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EVALUATION OF THE RISK ASSOCIATED WITH KARSTIC PROCESSES IN MIOCENE GYPSUM IN SOUTH-EASTERN MADRID (SPAIN)

OCENA TVEGANJ POVEZANIH Z ZAKRASEVANJEM MIOCENSKE SADRE V JUGOVZHODNEM MADRIDU (ŠPANIJA)

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Abstract UDC 551.435.8:552.5 (460Madrid)"628.42"
Félix Escolano Sánchez, Alberto Mazariegos de la Serna & José María del Campo Yagüe: Evaluation of the risk associated with karstic processes in Miogene gypsum in south-eastern Madrid (Spain)

Relief formations characteristic of karstification processes affecting the Miocene gypsum formations existing in south-eastern Madrid have been discovered in that area of the city. These relief formations can pose significant risks to future urban development plans.

The purpose of this article is to present an integrated model created from a geomorphological analysis of south-eastern Madrid through aerial photographs, geophysical inspections (microgravimetry) and geotechnical studies (in situ drilling and testing), in order to identify and measure the morphologies associated with karstic processes whose locations, dimensions and geotechnical characteristics are prone to causing damages that could pose a potential risk. The risk analysis is based on a study of the risk factors, focusing on vulnerability and the measurement of structural mitigation measures capable of preventing the damages that could be caused by the interaction between structural foundations and the morphological consequences of karstic processes on the soil.

Key words: Gypsum, karstic processes, risk factors, vulnerability, structural mitigation measurements.

Izvleček UDK 551.435.8:552.5 (460Madrid)"628.42"
Félix Escolano Sánchez, Alberto Mazariegos de la Serna & José María del Campo Yagüe: Ocena tveganj povezanih z zakrasevanjem miocenske sadre v jugovzhodnem Madridu (Španija)

V jugovzhodnem Madridu je veliko reliefnih oblik, ki kažejo na zakrasevanje miocenske sadre. To predstavlja tveganje, ki ga moramo upoštevati pri urbanističnem načrtovanju. V članku predstavljamo celovit pristop, ki temelji na geomorfoloških analizah aeroposnetkov, mikrogravimetričnih in geotehničnih raziskavah, s katerim smo zaznali in izmerili morfološke značilnosti, ki so povezane z aktivnim zakrasevanjem sadre. Analiza tveganj temelji na študiji dejavnikov tveganja in se osredotoča na ranljivost in oceno uspešnosti strukturnih ukrepov za blažitev vpliva zakrasevanja v prsti na strukturne temelje.

Ključne besede: Sadra, kraški procesi, dejavniki tveganja, strukturni blažilni ukrepi.

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INTRODUCTION

The geological and geotechnical inspections being conducted in advance of future construction and infrastructure projects to be carried out in south-eastern Madrid have revealed the presence of karstification processes in the gypsum formations existing in this area of Madrid.

Despite the advances made in the understanding of these processes, there are still very important aspects that have not yet been studied, among them a thorough understanding of the karstic processes detected in these gypsum formations and the areas where these processes have been most intense and whose effects pose a risk to the safety of future urban development activities. The work done by Escolano (2015) has contributed decisively to the understanding of these processes.

However, the research conducted to date on the karstic processes affecting Miocene gypsum formations in south-eastern Madrid has not provided enough knowledge, or at least not levels that are comparable with other countries where these types of processes have taken place, such as Ukraine, where cavities up to 100 km long are known to exist in Miocene gypsum.

It is therefore necessary to find answers to such basic questions as how the location and potential grading of risk is linked to the karstic process in the Miocene gypsum formations in south-eastern Madrid in an area that is expected to see intense urban development activity in the coming decades (Fig. 1).

This article strives to offer a reliable response to the following fundamental aspects of this process:

a) Description of the karstic processes that have affected the Miocene gypsum in this sector of the Madrid Tertiary Basin.

b) Identification and location of the morphological consequences left behind by the karstic process on the soil and what this means for future civil engineering and construction work, particularly the geological risks.

c) Risk analysis focused primarily on the vulnerability of future actions so as to uphold the safety criteria which society demands in relation to future urban development activities in Madrid.

