Sinkhole threats management in urban developments

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ABSTRACT

Subsidence and sinkholes in urban areas pose catastrophic consequences if not detected and addressed effectively. Such phenomena have been observed in recent new urban developments in Madrid (Spain), highlighting the urgency of soil treatment to mitigate these risks. Upon discovering significant underground voids, traffic was halted until viable solutions could be identified. Preliminary studies utilizing microgravimetry, ground-penetrating radar, and boreholes revealed the presence of large cavities due to karstification. Subsequent research proposed testing plans, inspection programs, and intervention methods to repair existing sinkholes and prevent future occurrences. Throughout this article, the most suitable investigations for such terrains are explained, following a detailed study in a test area that has served as the basis for establishing a methodology for future work. This research underscores the critical need for proactive measures, emphasizing the necessity of soil treatments within urbanized areas to efficiently address situations and mitigate the potentially catastrophic impacts of subsidence and sinkholes while fostering a sense of security and stability within the community.

Keywords: Metropolitan, sinkholes, karstification, soil treatment, work methodology

1 INTRODUCTION

In the last quarter of the year 2019, a series of sinkholes and depressions occurred in the roadways of La Gavia Avenue at its intersection with Cerro Milano Avenue in one of the Southern's land development areas in Madrid.

The contractor awarded was required to address the issue by removing the pavement debris to fill in the sinkhole, where a large cavity was detected. As a result, traffic on the roadway was halted until a thorough understanding of the causes and feasible solutions could be determined.

Figure 1. A sinkhole discovered on La Gavia Avenue, situation in March 2018.

Preliminary studies using microgravimetry, ground-penetrating radar (GPR), and boreholes revealed the existence of numerous cavities in the subsurface due to the karstification of the gypsum terrain without fully delimiting their development and extent. In some cases, these cavities were located in areas where no surface movement had yet been detected.

Figure 2. Sinkhole discovered on V-5 roadway, May 2006.

Due to the geotechnical and geological risks and the traffic inconveniences for the population, an urgent remediation study was prepared, including:

- A proposal for a geotechnical investigation plan to analyse the causes of the affected area by the karstification process and risk zoning.
- Definition of an inspection program to monitor the subsurface evolution and estimate action thresholds.
- The most advisable intervention methods for future actions.
- A solution proposal for the repair of the existing sinkhole and other potential sink holes.

2 BACKGROUND

A large amount of existing geotechnical documentation from project and construction phases in the area was collected and analysed, including at least a dozen reports made between March 1999 and February 2016, confirming similar and ongoing problems since their inception.

The investigation techniques employed across the various studies were mainly: GPR, microgravimetry, mechanical boreholes, and electrical tomography.

In general, the GPR methodology did not provide good results, with low penetration due to shielding by the present materials (low resistivity of the superficial clay soil).

As result of the various geological-geotechnical studies conducted in the area, the explanation for the detected karstification problems centres on the gypsum nature of the area and its dissolution process in contact with water, coupled with the existence of old gypsum mining zones in the region (now covered), and also the presence of old tributary creeks of the Arroyo de La Gavia River, with manifestations of groundwater movements following the same paths. This would explain many of the detected tunnels and caverns.

3 PROBLEM IDENTIFICATION

3.1 Geological Framework

The study area is located on the Central Facies, tertiary sediments of the Madrid Basin, where the gypsum has evolved through a karstification process, favouring dissolution fissures, which potentially lead to cavities (sinkholes) and collapses. These are covered by thin quaternary deposits.

Additionally, the presence of old, abandoned mines in the area and karstic cavities filled with sandy clays containing rock fragments was confirmed.

The established geological-geotechnical units were:

- Anthropogenic fills (GU-1): with variable thicknesses ranging from 6 to 14m.
- Gypsum-bearing marly clays and green gypsums (GU-2a): down to approximately 20m in depth.
- Gypsums and greyish marly clays (GU-2b): averaging more than 20m in depth.

3.2 Photogeological and Historical Study of the Area

The comparative photogeological study of aerial photos from 1946 to 2020, as well as their corresponding cartographies and historical topographies, allowed the detection of old gypsum mining operations. These operations favoured previous ground collapses and incision by a tributary stream of the Arroyo de la Gavia Creek, which was located over an old cattle path and is now filled.

