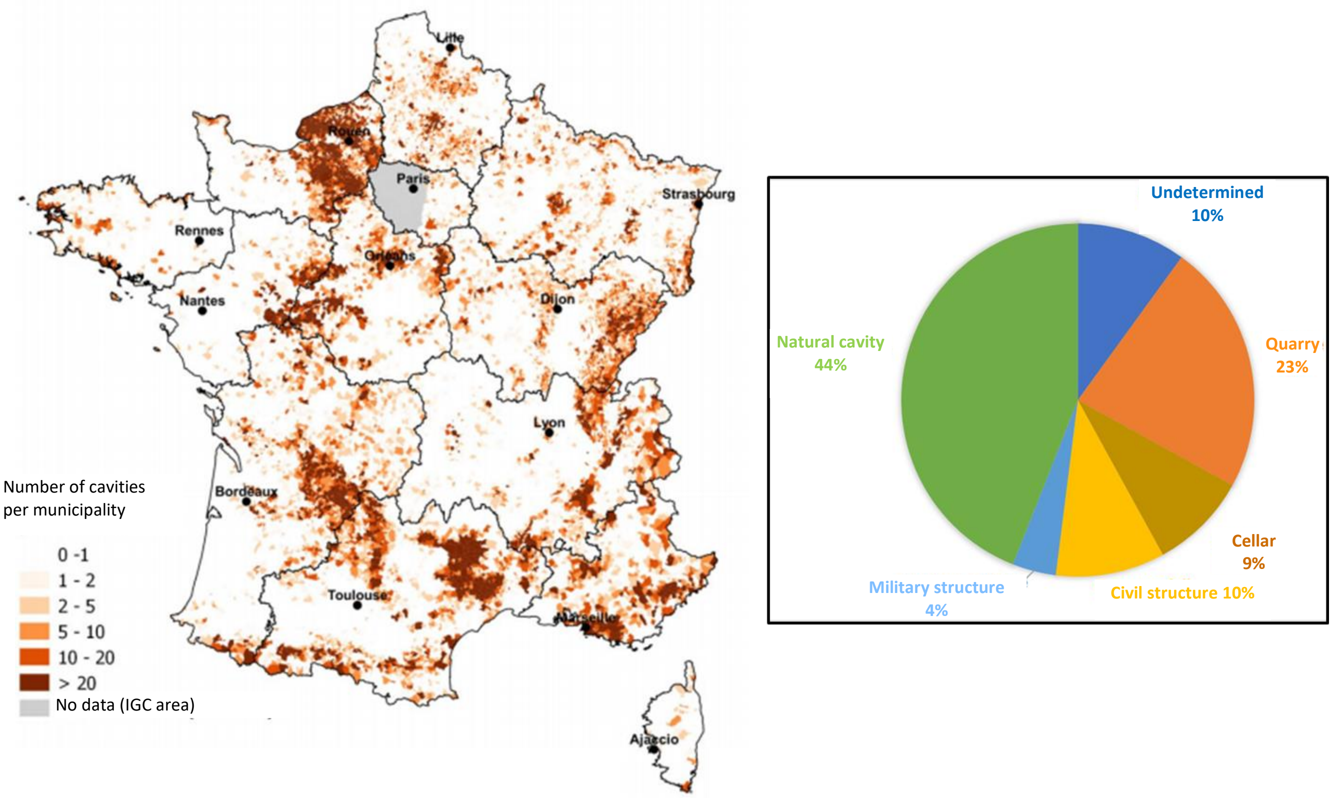


Figure 1 : Inventory of natural and man-made underground cavities (excluding mines) - source: BRGM (2019)

Underground cavities are a source of danger to people, property and, in a wider sense, to economic activity. They can result in severe urban planning and development constraints. Accidents or incidents related to the instability of such structures occur regularly and are

[2] https://www.ecologique-solidaire.gouv.fr/sites/default/files/2014_DGPR_plan_national_cavites_def_web.pdf

particularly worrying when they impact highly urbanised areas crossed by national or international road infrastructure.

In France there are over 500,000 underground cavities, and accidents or incidents (collapse or subsidence) occur regularly due to the instability of these natural or man-made cavities.

2.1. Anthropogenic cavities

Man-made cavities, i.e. cavities excavated by man, have had many purposes, the most common being:

- **the extraction of building materials** (building stone), of agricultural materials (soil improvement) or industrial materials (cement, salt, coal, various ores, etc.);
- **permanent dwellings** (troglodyte dwellings and their associated cellars and outbuildings) and temporary housing (tunnels and shelters);
- **storage** (cellars, warehouses, etc.);
- **the passage of in-ground services** (water, electricity, gas, etc.);
- **movement or shelter for property and people** (tunnels, wartime sapping, tunnels, etc.).

Although the oldest underground mines date back to prehistory, mining activity grew considerably from the Middle Ages onwards and remained important until the mid 20th century, associated with energy needs and the gradual urbanisation of the territory. Today, the underground extraction of materials (mines and quarries) in France is relatively rare, most workings are closed down and abandoned, a few are reused for agriculture (wine cellars, mushroom-growing, etc.), for tourism (museums, restaurants, etc.) or for industry (storage areas). If several factors conditioned underground mining activity, the main one was a favourable geological context, i.e. the presence of useful and extractable material at shallow or medium depths (generally up to a few dozen metres). This geological predisposition partly explains the distribution of man-made cavities in Ile-de-France outside Seine-et-Marne (Figure 2), including in areas currently subject to high real estate pressure.

For example, according to the Inspection Générale des Carrières (IGC or Quarry Inspection Service), there are over 3,000 hectares of land spread over 70 municipalities that are impacted by abandoned quarries (Figure 2) in the Paris region. The density of marl pits (former chalk extraction workings for soil amendments) in the plateau area is potentially 14 per km², i.e. 100,000 to 120,000 marl pits in Haute-Normandie alone (Georisques Portal, underground cavities). In the Lorraine iron basin, over 2,000 ha are undermined in urban zones.

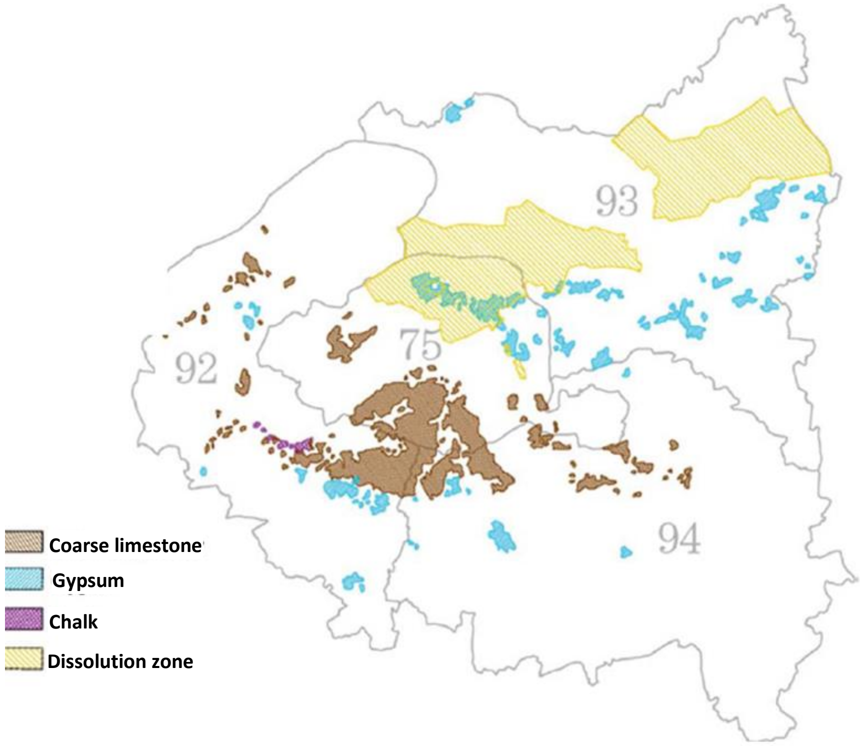


Figure 2 : Location of abandoned underground quarries in Ile de France, by type of extracted material (excluding Seine et Marne) - Source: IGC

There are also thousands of vertical structures, in particular access shafts and ventilation or dewatering shafts for underground cavities. They are critical points in terms of local collapse risks.

2.2. Natural cavities

Natural cavities are also numerous and often poorly known. They develop in the subsoil as a result of dissolution (Ineris 2017), suffusion or volcanic activity for example. Dissolution is still very widespread throughout the country and concerns regions where there are formations that are more vulnerable to this phenomenon: evaporites, limestone (Karst - Figure 3).

Dissolution phenomena in the subsoil cause the alteration of the properties of the surrounding formation and in the long term can lead to the formation of cavities. The dimensions and depth of these cavities vary greatly, and they can reach volumes of several thousand m^3.

Ultimately, the volume of these cavities can change and, as a result, generate surface collapses similar to those of man-made cavities, phenomena that are difficult to predict and potentially dangerous for people and property.

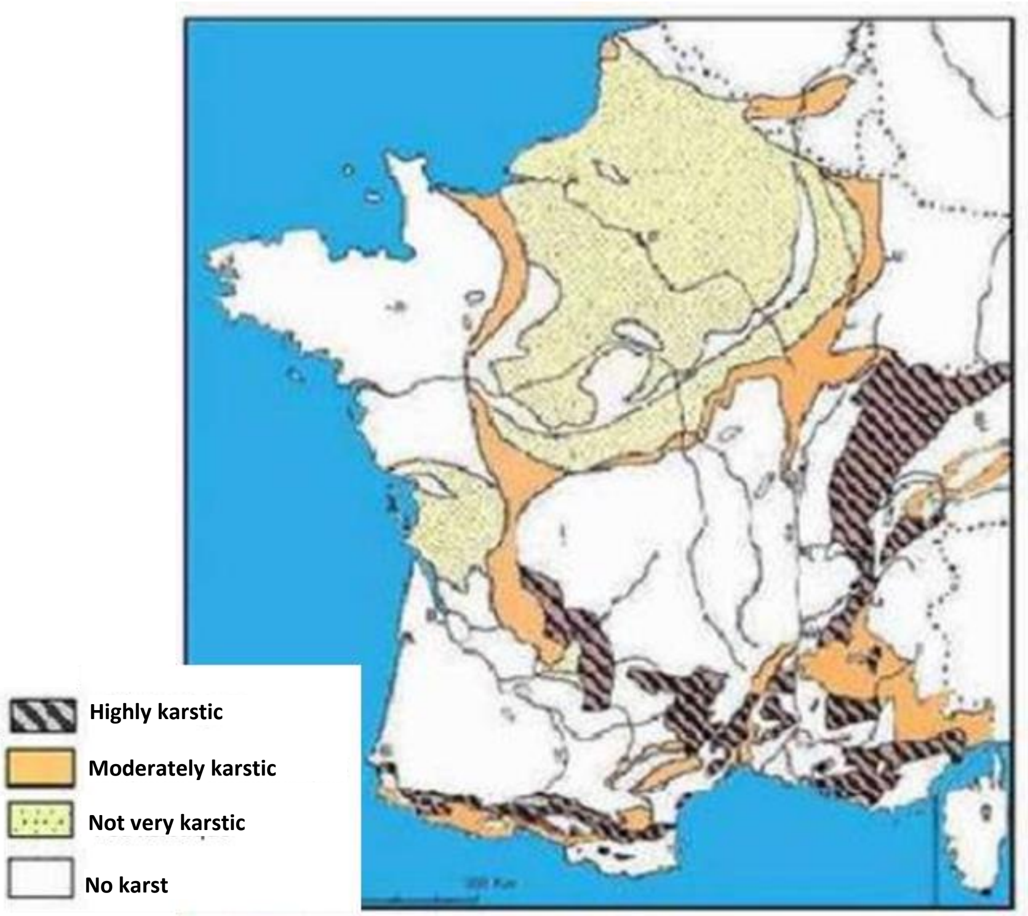


Figure 3 : French karst vulnerability map - Source: © DR

3. Cavity deterioration and collapse and associated ground movements

Natural and man-made cavities evolve over time and deteriorate in conditions that are intrinsic to the formation and/or external factors. In the long term, local instability phenomena occur inside the structure (deterioration of the pillars, the immediate roof (Figure 4). When there is propagation towards the surface (Figure 5), natural or anthropogenic underground cavities are a threat to surface assets located in the collapse area. Such collapses may be gradual or sudden depending on the void configuration and the type of overlying ground. On the surface, different more or less predictable and feared ground movements types occur, which damage the structures located in the movement zone.

Figure 4 : Deteriorations in an underground quarry - Source: Ineris

Figure 5 : Local collapse over a former iron ore mine in Lorraine (left) and a former chalk quarry (right) – Source: Ineris

3.1. Subsidence

Subsidence is a continuous depression of the ground over one or more natural or man-made cavities (Figure 6). When single or multiple underground cavities collapse, the overlying ground may partially or completely fill the voids. If the expansion and depth conditions are right, subsidence causes a gradual deformation of the land, forming a topographic depression without significant brittle failure. It often develops in the form of a bowl. The extent and extension of this subsidence bowl depends on the cavity size, its depth and the quality of the expansion on the overhead land.

Figure 6 : Example of a subsidence bowl - Source: Ineris

3.2. Local collapse (sinkhole)

Local collapse (or sinkhole) following the rupture of the formation above a natural or man-made cavity located at a shallow depth, generally less than 50 m, according to the numerous observations associated with the expansion of the terrain. The rise of sinkholes to the surface depends on the cavity type, its geometric shape and the type of overlying ground.

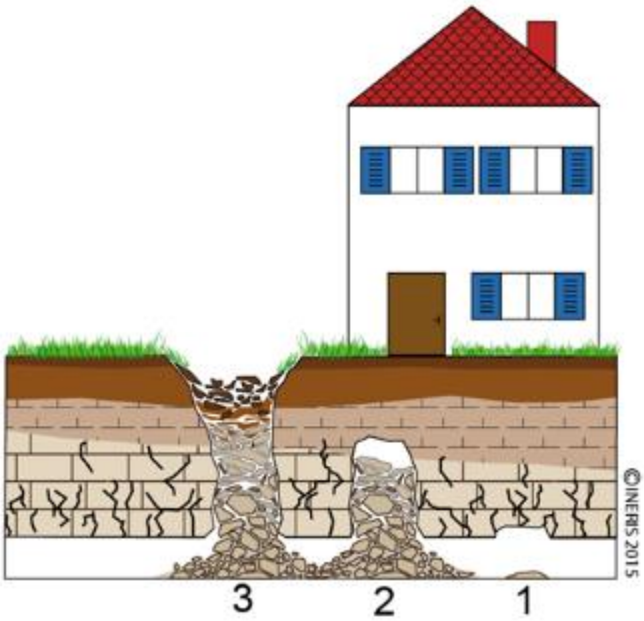
In the following part, we indicate the conditions in which sinkholes appear for the three cavity types: man-made, natural and vertical structures (shafts).

3.2.1. Man-made cavities

In underground operations, there is often a vault rising towards the surface by successive ruptures of the ground above the initial cavity. This process is initiated by beds falling away and then by a local rupture of the cavity roof (Figure 7). This roof fall occurs when the first roof bed is not strong enough to withstand the stresses it is subjected to. The term cave-in or sinkhole refers to both the collapse mechanism and the crater that is typically seen on the surface.

Two situations can be seen: either the process stops by itself at a height corresponding to a self-stable vault (which remains a balancing situation), or it develops vertically until it reaches the loose cover materials and then the surface. The speed at which the cave-in or sinkhole progresses, and therefore the time between the collapse at depth and the appearance on the surface, is highly variable; it depends on the sinkhole size, the cavity depth, the materials and the local conditions (presence of water, faults, traffic, vibrations, etc.). From a few days for weak ground, to several years for strong ground.

The presence of a water table or water flow which will spread the scree in the galleries, favours the development of the cave-in or sinkhole towards the surface.



1: roof fall

2: Rising vault

3: Cave-in or sinkhole (and surface disorders)

Figure 7 : Rising sinkholes and cave-ins - Source: Ineris

The foreseeable consequences for the safety of people and property on the surface in the area of influence of the disorder depend on:

- **the surface collapse diameter** (Table 1). The funnel diameter in a stabilised configuration (Figure 8) is differentiated from the "instant" diameter of the area affected by the collapse (often of a significantly smaller cylindrical shape than the former);

- **the crater depth**: sinkholes are characterised by a gravitational movement consisting of an essentially vertical component which can reach an amplitude approximately equal to the cavity height (Figure 8).

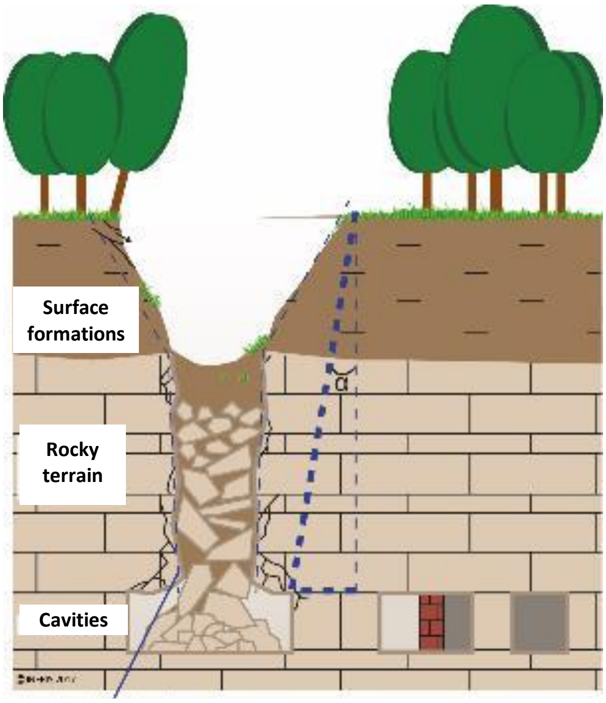


Figure 8 : Evolution of the collapse diameter and final surface area - Source: Ineris

The disorder at the bottom can also be caused by the sudden or progressive collapse of all or part of a support pillar, which will cause a landslide in several galleries adjacent to the bottom. Even if the rock fall blocks on the neighboring pillars, the consequences on the surface will be more significant than those of the collapse of a single or isolated cavity.

Thus, depending on the mechanism that causes the collapse and the type and thickness of the overlying ground, the surface characteristics of a local collapse may vary from one site to the next. Their importance can be graded according to levels of intensity which will have an impact on the preventive measures to be implemented (posting, securing of surface assets).

Table 1 shows the commonly accepted intensity classes for cavity cave-in risk analyses. Figure 9 shows examples of local collapses (sinkholes) of underground cavities.

Table 1 : Examples of potential damage intensity classes depending on the collapse diameter

Surface collapse diameter	Damage intensity class (on the surface)
Self-backfilling collapse nearby or limited collapse	Very limited
Diameter < 5 m	Limited
Diameter ≥ 5 m and < 10 m	Moderate
Diameter ≥ 10 m	High to very high

Figure 9 : Examples of local collapses near man-made cavities - source: Ineris

Figure 10 shows a breakdown of the diameters of 420 sinkholes that appeared above disused quarries in the Paris region. It should be noted that 90% and 84% of the disorder population have a sinkhole diameter of less than 5 m and 4 m respectively. Over 74% have a diameter less than or equal to 3 m.