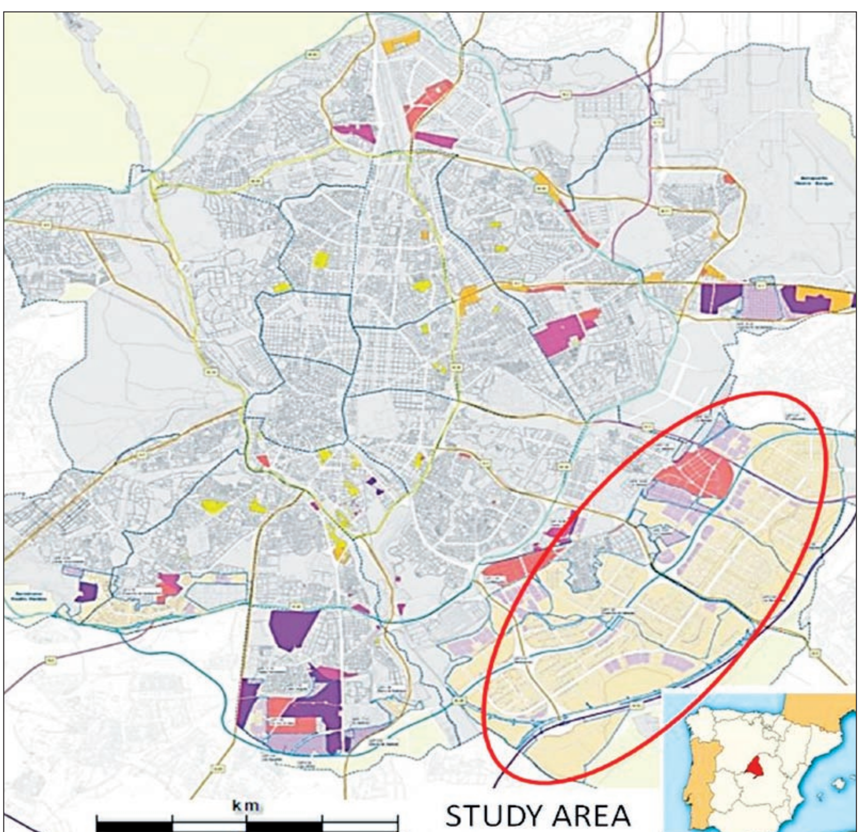

Fig. 1: Location of expansion plans for south-eastern Madrid.

METHODOLOGY

The study was divided into the following phases:

- Cartography of the morphological surface of the south-eastern sector of the city of Madrid.
- Soil inspection using geophysical prospecting techniques.
- Drilling for verification purposes.
- Integrated model.

Cartography of the morphological surface of the south-eastern sector of the city of Madrid.

The surface morphology of south-eastern sector Madrid was studied by observing aerial photographs that were used to develop the original cartography on a scale of 1:10,000 (Fig. 2), where the network of fractures and the distribution of the exokarstic marks are reflected in the form of dolines and collapses in the Miocene gypsum formations.

The cartography was verified by exhaustive field studies and supplemented by reviews of drilling samples from the geotechnical inspections conducted in this area.

Inspection of the terrain using geophysical prospecting techniques.

Given the size of the terrain under study, we selected certain zones where the karstic processes could pose the most significant risk to the safety of future urban development actions.

In these areas of interest, the terrain was studied using geophysical inspection techniques, which were then verified by mechanical rotary drilling in order to obtain a more precise evaluation of the risks associated with the karstic processes in the Miocene gypsum formations in south-eastern Madrid (Ravbar & Kovacic 2010)

The microgravimetric method was used for the geophysical prospecting. The gravimetric method consists of measuring slight variations in the terrestrial gravitational attraction, microgravimetry, in the area under study. The variations are interpreted in relation to the existence of possible effects on the subsoil, such as cavities and karstifications, whose densities are in sharp contrast with that of the surrounding area (Fig. 3).

The existence of a cavity or karst in the subsoil indicates a relative loss of mass and this in turn implies a reduction in the gravitational attraction at any point above it on the surface of the earth.

JUSTIFICATION OF THE TERRAIN INSPECTION METHOD.

From the point of view of the microgravimetric method, the consequences of the karstification process include a relative loss of mass and therefore a reduction in the gravitational attraction.

According to the general gravity formula, this reduction is proportional to the volume of the crater or the anomalous body and inversely proportional to the quadrant depth at which the mark left by the karstic dynamic is located.

It is therefore feasible to detect the presence of these types of morphological sequelae in the subsoil by analysing the gravitational attraction measured from the surface of the earth.

At this point it is important to clarify certain basic concepts related to terrestrial gravitational attraction, whose value on the surface of land ranges between 9.78 and 9.83 m/s^2. However, in order to observe and characterise small gravitational variations it is common to work

Fig. 2: Layout of the fracture network, areas with dolines and collapses in south-eastern Madrid.

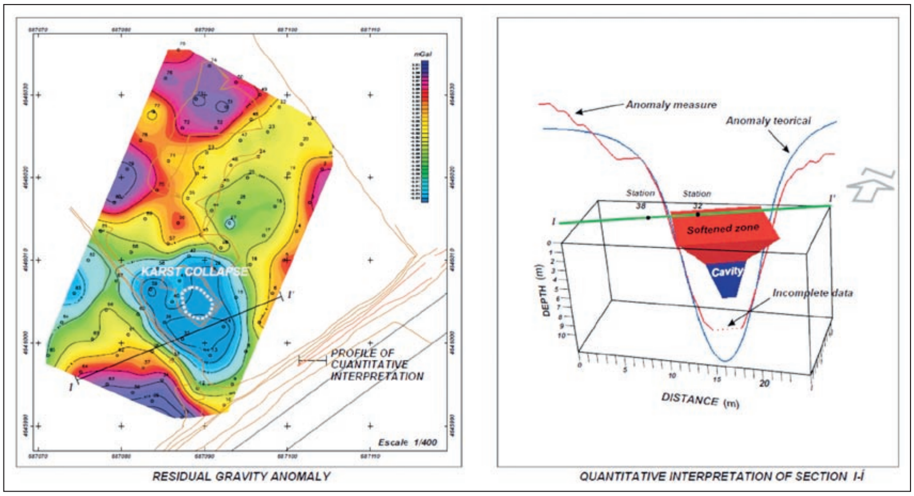

Fig. 3: A Collapse or cavity by karst in the subsoil indicates a relative loss of mass implies a reduction in the gravitational attraction.

with a smaller acceleration unit. This unit is the Gal (in honour of Galileo) and it is equivalent to 1 cm/s^2. The average gravitational attraction on the earth's surface is approximately 980 Gals.