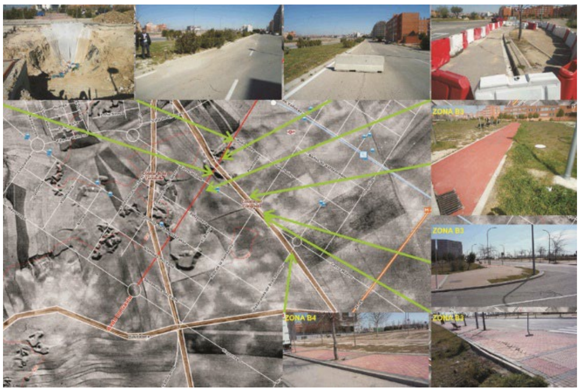

Figure 3. Damage Inventory, over 1956 aerial photo, showing ancient gypsum excavations, collapses, and linear incisions in the study area.

3.3 In Situ Problem Identification. Inventory

An initial analysis of the problem began with a field-work visit, during which an inventory of damages was made, noting the zoning of pathologies detected during the visits carried out.

Additionally, for the specific case of the sinkhole on La Gavia Avenue an underground inspection was conducted to understand the possible ramifications of the karst process under the roads, as well as a visit to the nearby collectors to rule out leaks.

3.4 Investigation Proposal to determine the Scope of Damages (Test Area)

The proposed geotechnical campaign was planned in locations established as 'Test Areas' to comparatively analyse the different subsurface investigation techniques and determine which best suited the karstification problem in gypsum materials detected that affected the pavement of numerous roads, sidewalks and basements.

A critical phased investigation was proposed, focusing on zoning areas with pathologies identified in the damage inventory and executed with a strategic plan for traffic cuts and diversions:

- 1st Stage: Geophysical surveys were conducted using electrical tomography profiles and passive seismic profiles (Multichannel Analysis of Surface Wave (MASW) type), with overlapping, longitudinal, and transverse alignments.
- 2nd Stage: Based on anomalies detected in the first stage, a microgravimetry grid was implemented to delineate the extent and geometry of the karst formations.
- 3rd Stage: For anomalies identified in the first and second stages, geotechnical-mechanical boreholes were used to determine the existence and depth of cavities. In shallower areas, test pits were conducted as an alternative.

Table 1. Summary of the geotechnical campaign by type of investigations in the test area.

Investigation	Number	Metres executed
Boreholes	21	525m bored (Average depth of 25m each).
Test Pits / Trenches	2	To max. depth (3 – 4m bgl each one)
Electrical Tomography	74 (28 long. and 46 transv.)	10,345m. (Total length of all tomography lines).
Passive seismic profiles (MASW type)	74 (28 long. and 46 transv.)	9,450m. (Total length of all seismic profiles).
Microgravimetry	1,401 stations in 3 areas	Variable Mess (Stations spaced from 2.5 x 2.5 to 5 x 5m).

This multi-stage approach was essential to accurately assess and address the karstification problem, ensuring comprehensive risk mitigation and effective intervention strategies.

The investigation methods that worked best for the sought objectives (karstification problem in gypsum materials) were electrical tomography in the first instance (not the MASW seismic method, which did not yield good results), followed by microgravimetry in a second step, and finally direct explorations (boreholes and pits).

4 PROPOSED METHODOLOGY TO ADDRESS SIMILAR ISSUES

The proposed methodology to address the problems caused by karstification in gypsum materials comprises the following work stages:

- Identification, zoning, and damage inventory: visual inspection program with a frequency of 6 months.
    - Zone A: Areas requiring immediate attention due to significant instability or the presence of sinkholes, voids, or other critical issues. Treatment may include high-pressure grouting, extensive material clearing, and reinforcement.
    - Zone B: Areas with moderate instability or potential for future issues. Treatment may include selective and repeated injections, moderate material clearing, and localized reinforcement.
    - Zone C: Areas with minor issues or those that serve as buffer zones. Treatment may include light material clearing, minor grouting, and regular monitoring.
- In areas indicated by the damage inventory, geotechnical campaigns will be carried out annually, except for urgent cases which will be addressed semi-annually. The following techniques will be employed, excluding passive seismic (MASW or Refraction Microtremor REMI)) and ground-penetrating radar due to their low effectiveness in the testing area:
    - 1st Stage: electrical tomography profiles using a Wenner-Schlumberger device with a 2.5m electrode spacing (longitudinal and transverse to the roads).
    - 2nd Stage, in areas with anomalies from stage 1: micro-gravimetry.
    - 3rd Stage, in areas with anomalies from stage 2: drilling for deep anomalies (>4m) and trenches (<4m).
    - 4th Stage, laboratory tests on samples from drilling and trenches.
- A geological-geotechnical interpretive study of the field investigations results will be conducted to better understand the extent and nature of the problem. To define the extent of the problem and possible treatments, it was necessary to forecast the collapse using the formulations of Jiany and Jian (1987), also noted by authors such as Mancebo Piqueras, J.A., which establish two scenarios based on the position of the water table, with K being the equilibrium factor, and for K>1, the cover would be in a relatively stable state.