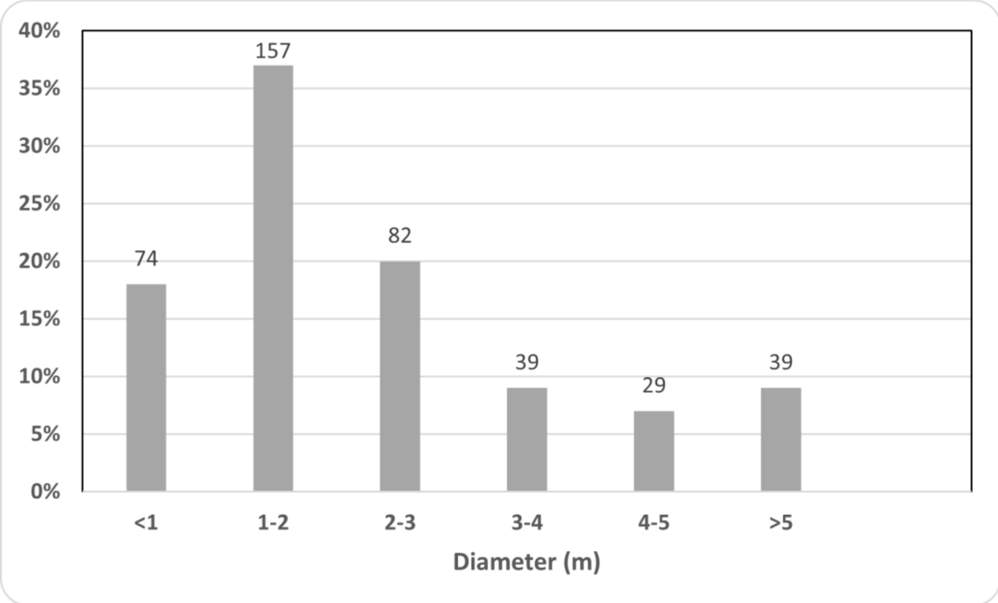


Figure 10 : Sinkhole diameter distribution (on the surface) and in the absence of treatment for gypsum and limestone quarries in the Paris region - Population of 420 sinkhole cases (IGC data, processed by Ineris)

It is difficult to establish a correlation between sinkhole diameter and cavity depth (Figure 11). Sinkhole diameter depends on the cavity depth and size, but also on the type of ground above the cavity and the expansion coefficient.

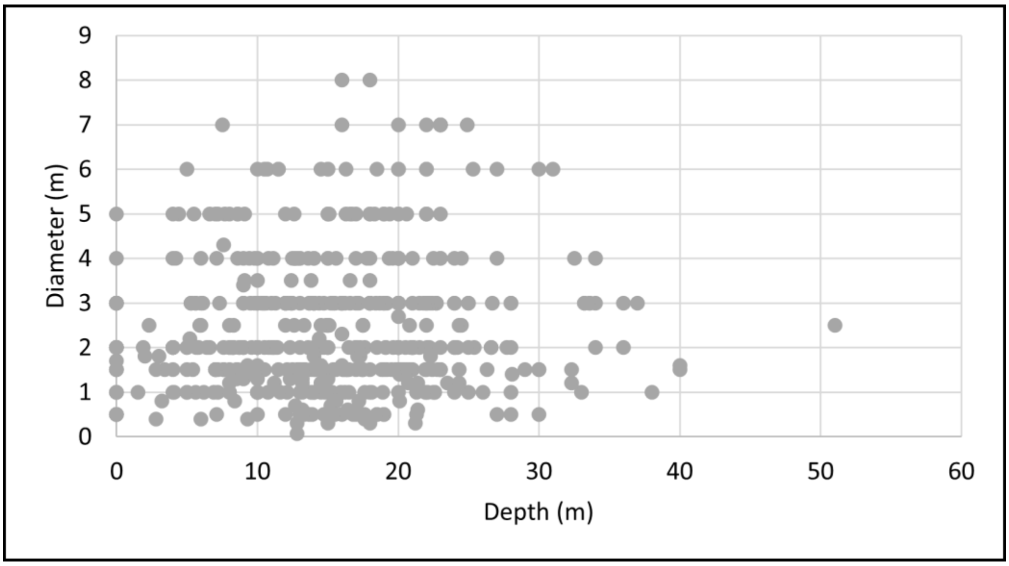


Figure 11 : Sinkhole diameter (on the surface) and depending on depth for gypsum and limestone quarries in the Paris region - (IGC data, processed by Ineris)

3.2.2. Natural cavities

The consequences of the growth of natural cavities to the surface, whether they originate from the dissolution of evaporites or limestone karst, are identical. Two possible examples of surface consequences for karst dissolution cavities are shown in Figure 12.

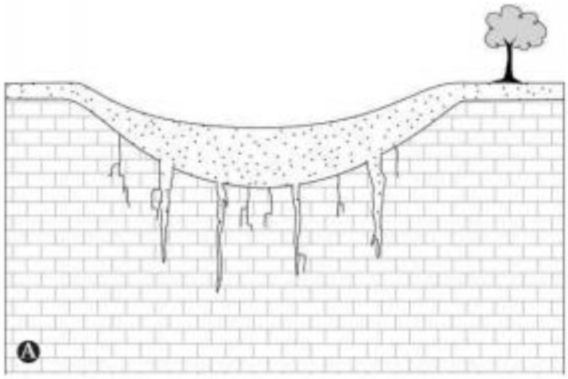


Diagram of a dissolution doline

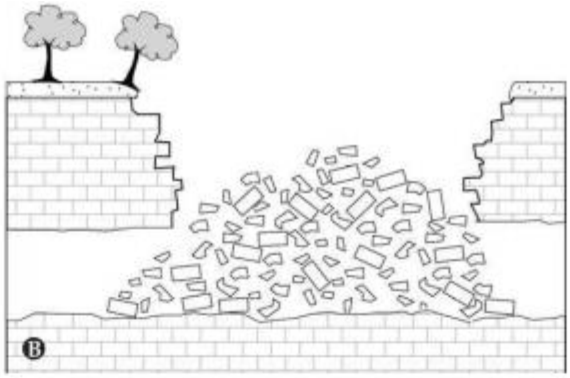


Diagram of a collapse doline

Example of a dissolution doline (76)

Example of a collapse doline (76)

Figure 12 : Different types of dissolution cavities and their consequences on the surface (Salvati and Sasowsky, 2002)

In a gypsum context, void propagation can be further accentuated by the presence of water. This will have a double impact: the modification of the expansion (coefficient reduction) and the accentuation of the void's progress towards the surface, in particular when the cavity's cone of influence causes the rupture of the overlying water table's impermeable screen and the connection of two aquifer systems (Toulemont, 1981). Once this situation is reached by the collapse, the erosion and suffusion processes begin due to the pressure difference between the aquifers.

Ground movements are often associated with horizontal deformations. Those risk causing damage to ground, structures and infrastructure. Different analytical and digital methods are available to estimate the horizontal deformation in particular relative to subsidence. The NCB (National Coal Board, 1975) empirical method calculates the maximum horizontal deformation depending on the maximum subsidence at surface level (S), the cavity depth (H) and an empirical coefficient k depending on the type of overlying ground. This relationship

(ε_{max} = k (S/H)) has been adapted for shallow cavities. Appendix A gives an indication of horizontal ground deformations for different cavity configurations.

For reinforced ground, the sought-after result is for the geosynthetic to transform the sinkhole into a subsidence. The horizontal ground deformation at the geosynthetic level can be considered approximately equal to that of the ground at the surface.

3.2.3. Shafts and vertical structures

In several regions, former underground workings are only accessible through vertical shafts that were dug from the surface (marl pits, chalk mines, chalk quarries, mines, etc.). These shafts which are often poorly filled and little-known shafts are particularly vulnerable to the appearance of sinkholes (Figure 13). The diameter of these shafts is usually less than 5m and is more often between 2 and 3m. These shafts are abandoned after having been plugged and/or after they have been filled with material (often rubble). An incorrectly filled disused shaft can leak, in particular in the presence of water i.e. its backfill can flow into the underground works to which it is connected resulting in the formation of a crater on the surface with the same dimensions as the shaft column.

This leakage may be accompanied, or followed, by a shaft lining failure and the collapse of the surrounding usually low cohesive surface ground. A collapse cone then forms, the dimensions of which depend on the local geological, hydrogeological, and mechanical characteristics of the terrain (Figure 13).

Figure 13 : Examples of leakage in different shafts - Sources: Ineris and ORRNA

3.3. General collapse

General collapse, also known as mass collapse, is the rupture, often dynamic (a few seconds), of all or part of an underground operation that impacts the stability of the surface terrain over surface areas that can cover several hectares (Figure 14). The collapse height in the central part can be of several meters, and even several dozen meters. This central zone is bordered by open, subvertical fractures, resulting in "steps" of which the consequences can also be very damaging for the people and property on the surface. These are rare phenomena of which the consequences are nevertheless potentially serious because they involve a considerable amount of energy. They can be accompanied by seismic shocks and blast effects that can eject material from galleries and open shafts over long distances.

Figure 14 : Example of a general collapse - Source : Ineris

3.4. Crevices

Crevices are associated with mining hazards related to subsidence or the collapse of underground cavities. They can also be associated with karsts. They are defined in a purely geometric manner, they correspond to marked discontinuities, with a multi-centimetre to multi-decimetre opening, extending from several metres to several tens of metres, and a variable depth that can reach several metres. Several types of phenomena can be at the origin of their formation, such as subsidence or general collapse. A crevice can appear several years after it has formed (Figure 15). They are often discovered during surface works (soil stripping and earthworks for roads, infrastructure or buildings). More rarely, they can appear on the surface during specific weather episodes (significant rainfall, freeze-thaw episodes) or when human activities generate significant water flows (network leaks). The surface phenomenon is comparable to a local longitudinal collapse.

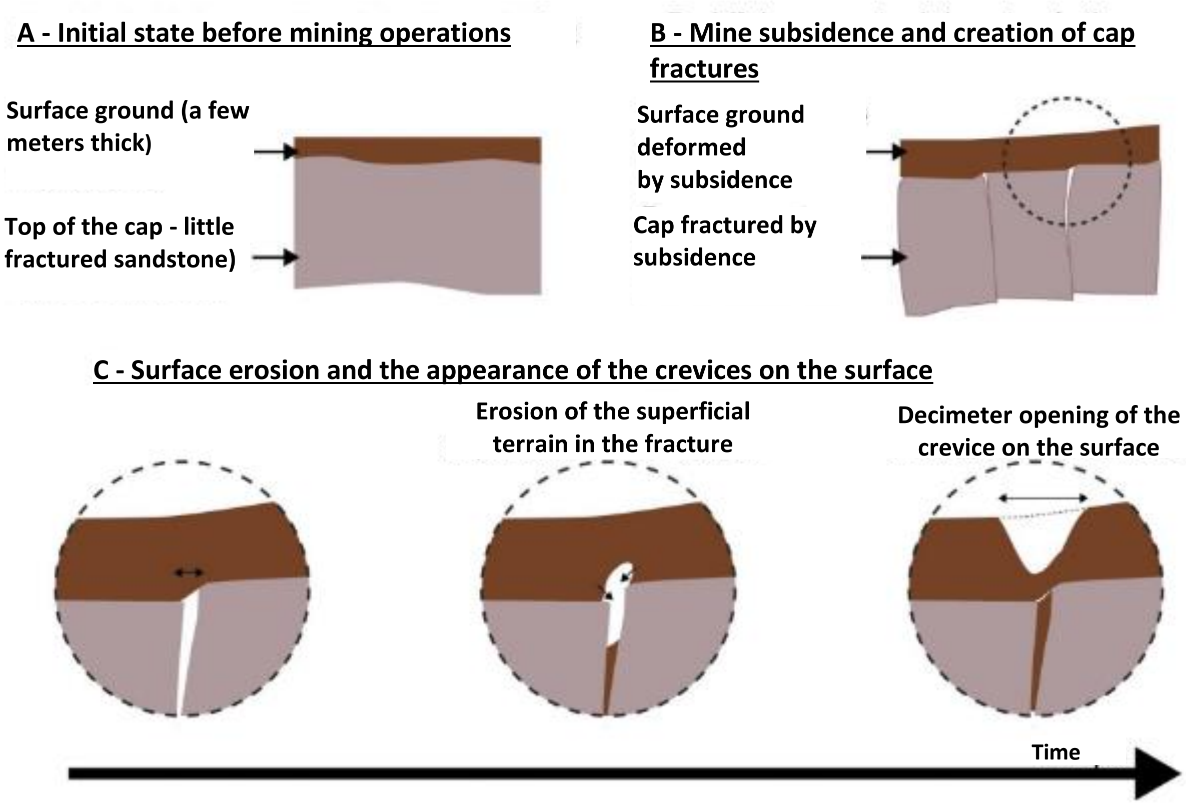


Figure 15 : Formation (A, B) and evolution of a mining crevice - Source: 2017 Ineris Guide

The sudden and unexpected collapse of natural or man-made cavities leads to the formation of a sinkhole on the surface, also known as a "ground movement" hazard. People, property, activities, infrastructure, heritage, etc., also known as assets, are likely to be impacted by such a formation.

4. “Ground movement” risk reduction methods

Hazard is a term commonly used in risk prevention. It corresponds to the probability that a phenomenon occurs on a site during a given reference period, reaching a qualifying or quantifiable intensity. Hazard characterization is classically based on the crossing of the predictable intensity of the phenomenon with its probability of occurrence.

In terms of risk prevention, a reference period of several decades or even centuries is used to define an order of magnitude. The analysis must therefore include the inevitable deterioration over time of disused man-made cavities. The intensity of the phenomenon corresponds to the extent of the disorders, after-effects or damage likely to result from the expected phenomenon. This includes a notion of the magnitude of the feared events (sinkhole size and depth), but also their potential effects on people and property. The probability of occurrence reflects the vulnerability of the site to the impact of a phenomenon. Whatever the nature of the feared events involving cavities, the complexity of the mechanisms, the heterogeneous nature of the natural environment, the partial nature of the available information and the fact that many disorders, after-effects or damage are not repetitive, explain why it is usually impossible to reason by a quantitative probabilistic approach. A qualitative classification is therefore used which characterises the vulnerability of the site to the impact of a particular type of phenomenon. It is therefore this notion that is used for the qualification of the "sinkhole or local collapse” hazard.

So the presence of cavities is associated with a **ground movement hazard** (subsidence, local collapse, etc.), **the risk** is the manifestation of the consequences on surface assets.

Risk = Hazard x assets

Several preventive treatment methods exist to reduce or eliminate the hazard, whether passive (reacting to the formation of sinkholes on the surface) or active (preventing the development of a failure mechanism within the formation). Other methods are designed to reduce structure or infrastructure vulnerability.

Table 2 is an element in the choice of treatment method according to the current or future use of the land (e.g. green space or infrastructure) and the expected results after the treatment (total elimination of the hazard or reduction of the hazard intensity).

The guide (Ineris guide, 2016) provides more information on each treatment method. These guides also include the advantages and disadvantages of each method and their area of application. It inclues :

- **a description of the most commonly used treatment methods**, both in the preventive phase (when the presence of voids is known but subsidence or collapse has not occurred) and in the crisis phase, after collapse (e.g. formation of sinkholes);
- **a description of the decision-making process** with the definition of selection criteria for a securing method;
- **a summary of the main constraints** and precautions to be taken when securing.

It is strongly recommended that these guides be consulted when choosing the most appropriate treatment method.

The choice to implement one or other of these treatment methods depends primarily on:

- the objectives in terms of risk control and site use (to prevent the sinkhole from forming and reaching the surface, to reduce the sinkhole intensity, to reduce damage on the surface);
- the cavity configuration and the type of the surrounding formation;
- the acceptable residual risk on the surface after treatment;
- economic aspects.

Figure 16 is a decision flowchart for the treatment method of an underground cavity presented in Table 2. The first step is to qualify the hazard. The hazard is characterised by geological, geometric and hydrological factors. These factors are used to qualify the hazard. The second step is to qualify the damage to the assets, in particular the impact of sinkholes on socio-economic assets and the environment. Following technical and economic analyses, the best treatment method is adopted.

Table 2 presents the treatment methods ranging from total filling to completely eliminate the "sinkhole" hazard and the measure to prohibit access to the hazard zone by installing a fence. The choice of the method is mainly made according to the surface occupation (assets) and technical and economic considerations. Some methods can mitigate the hazard or its consequences; others can eliminate it completely. Table 2 also mentions the residual risk that may remain after treatment, particularly in terms of small-scale subsidence. Reinforcement using geosynthetic material is one of the methods used to secure the hazard.

Chapter 5 of the document covers the geosynthetic reinforcement method. It describes the product, its use, application cases and the sizing steps.

The purpose of treatment is to reduce the "ground movement" hazard intensity associated with the collapse of underground cavities or/and its consequences on surface assets. The choice of treatment method depends on the hazard level, the surface assets and the acceptable residual movement. This choice also depends on the cost-benefit ratio.

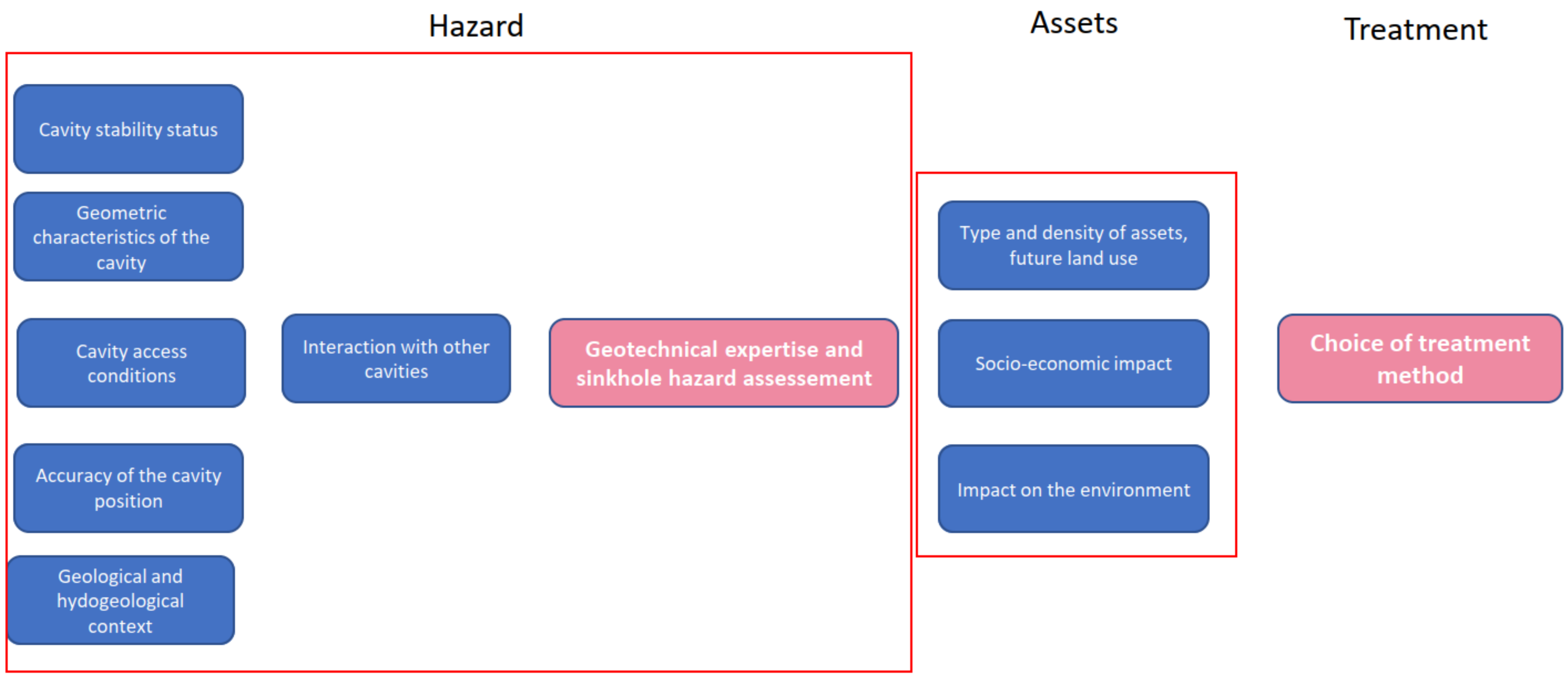


Figure 16 : Decision flowchart for the choice of the treatment method for an underground cavity presented in Table 2

Table 2 : Assistance for the choice of methods to reduce the "sinkhole" hazard (adapted and completed from the Ineris guide, 2016a)

Methods	Surface uses	Technical productions	Consequences	Residual risk
Complete filling of cavities (with or without keying)	• green spaces • roads • existing constructions • new constructions	• from the bottom using mechanised plant • by gravity discharge from the surface • mortar or grout injections • thermosetting foams	Hazard elimination	Subsidence (if no keying)
Consolidation (reinforcement) of cavities	• green spaces • roads • existing and new buildings	Reinforcement and containment of the formation by: • concrete or resin spraying • bolting • construction of artificial pillars / pillar formwork	Reduction of hazard vulnerability	Long-term sinkhole and subsidence
Partial filling of cavities	Green spaces	• from the bottom using mechanised plant • by gravity discharge from the surface	Hazard intensity reduction	Subsidence
Installation of geosynthetic material	• green spaces • roads/railways • standard structure backfill* • services	Geosynthetic reinforcement placed over the cavities with an anchoring system, possibly instrumented	Hazard modification + Reduction of the consequences on structures and infrastructure	Controlled subsidence (possibly no surface subsidence if necessary)

Ground reinforcement or foundation adaptation	New or existing buildings	Piles, micro-piles or rigid inserts from the ground surface created by drilling and filling + injection	Structure and infrastructure vulnerability reduction	Sinkhole / subsidence external to buildings (untreated areas)
Ground improvement Surface foundations with beams Structural reinforcement Rigid inserts	• new constructions • roads • construction backfill	• continuous foundations • reinforced concrete slab or invert		Sinkhole / subsidence - cracks in buildings
Fences (fencing, mesh, etc.)	Restricted green spaces	Fences (fencing, mesh, etc.)	Protection of people	Subsidence / sinkhole

** standard structures: projects in geotechnical category 2 (according to the Eurocodes), i.e. structures that do not present an exceptional risk and are not exposed to difficult ground or load conditions.*

5. Geosynthetic reinforcement

5.1. Physical and mechanical characteristics of geosynthetics

According to the NF EN ISO 10318 standard, geosynthetic (GSY) is a generic term referring to a product, at least one of the components of which is based on a synthetic or natural polymer, in the form of a sheet, strip or three-dimensional structure, used in contact with the ground or with other materials in the geotechnical and civil engineering fields. The main polymers used to manufacture geosynthetics are:

- polyester (PET): UV resistant, filaments, elongation at break about 10%, low creep, if pH < 4 or pH > 9 degradable;
- polypropylene (PP): improved version of PET, filament, elongation at break about 15%, vulnerable to creep, stable for a pH ranging from 2 to 13;
- polyvinyl acetate (PVA): filaments, very high modulus, elongation at break about 7%, low creep, if pH < 4 or pH > 9 degradable;
- aramid (HTA): filaments, very high modulus, elongation at break about 4%, low creep, if pH < 4 or pH > 9 degradable.