The microgravimetric method is a significantly more precise method since it is capable of determining variations of one-thousandth of a milligal. Variations in the range of $1x10^{-9}$ milligals of the gravitational attraction on the earth's surface are considered negative gravity anomalies.

This conditioning factor, combined with the gravimetric anomalies caused by the craters or soft spots in the earth which are very tenuous and may appear superimposed with other variations conditioned by latitude, topographical elevation and geology, would be difficult to detect using conventional gravimetric methods (Coyette *et al* 1985). Consequently, the microgravimetric method is the most suitable geophysical prospecting method for these types of gypsum formations.

Hence, the microgravimetric method made it possible to detect, on the one hand, the negative gravimetric anomalies (caused by an empty crater or the loose fill inside the crater) and on the other to determine the depth at which it was located and the contrast in density compared to the gypsum rock that showed no signs of erosion.

As a result of the microgravimetric study, various sectors of microgravimetric anomalies were defined which were interpreted as areas of earth that could be affected by karstification processes in the gypsum substrate. Fig. 4 shows one of those sectors and its microgravimetric zonification.

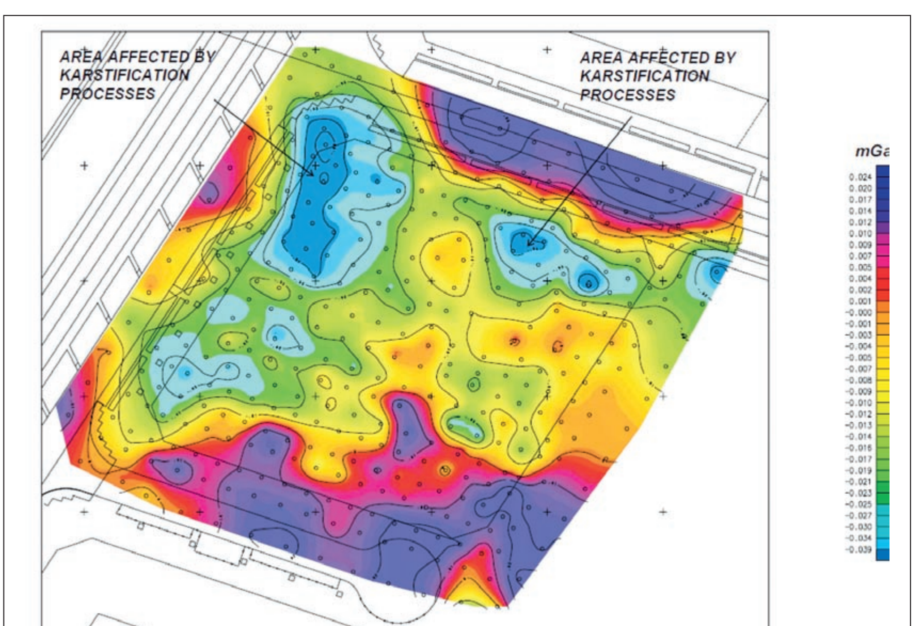

Fig. 4: Microgravimetric zonification map showing significant gravimetric minimums.

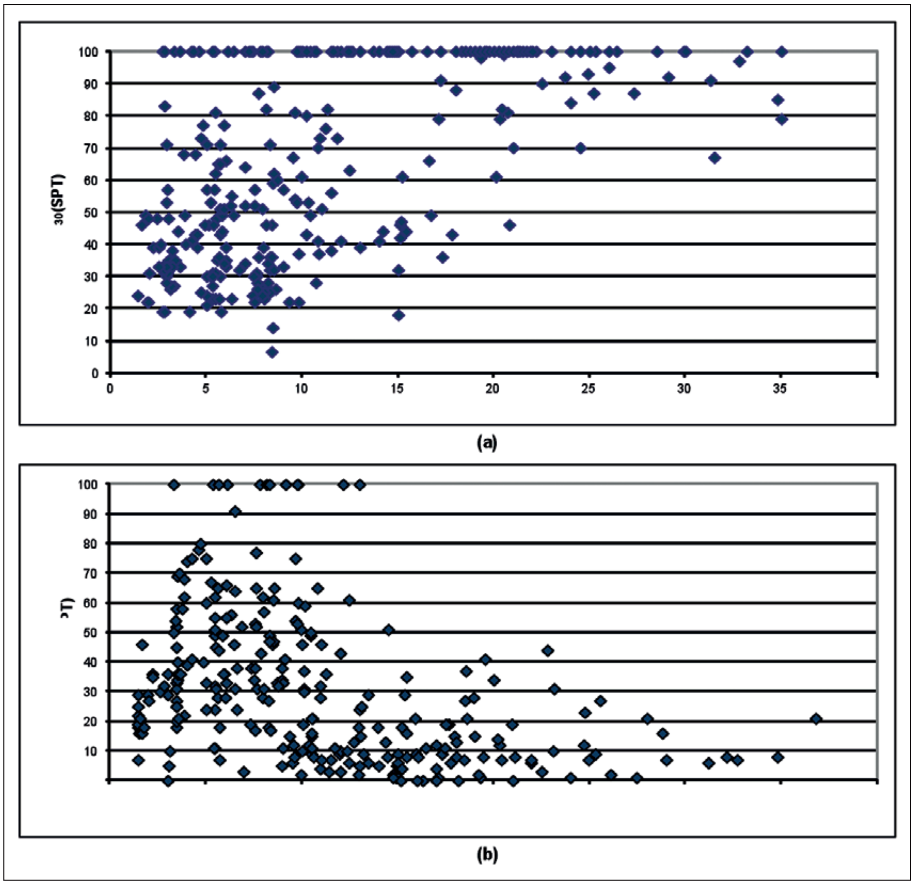

Fig. 5: List of SPT values with the depth: (a) Non-karstified land. (b) Karstified land

VERIFICATION BY DRILLING ROTARY BOREHOLES. INTEGRATED MODEL.