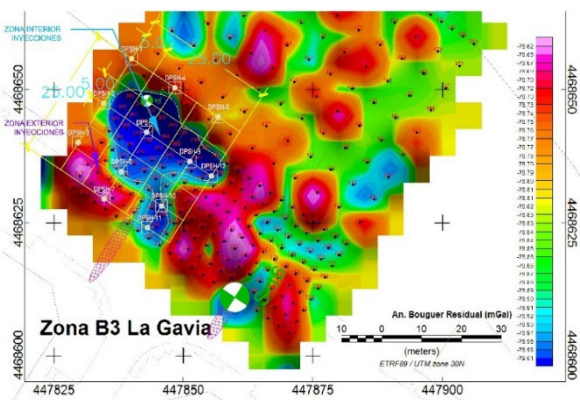

Figure 4. Damage Inventory, over 1956 aerial photo, showing ancient gypsum excavations, collapses, and linear incisions in the study area.

- Proposal of generic solutions for ground improvement. Based on the findings, generic solutions for ground improvement will be proposed, tailored to the geometric and geotechnical characteristics and depth of the anomalies.
    - Treatment A: For anomalies at depths between 0 and 6m (shallow): opening, partial clearing of the embankment, replacement, and reinforcement.

Figure 5. Start of the works. Treatment type A.

Figure 6. Test area for injections. Treatment type B.

- Treatment B: For anomalies at depths between 6 and 12m (deep, with a maximum point of -19.50m): dry mortar injections by gravity, sleeve-type injections (SRI), and slight clearing of the embankment.
- Treatment C: For small anomalies at depths between 0 and 6m (shallow): opening, slight clearing of the embankment, replacement, and reinforcement.

- Detailed analysis with the scope of the solution that will encompass a comprehensive study of the proposed solutions, ensuring they effectively address the identified issues and are feasible for implementation.

Table 2. Summary of actions taken in the project area.

Action number	Area	Details	Treatment
1	Gavia Av. and Cerro Milano Av. Intersection	A 6.0m deep sinkhole cut off the roads, with branches through tubes and karst caverns extending towards the main road. Borehole S-4 also showed a void between 3.90 and 10.40m, as identified in microgravity studies.	Type A: opening, medium level surface replacement, and reinforcement.
2	Gavia Av. and Cerro Milano Roundabout	A hole was detected in trench C-1, below 1.80m, estimated in the project to be up to about 4m deep. This area showed a topographic depression indicative of a concentric collapse, also detected in microgravity studies. It was marked and sealed.	Type A: opening, medium level surface replacement, and reinforcement.
3	Gavia Av.	A hole was detected in borehole SR-02, between 3.00 and 6.50m, in an area with clearly recognized concentric cracks indicating subsidence, also detected in microgravity studies.	Type A: opening, medium level surface replacement, and reinforcement.
4.1	Cerro Milano Av. and Alto de la Sartenilla Street	A series of surface damages were detected, affecting both the sidewalk and occasionally the roads, but no significant geotechnical anomalies were found in the studies conducted, only a slight anomaly in microgravity, but in this case closer to the road.	Type C: opening, light surface replacement, and reinforcement.
4.2	Alto de la Sartenilla Street and Cerro Milano Av. (bike lane)	A hole was detected in borehole S-17 between 6.00 and 14.50m, affecting the bike lane, park, and sidewalk. This area, already noted for radial cracks indicating karstification and collapse, showed a gravimetry amplitude of >0.6mGal with a wavelength over 10m. Cavities were identified from low SPT values around 6 and 12m depth.	Type B: sleeve-type injections (SRI) and light subgrade replacement.

