Modelling the spatial variability of karstified processes in gypsum deposits – the case of a high-speed railway bridge in the Madrid Miocene Basin

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ABSTRACT

The presence of karstification processes in the terrain poses a threat to the safety of the foundations of structures, which in the case of gypsum materials becomes more dangerous due to the rate at which they can progress. This work describes the case of a Spanish high-speed railway bridge whose route runs over a Tertiary gypsum formation belonging to the lower Miocene unit of the Madrid Basin. These are very firm materials in a healthy state, that allow the direct support of shallow foundations, which stand out for their high heterogeneity, with the presence of massive gypsum banks as well as alternating levels of gypsum and clay. However, these materials can be affected by karst processes of dissolution, weathering, and replacement by clays, in which case there is a marked degradation of their mechanical properties, and the eventual local appearance of cavities. In these circumstances, it is necessary to carry out soil improvement treatments, such as compaction grouting, or resort to deep foundations with piles that transmit the loads of the structure to a lower substrate in a non-disturbed state. By its nature, the detection of this type of processes by drilling rotary boreholes is not trivial, and there is often uncertainty associated with its spatial variability. This communication presents the results obtained after the execution of a geotechnical research campaign, consisting of the realization of seismic tomography borehole-profiles under each support of the viaduct, supported by the execution of conventional rotary boreholes. The results of this exploration have made it possible to understand and define the spatial extent of the materials degraded by karstification and the selection of robust foundation typologies that favour the sustainable and resilient nature of the infrastructure.

Keywords: karst; gypsum; cross-hole; high-speed railway.

1. Description of the case study

1.1. General introduction

The Mayoral Viaduct is a bridge with a total length of 653 m, composed of 19 spans with variable lengths between 29 m and 35 m, which is under construction and on which a double track platform will be installed that will allow the connection between two high-speed railway lines in Spain.

It is located in the south of the municipality of Madrid, shown in Fig. 1, where deposits belonging to the Lower Miocene sedimentary unit of the Madrid Basin emerge, which are made up of massive gypsum and intercalations of gypsum and firm plastic clay levels.

In these materials, the presence of important karstification processes has been described (Rodriguez-Aranda et al., 2002), which gives rise to the formation of voids and soft clay zones, a product of the dissolution of the gypsum materials (Castellanza et al., 2018), whose location and dimensions are irregular and, in principle, difficult to predict and define. The problems associated with karstification in this area are well known (Escolano et al., 2015), having generated pathologies in the transport infrastructure in the district of Vallecas, as well as the damage and demolition of several residential buildings in San Fernando de Henares, affected by gypsum dissolution processes and subsidence that, according to some sources, could be associated with water seepage and flow into the tunnel during the construction of Line 7 of the Madrid Metro.

Figure 1. Location of the Mayoral Viaduct and of the buildings recently demolished in San Fernando de Henares

1.2. Strategies adopted in the design to manage the risk associated to karstic processes

In the layout of the viaduct, the presence of weathered soil on the surface of variable thickness was detected in the design phase, opting for direct foundations in six supports, when their thickness is less than 5 m, and deep piled foundations for the remaining thirteen supports. In addition, for the treatment of areas altered by karstification, the final design established the following treatments:

- Low pressure mortar injections from the ground surface, under the two abutments, where areas altered by karstification had been detected.
- In pile foundations, on potentially karstified ground, a vertical drilling will be carried out that explores 5 m below the tip of the pile and if altered sections are detected, the region would be treated with mortar injections.

As can be seen, the strategies adopted in the project are based on assuming that the spatial distribution of cavities and areas altered by karstification is not predictable. Therefore, it is decided to explore the region beneath each foundation and to execute systematic injection treatments at those points where anomalies are detected.

It is worth mentioning that the treatments designed in the final design phase offer a potential improvement under the tip of each pile, without considering that since these are groups of piles, the area to be treated with injections should be larger, in line with the mechanical response of the ground under the base of pile groups. On the other hand, the design does not indicate the treatments to be carried out under the supports using direct foundations by footings, which represents an additional source of uncertainty.