The results obtained from the geophysical prospecting were contrasted and verified by drilling rotary boreholes and conducting standard penetration tests (SPT) and pressure meter tests at regular depths.

With the results obtained from these direct tests it was possible to determine the real meaning of the gravimetric minimums, corroborating their presence and validating the results obtained from the geophysical study.

STANDARD PENETRATION TESTS (SPT)

Using standard penetration tests (SPT) we were able to confirm that since the consistency of the gypsum and clay sediment located on top of the non-karstified gypsum rock was high and increased with depth it was classified as hard soil (Fig. 5a).

In the soil affected by karstic processes, the consistency of the sediment decreases as you go deeper, i.e., underneath deposits of hard consistency there are layers of soft deposits (Fig. 5b).

It is worth noting that some of the values obtained from the SPT tests (N_{30}), are extremely low and even nil for a certain type of deposit characterised by a high consistency that increases with depth. It is also observed that once a certain depth is reached, there is a gradual decrease in the resistance to penetration until the point of sudden rejection on contact with the gypsum layers.

PRESSURE METER TESTS

The pressure meter tests were conducted using a Menard pressure meter. This test consists of exerting lateral pressure in order to measure the deformation of the walls of the borehole, at 2-bar intervals of pressure and constant intervals of time. The object of the test is to obtain a curve that relates the pressure applied to the soil and the deformation that occurs in order to establish certain characteristic soil parameters such as:

- The deformation modulus (Em). Presiometric modulus
- Limit pressure (LP). Breakpoint of the soil
- Fluency pressure

Twelve pressure tests were conducted at different depths using the same equipment. The results obtained for the deformation modulus varied greatly, between 46 and 327 bar. As occurred with the standard penetration testing, we observed a gradual decrease in the presiometric modulus at increasing depths, with a minimum of 46 bar.

This can be explained by the presence of gypsum masses at very deep levels, whose contact is resolved by a karstification surface. This process causes erosion and occasionally leads to the collapse of the walls of the craters, channels or cavities in the gypsum deposits.

This in turn leads to the overlying sediment settling in the crater that is created, which causes breakage, shifting and weakening of the clay deposits above (Fig. 6).

The main problem is that the consequences of this phenomenon on the soil can go unnoticed and ultimately trigger serious geotechnical problems.

Although karstified zones come in a variety of shapes, there are three main types (Fig. 7).

The diagrams in Fig. 7 reflect the approximate scale of the dimensions of the different singularities that appear regularly in the Miocene gypsum formations in south-eastern Madrid. It is very common in this area to find a karstified rock substrate underneath a layer of clay with thicknesses that vary between 15 and 30 m.

Fig. 6: Areas with folding and softened clay.

Fig. 6 also defines the geometric parameter of the softened clay zones, which is the dimension of the "tectonic folds" (L). This parameter is the total minimum