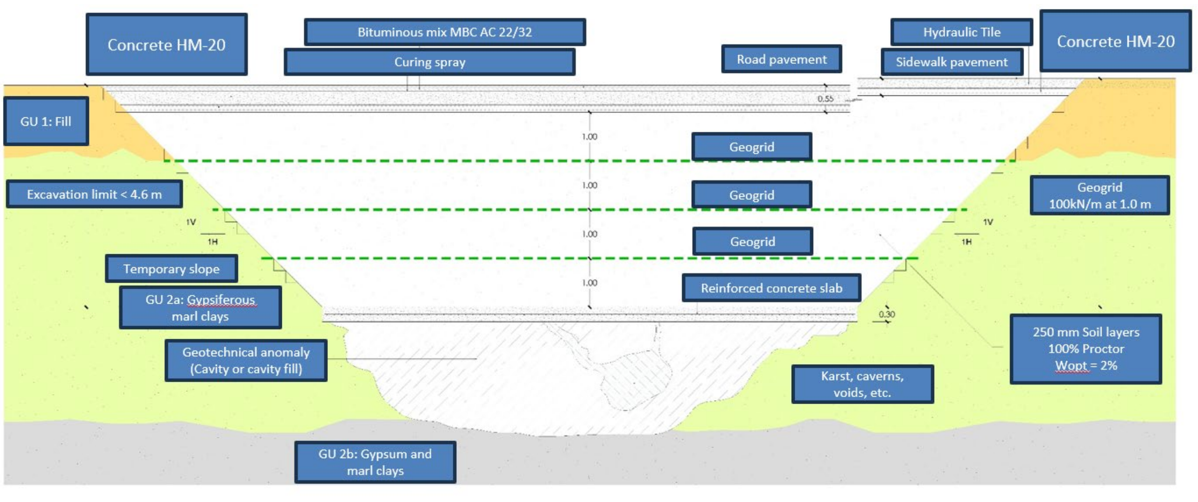

Figure 7. Treatment Type A cross section.

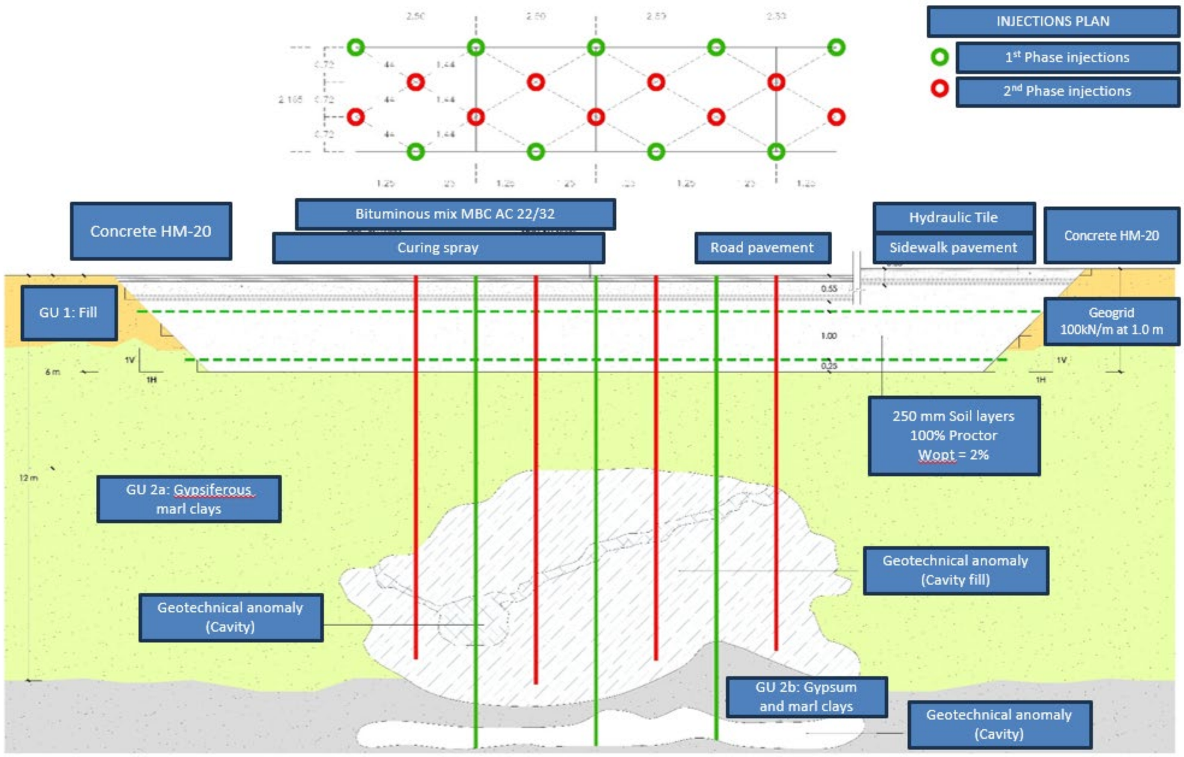

Figure 8. Treatment Type B cross section.