A geosynthetic in such applications is characterised mainly by its tensile strength and possibly its puncture resistance. The tensile behaviour of a geosynthetic, determined as per EN ISO 10319, is characterised by the relationship between the tensile force T (force per unit of width expressed in kN/m) and the elongation or deformation ε of the geosynthetic (expressed in percentage). The ultimate tensile strength (also known as the breaking force T_r (kN/m)), the deformation at maximum load (also known as the elongation at break ε_r (%)) are determined using the tensile stress - elongation curve. In addition, the tensile stress - elongation curve can be used to calculate the secant stiffness J of the geosynthetic at elongation ε or over a range of deformation $\varepsilon_1 - \varepsilon_2$, as the ratio of the tensile force T per unit of width (respectively the difference in force T_1-T_2 to the elongation ε or the corresponding deformation range $\varepsilon_1 - \varepsilon_2$ (Figure 17) Different stiffness values can be calculated using the (stress-strain) curve depending on the deformation range.

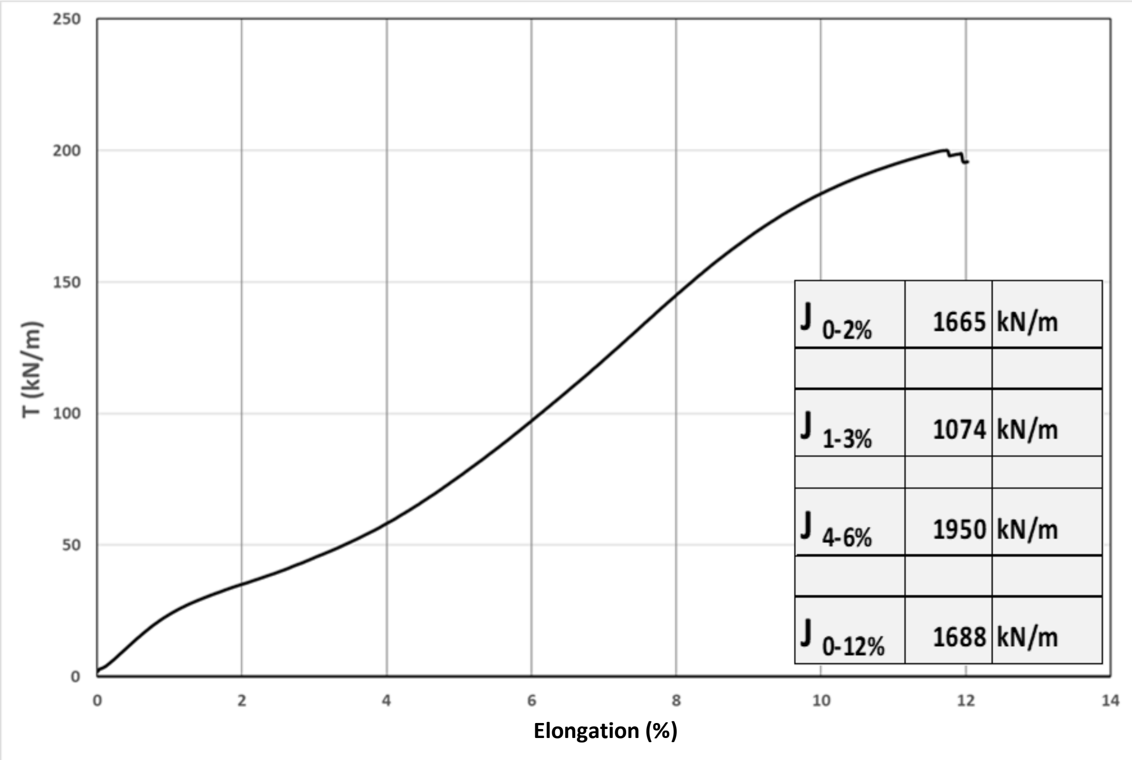


Figure 17 : GSY stress-strain behaviour, example of secant stiffness assessment for two defined stress ranges for a polyester GSY tensile curve - elongation. Source: Afitexinov

Afitexinov has developed an innovative geosynthetic (Patent No. FR3029943 - 2016-06-17) under the name "ground reinforcement geosynthetic with reversed multi-module behaviour", which gives the reinforcement sheet two tensile stiffnesses that activate one after the other; the first being weaker than the second (contrary to the classic "dual-stiffness" geosynthetic for which the first is higher than the second).

Using a knitting technology, sensors can be included in this geotextile as in the previous ones (mono-modules). These are optical fibres (OF) which are inserted into the GSY during production (Figure 18). The inclusion of optical fibres in geosynthetics is a mean of measuring deformations. Associated with this measurement system, the instrumented "reverse dual stiffness" geosynthetic allows to detect the onset of ground layer failure (thanks to the geosynthetic’s lower first stiffness) while guaranteeing the same level of safety as a single stiffness geosynthetic (the second higher stiffness is activated after the deformation threshold required to detect cavity-related movements).

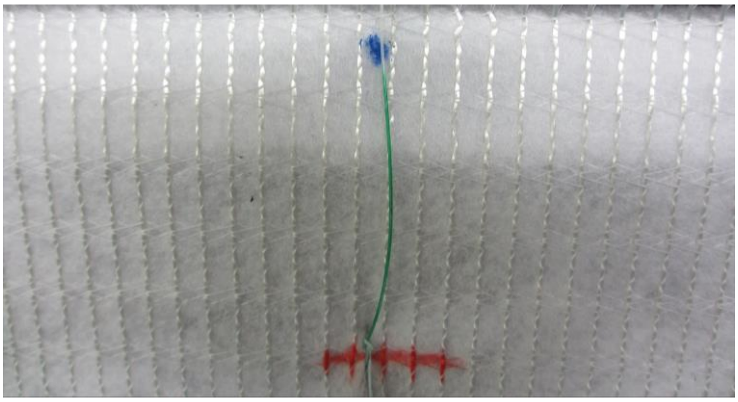


Figure 18 : Insertion of optical fibre (in green) into a reinforcing geosynthetic during production using knitting technology - Source: Afitexinov

Geosynthetics are based on synthetic or natural polymers, in the form of a sheet, strip or three-dimensional structure, used in contact with the ground or with other materials in the geotechnical and civil engineering fields. The geosynthetic is characterised by its tensile strength and possibly its puncture resistance.

Mono-module geosynthetic (mono-stiffness) is characterised by a single stiffness, whereas dual-stiffness geosynthetic is characterised by two stiffnesses, the first being very low allowing to detect the first deformations, and the second being very high, allowing to maintain surface stability and surface structures.

5.2. Objectives and benefits of geosynthetic reinforcement

According to the EN ISO 10318 standard, geosynthetic reinforcement is the result of the mobilisation of the strength-deformation behaviour of a geotextile or a geosynthetic-related product. Geosynthetic reinforcement can be used to improve the mechanical properties of ground or other construction materials. Strengthening using GSY reduces the hazard intensity, protects people and significantly reduces damage to structures and infrastructure (Figure 19). It is used for mitigating cavities in the subsoil where a sinkhole hazard exists. Reinforcement using geosynthetics has a very low environmental impact when compared to other traditional solutions (e.g. reinforced concrete slab/void filling).

Several studies have been conducted to assess the environmental impact of solutions using geosynthetics as a reinforcement system. One example is the study by ETH Zürich (Swiss Federal Institute of Technology) and ESU-services Ltd (https://www.eagm.eu) at the request of EAGM, which presents a series of comparative life cycle assessment studies for various geosynthetic application cases compared to conventional construction methods.

More specifically for reinforcement over cavities, note the study conducted as part of the REGIC project (Riot et al. 2022). It analysed the environmental impact of different backfill construction solutions to solve the problem of building over potential cavities. Among other things, it identified the most influential parameters on the environmental footprint, as well as confirming and quantifying the value of using geosynthetic reinforcement coupled with an autonomous and remote warning system to detect and locate the cavity and monitor the structure.

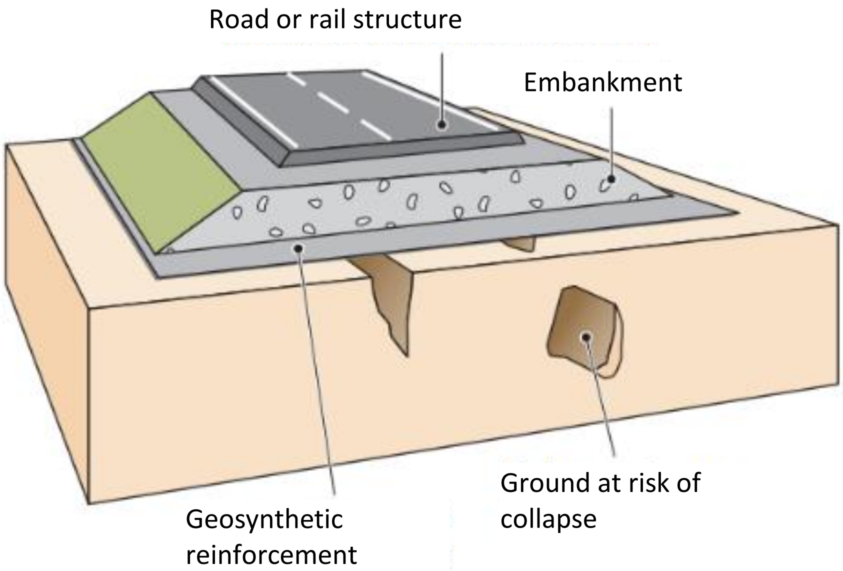
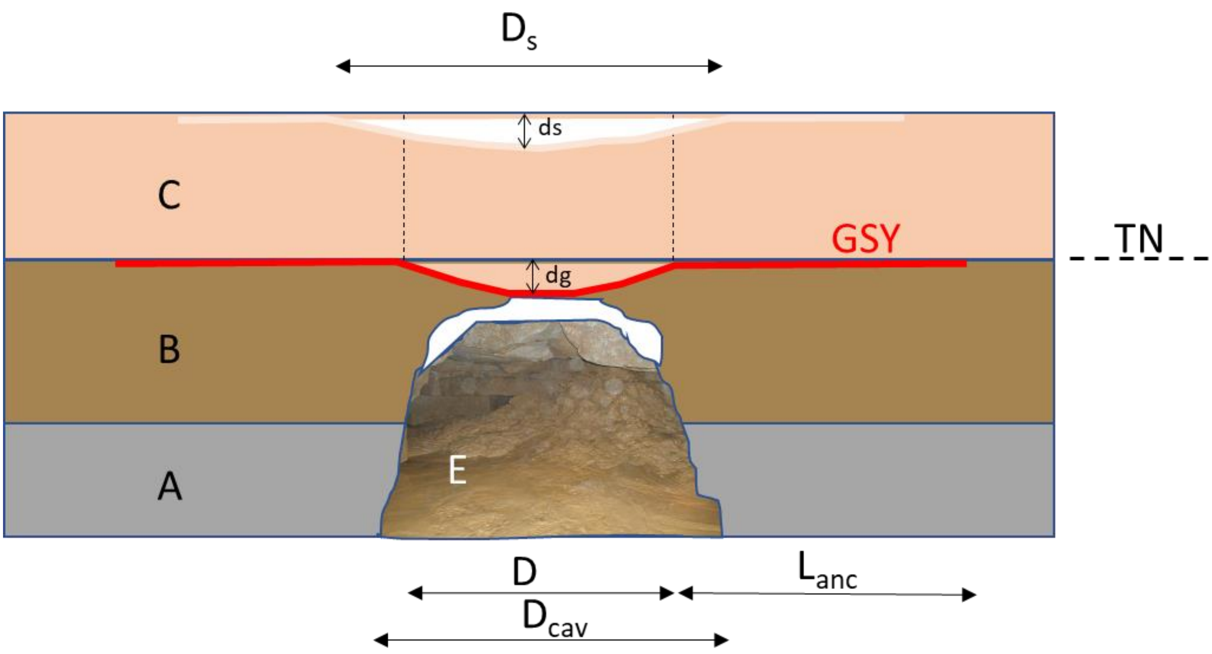


Figure 19 : Application of a geosynthetic reinforcement on cavities - Source: CFG, Le Moniteur, 2015

Provided that the designing rules are respected, the geosynthetic reinforcement can provide temporary safety or safety for the duration of service[3], before the implementation of a final treatment corresponding to the filling of voids in areas where collapses have occurred (guide to natural dissolution of gypsum, Ineris, 2017). In that case, the objective is to provide a preventive-passive reinforcement to stop or limit the sinkhole's progress to the surface. The collapse of an unreinforced cavity could lead to the formation of a sinkhole on the surface. On the other hand, the collapse of a cavity reinforced using geosynthetics leads, if the reinforcement is correctly designed, to a subsidence basin with a settlement amplitude less than or equal to the admissible settlement (d_s) in terms of the impact on surface assets (*Figure 20*). The geosynthetic is stressed and a deflection corresponding to a vertical displacement occurs (dg).

[3] The service life of the structure is defined by the contracting authority or by Eurocode standards and recommendations



A: cavity layer
B: cover
C: backfill
D: sinkhole width or diameter
E: caved-in ground
Ds: width or diameter of surface subsidence

Dcav: width or diameter of the cavity
Lanc: anchoring width
Ds: maximum subsidence amplitude
Dg: maximum geosynthetic deflection
TN: natural ground

Figure 20 : Cross-sectional view - Illustration of a geosynthetic installed over a cavity - Source: Ineris

The geosynthetics currently available in the market are mostly used for cavities having a diameter < 5 m. Beyond 5 m, GSYs may not meet current designing requirements. Large-diameter (>5 m) sinkholes are less frequent, as shown by the example of sinkhole data observed in the Paris region (Figure 10).

For an "instrumented" geosynthetics, i.e. equipped with optical fibres associated with an appropriate monitoring system, a second objective for the use of geosynthetic is the detection of sinkhole propagation towards the surface, thanks to the measurement of the cover deformations, before the sinkhole roof arrives at the GSY level.

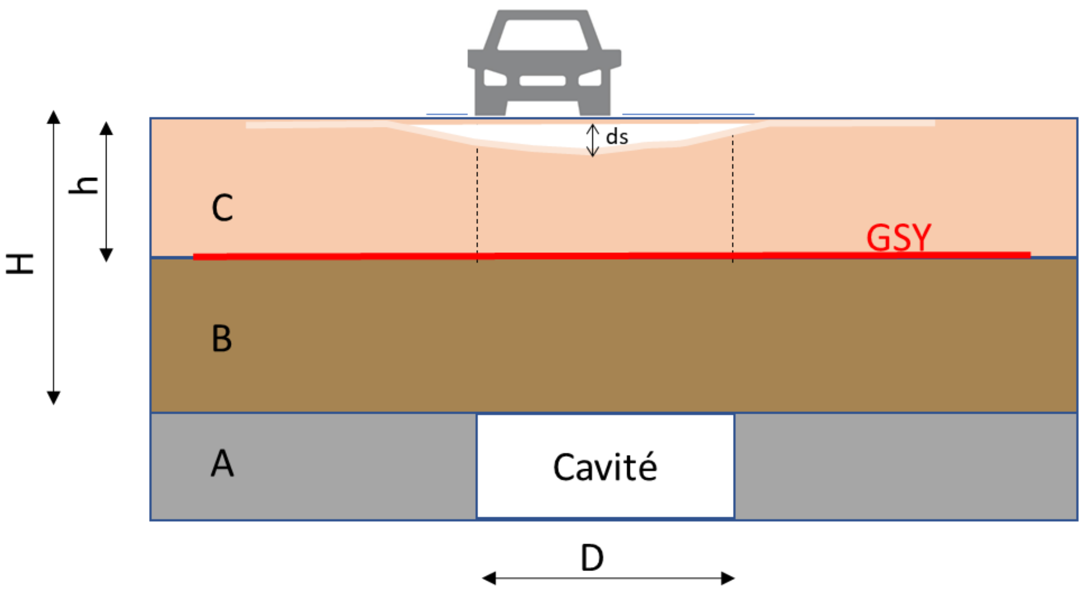
The two photos in Figure 21, below, show a live example of the impact of the solution at the Trois-Luc site in Valentine (Delmas and Gourc, 2017). This case shows the benefit of the reinforcement, which, when mobilised, allows for low amplitude subsidence.

Figure 21 : Subsidence obtained in 2015 over an area reinforced using geosynthetic - Source: Trois Luc in La Valentine, Delmas and Gourc, 2017

Reinforcement using GSY reduces the intensity of "ground movement" hazards, protects people, and significantly reduces damage to structures and infrastructure. "Instrumented" geosynthetic, equipped with optical fibres associated with an appropriate monitoring system, allows the detection of the propagation of sinkholes towards the surface thanks to the measurement of the cover deformations before the sinkhole reaches the GSY.