Under these circumstances, during the construction phase it is planned to carry out a complementary geotechnical investigation campaign in order to delimit, as far as possible, the true extent of altered areas under each of the viaduct supports.

2. Geophysical and geotechnical investigation

2.1. Methodology

In order to investigate the presence of karstic processes, a combined investigation survey was designed and conducted under each element (abutments and piles) comprising the following works. The depth of these investigations was between twenty-seven and fifty-two meters, more than enough to cover the tension bulb under each foundation, regardless it was a footing or a group of piles.

Firstly, a rotary borehole was drilled for each support, with core recovery and inspection for the detection of voids and altered materials. This geotechnical borehole was accompanied by an additional parallel drilling , at a horizontal distance between fourteen and eighteen meters, as shown in Fig. 2. Every pair of boreholes was used to perform a geophysical campaign based on P-wave cross-hole seismic tomography (Chen et al., 1990; Link et al., 1993; Jackson and McCann, 1997), as discussed below.

The seismic P-wave velocity of a material is closely tied to its elastic properties. P-waves, or primary waves, are seismic waves that propagate through the Earth's interior and other materials. They travel faster than other seismic waves and can pass through both solid and liquid materials.

The velocity of P-waves depends on the elastic properties of the material they travel through. Elastic properties such as density, stiffness, and compressibility influence how quickly P-waves can travel through a substance. In general, materials with higher densities and greater stiffness tend to have higher P-wave velocities.

For example, in solid materials like rocks, higher densities and greater stiffness typically result in higher P-wave velocities. Conversely, liquids like water or molten rock have lower P-wave velocities due to their lower densities and lack of structural rigidity.

Understanding the relationship between P-wave velocity and elastic properties is crucial in fields such as geology and seismology, where it helps scientists infer the composition and structure of Earth's interior or other materials based on seismic data.

The boreholes were prepared with a PVC casing and filled with water. In one of the boreholes (receiving borehole) a set of hydrophones was introduced. This array of sensors is composed of 24 elements spaced every meter. At the opposite borehole (the emitting borehole), a seismic source (sparker) was introduced at a given depth. For the whole length of the emitting borehole, the sparker was placed at one-meter intervals. At each depth point, the sparker generated seismic P-waves that were received by the hydrophone array located at the opposite borehole.

2.2. Results

P-wave traveltimes were extracted from the seismic records and used in an inversion scheme to derive velocity models of the ground around the foundation elements. The inversion process is an iterative procedure where the observed P-wave traveltimes are compared with synthetic traveltimes generated by a velocity model. This model is updated iteratively until the difference between observed and synthetic traveltimes (residuals) reaches a minimum.

The derived models, shown in Fig. 3 and Fig. 4, represent the wave speed of seismic P-waves in the ground, which is a parameter directly related to the dynamic properties of the ground. High velocity values are associated with stiff materials whereas low velocities are associated with less rigid layers or voids.

2.3. Interpretation and ground model derivation

In the above-mentioned figures, the results from the rotary drilling core inspections have also been presented, indicating the depth at which any sign of karstification was observed, including open voids, and altered clay levels with a softened consistency. As can be seen, there is a reasonable relationship between the regions with lower values of P-wave velocities and the depths where signs of karstification were recorded, showcasing the positive synergy and robustness that these combined geotechnical and geophysical exploration techniques can provide for these ground conditions.

Another striking aspect, in view of the results obtained, is that apparently the zone of karst alteration under the Mayoral viaduct would present a marked lateral continuity from abutment 1 to pier 15. Indeed, under these sixteen supports, the disturbed zone would be present up to depths of around 18 m to 22 m, observing that below this level the Tertiary gypsum substrate would be completely unaltered and healthy. This lateral continuity of the karstified zone, and the almost horizontal arrangement of its lower limit, is in line with what has been observed in various outcrops available on the slopes of open cuts of the linear transportation infrastructures that have been built in the area (Escolano 2005).

