

Article

Investigation and Monitoring of Sinkhole Subsidence and Collapse: Additional Data on the Case Study in Alcalá de Ebro (Zaragoza, Spain)

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Abstract: Alcalá de Ebro is located 35 km northwest of the city of Zaragoza, on the right bank of the Ebro River at the outlet of a ravine (Juan Gastón) towards the river, with a catchment area of more than 230 km². Over time, urbanisation and agricultural development have eliminated the last stretch of the drainage channel, and these water inputs have been channelled underground, filtering through the ground. This section of the Ebro Valley rests on a marly tertiary substratum, which promotes dissolution-subbing processes that can lead to sinkholes. The ground tends to sink gradually or suddenly collapse. Many studies have been carried out to understand not only the origin of the phenomenon but also its geometry and the area affected by it in the town of Alcalá de Ebro. In this sense, it has been possible to model an area around the main access road, where numerous collapsing sinkholes have been found, blocking the road and affecting houses. It also affects the embankment that protects the town from the floods of the river Ebro. These studies have provided specific knowledge, enabling us to evaluate and implement underground consolidation measures, which have shown apparent success. Several injection campaigns have been carried out, initially with expansion resins and finally with columnar development, using special low-mobility mortars to fill and consolidate the undermined areas and prevent new subsidence. These technical solutions propose a method of ground treatment that we believe is novel for this type of geological process. The results have been satisfactory, but it is considered necessary to continue monitoring the situation and to extend attention to a wider area to prevent, as far as possible, new problems of subsidence and collapse. In this sense, the objective is to continue the control and monitoring of possible phenomena related to subsidence problems in the affected area and its immediate surroundings, to detect and, if necessary, anticipate subsidence or collapse phenomena that could affect the body of the embankment.

Keywords: collapse hazard; sinkhole mitigation; gypsum karst; injections; geogrid; evaporitic rocks; topographic auscultation



Academic Editor: Giulio Iovine

Received: 30 March 2025

Revised: 29 April 2025

Accepted: 4 May 2025

Published: 6 May 2025

Citation: Gracia, A.; Torrijo, F.J.; García, A.; Boix, A. Investigation and Monitoring of Sinkhole Subsidence and Collapse: Additional Data on the Case Study in Alcalá de Ebro (Zaragoza, Spain). *Land* **2025**, *14*, 1006. <https://doi.org/10.3390/land14051006>

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1. Introduction

Alcalá de Ebro (Spain) is a small town on the banks of the Ebro River, the largest river in the Iberian Peninsula, which collects much of the snowmelt from the southern slopes of the Pyrenees. (Figure 1a,b) Thus, Alcalá de Ebro is in the Ebro corridor, a 6-km-wide corridor defined by a succession of low and medium terraces on the right bank of the

river, which make the relief descend in a staggered manner from an altitude of around 300 m to 215 m above the current riverbed. The urban centre is located between 221 m and 226 m, occupying the lowest terrace (considered the current flood plain). The river here adopts a meandering geometry due to its low longitudinal gradient (around 0.06%) and forms the regional base level. Geologically, it is in the sedimentary basin of the Ebro River and is surrounded by three mountain systems: the Pyrenees, the Iberian Mountain range, and the Catalan coastal mountain range. The stratigraphy of the area consists mainly of a tertiary marl and gypsum substratum, strongly altered in its surface layers, on which quaternary materials of varying thickness and compactness are deposited. The gypsum has a rather uniform appearance, consisting of white gypsum with a nodular structure. Grey-greenish marls and lutites appear, associated with the gypsum materials or alternating with them [1,2]. Quaternary formations are widespread throughout the area, arranged in several terraces associated with the Ebro River, as well as various alluvial deposits and colluviums [2] (Figure 1c).