5.3. Examples of GSY applications

Table 3 shows some examples of the use of geosynthetics as a solution to reduce sinkhole hazards. These cases show the different geosynthetic reinforcement possibilities for ground over areas prone to cave-ins. The main geometric information characterising the structure or infrastructure, the cavity and the geosynthetic was filled in as best as possible (Figure 22).



h: thickness of the backfill / GSY position
H: cavity depth
Ds: permissible surface settlement

A: cavity layer
B: cover
C: backfill
Nature of the surface structure

D: cavity width/diameter
GSY: polymer, tensile strength, anchoring

Figure 22 : Main parameters collected for application case analysis - Source: Ineris

In the cases presented below, the geosynthetic was mobilised during a collapse that occurred after the geosynthetic had been installed (e.g. Trois Lucs in La Valentine). It should be noted, however, that few cases of reinforcement refer to an instrumented geosynthetic. The following observations can be made:

- The application cases concern both natural cavities (karstic cavities) and man-made cavities (mines and quarries).
- The assets concerned are major infrastructures (motorways, roads, railways) and public spaces (parks and car parks).
- The diameter of potential sinkholes is less than 6 m (the only 6 m recorded case is a park). It should be noted that this diameter is greater than the limit recommended in this document; the main objective in this case is to reduce the risk of people falling into sinkholes. Surface settlement is not the main objective here.
- The initial cavity depth is rarely mentioned in the sources.
- Geosynthetics are mostly used before the formation of sinkholes, sometimes combined with other treatment methods such as cavity backfilling. It is also sometimes used to secure the surface after the formation of sinkholes.

Table 3 : Examples of geosynthetic applications over natural and man-made cavities (NF: data not provided)

PP: polypropylene geosynthetic; PET: polyester geosynthetic;

d_s: permissible surface settlement

Site	Infrastructure	Cavity			Geosynthetic / infrastructure				Remarks/authors
		Type	Diameter (m)	Depth (m)	d_s (cm)	Polymer/ strength (kN/m)	Backfill height (m)	Anchoring (m)	
Montbéliard	A36 Motorway	Karst	0,8	Variables	0,2	PET/300	1	2	Several cavities - Riot and al., 2013
Kukruse (Estonia)	E20 Motorway	Mine	4	3 to 14	16	PET/1350/ 135	2	Horizontal	Cracks and cavities found on the site. Auray and Garcin, 2010
Glan Liyn (UK)	A55-E22	Karst	Variables	1 to 10	NF	NF /150	0,50	NF	Nichol, 1998
Tunis	A3 Motorway	Karst	2 à 4	NF	NF	NF	0,80	NF	Several cave-ins before the works. Zaghouani, 2017
Paris-Vendenheim	LGV-Est	Karst	0,5 (fissures)	Variables	0,1	PP/75/75	0,5 - 1,05	2 m	Exbrayat and Garcin, 2006
St Lô	RN 174		3		15	PP/200	1,17	1m	Jaffrot and al., 2009

Meaux	A140-RD5	Quarries	2	20 - 40	10	HTA-PP/190	1	Horizontal	Blivet and al., 2006
Trois Lucs à la Valentine	Road	Mine	2	18		HTA-PET/200	NF	Trench	Several local collapses. Delmas, 2017
Gauteng South Africa)	Road N14-P158	Karst	NF	NF	NF	PC/100-100	0,5	Horizontal	After subsidence. Kaytech, 2006
Arras	Square	Chalk Quarries	4	14 - 20	20	PET/1800	1	Trench	Abdelouhab and al., 2018
Vitry-sur-Seine	Parc	Carrière	6	45	Important	PET/625	< 0,50	Variables	General subsidence. Dubreucq and al, 2006
Lille	Parc	Quarry - Chalk mine	2	8 - 15	15	1550	0,50	5	Masonry chalk mine head. Hassoun and al, 2017
Fife (UK)	Embankment - Park	Mine	4	15	NF	PET/500-50	2,75	NF	2 layers were used, one perpendicular to the other. TenCate, 2012

5.4. Geosynthetic reinforcement fields of application

In the following part of the document, the "Treatment" part of Figure 16 is indicated, i.e. an approach is proposed to choose between two treatment method configurations using a geosynthetic or another treatment method such as partial or total filling (Figure 23). This figure also indicates the choice of monitoring (observational and/or instrumental) in the absence of total cavity filling. Two configurations can be differentiated according to the objectives for securing the cavity:

- **Configuration 1:** treatment where the cavities are well known and less than 5m in diameter;
- **Configuration 2:** treatment where the cavities are difficult to locate or unknown or in cases of known cavities of a diameter greater than 5 m. In that case, measurements of the geosynthetic deformation and of the ground movements make it possible to locate the cavity and to anticipate possible serious consequences on structures and infrastructure. There are two sub-configurations depending on the extent of ground movement under the geosynthetic (Figure 23):
    - relatively small movements (for example for a cavity of a diameter ≤ 4 m, exceptionally ≤ 5m), in that case the geosynthetic ensures the stability of the infrastructure and its instrumentation is used to monitor the structure;
    - for large-scale movements (e.g. cavity or collapse size greater than 5m), the geosynthetic reinforcement solution is not appropriate to stabilise the infrastructure. The instrumented geosynthetic (without reinforcement function) can be used to measure the progression of ground deformations and detect the rise of unlocated cavities to avoid costly or unplanned treatment following a ground movement. In that case, it would make it possible to locate the cavity based on an assessment of the geosynthetic deformations. If the movements exceed the threshold values, further cavity treatment should be planned (e.g. filling, or other, see Table 3).

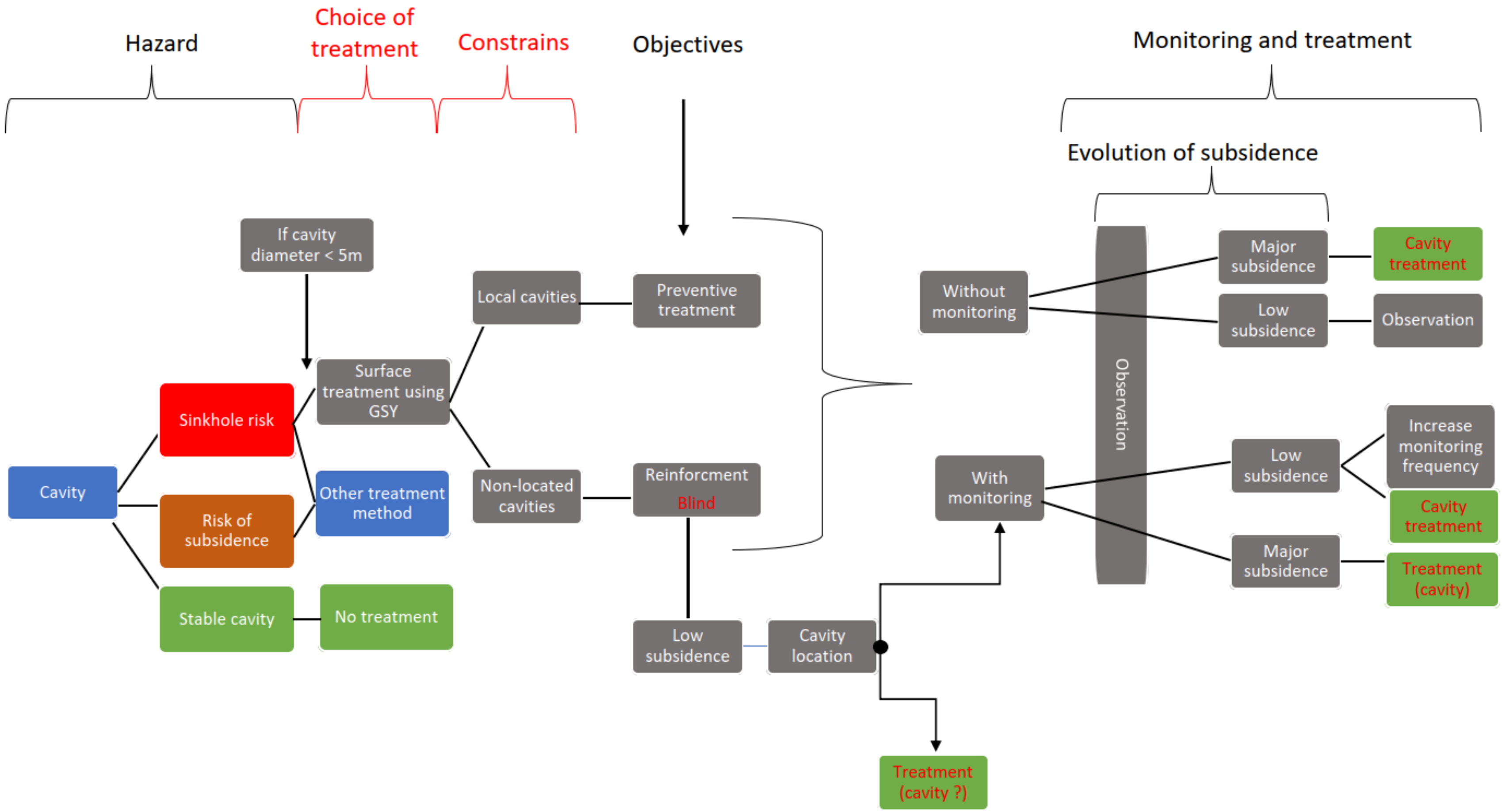


Figure 23 : Approach to choosing a suitable treatment method - Source: Ineris

Table 4 : Use of GSY depending on the the assets and whether the GSY is instrumented or not

Assets and risks		**GSY type and objectives**		**Treatment**	
Type	**Examples**	**Type**	**Objectives**	**Short-term actions**	**Long-term actions**
Limited	**Forests, low-traffic areas, paths, etc.**	Instrumented	Monitor deformation	Strengthening of GSY monitoring	If necessary, review the GSY reinforcement Partial or total filling of the cavity if necessary
		Not instrumented	Observations of surface MVT Calculation check	Implementation of a monitoring system for the structure	If necessary, review the GSY reinforcement Partial or total filling of the cavity if necessary
High	**Transport infrastructure**	Instrumented	Monitor GSY deformations	Strengthening of GSY monitoring	If necessary, review the GSY reinforcement Partial or total filling of the cavity if necessary
		Not instrumented	Monitor structure or infrastructure deformations	Set up a monitoring system for the structure or infrastructure Cavity filling if necessary	Cavity filling if necessary

5.5. Operating principle of GSY reinforced ground

Figure 24 shows the operating principle of geosynthetic reinforced ground from its installation to the moment after the formation of a sinkhole. The main operating periods are as follows (Delmas et al., 2015):

- **period (I):** installation of the geosynthetic on the natural ground and construction of the structure; the geosynthetic is only subject to the possible stresses and strains of installation;
- **period (II):** the cavity has not yet risen to the surface and the structure rests on the cover layer;
- **period (III)** is the cavity opening phase at the geosynthetic level until the nominal dimension is reached; this phase can be sudden, but also extend over a more or less long period during which the lateral collapse of the cavity walls occurs; the geosynthetic is tensioned over the cavity and laterally in the anchoring zones; due to the expansion properties of the backfill soil, the settlement of the structure on the surface only appears when the cavity diameter has reached a certain size, before the cavity is not detectable on the surface;
- **finally, at the beginning of period (IV),** the cavity has reached its final geometry until the end of the infrastructure's service life; this may correspond either to the planned infrastructure service life (e.g. 100 years) or to the time required for the reinforcement and repair of the infrastructure once the cavity has risen to the surface (generally a few months, at the most a few years); under the effect of the loading of the structure and the traffic, the geotextile is maintained tensioned; it is then subjected to creep in addition to the actions linked to the ground's chemical environment; this results in a deformation of the geotextile which leads to an increase in its deflection and thus the settlement of the structure on the surface.

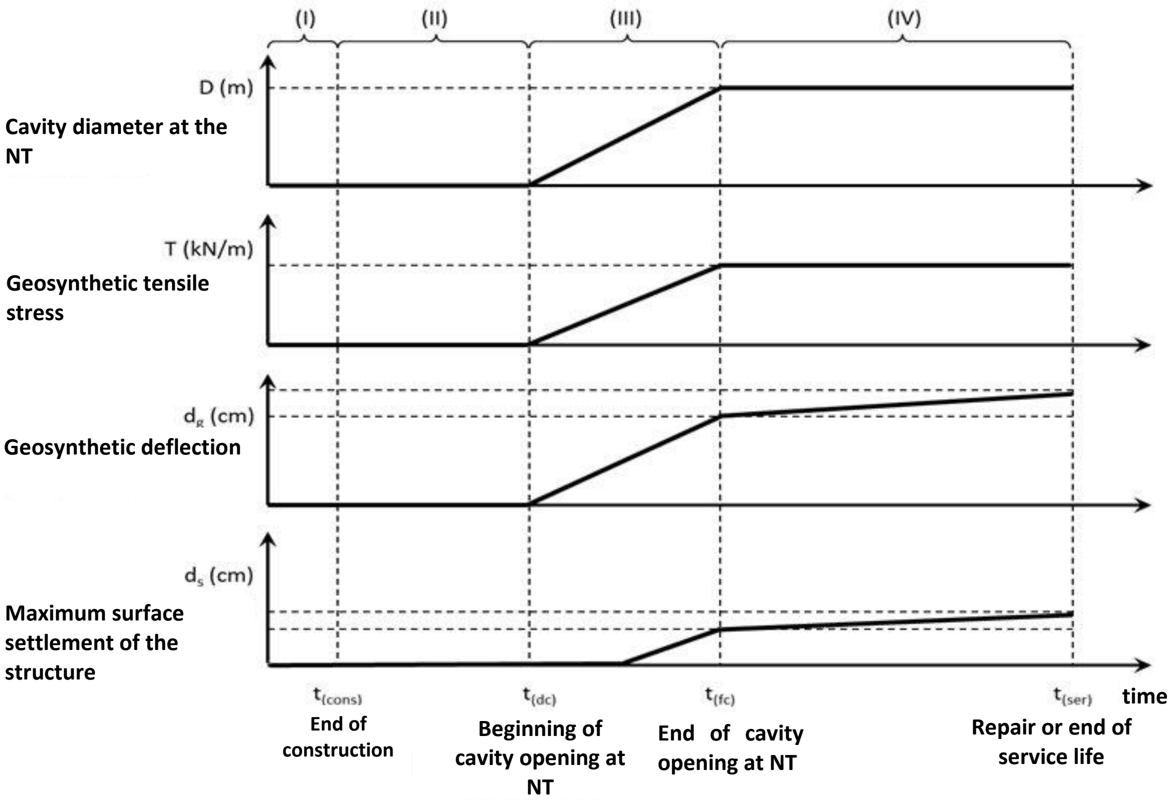


Figure 24 : Principle of operation of a geosynthetic reinforced soil, before and after the cavity has risen - Source: Delmas et al. 2015

When the collapse meets the geosynthetic, it begins to tension above the cavity and laterally in the anchoring areas. The surface structure settlement only occurs when the collapse diameter reaches a certain size, before that, the cavity is not detectable on the surface. When the cavity has reached its final geometry and under the effect of the structure and traffic load, the geosynthetic is kept tensioned and subjected to a deformation which leads to an increase in its deflection and thus to the surface settlement of the structure.

5.6. Basic reinforcement mechanisms

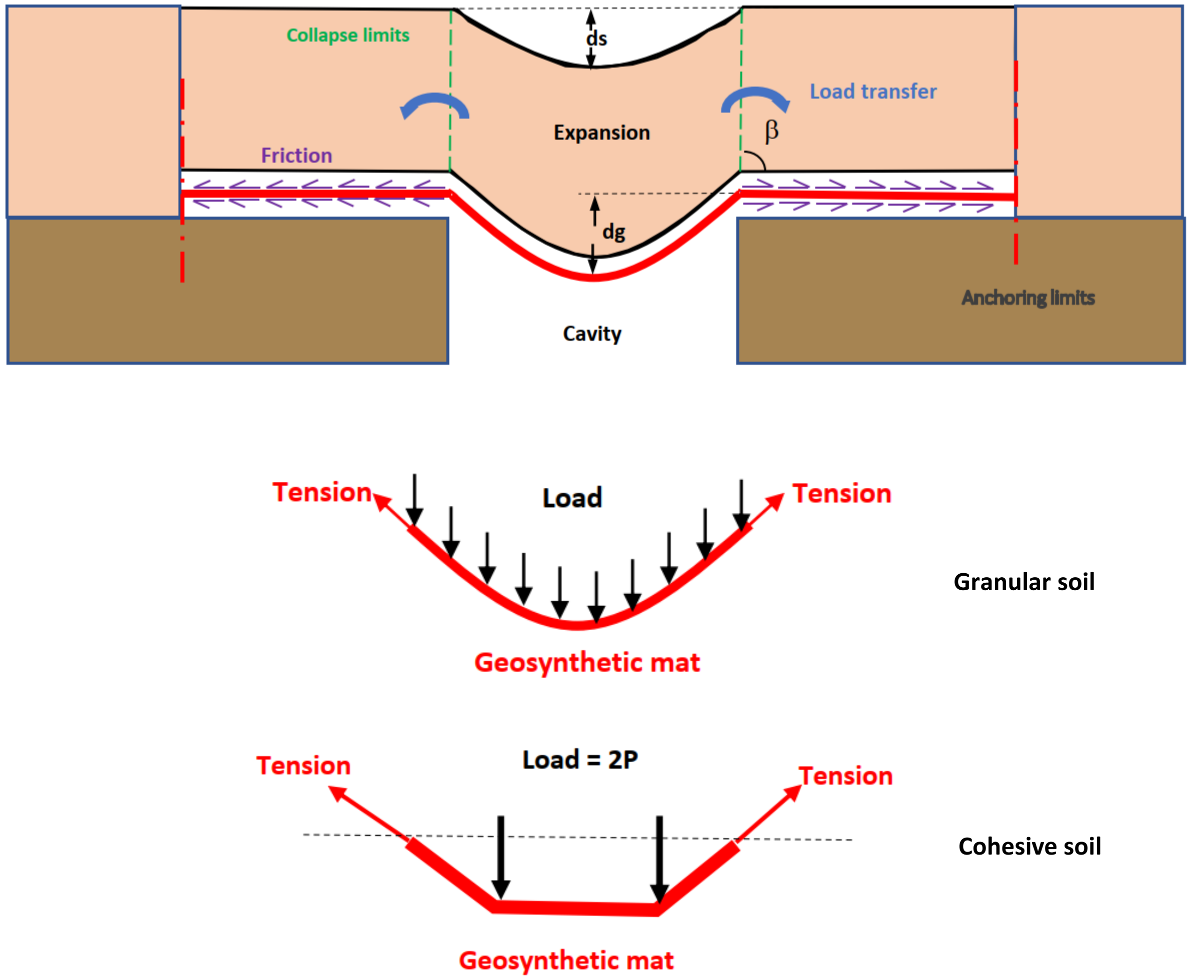
Figure 25 illustrates the basic principles of geosynthetic reinforcement over a cavity, which allows it to be tensioned after the formation of an underlying cavity and Figure 26 illustrates the tensioning of the geosynthetic following its loading by the backfill over the cavity.

When the cavity rises to the base of the geosynthetic (corresponding to periods II and III of Figure 24), the geosynthetic prevents the ground and the structures and infrastructure collapsing into the cavity. Under the effect of loads (embankment, road, or even traffic loads), the geosynthetic will deform like a membrane over the cavity (Figure 25). The membrane effect corresponds to the sheet deformation mechanism which bends to balance the forces it supports above the void thanks to its tensioning.

There are two behaviours depending on the type of ground over the geosynthetic: that of a granular soil where the load is spread more or less evenly over the geosynthetic, and that of a cohesive soil where the load is more concentrated and local (2P) following the collapse of blocks of ground on the geosynthetic sheet.

For granular ground, the area of ground collapsed onto the sheet is close to a cylinder, the angle β varies between 85° and 95° depending on the backfill type. It is generally taken to be 90° in sizing methods. During this subsidence phenomenon over the cavity, the underlying ground will deform leading to settlement of the surface structure (d_s). The backfill expands, the surface settlement (d_s) is equal to or less than the geosynthetic deflection (d_g). For cohesive ground, the ground failure corresponds to blocks of which the shape and size depend on the ground type, the backfill thickness and the loading method.