On the other hand, the existing terrain under the last three supports of the viaduct (pile 16, pile 17, and abutment 2) would not be affected by karstification processes, which could be interpreted by a fault jump between the altered zone and the unaltered viaduct.

2.4. Selection and design of reliable foundations

As mentioned before, there are several support locations that do not seem to be affected by karstification processes. In the case of pile 16 and pile 17, a direct foundation has been designed using footings, having estimated the values of admissible vertical load based on the results of the 77 pressuremeter tests that were carried out inside rotational boreholes around the Mayoral viaduct. In abutment 2, although apparently the underlying ground is not affected, it was determined to use a deep foundation because this support is the fixed point of the structure that must receive the important horizontal loads associated with the braking of railway convoys.

For all supports that are affected by karstification processes, it has been chosen to transfer the loads of the structure through groups of end-bearing piles, embedded in the healthy substrate existing under the sub-horizontal band of alteration described above. Once again, the ultimate and allowable vertical loads on the piles were estimated using the available pressuremeter tests, which are also useful to assess the horizontal deformation modules of the ground in the disturbed regions and in the underlaying non-altered ground areas.

3. Conclusions

The presence of karstification processes always represents a serious problem with the correct functioning of the foundations of structures. In the case presented here, the problem is even greater if possible due, firstly, to the fact that, since these are gypsum-type deposits, the progress of dissolution processes occurs even more rapidly than, for example, in limestone rocks. Furthermore, the fact that it is a viaduct of a high-speed railway line means the imposition of significant loads on the natural ground as well as the need to reduce the geotechnical vulnerability of the infrastructure as much as possible.

This work has highlighted the suitability of combined geotechnical investigation techniques, consisting of the use of advanced geophysical techniques (vertical seismic tomography) together with the drilling of conventional geotechnical rotary-drilling boreholes. The results obtained in the geotechnical investigation have made it possible to define with appreciable clarity the geometric extension of the areas altered by karstification, as well as the lower limit from which it has been verified that the underlying natural terrain is not affected, offering thus a reliable level of support on which groups of piles can be embedded. Likewise, the spatial delimitation of altered areas and healthy areas favours the execution of the works, considerably reducing the uncertainties associated with the techniques that have been used until now, such as the systematic drilling of boreholes under the tips of the piles and of treatments of injection whose effectiveness is not always verified.

Acknowledgements

The authors are grateful for the permission granted by ADIF for the publication of this work.

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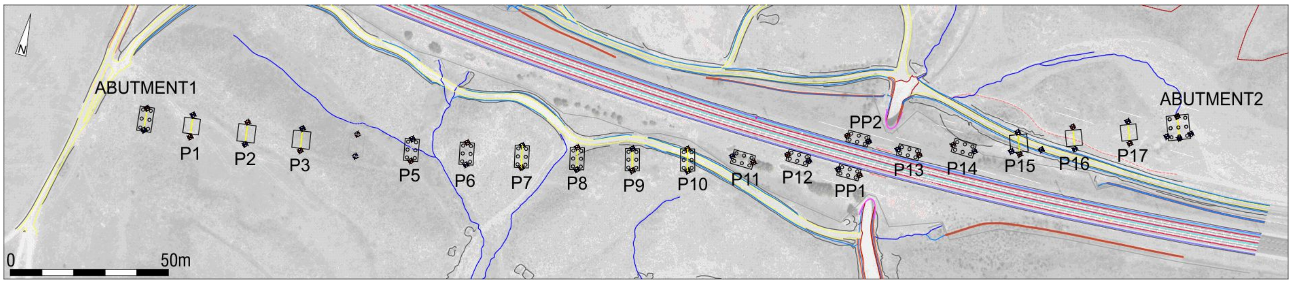

Figure 2. Aerial view of the viaduct support locations and boreholes used for the geophysical survey.