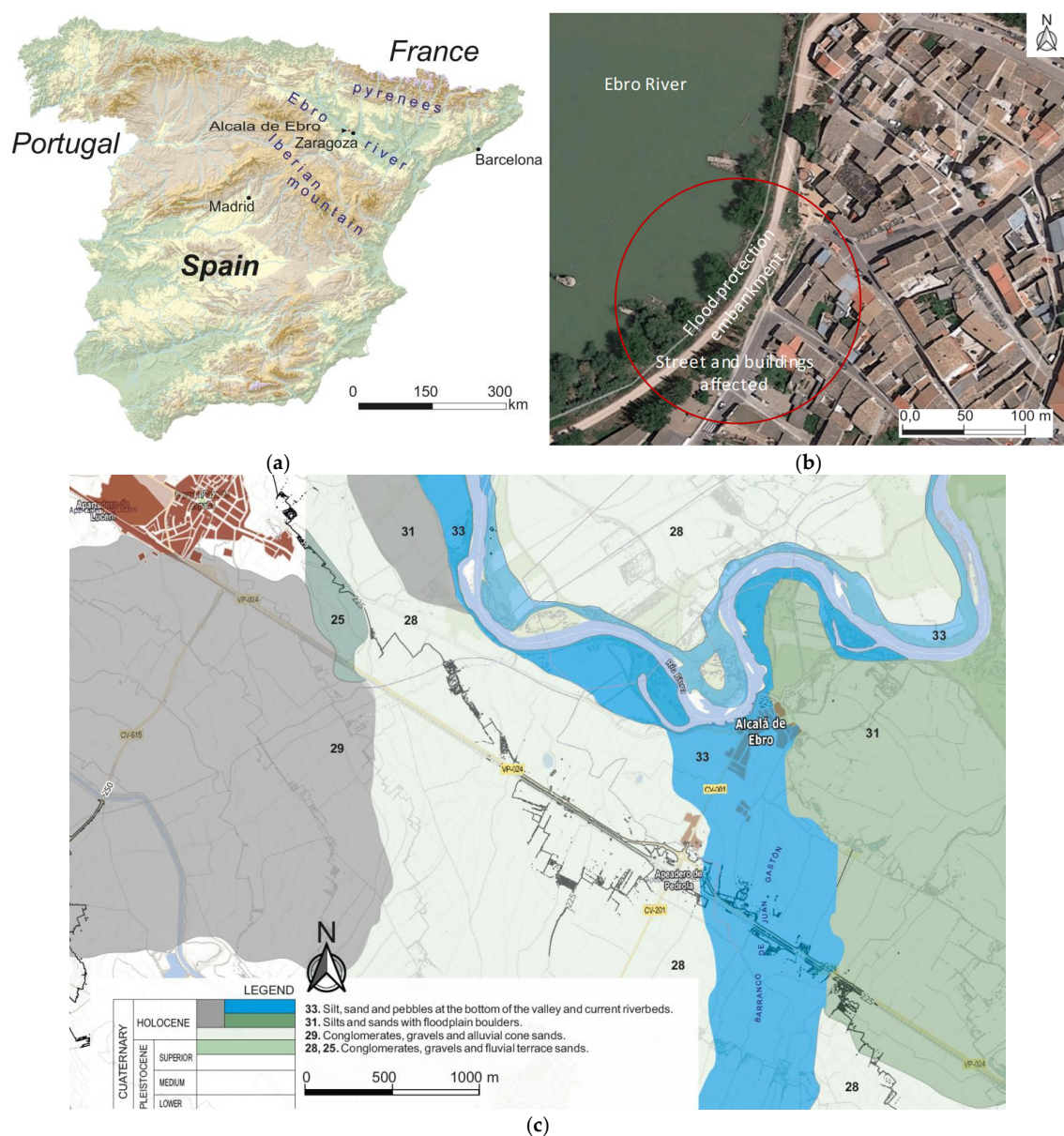


Figure 1. Geographical and geological framework: (a) location of Alcalá de Ebro in the Iberian Peninsula; (b) aerial view of the area under study (source: Google Maps); (c) geological map of Alcalá de Ebro and its surroundings, modified with permission from [2].

The marl-gypsum substratum is made up of soft silty, clayey rocks alternating with layers of gypsum and other more soluble minerals, such as halite and glauberite. The infiltration of groundwater, combined with fluctuations in the Ebro River's water level, leads to the dissolution and transport of fine materials. These processes of dissolution and piping can create hollows that may extend toward the surface, resulting in subsidence and sinkholes. In the city of Alcalá de Ebro, Spain, these processes have led to the emergence of sinkholes that have impacted both streets and houses. These sinkholes are caused by the presence of soluble salts, such as halite and glauberite, which have been identified in drill holes at depths between 14 and 21 m. As these salts dissolve and the ground above them collapses, subsidence and sudden sinkholes that can drop up to 10 to 30 m have occurred, leaving openings on the surface.