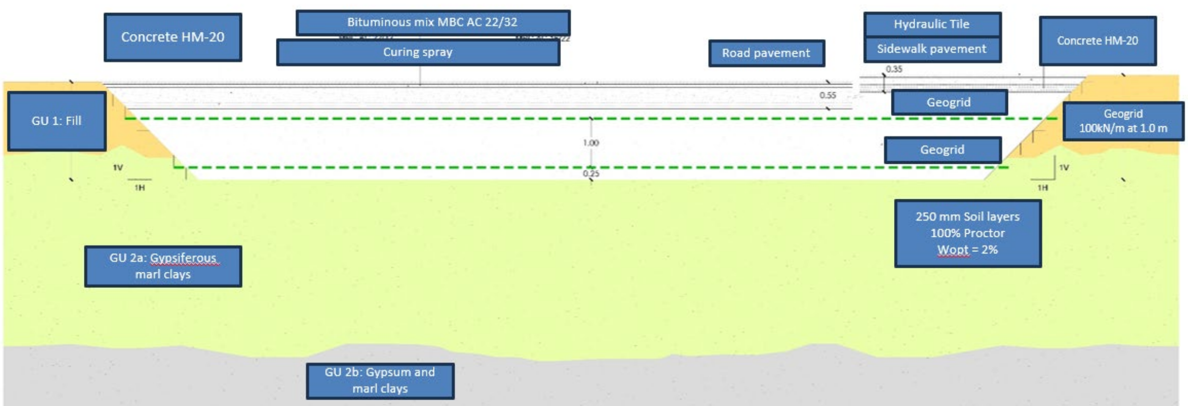

Figure 9. Treatment Type C cross section.

5 EXECUTION AND MONITORING

Below are descriptions of two of the most significant interventions carried out:

Intervention 1, Zone A, La Gavia Avenue:

Level 1 geotechnical supervision allowed for adjustments to match the actual ground conditions. The work involved clearing to depths of up to 8m, constructing intermediate berms and buttress of 0.5x0.5m with slopes varying from 1H:1V in soils to 1H:2V in rock. Fluid concrete mortars to fill cavities. Adapt the geometry of the reinforced slabs on-site and adjust the positions of the 100kN/m reinforcement geogrids.

Figure 10. Treatment Type A progress.

Intervention 4.2, Zone B3, Alto de la Sartenilla Street with Cerro Milano Avenue bike lane:

The injection test field was redesigned on-site, experimentally setting a maximum depth of 12m, slurry pressures between 6 and 8 bars, and a maximum of 600 litres per 3m injected section. The initial grid was staggered with a spacing of 2.5m.

- The maximum selected area was 25x25m (outer injection zone), with an inner area where actions were only taken on paved or infrastructure areas like bike lanes.
- From 12 to 19.50m BGL, dry mortar injections by gravity were tested.
- From 6 to 12m BGL, slurry injections using sleeve tubes were tested.

Validation of the treatment on-site was carried out by comparing dynamic penetration and geophysical tests before and after the treatment.

6 CONCLUSIONS

The main objective of this work was to establish general guidelines for addressing identified sinkhole issues and to create a compendium of common problems and solutions applicable to future development areas. Supported by an annual program of roadway monitoring and maintenance, this effort culminated in a practical and rigorous methodology for the Madrid City Council.

The study's key conclusions were derived from geotechnical investigations, including electrical tomography, micro-gravimetry, drilling, and laboratory testing. These methods provided valuable insights into subsurface conditions, enabling precise identification of problematic areas, and informing appropriate treatment designs. It was determined that passive seismic techniques like MASW and REMI, as well as ground-penetrating radar, were ineffective in gypsum materials and thus not suitable for this context.

Effective treatments for urban areas with gypsum materials were identified based on the size, shape, and depth of the issues. Treatment A, for shallow anomalies, involved site opening, embankment clearing, material replacement, and reinforcement. Treatment B addressed deeper anomalies (from 6 to 12m depth) using dry mortar and injections, while Treatment C was similar to Treatment A, but included measures for slightly shallower anomalies as a preventive measure.

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