There are two available sizing methods, one for granular ground based on the RAFAEL project results, and one for cohesive or treated soil based on the REGIC project work.



d_g: deflection of the geosynthetic; ds: surface settlement; β: collapse limit angle.

2P: two linear vertical forces acting on the central geosynthetic strip

Figure 25 : Principle diagram of geosynthetic cavity reinforcement and the membrane effect - Source: Hassoun et al. 2018 amended

The tensile stresses required for the stability of the geosynthetic membrane are balanced by a progressive mobilisation of the anchoring on either side of the cavity (Figure 25). Ground-geosynthetic friction is then decisive to make sure the reinforcement functions, insofar as it is the relative movements of the covering ground and the backfill which allow the mobilisation of tangential forces and which finally lead to its tensioning and ensure its anchoring.

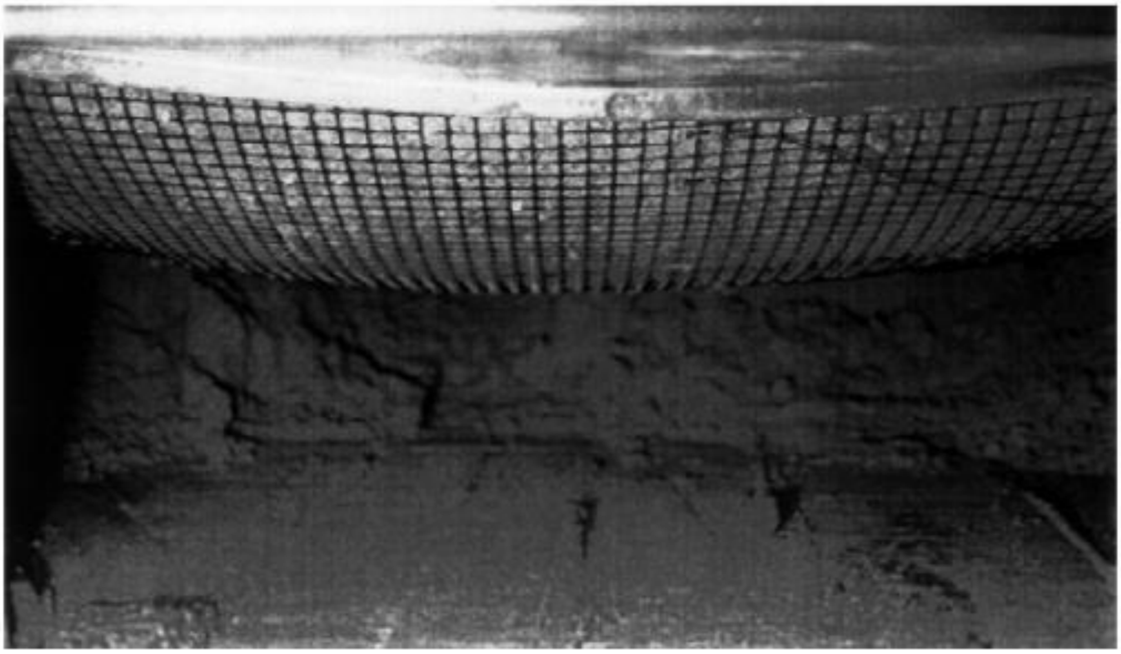


Figure 26 : Geosynthetic tensioning after the collapse of the ground over the cavity - Source: Bridle and Jenner, 1997

6. Geosynthetic design method principle

In France, the design methods for reinforcement using geosynthetics are defined relative to the NF EN 1990 standard, in terms of action combinations (AC), safety classes (SC), and load cases (LC). Reinforcement should be selected to make sure serviceability is maintained and that the ultimate limit state does not occur. Thus, the presence of reinforcement must meet the structure's serviceability limit states (SLS)[4] and ultimate limit states (ULS)[5]. The purpose of the serviceability limit state check is to make sure the surface settlement remains acceptable after the opening of the cavity and the tensioning of the geosynthetic.

The XP G38065 standard covering to the design and sizing of the reinforcement of the base of embankments (granular soil) in areas at risk of collapse using geosynthetics, taking into account recent developments in this field, has just been adopted (Nancey and Delmas, 2019). The sizing of geosynthetic reinforcement on cavities uses the ultimate and serviceability limit states approach as defined in the Eurocodes (NF EN1997-1).

The methods proposed for geosynthetic sizing are derived from those developed for granular ground during the RAFAEL research programme (Gourc et al., 1999) and improved by (Villard and Briançon, 2008), and from the work carried out as part of the GEO-INNOV research project (Huckert et al., 2016) for cohesive ground. Improvements to both methods have been made by the REGIC project (Hassoun, 2018).

Geosynthetic reinforcement must be selected to make sure the serviceability of the surface structures is maintained and that the ultimate limit state does not occur.

6.1. Geosynthetic reinforcement solution design approach using detection/auscultation

The proposed approach for the design of a geosynthetic reinforcement solution with detection/auscultation under threat from natural or man-made cavities is shown in Figure 23. It can be summarised by the following steps:

1. **Assessment and characterisation of the potential collapse type:**
    - risk of subsidence, sinkholes, stable cavity;
    - size and shape of the subsidence or sinkhole in the case of a rise;

[4] The ultimate limit states are the limit of mechanical strength beyond which the structure will fail.

[5] Serviceability limit states are the criteria of which the non-fulfilment does not allow the element to be operated in satisfactory conditions or compromises its durability.

- known or unknown cavity location.

2. **Choice of the infrastructure reinforcement objective using geosynthetics:**
   - "temporary" treatment after the cavity has risen, pending the final treatment (short term);
   - "permanent" (long-term), typically for a service life of 100 years after the geosynthetic has been installed.
3. **Definition of the maximum permissible surface subsidence to maintain infrastructure operation;**
4. **Definition and sizing of the instrumented geosynthetic:**
   - to meet the infrastructure ULS and SLS stability requirements: mechanical stability, maximum permissible surface subsidence;
   - to meet the requirements of fibre optic instrumentation (fibre type and spacing, possibly choice of dual-stiffness, layout, connections);
5. **Monitoring system design (detection/acquisition)** adapted to the infrastructure requirements, the collapse type and the chosen geosynthetic.

Item 1 is a prerequisite for the following items, items 1, 2 to 3 are the contracting authority's responsibility and must be the subject of an appropriate geotechnical study as per the NFP 94500 standard and must be finalised before items 4 and 5 are addressed.

6.2. Cavity rise mechanism

The cavity exists in the subsoil, it may become unstable and it progress until it comes into contact with the GSY. The rise of sinkholes to the surface depends on the cavity's geometric shape and the type of cover ground over and under the geosynthetic. There are two types of covering ground (Figure 27). The first type (a) is strong and fractured ground, the bell shape is more parabolic, of a diameter (D) in contact with the geosynthetic that is smaller than that of the cavity (D_{cav}). The second type is that of soft ground (Figure 27b) with low cohesion, the bell shape is generally cylindrical. The cavity diameter (D_{cav}) is generally equal to its diameter at the geosynthetic base (D). The rupture shape may be modified and asymmetrical depending on the slope of the land, the presence of significant discontinuities and the surface loads applied to part of the cavity surface. The geometric and geological data must be taken into account to assess the rising sinkhole geometry. The surface sinkhole diameter (Ds) is usually equal to or slightly larger than the cavity diameter (D) in contact with the geosynthetic. It is often taken to be equal to the cavity diameter (D).

It should be remembered that current sizing methods consider that the cavity is in a horizontal layer and that the rise of the sinkholes develops vertically above the cavity. For other configurations, a specific study is required to take into account the specificities of each situation.

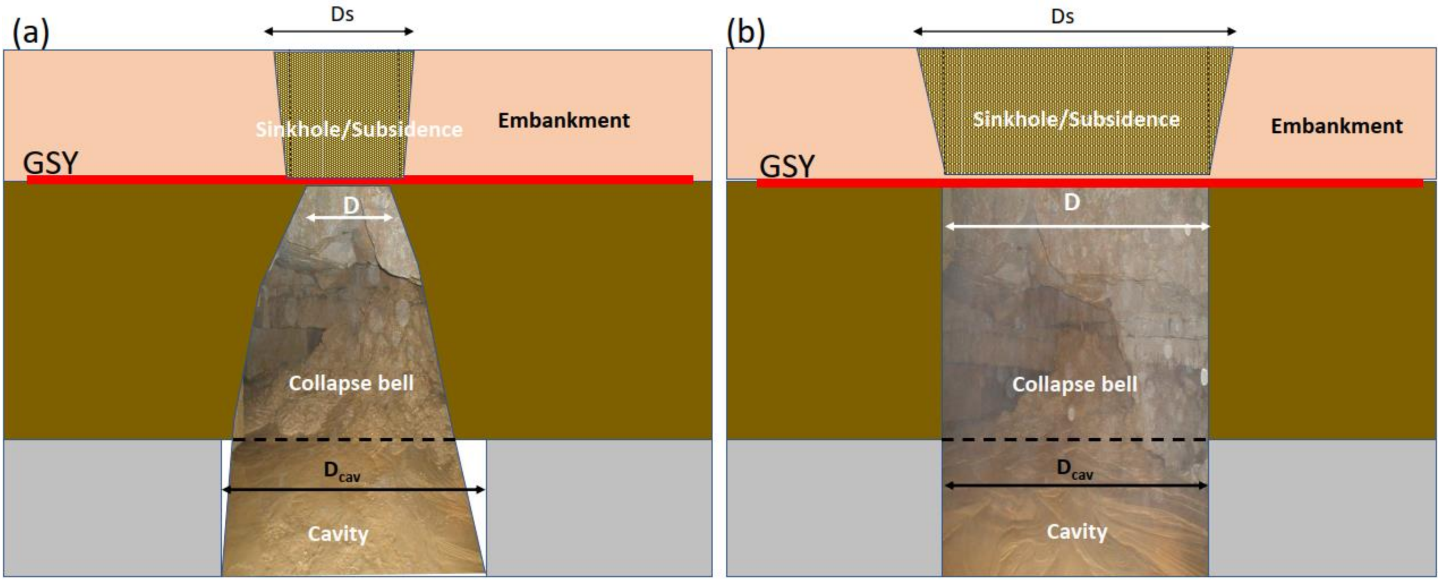
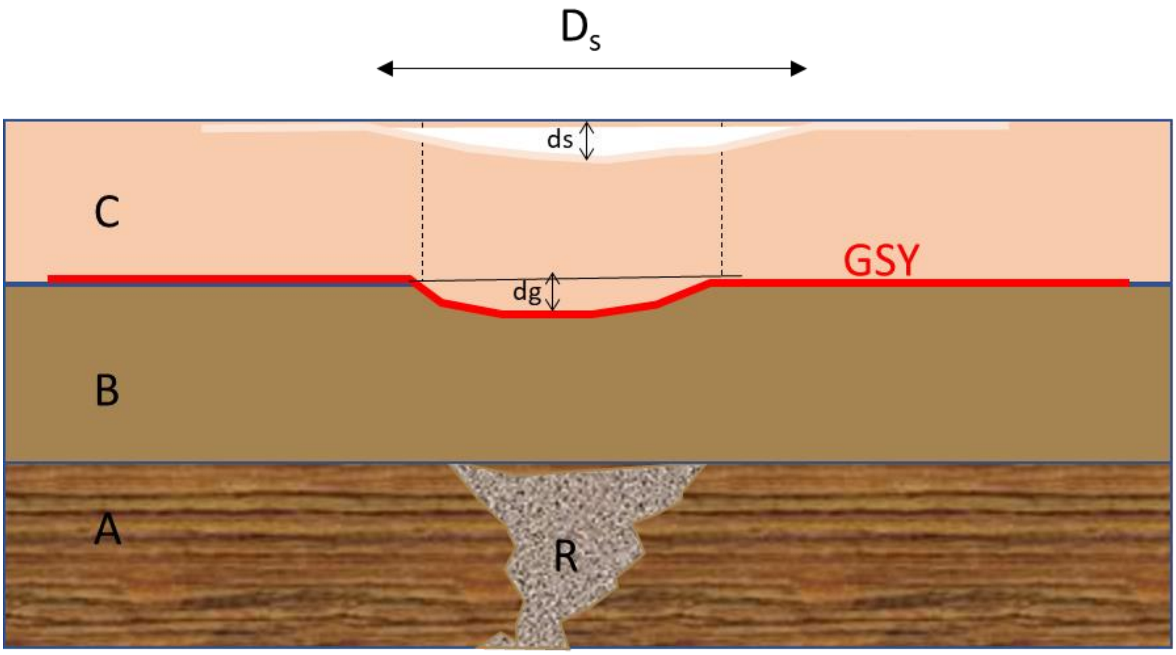


Figure 27 : Types of sinkhole rise (collapse bell) and cratering on the surface depending on the type of overlying ground (a: strong and fractured, b: loose) - Source: Ineris

For natural cavities (gypsum or karst cavities), it is often difficult to know the precise location and dimensions of the cavities relative to the structure or infrastructure to be protected on the surface. In that case, geological and geotechnical investigations of the area concerned are required (guide to natural gypsum dissolution, Ineris, 2017). Figure 28 typically corresponds to the case of a karst network. The karst chimney rise develops in the karst terrain up to the surface ground or to the embankment.



A: karst terrain
B: cover

C: land or embankment
R: karst chimney rise

Figure 28 : Sinkhole rises in karst networks - Source: Ineris

6.3. Reinforcement sizing parameters

Current analytical sizing methods are based on observations, experiments (in situ and laboratory) and digital simulations. They most often use the same geosynthetic behaviour on cavity analysis. The sizing is carried out on the central strip of the sheet suffering the most strain (the geosynthetic is then considered mono-directional). Depending on the case (granular or cohesive ground), the load intensity and geometry (even. occasional, etc.) must be estimated. Geosynthetic reinforcement over a cavity can reach destruction either:

- by the rupture of the geosynthetic,
- or by the breakage or slippage of the anchoring,

which occur:

- due to insufficient geosynthetic tensile strength,
- due to insufficient anchoring shear strength,
- due to deterioration caused by the presence of angular blocks,
- or by excessive overshooting of geosynthetic deformation.

To apply these methods the following must be determined successively:

- the cavity diameter and the cavity rise mechanism to the surface,
- the permissible surface subsidence,
- the load (q) acting on the geosynthetic,
- the induced tensions (T_{max}) and the maximum geosynthetic deflection (dg),
- the corresponding surface settlement (d_s), which can be decisive for the assessment of the GSY characteristics,
- and the type and length of anchoring required to ensure the stability of the reinforced structure.

They require successive iterations on the geosynthetic stiffness to achieve the required surface settlement (d_s).

The sizing method must indicate:

- **the cavity diameter and the cavity rise mechanism to the surface,**
- **the permissible surface subsidence,**
- **the load (q) on the geosynthetic and the induced geosynthetic tension (T_max) and maximum deflection (dg),**
- **and the anchoring type and length.**

6.3.1. Permissible subsidence

An important parameter in geosynthetic sizing is the permissible surface subsidence value (d_s) if a cavity caves in. This value is defined according to the infrastructure's operating constraints: the maximum permissible settlement is the settlement that allows the infrastructure to continue to operate, even if reduced. The calculated settlement value must be less than or equal to the permissible settlement.

Table 5 gives examples of the order of magnitude of the ratio d_s/D_s for maximum subsidence (d_s) depending on the subsidence basin diameter D_s. The surface settlement is calculated using the thickness and expansion ratio of the ground above the geosynthetic and the maximum geosynthetic deflection.

Table 5 : Permissible movement $d_{s,adm}$ depending on the project type - Source: Standard -XP G38065 (Ds is the cavity diameter)

Project type	Examples of values from d_s/D_s.	d_s (cm) for D_s = 5 m
Railway tracks	0 %	0
Motorways (High speeds)	$1{,}0\% \leq {d_s}/{D_s} \leq 1{,}7\%$	5 à 8,5
Secondary roads (low speeds)	$1{,}7\% \leq {d_s}/{D_s} \leq 2{,}5\%$	8,5 à 12,5
Other urban roads, car parks, etc.	$2{,}5\% \leq {d_s}/{D_s} \leq 7\%$	12,5 à 35
Parks and pedestrian areas	${d_s}/{D_s} \leq 10{,}0\%$	< 50

Examples of the order of magnitude of permissible settlement and permissible differential settlement for different infrastructures are given in Table 6. The settlement to be taken into account is the movement $d_{s,\ adm}$ at the centre of the settlement basin (Table 5).

Table 6 : Settlement and permissible differential settlement for different types of construction as per the NF P94-261 standard

Buidling type	Permissible settlement (mm)	Permissible differential settlement
For most structure (SLS)	50	1/500
For an open frame (SLS)	50	1/300 à 1/2000
For most structures (ULS)	100	1/150

It should be noted that the NCB (National Coal Board) empirical method first estimates the amount of deformation the geosynthetic is likely to suffer. The table in Appendix A provides a first estimate of subsidence-related deformations depending on cavity depth and the magnitude of ground subsidence at the surface. The depth and subsidence values were selected based on the characteristics of cavities likely to collapse.

6.3.2. Load acting on the geosynthetic

The action of the backfill on the geosynthetic greatly depends on the type of backfill and how the cavity opens. The load taken into account in the sizing, corresponding to the actions of the collapsed ground and the surcharge, acts on the central strip of the geosynthetic. According to this assumption, it is 2D sizing.

There are two cases of ground over the GSY, granular ground and cohesive ground:

For granular (non cohesive) **ground**, based on observations on full-scale experimental sites (Gourc et al., 1999; Huckert et al., 2013; Huckert, 2014) and methods commonly used in France and in some countries (RAFAEL project (Blivet et al., 2001), EBGEO (2011) and NF P G38065), it is accepted that the collapse zone in the backfill is approximately a vertical cylinder (D_s = D). The model proposed by Terzaghi (1943) is representative of granular ground behaviour over reinforced cavities, with proper consideration of lateral thrust. This assumes a transfer of part of the loads from the ground formation above the cavity to the lateral edges through ground shear mechanisms or vault effects. The Terzaghi model (1943) thus allows the stress above the geosynthetic to be assessed. This model takes into account the cavity geometry, the backfill thickness, the ground friction angle and the ground thrust coefficient. In the light of the observed experimental results, the XP G38065 standard considers that the sheet deformation is parabolic when it is put under tension, which leads us to consider a uniform distribution of vertical stresses on the sheet (Figure 5).

For cohesive soils: for a cohesive backfill (clay, silt) corresponding to a natural or treated ground, (using lime or cement[6]), and of which the behaviour depends on water content, layer thickness and surface load. Currently, the analytical approach proposed by Huckert et al. (2016) proposes geosynthetic sizing for cohesive soil. This model was developed by Huckert as part of the GeoInov project and validated by model tests as part of the REGIC project (Hassoun, 2018). The grounds used in the REGIC and GeoInov projects are characterised by sufficient cohesion to ensure the stability of the backfill in the absence of an external load. Ground failure is achieved by applying an overload (q) to the backfill surface. The geometry of the failure mechanisms depends on the cavity shape (2D and 3D). For linear cavities (trenches), it is assumed that the ground above the geosynthetic collapses in blocks, especially when the overload is on the surface. Collapsed blocks are considered rigid and non-deformable. The weight of the collapsed ground blocks and the geosynthetic overload on the surface are replaced by two linear vertical forces (2P) defined per metre of geosynthetic width (Figure 29). For a circular cavity, equivalent spot forces acting on the central band of the geosynthetic above the cavity must be determined.