These karstic phenomena have long made access to the town difficult and have caused the collapse of several houses. It has also affected the embankment that protects the town from the frequent flooding of the Ebro River.

The occurrence of sinkholes in this area is referenced in historical memory. For example, in the classic book 'Don Quijote de la Mancha' by Miguel de Cervantes (1615), there is a reference to his squire Sancho falling into a sinkhole, probably inspired by this type of phenomenon that is so common in the area. Despite being a historically known issue, the sinkhole problem has been documented in this area since 1980 [2–4]. Sinkholes like the ones in Figure 2 frequently appear, increasing in size with the appearance of new sinkholes adjacent to them, and have been blocked either naturally or, in most cases, by filling with large boulders and gravel. Unfortunately, these holes have been filled in the past in unorthodox ways without solving the problem.



Figure 2. View of collapsing sinkholes that appeared next to C. de la Estación Street in August 2016.

Previous geological exploration works were used to define the best treatment to remediate this subsidence in the study area [2,5]. Geotechnical investigations were carried out (Figure 3), which included a total of 59 in situ DPSH tests and 16 boreholes with depths up to 30 m. Between these boreholes, cross-sectional seismic tomography was performed. This geophysical technique estimates the value of the P and S wave velocities of the ground and allows the identification of point features, possible disturbed areas and contacts between the different geotechnical units of the ground.