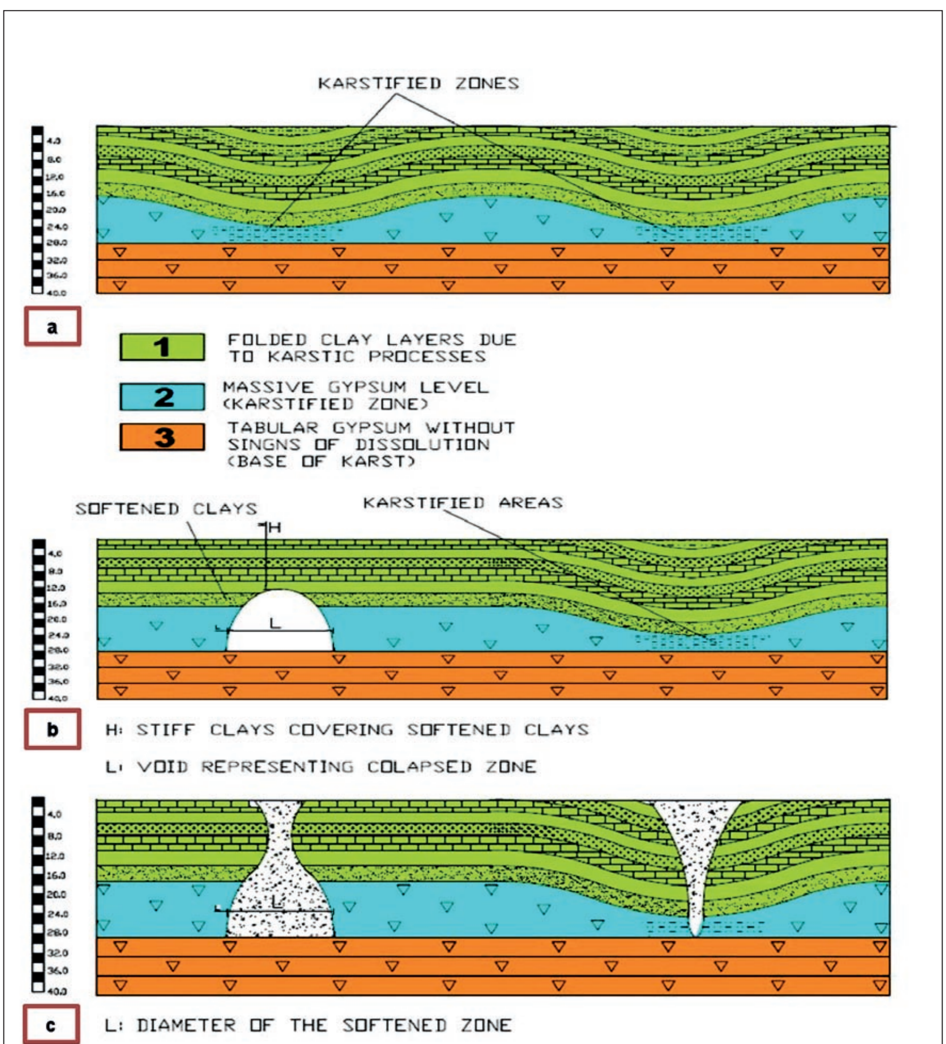

Fig. 7: Typical geotechnical profile: (a) Areas with folding. (b) Areas with folding and softened clay. (c) Areas with folding and chimney type collapse structures.

span or free span that is bridged by the upper strata. In the case of the chimneys, there is a single diameter (L) that defines the size of the conduit.

In addition, in softened clay zones the geometric parameter (H) represents the minimum thickness of the layers of clay bridging the areas of softened materials.

ANALYSIS OF THE RISKS ASSOCIATED WITH KARSTIC PROCESSES

The geotechnical characteristics and dimensions of the karstic processes affecting the gypsum in south-eastern Madrid and the morphology of the resulting soil have the potential to cause serious damage to structures built on the land in this area and therefore pose a risk (Beck 1995).

Unlike other geological risks that can be analysed based on the cumulative risk factors, the risks associated with karstic processes in south-eastern Madrid cannot be analysed in this way. This is due to the complexity of the phenomenon (because of the multiple factors that influence the karstic process and the variety of marks or consequences on the soil) and the shortage of sufficiently detailed statistical data, especially when compared to the data for other natural risks in Spain (floods, landslides, earthquakes, etc.).

The risk is therefore analysed by taking a rational approach to the problem based on an understanding of the risk factors involved: hazardousness, vulnerability and exposure.

The ultimate goal is to prevent or minimise, to the extent possible, the damage that could potentially be caused by the consequences of gypsum karstification processes on the soil.

ANALYSIS OF RISK FACTORS

We analysed the hazardousness, vulnerability and exposure risk factors using different, interrelated conditioning factors.

Hazardousness. Analysis of hazardousness.
Defined as the probability that the effects of a natural phenomenon such as gypsum karstification and the processes generated by this phenomenon could cause damage to buildings, road structures and services.

The hazardousness analysis is based on the study of three factors:

1. Factor A: Identification of karstic processes.
2. Factor B: Spatial location of the karstic process.
3. Factor C: Level of hazardousness depending on triggering factors.

Factor A: Identification of karstic processes.
The karstification process in gypsum formations in south-eastern Madrid can be described in four evolutive phases (based in Duran 2002 and Ege 1984). These are hypothetical phases that can occur simultaneously (Fig. 8):

a) Phase 1.

Initially, all of the interconnected fractures, families of discontinuities and weaknesses of the gypsum layers are equally subjected to the action of the water. Areas that are subjected to a higher hydraulic gradient as a consequence of greater permeability (permeability by fracturing) due to their structural characteristics will be selectively enlarged by erosion due to the high solubility of the gypsum (Shearman 1966)

b) Phase 2.

The channels thus selected generate underground water drainage. The circulation of water through these channels increases as the hydraulic gradient increases due to gradual erosion.

This vertical and subvertical water circulation process creates the first channels, along with small craters and cavities created by erosion.

c) Phase 3.

The main water circulation channels gradually become interconnected, creating a three-dimensional drainage network characterised by a certain transmissivity that is in contrast with the low permeability of the gypsum massif (Alonso-Zarza &Tanner 2010).

As a result of the erosion caused by the water, the soil particles are dragged and eventually settle in small caverns and cavities, which in turn causes a gradual loss of soil on the surface layer and the formation of small depressions in the surface in the form of dolines and funnels (Gospodaric 1985).

This process will continue unless the environmental conditions are modified (lithological, structural, climatic and/or hydrodynamic) and the size of the channels, chimneys, craters and caverns will continue to grow.