[6] For more information, see for example the Good practice code for the treatment of ground using lime and/or hydraulic binders - Centre de Recherches Routières - Recommendations 81/10 - 2009

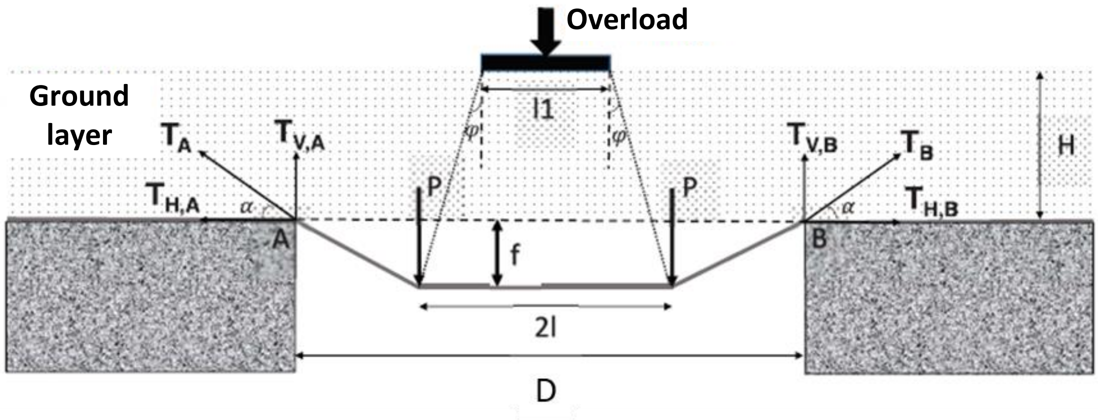


Figure 29 : Balance of forces exerted on the geosynthetic over the cavity in the case of cohesive soil - Source: Huckert et al. 2016

To be able to use the Huckert model for a cohesive soil, the weight of the collapsed block(s) on the geosynthetic must be determined. The determination of the geometry of these blocks is mainly based on the results of the in-situ tests carried out by Huckert as part of the GeoInov project and those carried out in the laboratory by Hassoun (2018) as part of the REGIC project.

The maximum deflection d_g and the maximum tension T_{max}, are determined using a geosynthetic behaviour law (Figure 17). The calculation of the maximum geosynthetic deflection is related to the maximum permissible settlement, the thickness of the ground layer over the geosynthetic layer and the expansion. The maximum permissible deformation is determined based on the GSY deformation shape.

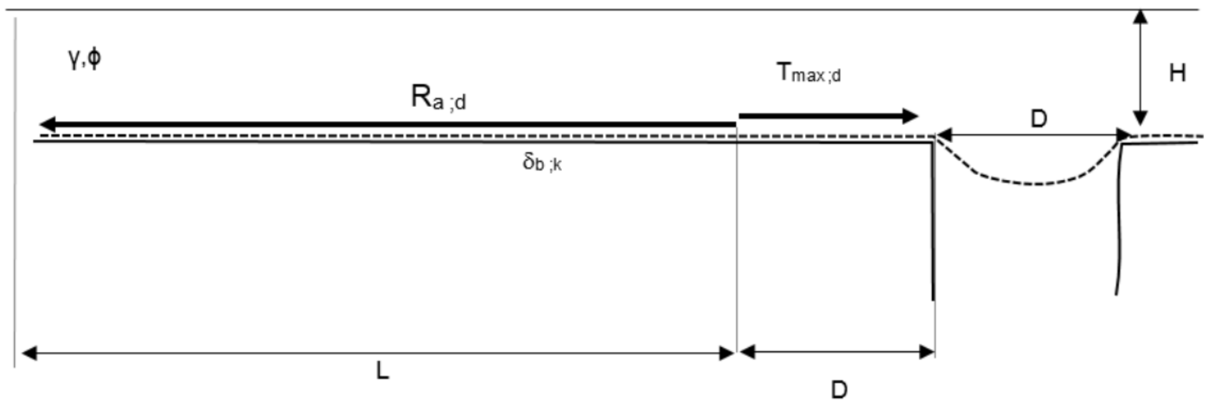
6.3.3. Anchoring and overlap sizing

The tensile stresses required for the stability of the geosynthetic membrane are balanced by progressive mobilisation of the anchors on both sides of the cavity. Two anchoring principles can be considered (Figure 30-a and Figure 30-b): flat anchoring or trench anchoring (presented in appendix C of standard XP G38-065). The choice of anchoring type depends on the ground-geosynthetic interface types as well as the site geometry and the available surfaces. The geosynthetic anchorage length is limited to the available space which depends on the backfill geometry.

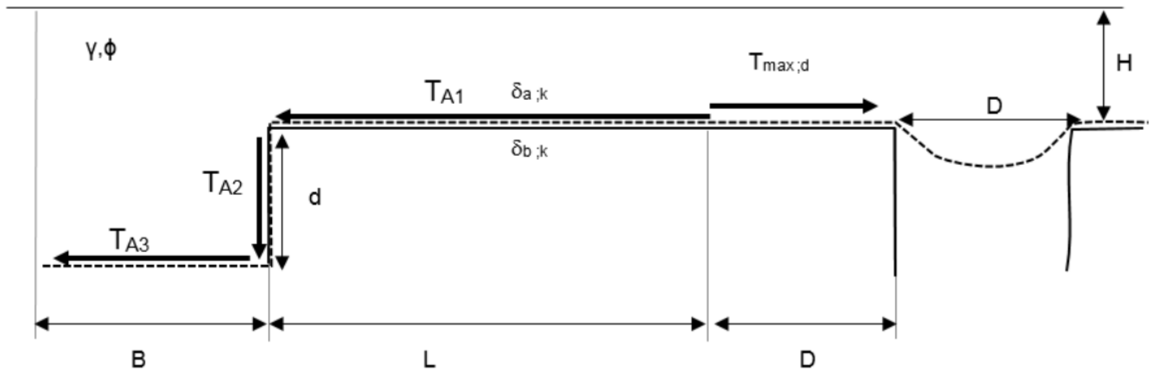
The anchorage length at each end of the sheet (in the case of single direction reinforcement) or of crossed sheets should be outside the potential collapse zones. To achieve that, the anchoring system is placed at a distance D from the edge of the potential collapse, which makes it possible to differentiate the potential collapse area from the surrounding anchoring area.

If the available space does not allow for sufficient flat anchoring, a trench-type anchoring system should be used.

The interface shear strength can be measured according to standards (NF EN ISO 12957-1 and NF EN 13738). Default values for the different interface friction angles are proposed in the XP G38-065 standard.



a) flat anchoring principle



b) trench anchoring principle

Figure 30: Flat or trench anchoring principles in (Annex C of the XP G38-065 standard).

6.3.3.1. Flat anchoring

The calculation of the mobilisable anchor force is carried out:

- **for the current area**, considering the geosynthetic/ground friction over the geosynthetic plus the geosynthetic/ground friction under the geosynthetic;
- **for geosynthetic overlap zones**, considering the worst case ground-geosynthetic interface friction plus the geosynthetic/geosynthetic friction. The longitudinal overlap (direction of geosynthetic production) is in the T_{max} stress direction.

6.3.3.2. Trench anchoring

The calculation method proposed in the standard is based on the assumption that the forces at the anchorage are only taken up by friction on the linear parts without any angle effect. Considering that there is no adhesion between the geosynthetic and the studied ground, the anchorage resistance force is equal to the sum of the three forces T_{A1} on the horizontal overlap (L), T_{A2} on the vertical facet of the trench (d) and T_{A3} on the trench bottom (B) (Figure 30).

It should be noted that the Villard and Chareyre (2004) method which allows the effect of the angle at the top and bottom of the trench to be taken into account, allows for a more precise approach to the mobilizable force.

6.3.3.3. Longitudinal and lateral sheet overlaps

The longitudinal overlap is in the direction of the forces. For its justification, see section 6.3.3.1.

The lateral overlap (direction across the geosynthetic production) is perpendicular to the main forces. To provide the continuity of the reinforced surface and avoiding the opening between two sheets placed side by side at the cavity level, the lateral overlap width must be calculated according to the sheet vertical movement value in the centre of the cavity (minimum recommended overlap of 50 cm).

Existing methods allow the geosynthetic and the anchorage area to be sized for an isolated cavity. For multiple cavities (e.g. chambers and pillars, chalk mines, networks of close karst cavities, etc.), the distance between the cavities must be taken into account and compared to the anchorage length. If the distance between two neighbouring cavities is greater than the anchorage length, the cavities are treated as separate cavities. In other cases, the geosynthetic is anchored beyond the cavity area.

It should also be noted that the choice of anchoring type can also often be guided by the project layout, cavity surface area and position. The choice of the trench anchoring solution often solves the problem, even if it means filling the trench with a coherent material such as treated gravel, as was done at the Trois Luc site in La Valentine (Table 3).

Note: it is not advisable to sew geosynthetics together because the tensile strength of the seams is generally much lower than the nominal strength of the geosynthetic; note the counterexample of the Trois Lucs site in La Valentine where the connection between the grids allows 100% of the nominal strength to be used.

7. Implementation

Once the sizing is complete, and before installing the geosynthetic, it is essential to draw up a detailed layout plan which indicates:

- the lengths and widths of the geosynthetic sheets,
- the installation direction relative to the structure and cavities (if known),
- the various longitudinal and lateral overlaps,
- the installation methods (anchoring, pouring of embankment layers, compaction, protective layers if necessary)
- the possible implementation of an instrumentation system, etc.

This is usually finalised with the contractor depending on the type of geosynthetic selected for the project.

The installation of a geosynthetic must be carried out in accordance with applicable safety standards and regulations (CFG recommendations for installation and/or NF G 38060 standard). The following is a very brief description of its implementation, which can be in two configurations:

- Placed on the natural ground and covered by an embankment (Figure 31).
- Excavation of the ground, installation of the geosynthetic and backfilling with the original soil (Figure 32).

Where the geosynthetic is installed under an embankment or structure or infrastructure, the reinforcement is placed directly on the ground surface (after stripping the topsoil if necessary) before the embankment is placed and compacted (Figure 31).

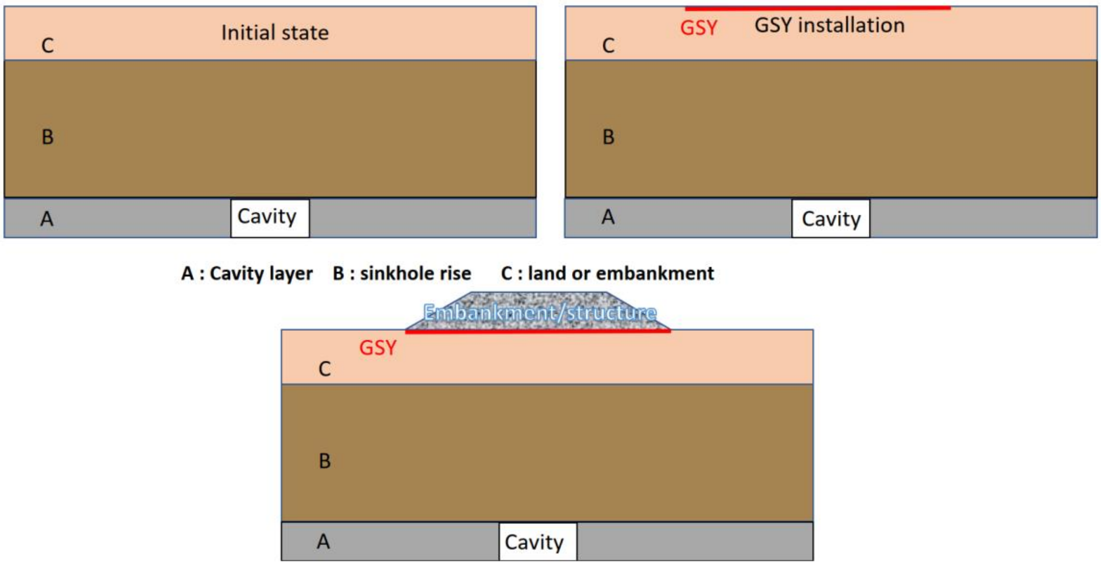


Figure 31 : Steps in the installation of geosynthetic without excavating the original soil - Source: Ineris

The second configuration is the installation under a layer of soil in place (Figure 32), where the soil is excavated to the required depth or to the level of resistant ground, chalk mine head, etc. The geosynthetic is installed followed by backfilling and progressive, low-energy ground compaction.

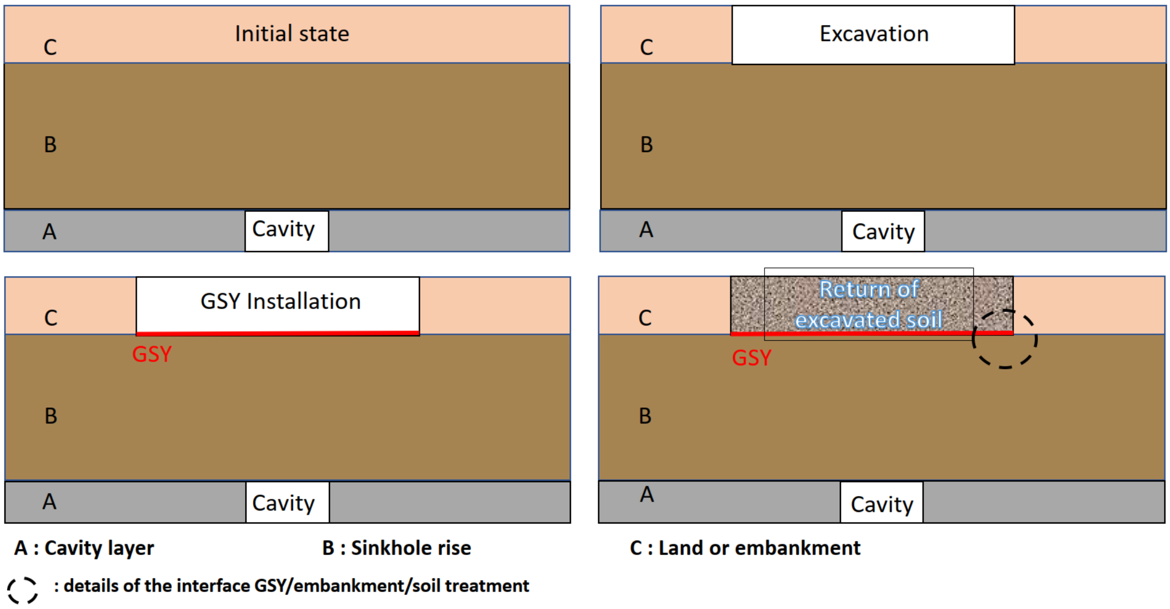


Figure 32 : Steps in the installation of a geosynthetic under an infrastructure or backfill - Source: Ineris

It is also recommended to add a layer of soil rubbing against the ground-geosynthetic interfaces on either side of the anchorage areas to increase shear strength and reduce geosynthetic slippage during tensioning (Figure 33).

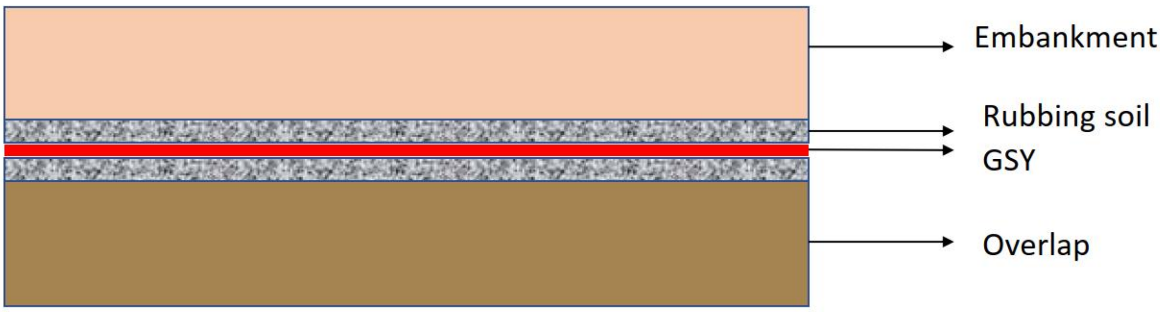


Figure 33 : Addition of a rubbing soil to increase the GSY-backfill and GSY-overlap interface strengths

For of the installation of instrumented geosynthetic, before any backfilling, it is important to pay attention to the following points:

- It is essential to check that the direction of the instrumented geosynthetic installation is consistent with the reinforcement calculations. Individual sensor positions must be adjusted to the measurement positions. The sensors will be identified by coloured areas on the geosynthetic and the measurement positions must be identified on site.
- A technician will have to make the optical connections from the geosynthetic with reinforced extensions to the measurement recovery box.
- The fibres will be protected by a non-woven geotextile and fine sand to prevent damage. (Figure 34).

Figure 34 : Example of an instrumented geosynthetic installation - Source: Afitexinov

When backfilling the sheets with materials, it is sometimes advisable to manually pre-tension the sheets to limit folds and other waves that could cause deformations when the structure is put into service as much as possible.

Care should be taken to make sure the extension cables are not covered when backfilling.

Once the reinforcement has been installed, the existing or imported soil must be compacted according to the rules of the trade (NF P11-300, GTR 1992 and 2000). Compaction is a mechanical process to increase the soil density in place. Compaction guarantees containment, limits slippage at the interface and the risk of internal backfill layer settling.

As with any compaction operation, particular attention should be paid to assessing the suitability of the soil for compaction (type, water content, etc.), defining the thickness of each layer, the type of compactor (size and compaction method), the total compaction energy applied and the procedure used (number of passes, speed, etc.).

In the specific context of areas subject to cavity cave-in risks, thin layers and small compaction equipment generating very little vibrations are recommended to prevent damage to the overlying land above the cavity. A specific study must therefore be conducted to size the soil compaction over the cavity area.

During the compaction phase, it may be necessary to check the cavity stability from the cavity itself if it is accessible or from the surface if it is not accessible. This check can be visual or instrumented (Figure 35), the type of instrumentation being adapted to the type of compaction being used. Alert criteria or thresholds should be specified, as well as the action to be taken if they are exceeded.

On acceptance of the works, a compaction quality check is mandatory or recommended, depending on the subsequent use of the backfilled soil layer.

Figure 35 : Backfill example - Source: Afitexinov

8. Monitoring of cavities using instrumented geosynthetic

8.1. Introduction

Monitoring the risks associated with ground movements caused by the collapse of underground cavities is one of the solutions to guarantee the safety of people and property located in the vicinity in the absence of a final treatment such as full filling (underground cavity monitoring guide, Ineris, 2016b). In that case, monitoring is a palliative solution, pending works to secure the area or other means of remediation. However, it can be extended in time when it is considered advantageous compared to other solutions that are not technically or economically feasible.

Monitoring is based on qualitative or quantitative data acquired over a sufficient period of time to predict and anticipate the behaviour of the structure. The first step is to identify the physical parameters that best characterise the underground cavity instability mechanism that could lead, in the final stage, to the feared phenomenon. In particular, as much attention as possible should be paid to the early signs of this development. These can be expressed through a number of parameters, measurable but not necessarily visible, the main ones being:

- movements or deformations;
- pressure and stress variations;
- vibrations caused by a rupture or rock movement.

Monitoring may cover the cavity itself, its roof or surface movements. The mobilisation and equipment of a cavity depends mainly on the surface assets. A cavity on a motorway probably requires more vigilance than a cavity in a field.

Amongst the methods, the regular visual inspection of a site is the most deployed monitoring for uncomplicated and local cases, where cavities are located and accessible, with acceptable safety conditions. Such visual inspections are to be preferred in those conditions.

The purpose of geotechnical monitoring is to assess the amplitude and speed of the movements generated by the deterioration in the key areas of the cavities defined by the geotechnical study, and to assess their evolution to anticipate the failure. There are many systems for measuring vertical, horizontal and even angular ground movements (convergence meter, extensometer, crack measurement device, etc.).

Micro-seismic monitoring of the terrain in the vicinity of the cavity using geophones or accelerometers, is used for inaccessible cavities. The method is based on the analysis of the number of events, their energy, their location, etc. This monitoring would provide early warning signs that would be very useful for the management of risk areas.