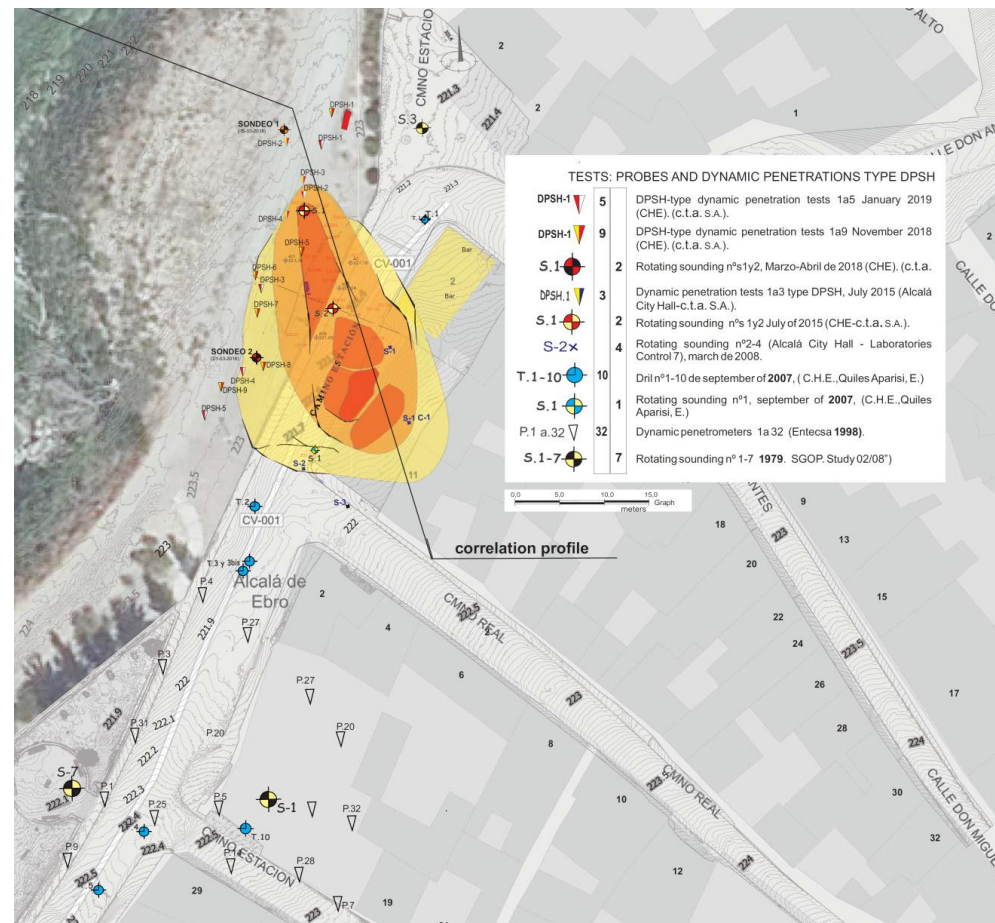


Figure 3. Location of the geotechnical investigation works carried out. The areas marked in red indicate sinkholes that occurred in the last 17 years. The areas in orange and yellow indicate the contour zones affected by cracks in pavements and buildings, which show evident signs of subsidence. The correlation profile is shown in Figure 9, modified with permission from [2].

The use of previous data from the bibliography, as well as the data obtained from the new boreholes and the transversal seismic technique, made it possible to construct a geotechnical profile of the ground [1,2].

In this context, this paper discusses the types of procedures that can be used to consolidate soil and the control procedures that can be used to monitor and prevent subsidence in this specific area. Specifically, this paper presents the results obtained to date. The situation of the dolines in the study area can be seen in Figure 3.

In a first research phase, between 2013 and 2021, work was carried out on the identification of the area affected by the sinkholes, the development of a geological–geotechnical model, and the evaluation and application of measures (between 2015 and 2018) to improve the ground conditions by injection, initially with expansive resins and later with special low-mobility mortars [3]. For the latter, the injection volumes and pressures were methodically controlled. These injections reached depths of between 21 and 24 m and presented very different mortar admissions depending on the compactness–cohesion of the terrain, recorded at different depths. The largest deposits are mainly concentrated in a section between -14.0 and -21.0 m (between 5 and 7 m thick), where it has been found that there is a dissolution-undermining process associated with levels or layers of salts (type glauberite, halite...) that are exceptionally soluble [2].

In a second phase of work, between 2021 and 2024, all the existing data obtained for the study of the subsidence recorded, both geotechnical tests (probing and dynamic penetration tests) and geophysical prospection (gravimetry, georadar, and electrical to-

mography), were re-examined and new research will be incorporated to extend the study area. However, a specific procedure has been performed to analyse the topography, at the highest possible level of detail, to obtain maps with which to interpret the apparent areas of relative subsidence that may be associated with all these previous collapses that have occurred.

Topography obtained by means of the terrestrial laser scanner (a Leica Geosystems RTC360 laser scanner) has been used to better locate the affected areas and evaluate the effectiveness of the ground treatment applied (column injections of low-mobility mortar), assessing how they are evolving.

In the last 6–7 years, the results confirm the good performance of the treated areas (on the embankment and on the access road to Alcalá), except for one point on the eastern border, where the injection campaign was apparently not sufficiently completed. The objective is to continue the control and monitoring of possible phenomena related to subsidence problems in the affected area and its immediate surroundings, as well as to detect and, if necessary, anticipate subsidence or collapse phenomena that could affect the body of the embankment.

2. Methodology

The methodology used is detailed below and illustrated in the flowchart in Figure 4.