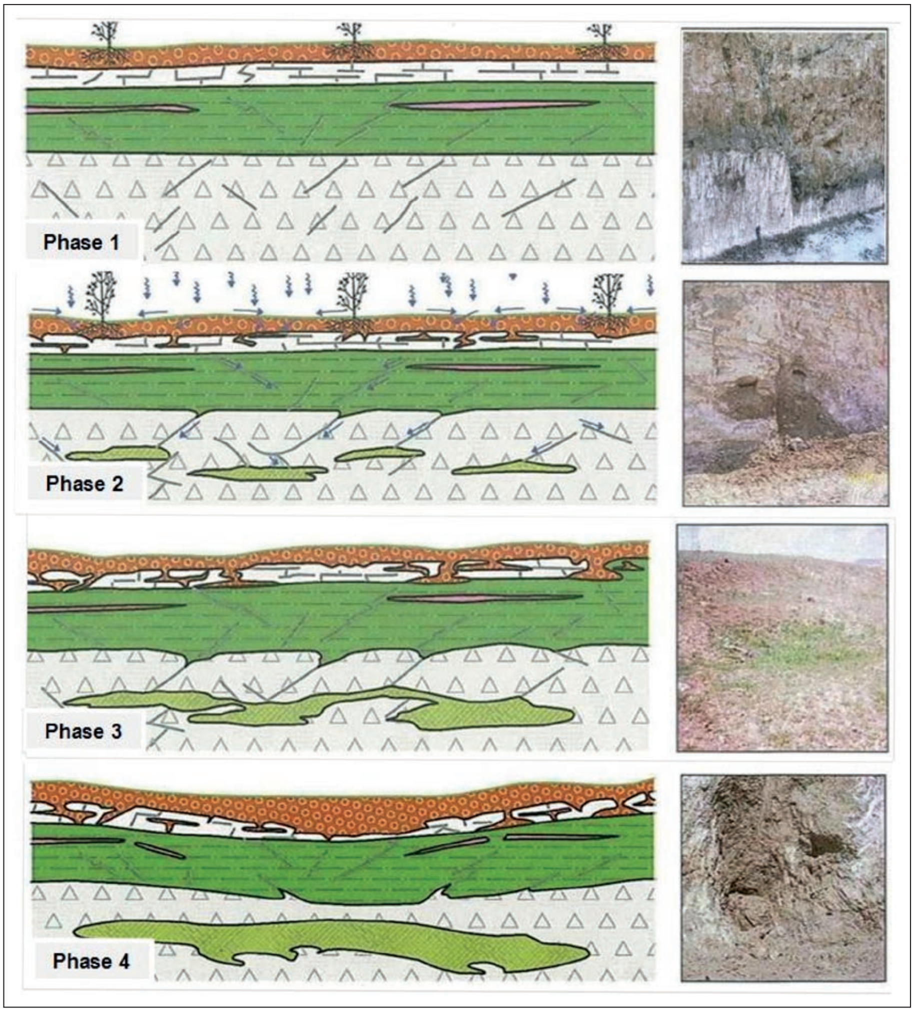

Fig. 8: Hypothetical phases of the karstic process.

d) Phase 4.

This phase represents the current state of the soil. The paleokarstification of the gypsum deposits are manifested in the form of vertical conduits with diameters ranging in size from 15–25 cm or from 2–7 m metres and lengths measured in metres and centimetres that develop in the thickest gypsum deposits.

These conduits are frequently connected to subhorizontal cavities which are generally small in size (several dozen centimetres) and which normally do not collapse.

The funnels, chimneys, channels and cavities formed by the conduits are often filled with greenish gypsum and sandy sediments with angulous fragments and gypsum particles, creating an overall appearance of a breccia that is easily spotted by its contrasting colours (Fig. 9).

Factor B: Spatial location of the karstic process

We created a hazard map on a 1:5,000 scale for the purpose of delimiting this process geographically.

From our analysis, we deduced that 2/3 of the total land area earmarked for the expansion of the city of Madrid (Fig. 10) was located in areas where this type of karstic process was mostly likely to occur.

Fig. 9: Cavities formed by Karstic duct clogging by silty and clay deposits.