The purpose of monitoring underground cavities exposed to ground movements is to guarantee the safety of people and property in the vicinity in the absence of a final treatment such as full filling.

8.2. Monitoring using instrumented geosynthetics

The "reverse dual-stiffness" geosynthetic makes it easier to detect low amplitude settlements even for infrastructures or structures requiring very high stiffness (e.g. for infrastructures or structures with low or no tolerated surface settlements in large diameter cavities).

The inclusion of optical fibres allows the evolution of the geosynthetic deformation and the temperature in the immediate environment of the unstable cavity to be monitored. The density and location of the optical fibres and sensors depend on the cavity location and the surface assets. Fibre optic measurement also provides an indicator, thanks to the correlation between the temperature and humidity of the soil, of the water status of the cover, particularly in the event of a pipe leak or the rise of the water table.

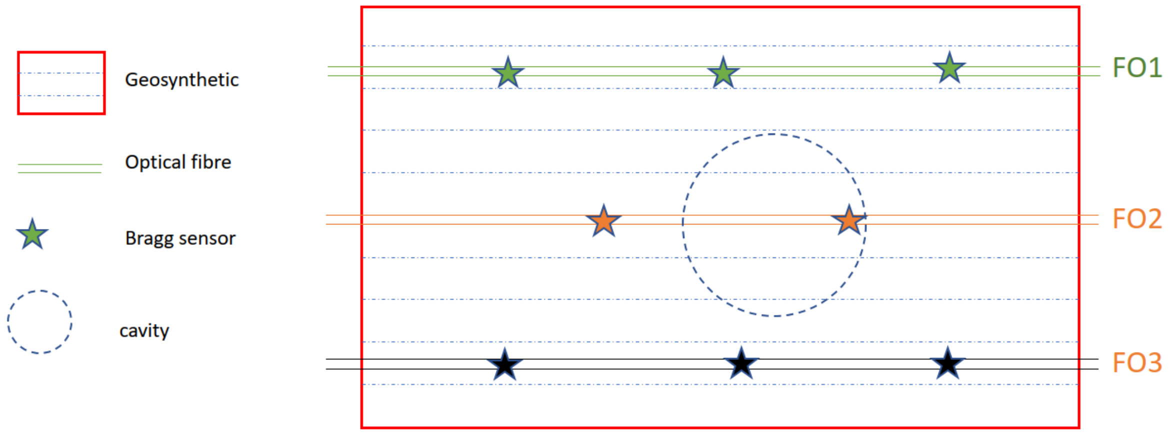


Figure 36 : Geosynthetic reinforcement equipped with fibre optic measurement system and Bragg sensors - Source: Ineris.

Three fibre optic measurement technologies can be used for deformation and temperature measurements over cavities:

- A technology using a system of multiple spot measurements distributed along the fibre, they create Bragg gratings. The operating principle is described in Figure 37.
- A technology using a measurement system distributed along the fibre, known as Brillouin.
- Rayleigh type technology, although less used in actual structures, but of which the characteristics make it a tool that can be used for the detection, investigation and

monitoring of infrastructure where the cavity location is known or of "spot" infrastructure (of reduced size). The operating principle is described in Figure 38.

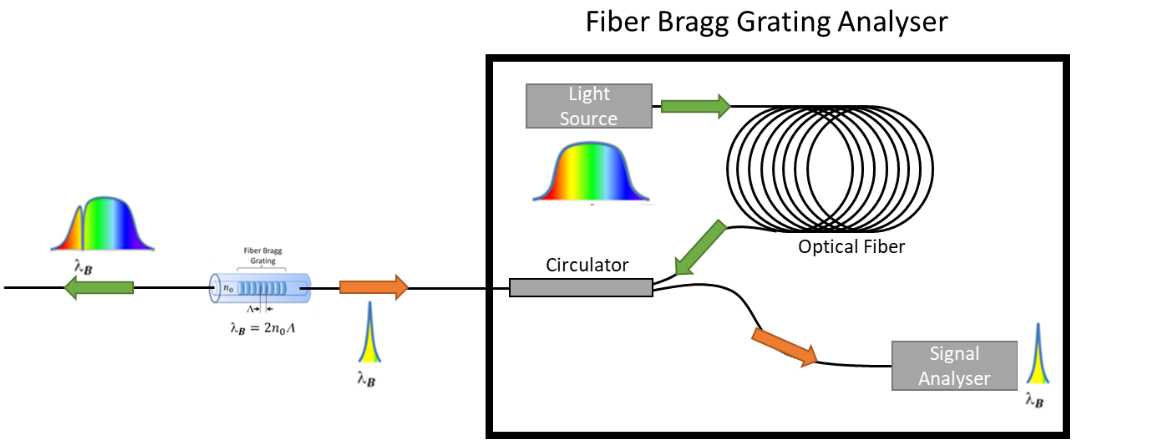


Figure 37 : Bragg-type fibre optic measurement principle - Source: Afitexinov

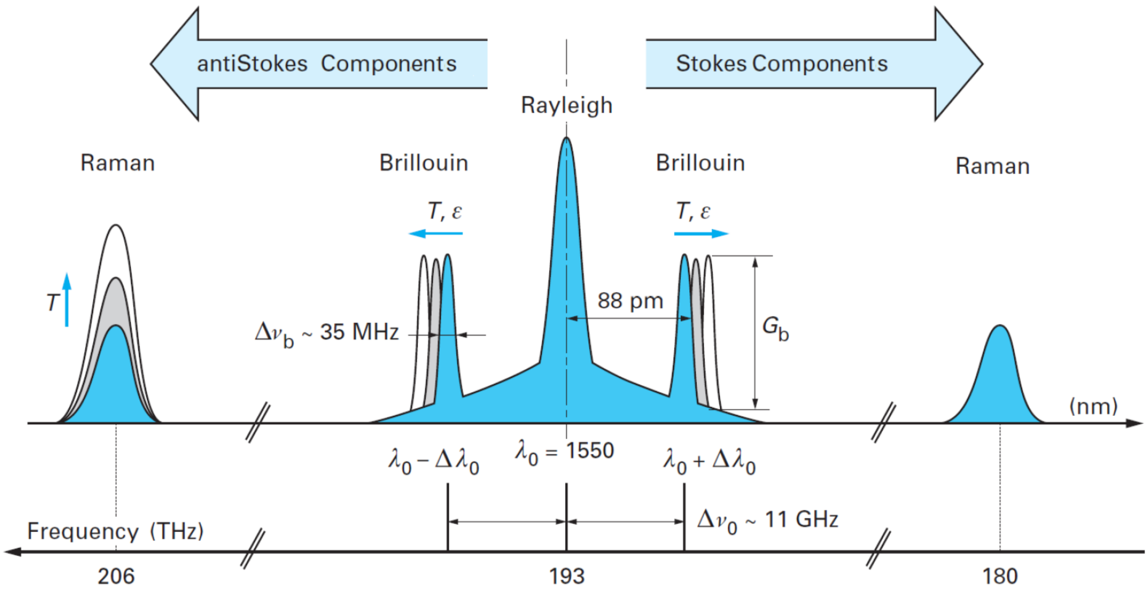


Figure 38 : Variation of scattering spectra for the so-called Raman, Brillouin and Rayleigh methods with a 1.55mm wavelength source (Ferdinand, 2014).

In this case, the Bragg grating sensors are mainly placed over the cavity (Figure 39). The light source sends a signal inside the fibre. Each sensor, responding to a single wavelength, sends it back to the analyser in the opposite direction. The analyser then converts the wavelength to µdeformations. During an event (collapse), the sensor will undergo a deformation (traction or compression), which will modify the wavelength. This change will be analysed and converted into a positive µdeformation for tension, negative for compression. Bragg gratings are particularly suitable for the instrumentation of a limited area corresponding to a local cavity or small size spot assets.

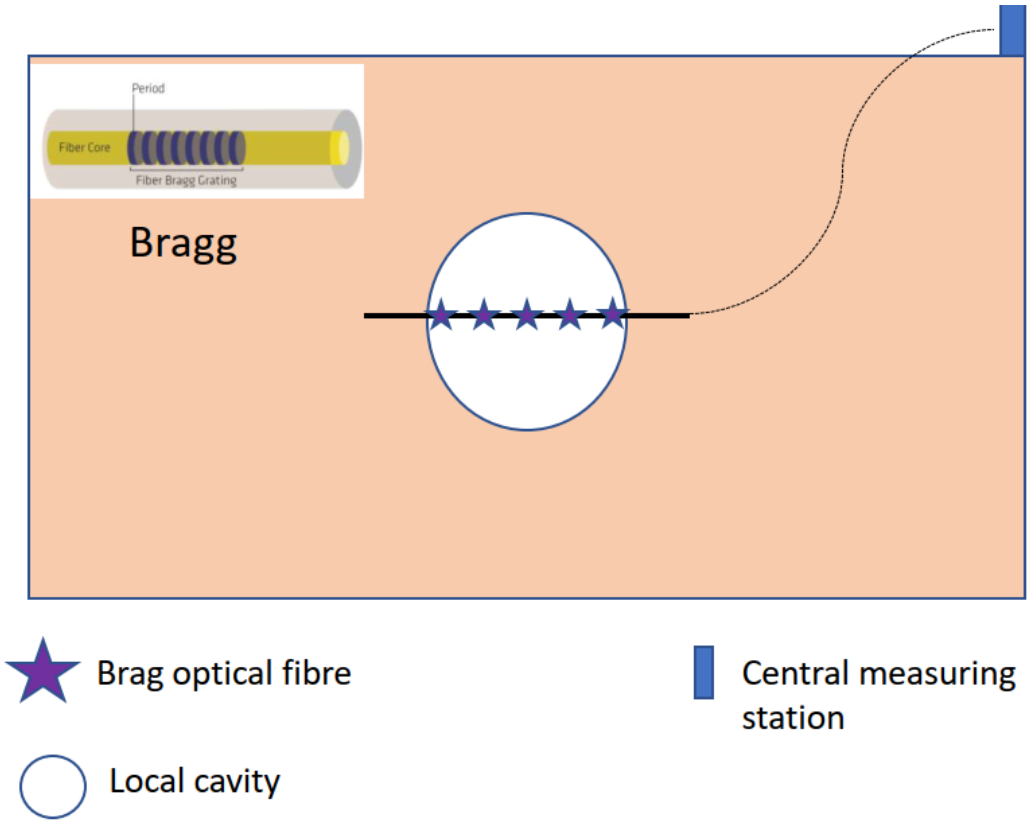


Figure 39 : Principle diagram (plan view) for the monitoring of a cavity using a Bragg fibre optic instrumented geosynthetic - Source: Ineris

The Brillouin analysis principle is based on the travel time of a laser wave through the fibre. To use this technology, there must be access to both ends of the fibre, as the wave travel time can be used to find the location (to within 1m) of the event.

Brillouin-type optical fibres are particularly suitable for the detection, investigation and monitoring of non localised cavities and/or known cavities for large linear infrastructure. They can also be used when there are several local cavities (Figure 39).

The sensor density or measurement lines depend mainly on the surface assets (e.g. low density for low-traffic areas and high density for infrastructure: roads and railways) and the size of the cavity or cavities. It is also possible to adapt the measurement frequency to the feared phenomenon and/or the vulnerability of the infrastructure or structures to be monitored.

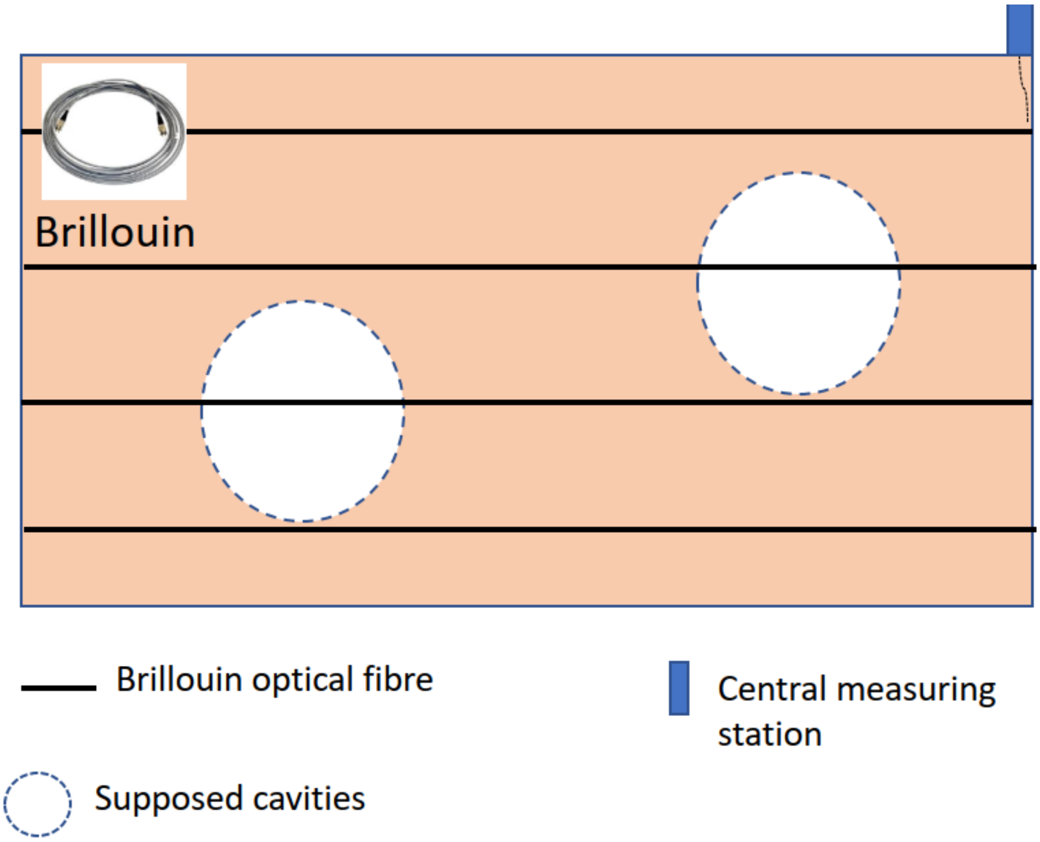


Figure 40 : Principle diagram (plan view) for the detection and monitoring of several cavities (localised or not) using a geosynthetic instrumented with fibre optics and Brillouin sensors - Source: Ineris

Table 7 presents the main characteristics of geosynthetic deformation measurements using three technologies: Bragg, Brillouin and Rayleigh.

Table 7: Main characteristics of fibre optic deformation measurement methods (according to Ferdinand, 2014)

Method/déformation	Bragg	Brillouin	Rayleigh
Spatial resolution (cm)	0,2	5-50	3
Max length (km)	10 (ponctuelle)	>30	2
Measurement frequency (kHz)	10-1000	0,01-0,5	0,1

Accuracy (±µm/m)	0,1	10	1
Window (%)	1-4	2	0,1

Table 8 presents the field of application of fibre optic deformation measurements depending on the number and location of the cavities.

Table 8: Main characteristics of fibre optic deformation measurement methods (according to Ferdinand, 2014)

Cavity type(s)	Bragg	Brillouin	Rayleigh
Isolated and local	x		
Isolated and non-localised		x	x
Several localised cavities	x	x	x
Several non-localised cavities		x	x

The "inverted dual-stiffness" geosynthetic equipped with fibre optic sensors facilitates the detection of low amplitude settlements. It also allows the evolution of geosynthetic deformation and temperature in the immediate environment of the unstable cavity to be monitored. Bragg-type sensors are suitable for localised cavities, Brillouin-type sensors are suitable for non-localised cavities.

9. Summary - benefits and limitations

9.1. Benefits and limitations

Geosynthetics can be used as a reinforcement solution in different contexts of local collapse risk areas such as sinkholes. They have several advantages, including ease of installation, low cost compared to other treatment methods (e.g. cavity filling) and limited environmental impacts, supported by a life cycle assessment carried out by the REGIC project, compared to other traditional solutions (e.g. reinforced concrete slab). These impacts are the energy required to manufacture and implement the treatment method and also its carbon footprint.

The use of a geosynthetic as a protection system is based on its ability to withstand weight and load stresses. These forces are taken up by the friction mobilised laterally between the ground and the geosynthetic. This reduces surface deformation and settlement. If it is instrumented, the geosynthetic also allows the detection of cavities in unknown areas and the monitoring of the rise of a sinkhole thanks to the deformations recorded by the deformation sensors using optical fibres.

In a certain number of cases, it allows surface assets (transport infrastructure) to be maintained in an acceptable state even after the cavity has been opened, pending the initiation of treatment operations and the final securing of the cavity by filling it in, for example.

By avoiding the filling of the cavity, the use of geosynthetics allows the preservation of natural resources, in particular by reducing the quantities of materials taken from the natural environment (aggregates, sand) to fill the underground cavities.

It also allows for better planning of interventions on developing sinkholes by supporting the surface soil and avoiding crater formation.

However, there are factors that limit its performance and reinforcement capacity. It should be remembered that this technique is only effective for local collapses of limited dimensions of a diameter of less than 5 m and in the case of horizontal ground. To guarantee required geosynthetic performance, the data and information on the cavity and the geosynthetic needed for the sizing are required, as well as the installation conditions and associated site constraints.

These factors may be associated with the lack of knowledge of the ground movement - sinkhole hazard, the change in the surface use conditions compared to the initial state (when the cavity was created) and after the installation of geosynthetic reinforcement which could modify the nature of the overloads.

Table 9 presents the main factors to be considered in reinforcement sizing and management. It is now possible to take these different factors into account in geosynthetic sizing, and to propose the most suitable product for the type of structure or infrastructure according to the local context. Table 9 mentions the main standards that need to be mastered in to achieve accurate sizing and implementation that guarantees proper operation if a sinkhole forms above the cavity.

The main advantages of geosynthetics are their behaviour, ease of implementation, low cost compared to other treatment methods and limited environmental impacts. Its use is limited to cavities of a diameter of less than 5 m. This limitation is overcome by the ability of instrumented geosynthetics to detect the rise of sinkholes in real time.

Table 9: Factors to be considered in sizing to guarantee geosynthetic reinforcement performance

	Factors	Comments / actions
Cavity	**Geometry**	Sinkhole rise shape
	Diameter/witdh	GSY base parameters
	Cavity depth	No sinkhole for cavities > 50 m deep
	Rise mechanism	Sudden or gradual
	Asymmetrical sinkhole rise	Specific design study
	Durability	With reference to the XP G38065 standard
	Creep	With reference to the XP G38065 standard
Reinforcement	**Chemical**	With reference to the XP G38065 standard
	Anchoring / property line	Check the soil in the anchorage area, seek permission if a property line is exceeded or adopt the trenching solution
	Positioning **Orientation**	Ensure GSY direction relative to sink-hole rise
	Dip	Specific design study
	Soil type	Use the appropriate design method

Soil/structure/ infrastructure	**Freeze - thaw**	To be taken into account depending on the depth adopted for the foundations, see regulatory map
	Variation in soil moisture content	Provide a drainage system associated with GSY reinforcement to guarantee sufficient friction between the ground and the GSY, drainage also helps to reduce the occurrence of the hazard
	Exceptional / permanent load	With reference to the XP G38065 standard
	Installation of reinforcement	With reference to the XP G38065 standard
	Bonding between geosynthetics	With reference to the XP G38065 standard
Implementation	**Geosynthetic overlaps**	With reference to the XP G38065 standard
	Trench	To be filled and compacted to guarantee durable anchorage
	Compaction	Controlled compaction, especially for shallow cavities Implement a procedure to check the condition of the cavity or surface
	Monitoring system implementation	Protection of sensors and optical fibre during and after GSY installation Sensor power supply Checks to make sure the system is in working order Ensure data acquisition and transfer to the processing centre throughout the service period Develop an alarm and intervention procedure if deformations are measured (threshold to be defined)

9.2. Summary of data and results

The geosynthetic reinforcement of areas at risk of collapse is a method adapted to natural or man-made cavities of small diameter, less than 4 m and exceptionally 5 m. The treated hazard is a local collapse (sinkhole).