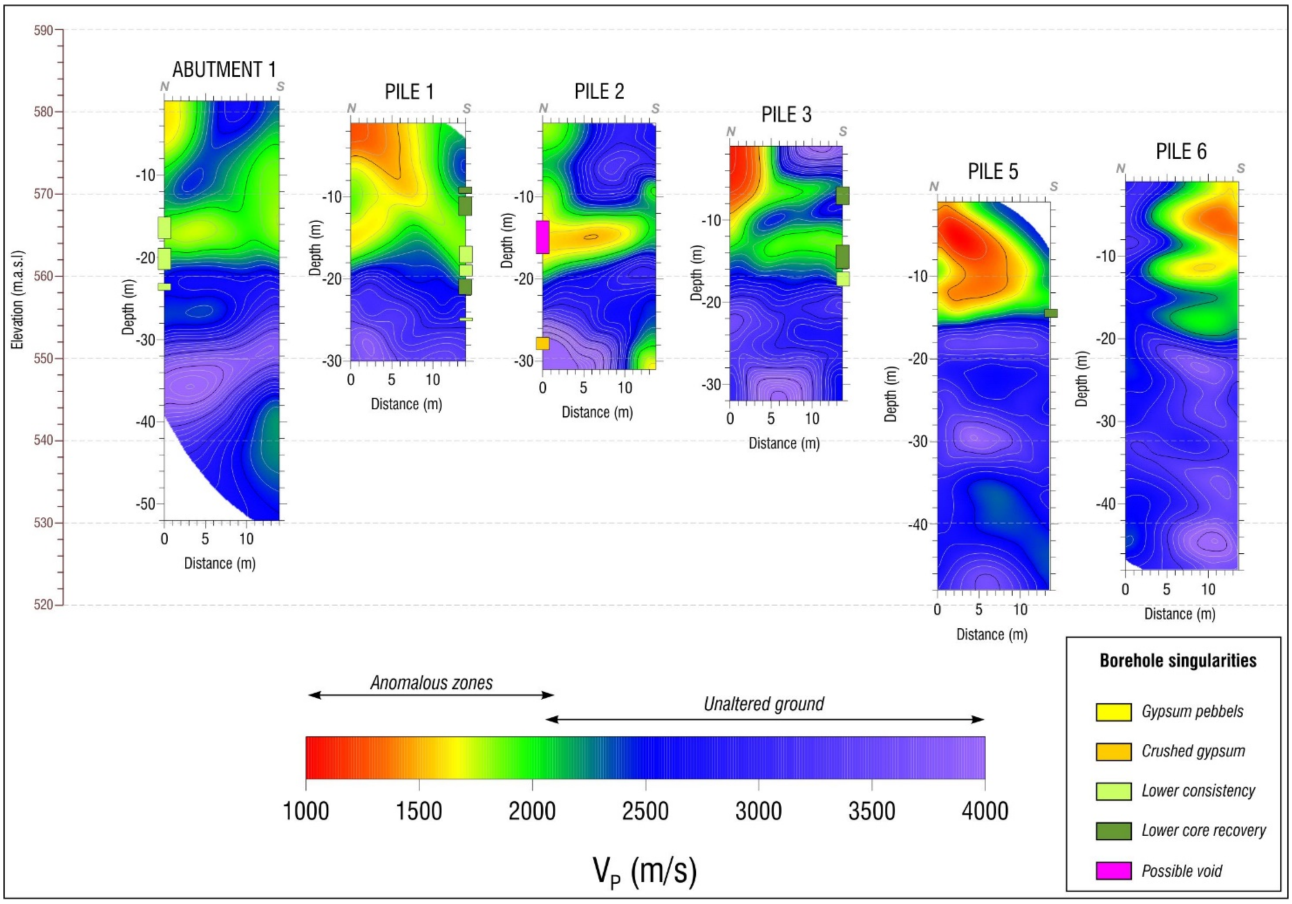

Figure 3. Estimated distribution of P-wave velocities and borehole singularities under a set of viaduct supports (1/2).