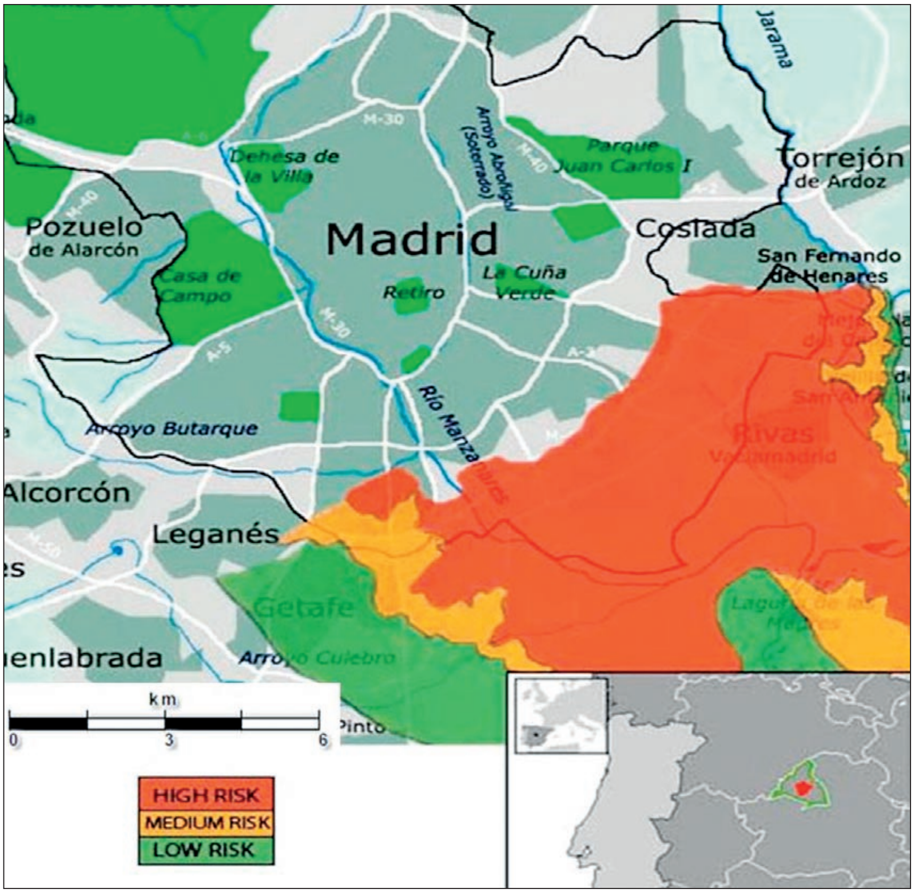

Fig. 10: Map of the level of susceptibility of karstic risk in the Southeast of Madrid.

Fig. 11: Area of fractures in clay and gypsum.

Fig. 12: Damages to a collector caused by broken pipes.

Factor C: Risk level based on triggering factors.

In the hazardousness grading process, we considered the risk factors that could reactivate the karstification process of gypsum in south-eastern Madrid.

Triggering factor 1.

Land movement work that exposes the gypsum, removing the impermeable protective cover (composed of clay deposits) and exposing preferential filtration areas (Fig. 11).

Triggering factor 2.

Broken pipes and leaks as well as intense irrigation on land where the karstic process has already taken place (Fig. 12).

This process causes the loose material fill inside the cavities, channels or chimneys previously created by erosion to be washed away, leaving these channels empty and allowing water to enter (Fig. 13).

Fig. 13: Damage to collector caused by broken water pipe.

Fig. 14: Crater formed by the collapse of a pile in karstified gypsum.

The main geological problem is related to the characteristic solubility of these types of materials, especially when compared to other rocks where the karstic phenomenon also occurs (carbonated rock). This feature is therefore a significant factor that must be considered taking the following aspects into account:

- The erosion speed of the gypsum material is directly related to the volume of sulphate-unsaturated water running through it.
- The climatological situation in south-eastern Madrid is characterised by very low precipitation.
- These materials are characterised by low permeability.
- The presence of impermeable clay materials in overlying positions.

In view of these conditioning factors, the amount of rainfall that infiltrates and circulates through the gypsum layers is negligible and therefore unable to trigger or activate the karstic process under the current natural conditions, as long as the environmental equilibrium is not altered by anthropic events.

The main problem therefore becomes the consequences or effects of this process on the land which go unnoticed and can cause serious problems. These morphological consequences come in a variety of forms (see Fig. 8), although they can be summarised in the three types described earlier.

Vulnerability. Analysis of vulnerability.
This is the second risk factor, which is expressed as a percentage of the destroyed assets (buildings, roads, services) or the effects on an exposed population (economic vulnerability).

Limiting our analysis to the risks associated with gypsum karstification processes, the vulnerability in south-eastern Madrid is defined as the potential threat of damages due to the effects which karstic processes on the land or the risk of this process being reactivated due to anthropic factors.

Hence, a building or a foundation structure built on land affected by karstic processes will be much more vulnerable, when these processes are not taken into account, than another building or structure where the presence of sinkholes and soft spots in the land has been factored in.

Clearly, the economic effects of overlooking the risks associated with karstic processes can be very significant in terms of building reconstruction, insurance companies, unusable services, etc.

The reality could be even worse if we add to this the cost of interrupting services, closing roads and closing businesses (large and small retail spaces and small businesses).

Measures to mitigate risk and reduce vulnerability are therefore critical.

Exposure. Analysis of exposure.
This analysis includes the population, property, infrastructure and services that could potentially be affected.

Clearly, the presence of karstification in the gypsum substrate in the Monegros district in the north-eastern part of the Iberian Peninsula, where the population density is less than 1 inhabitant per km^2, poses no risk since there are no people or property exposed to the risk.

However, the effects of karstic processes in the south-eastern part of the Madrid where there is a great deal of urban expansion taking place and where the estimated population density is 4,000 inhabitants per km^2, are considerable in terms of future exposure.

The cause for concern is highlighted by the fact that through the year 2020, south-eastern Madrid will be the site of some of the most intense urban development taking place in all of Spain.

MITIGATION STRATEGIES

The ultimate goal of mitigation strategies is to minimise, to the extent possible, the potential damage to future structures and services created as part of the urban development activities in south-eastern Madrid as a result of the effects of karstic processes on the soil.

According to this line of reasoning, the rational design of mitigation strategies should be focused on reducing economic vulnerability by properly designing and building structural foundations. Cooper (1995) has contributed decisively to the understanding of economic vulnerability.

Structural foundation design.
The type of foundations normally used in building construction include:

- Direct foundations with isolated elements such as footings or shafts.
- Direct foundations with continuous elements such as slabs.
- Deep pile foundations.

While all three of the foundation types mentioned here are possible in the areas affected by karstic processes, they will require contrasted and reasoned technical justification that takes the unique geological profile affected by this natural phenomenon into account.