It should be noted that for risks of larger diameter subsidence, if the use of a reinforcement geosynthetic is not currently suitable, the use of an instrumented geosynthetic associated with an adequate monitoring system may prove to be an interesting solution to detect, or even monitor, a rising sinkhole.

Current sizing methods apply to cavities and horizontal terrain.

To size a geosynthetic over a cavity or an area at risk of local collapse where a sinkhole is likely to occur, geometric and geomechanical data is needed. This information has been presented in this document (Figure 16 and Table 10). We differentiated 6 periods covering a reinforcement project using instrumented geosynthetics.

These are:

- **pre-project**: in this phase, the data concerning the cavity itself is required;
- design: in this phase, the necessary data is that of the project, generally provided by the contracting authority;
- **completion of the geosynthetic sizing calculation**: this involves carrying out the calculations according to the deformation and failure approaches; it includes the calculation of anchoring and overlaps
- **choice of product**: in this phase, the most suitable product for the sizing is selected;
- implementation: this phase corresponds to the installation of the geosynthetic and the construction of the structure. It may involve the installation of a monitoring system built into the geosynthetic;
- **monitoring**: after the reinforcement geosynthetic has been installed, the contracting authority owner or its representative monitors and observes the evolution of surface movements and, if necessary, analyses the deformation measurements of the geosynthetic if it is instrumented.

The analytical calculation using existing sizing methods allows the characteristics of the reinforcement to be determined (type, stiffness, permissible and ultimate resistances). It is also important to analyse feedback to improve sizing methods.

Table 10: Steps for the sizing of a geosynthetic - data and results according to the XP G38065 standard

Period	Step	Description
Pre – project	**Cavity data**	▪ Cavity type: isolated or multi-cavity ▪ Cavity location known or supposed ▪ Asset type ▪ Characteristics of the cavity to be reinforced (diameter in contact with the GSY) ▪ Geosynthetic positioning depth
Designing	**Project data**	▪ Maximum permissible surface movement ▪ Surface loads (traffic, backfill, etc.) ▪ GSY type and characteristics

Calculation	**Installation (Check and verification)**	1 Failure calculation (ULS) a. Calculation of the vertical load on the geosynthetic taking into account the weighting coefficients b. Determine the geosynthetic's long-term tensile strength c. Determine the geosynthetic's ultimate tensile strength (minimum geosynthetic strength prior to installation, taking into account damage and creep behaviour and the action of chemical ageing) 2. Deformation calculation a. Calculation of the vertical load on the geosynthetic b. Determine the long-term tensile modulus of the geosynthetic to guarantee surface movement c. Determine the tensile modulus of the geosynthetic product taking into account damage and chemical action
Product selection		▪ Choice of geosynthetic type relative to the calculation results (8 and 9) ▪ Anchoring sizing ▪ Checks and verification of the calculation and choice by an approved design office
Implementation	**Installation (Check and verification)**	▪ Check the delivered product ▪ Installation check ▪ Installation of a monitoring system (optional)

Monitoring		▪ Observation and measurement: a. GSY deformation b. Surface settlement c. Infrastructure or structure behaviour ▪ Decision-making and disaster response management

10. Conclusion

This document has been produced based on the experience gained over several years in various national projects (RAFAEL, GeoInov, etc.) and the REGIC project. Geosynthetic solution is a passive solution to reduce the consequences on the surface when a local collapse (sinkhole) occurs over natural or man-made shallow underground cavities or crevices.

Based on the knowledge of the hazard and the characteristics of geosynthetics, this document provides recommendations for the use of geosynthetics as a reinforcement and monitoring system over cavities. The purpose of these recommendations is to provide all the project stakeholders(contracting authority, project manager, contractor, etc.) with:

- the necessary knowledge of the phenomena that can occur depending on the cavity type and size as well as the characteristics of the covering, the dimensions, etc.
- a summary of the methods to treat "local collapse" hazards;
- the general principles necessary to establish the basis for the design and sizing of these reinforced and/or instrumented structures and infrastructure:
- the elements necessary for the development of their projects:
    - whether for geosynthetic reinforcement
    - or for auscultation and monitoring using instrumented geosynthetics.

In the first part of the document, the different types of underground cavities and the different "ground movement" hazards associated with their collapse are presented, in particular the "sinkhole" hazard. The various methods of reducing the "earth movement" hazard are also presented, in particular the solution of reinforcement by a geosynthetic instrumented using fibre optic sensors built into into the geosynthetic layer.

The document also describes the methodology and principles for the choice of a traditional or instrumented geosynthetics. This choice is based on the cavity characteristics, the hazard and the assets involved. It is also indicated that the geosynthetic can be used for cavities of less than 5m as a reinforcement system and above that as a monitoring system.

A table of case studies allows contracting authorities to compare their own case studies with the examples given to judge the benefits of using geosynthetics.

In the second part, the document presents the steps and data needed to size a geosynthetic, including those concerning the cavity, the overlying ground and the ground above the water table. It discusses the sizing principles for cohesive ground and for granular ground in the presence of external overloads. The inclusion of fibre optics, in particular the geosynthetic (dual stiffness), allows for the monitoring of the cavity. The principle of this monitoring is also described in the document. Finally, the steps involved in the installation of the geosynthetic are presented.

It should also be remembered that geosynthetic sizing must be based on various established and validated standards. This sizing is to be carried out by a specialised design office.

11. Bibliographic and standard references

Abdelouhab A. Pinon C. and AL Heib M. (2018). Sécurisation d'un secteur d'une ancienne carrière souterraine par géosynthétique de très haute résistance (1800 kN/m). Journée Nationales de Géotechnique et de Géologie de l'Ingénieur, Marne-la-Valée.

Auray G., Garcin P. (2010). Cas d'autoroute E20 – bilan carbone et terrassement d'une autoroute sur cavités potentielles avec géotextile de renforcement. Journées Nationales de Géotechnique et de Géologie de l'Ingénieur JNGG - Grenoble.

Blivet J.C., Khay M., Gourc J.P., Giraud H. (2001). Design considerations of geosynthetic for reinforced embankments subjected to localised subsidence. Proc. Geosynthetics'2001 Conference, February 12-14, Portland, Oregon, USA, pp 741-754.

Blivet J-C. Garcin P., Hirschauer A., Nancey A. Villard P. (2006). Renforcement par géosynthétique sur cavités potentielles, exemple de la déviation sud-ouest de Meaux (77). 6ème Rencontres Géosynthétiques, Montpellier, pp 281-288.

Bridle R.J. and Jenner, C.G. (1997). Polymer Geogrids for Bridging Mining Voids, Geosynthetics International, Vol. 4, pp 33-50.

Delmas Ph., Villard P., Huckert A. (2015). Dimensionnement à court terme et à long terme de structure renforcée par géosynthétique sur cavités potentielles : prise en compte de la sécurité. 1 10ème Rencontres Géosynthétiques, La Rochelle, pp 13-34.

Delmas Ph., Gourc J.P. (2017). Geosynthetics in transport infrastructures, the positive input of old case histories. Cas de Trois Lucs à la Valentine: GeoAfrica 2017 Conference.

Dubreucq F., Bruhier, Guillaud O. (2006). Une géogrille dans un parc paysager du Conseil Général du Val de Marne pour se protéger contre les fontis. Rencontres Géosynthétiques-Montpellier.

EBGEO (2011). Recommendations for Design and Analysis of Earth Structures using Geosynthetic Reinforcements (EBGEO). German Geotechnical Society, 265p.

Exbrayat L., Garcin P. (2006). LGV Est – Renforcement par géotextile sur cavités. Rencontres géosynthétiques. Montpelier. pp. 313-319.

Ferdinand P. (2014). The Evolution of Optical Fiber Sensors Technologies During the 35 Last Years and Their Applications in Structure Health Monitoring. Le Cam, Vincent and Mevel, Laurent and Schoefs, Franck. EWSHM - 7th European Workshop on Structural Health Monitoring, Jul 2014, Nantes, France.

Geo-Inov (2010). Programme de R&D GEO-INOV a pour but d'initier des techniques nouvelles pour le renforcement et le drainage des sols atypiques cf. Thèse Huckert, 2014.

Hassoun M., Villard P., Al Heib M., Emeriault F. (2017). Limitation par renforcements géosynthétiques des risques liés aux effondrements des toits de catiches. 11èmes Rencontres Géosynthétiques, Lille. pp 239-249.

Huckert A., Briançon L., Villard P., Garcin P., Delmas P., Auray G. (2013). Mécanismes de transfert de charges dans les remblais sur cavités renforcés par géotextiles : approches expérimentales et numériques. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, 2 to 6 September 2013, Paris, France.

Huckert A. (2014). Approches expérimentale et numérique du dimensionnement de renforcements géosynthétiques sur cavités et inclusions rigides. PhD thesis, 26 May 2014, University of Grenoble Alpes, 224p.

Huckert A., Briançon L., Villard P., Garcin P. (2016). Load transfer mechanisms in geotextile-reinforced embankments overlying voids: Experimental and analytical approaches. Geotextiles and Geomembranes 44: 442-456.

Ineris (2017). Dissolution naturelle du gypse dans le sous-sol Analyse et gestion des aléas mouvements de terrain de type affaissement et effondrement. 17-164710-03375A-Guide Ineris-Cerema.

Ineris (2016a). Guide sur les solutions de mise en sécurité des cavités souterraines abandonnées d'origine anthropique - DRS-15-149564-02401A.

Ineris (2016b). Guide de surveillance des cavités souterraines d'origine anthropique. DRS-16-156834-00810B.

Jaffrot S., Garcin P. and Nancey A. (2009). RN 174 – renforcement par géosynthétique sur cavités. Rencontres Géosynthétiques. pp. 95-101- Nantes.

Gourc J.P., Villard P., Giraud H., Blivet J.C., Khay M., Imbert B., Morbois A., Delmas Ph. (1999). Expérimentation en vraie grandeur d'effondrements localisés sous remblais ferroviaires et routiers, XII Congrès Européen de Mécanique des Sols et de la Géotechnique "La Géotechnique dans les infrastructures de transport", Amsterdam, 7-9 June 1999

Kaytech (2006). Road rehabilitation – sinkhole repair N14/P158-1 -South Africa. https://kaytech.co.za/wp-content/uploads/2013/12/Case-Study-Reinforcement-+-Rockgrid-PC-N14-Sinkhole.pdf

Le Moniteur (2015). Définition, mise en œuvre et dimensionnement des géosynthétiques. N°5811 www.lemoniteur.fr.

Le Plan National Cavités ou le plan national pour la prévention des risques d'effondrements de cavités souterraines. 2014-DGPR.

Martin R., Mathon C. (2000). Ville de Marseille (13): Route des Trois à La Valentine – Avis sur la cartographie existante des zones instables. Rapport BRGM RC-50300-FR. 18 p.

National Coal Board, NCB. (1975). Subsidence Engineer's Handbook, London, 111pp.

Nancey A., Delmas Ph. (2019). Renforcement de base de remblais sur zone à risque d'effondrement – nouvelle norme XP G 38063-2, 12ème Rencontres Géosynthétiques, Nancy. pp. 233-240.

Nichol D. (1998). Sinkholes at Glan Llyn on the A55 - North Wales Coast Road, UK. Engineering Geology (1998) 101-109.

Comité français des géosynthétiques (1995). Recommandations générales pour l'utilisation des géosynthétiques dans les centres de stockage de déchets, Fascicule 11.

Riot M., Rouffiac M. and Auray G. (2013). Chantier de l'autoroute A36: Etude de cas de renforcement par géocomposite sur zones à risques de cavités karstiques. 9èmes Rencontres Géosynthétiques. Dijon. pp. 123-129.

Riot M, Delmas Ph., Monet T. (2022). Life Cycle Analysis of an innovative reinforcement geosynthetic coupled with a detection and monitoring warning system.12th IGC – 18-22 September 2022, Rome

Salvati R., Sasowsky IR. (2002). Development of collapse sinkholes in areas of groundwater discharge. J. of Hydro, 264:1-11.

Tencate (2012). Embankments over voids – Habeath Park and Choose – UK. Fail safe geotextile reinforcement to support car park should old mine workings collapse.

Terzaghi K. (1943). Theoretical soil mechanics, John Wiley & Sons, New York.

Toulemont M. (1981). « Évolution actuelle des massifs gypseux par lessivage, cas des gypses lutétiens de la région parisienne », bulletin de liaison du Laboratoire Régional des Ponts et Chaussées de l'est parisien, pp. 35-47.

Villard P., Briançon L. (2008). Design of geosynthetic-reinforcements for platforms subjected to localized sinkholes. Can. Geotech. J. 45-196-209 (2008).

Villard P., Chareyre B. (2004). Design methods for geosynthetic anchor trenches, Can. Geotech. J. Vol. 41 No. 6, pp. 1193-1205.

Zaghouani K. (2009). Les géosynthétiques, quelques applications en Tunisie. Association Tunisienne de Mécanique des sols.

Zaghouani K. (2017). Technical Risk Management Linked to Underground Cavities: Gypsum Dissolution Phenomenon and Geotextile Reinforcement. GeoAfrica.

Standards

NF EN 1990, Eurocode 0. Basis of structural design (classification index P 06-100-1) with its National Annex (NF P 06-100-2).

NF EN 1997-1, Eurocode 7. Geotechnical Design - Part 1: General rules. (classification index P 94251-1) with its National Annex NF P 94-251-1/AN.

NF EN 1997-2, Eurocode 7. Geotechnical Design - Part 2: Ground investigation and testing. (classification index P 94-251-2).

NF EN ISO 10318, Geosynthetics - Terms and definitions

NF EN ISO 10319Geosynthetics - Wide-width tensile test

NF P 11 300, Earthworks - Classification of materials usable in the construction of road infrastructure embankments and subgrades.

NF EN ISO 13431, Geotextiles and geotextile-related products — Determination of tensile creep and creep rupture behaviour.

NF EN ISO 12957-1, Geosynthetics. Determination of friction characteristics - Direct shear test

NF EN 13738, Geotextiles and geotextile-related products. Determination of pullout resistance in soil

NF EN 14475, Execution of special geotechnical works. Reinforced fill

NF XP G38065 "Reinforcement of the base of embankments" Geosynthetics - Geotextiles and related products Reinforcement of the base of embankments in areas at risk of collapse Justification of sizing and design elements

NF EN ISO 12957-1, Geosynthetics. Determination of friction characteristics - Direct shear test

NF EN 13738, Geotextiles and geotextile-related products. Determination of pullout resistance in soil

NF P94-261, Justification of geotechnical structures - National application standard of Eurocode 7 - Surface foundations

12. List of illustrations

12.1. List of figures

12.2. List of tables

12.3. Glossary

Anthropogenic: Of human origin; caused by Man.

Assets: People, property, activities, infrastructure, heritage, etc... likely to be impacted by a feared phenomenon (in this case a ground movement)

Cavity (in geology) Hollow space, either natural or artificial, more or less wide, more or less deep, closed or not, in a rocky formation (e.g. underground quarry, karst, cave, cavern, ...).

Collapse: gravity movement with a mainly vertical component, which occurs more or less suddenly. It results from the rupture of the supports or roof of a pre-existing underground cavity.

Covering: all the land found above a quarry.

Doline: A circular depression in karst cavities, it is characteristic of the erosion of carbonate terrain in a karst context. This depression can measure from a few metres to several hundred metres in diameter.

Expansion: Increase in the apparent volume of a rock (due to its extraction or instability, as a result of its fragmentation) or of ground (due to its excavation or collapse).

Filling : The filling of a cavity using imported material (backfill), the filling of a trench, a ditch, a shaft. Synonyms: backfill, backfilling.

Géorisques: French Ministry For Ecological and Solidary Transition portal. https://www.georisques.gouv.fr/.

Geotechnical study: It is defined and codified by the NF-P-94 500 version 2013 standard (Geotechnical study). For underground cavities, depending on the case it includes analysis of existing documentation, field visits, geophysical campaign, soundings (possibly with videoscopy), topographical survey, repositioning of the void relative to the surface and, if possible, visual examination of the underground cavities, assessment of instability mechanisms, analysis of the structure stability, recommendations for safety solutions.

Ground movements: Manifestations of the gravitational movement of destabilised land masses under the effect of natural stresses (snow melt, abnormally high rainfall, earthquakes, etc.) or man-made stresses (earthworks, vibration, deforestation, exploitation of materials or aquifers, etc.).

Hazard: A threatening event or probability of occurrence of an event in a given area and time period of a phenomenon that can cause damage.

Internal erosion (suffusion): this term refers to the detachment and transport of finer particles through a coarser porous ground matrix due to hydraulic flow. The evolution of suffusion over time can alter the hydraulic and mechanical properties of ground and can lead to significant changes in the behaviour of such structures, even to the point of collapse.

Karst, Karstification: specific form of erosion caused by the dissolution of limestone or dolomitic formations by groundwater and characterised in particular by underground voids.

Leakage: Leakage is the instability of a backfill that flows into the underground structures to which it is connected, resulting in the formation of a sinkhole on the surface, the size of which depends on the shaft diameter.

Localised collapse or sinkhole: Crater formed on the surface by the sudden and unexpected collapse of the land when a sinkhole comes to light.

Mining crevice: crevices are faults that are visible or not on the surface, usually associated with subsidence caused by mining or the collapse of mining structures.

Monitoring*:* The sum of actions that consist in careful observation, examination, control, in order to be able to alert in time and thus reduce or avoid the risk.

Optical fibre: An increasingly common transmission technology that involves guiding a circularly polarised optical wave through a glass or plastic wire. The advantages include a very high transmission speed and limited attenuation of the initial signal from the sensor. In addition to transmitting information, optical fibres are also used as a distributed sensor of temperature, pressure variation and or deformation using an interferometric technique of transmitted light. Optical fibres allow numerous measurements (thermal, levels, displacements), with applications increasingly developed in geosciences.

Remediation*:* Action to correct or combat a problem by appropriate means and/or measures.

Risk: An order of magnitude that is assessed by crossing the hazard (a quantity itself estimated from two dimensions: the probability of occurrence of a phenomenon, and its intensity) and the assets (people, infrastructure, buildings, dwellings, but also economic or environmental assets, etc.).

Shaft: A vertical conduit connecting the surface to the underground cavity. The diameter and shape vary according to the use, ventilation, extraction, personnel descent or equipment transport.

Subsidence: surface deformation without visible rupture following the collapse of a cavity.

Suffusion: see Internal Erosion

Appendix A

The table shows the values of horizontal deformations for surface subsidence (S), for cavity depth H and for k = 1 (conservative assumption) according to the National Coal Board (NCB) method.

Table A: Horizontal deformation (ε_{max} %) depending on the NCB empirical relationship depending on maximum subsidence (S) and cavity roof depth (H)

	Depth H (m)					
S (cm)	**5**	**10**	**15**	**20**	**25**	**30**
1	*0.20 %*	*0.10 %*	*0.07 %*	*0.05 %*	*0.04 %*	*0.03 %*
5	*1.00 %*	*0.50 %*	*0.35 %*	*0.25 %*	*0.20 %*	*0.15 %*
10	*2.00 %*	*1.00 %*	*0.66 %*	*0.50 %*	*0.40 %*	*0.33 %*
20	*4.00 %*	*2.00 %*	*1.20 %*	*1.00 %*	*0.80 %*	*0.66 %*

13-15 rue Louis Blériot
28300 Champhol
Tél : +33 (0)2 37 18 01 51
afitex@afitex.com
www.afitex.com

Bâtiment Galilée
1270 rue de la piscine
38400 Saint Martin d'Hères
Tél : +33 (0)4 76 82 51 46
www.3sr.univ-grenoble-alpes.fr

Parc Technologique ALATA
BP2 60550 Verneuil-en-Halatte
Tél : +33 (0)3 44 55 66 77
ineris@ineris.fr
www.ineris.fr