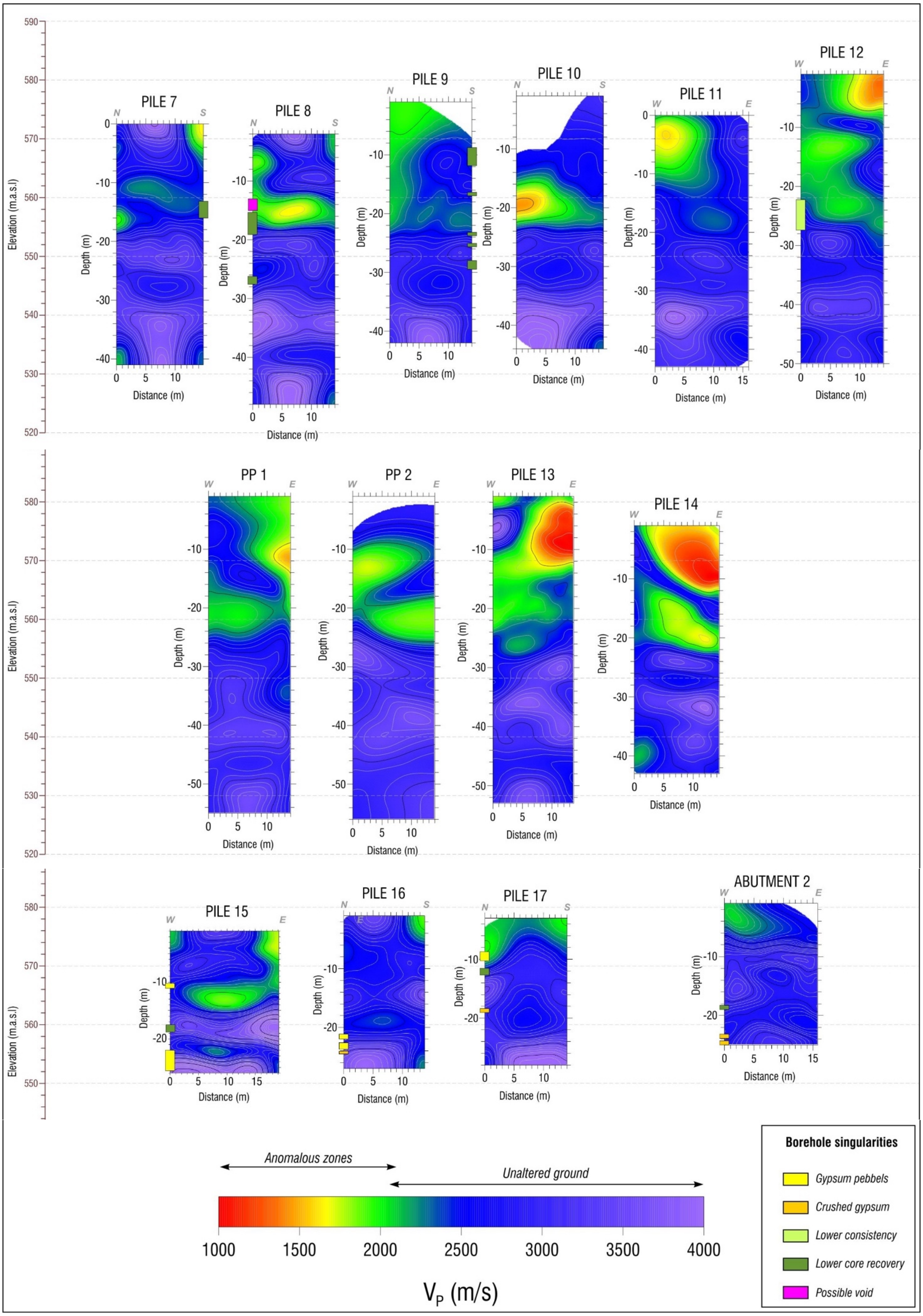

Figure 4. Estimated distribution of P-wave velocities and borehole singularities under a set of viaduct supports (2/2).