Below we will explain the procedure for designing special foundations for mitigating the vulnerability of soil affected by karstic processes using deep pile foundations with *in situ* excavation.

Deep pile foundation with *in situ* excavation.
The purpose of this structural mitigation measure is to decrease the vulnerability of the buildings raised on ground where the processes associated with gypsum karstification are particularly evident. Under these circumstances, foundations using continuous slab type foundations pose technical and economic risks (Escolano & Bueno 2015).

The piles should be driven to a point below the softened soil. If this conditioning factor is overlooked, there is a risk that the soft spots and karstic cavities in the gypsum substrate could cause the piles to collapse (Fig. 14).

Special treatments must be applied to verify that the piles of the deep pile foundation are properly supported.

We will analyse three deep pile foundation designs:

- Deep pile foundations using large diameter piles.
- Deep pile foundations using small diameter piles, deeply driven.
- Deep pile foundations using small diameter pile and intermediate depths.

Deep pile foundations using large diameter piles.
For large diameter piles (>1,000 mm), the terrain below the endpoint of each pile should be inspected (Fig. 15).

Fig. 15: Inspection samples of the endpoints of 1,000 mm diameter piles which confirm the presence of folded gypsum without signs of karstification.

The inspection serves a dual purpose:

- The earth directly beneath the endpoint of the pile is inspected to verify that it is correctly supported. This inspection is conducted using a probe with continuous sample extraction.
- If craters or soft spots are detected underneath the pile, cement is injected through the test probe.

In order to conduct this inspection properly, a metal tube measuring 10 cm in diameter is installed along the length of the pile, welded to the walls of the pile, which is used to carry the drilling and injection tools to the bottom of the pile. This tube is also used to conduct the sonic integrity test. The crater drilled underneath the pile should be six diameters.

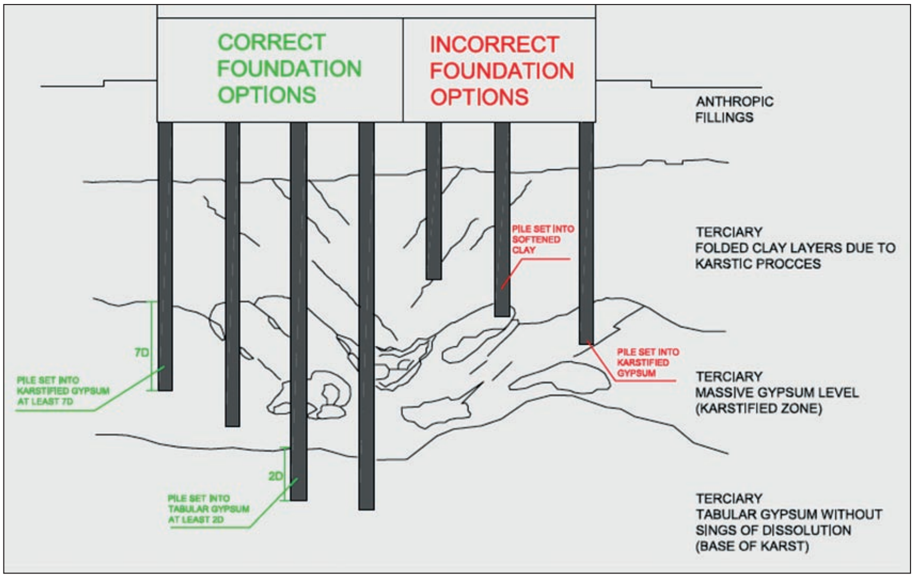

Fig. 16: Premises are fulfilled which will establish the number of diameters to insert into the massive gypsum.

Deep pile foundations using small diameter piles, deeply driven

For small diameter piles (< 850 mm), there is not enough room to install a metal tube inside the pile.

These piles therefore need to be driven deeper than the level of the karstified gypsum in order to find a rock substrate without signs of erosion.

This solution has a geological basis since karstic processes require the existence of an impermeable substrate to prevent further deepening. This substrate, located underneath the karstified gypsum, is composed of gypsum and black clay (recognised in the geological-geotechnical literature on Madrid as fold gypsum) without signs of erosion.

An alternative foundation solution would therefore consist of reaching the folded gypsum with the piles at depths of more than 30 m and this is a solution for small diameter piles which are very long.

Deep pile foundations using small diameter pile and intermediate depths

For this type of a solution there needs to be a specialist overseeing the installation of the pile.

This solution is only feasible when some of the following conditions are met, which will also determine the number of diameters to be set in the gypsum (Fig. 16).

The pile is valid when at least seven diameters are set in the gypsum without signs of karstification, which means that the pile's resistance is exhausted by the shaft.

The pile is valid when at least two diameters are set in the folded gypsum. This solution is considered value when there are signs of karstification in the gypsum.

CONCLUSIONS

In this article we have defined the karstic processes affecting the Miocene gypsum formations in south-eastern Madrid and the risks associated with the karst and their spatial distribution inasmuch as the effects they can have on the populations and assets involved.

A detailed study of the risks associated with karstification by analysing the karst factors was used to detect, quantify and delimit them geographically as a means of determining the risk zone.

Faced with this risk, the only viable mitigation strategy is one that decreases vulnerability by designing measures to mitigate the structural risks to building foundations, civil engineering structures and services.

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