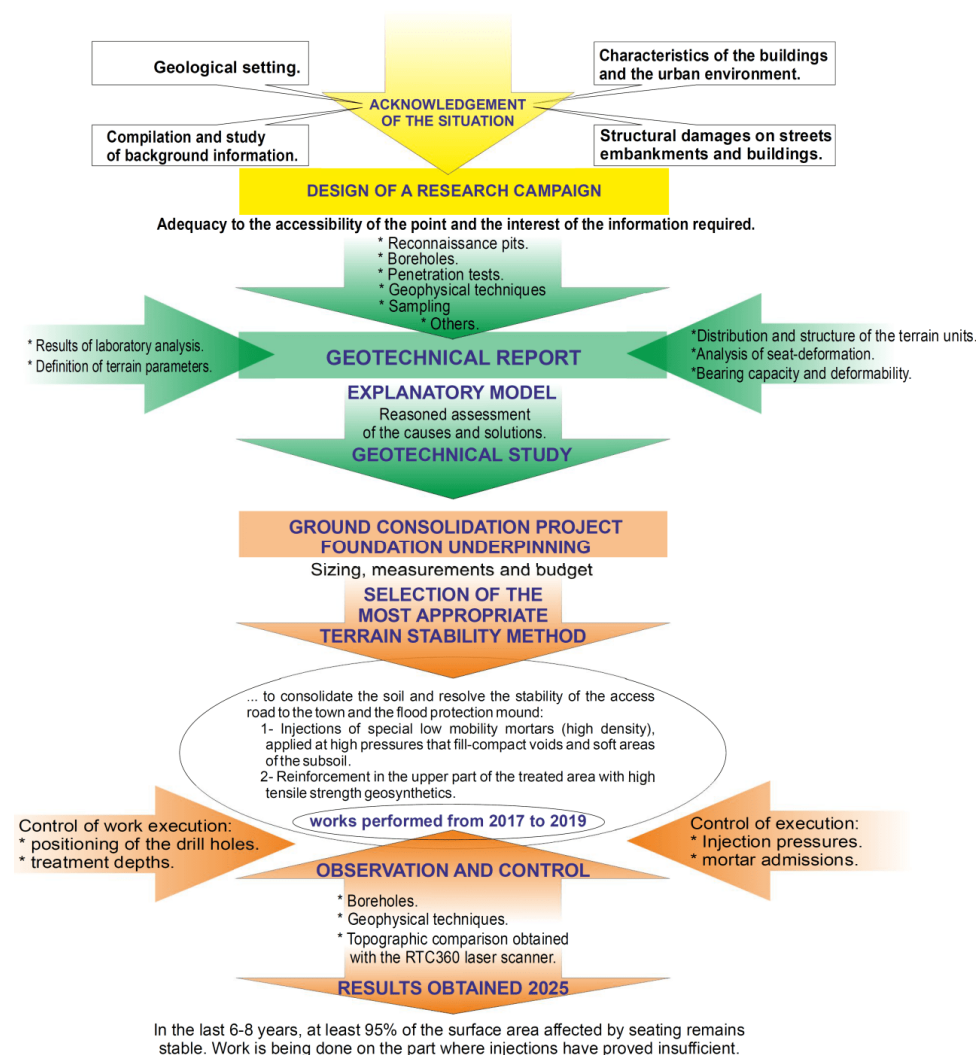


Figure 4. Flowchart of field studies, terrain stabilization works and post-treatment monitoring.

The topographic study consisted of the initial comparison of the digital model resulting from LIDAR measurements taken in 2010 and 2016 obtained from the National Geographic Institute of Spain (IGN) and the IGME (Spanish Geological and Mining Institute). These are laser measurements of points on the ground and buildings, with a density of 0.5 pts/m², distributed in 2 × 2 km files. Subsequently, we produced detailed topography using a Leica Geosystems RTC360 laser scanner (St. Gallen, Switzerland). These images were processed (CloudCompare v.2.13.2 software (France): 3D point cloud editing and processing software) to produce detailed, large-scale topographic maps, which were used to reposition all the existing information from the tests and trials carried out.

The specific studies carried out and the consolidation work have been described in a previous article [2].

The control and research method used was based on the following works [4]:

- Verification, at source, of all the information gathered in recent years and the results of the process of consolidating the undermined terrain by injecting “low mobility” (L.M.) mortar. Four rows of injection sites were established, starting from the river and heading towards the city. The number of injections carried out was 28 for Station Road Street (phase I) and 40 in the embankment (phase II). In Figure 5, the details of the relative position of the injection columns of L.M. mortar are displayed. The following aspects have been considered in their positioning:
 - General delimited scheme adjusted to the section of the embankment and Station Road Street affected by the subsidence and collapse problems analysed. The distribution follows the layout of the road that crowns the hill. Injections are incorporated towards the embankment that falls towards Station Road Street to complete the area affected by subsidence in the plan.
 - In both cases, the excavation was between 0.80 and 1.20 m above the respective slopes of the street and embankment.
 - The distribution is in alternate rows, in a staggered fashion, adapting to the floor plan of the embankment and the street.
 - The distance between rows is 2.40 m, and the distance between injections in the same row is 3.20 m.
- The preparation of a map integrating and synthesising all the information includes rotational surveys and other tests (pits, dynamic penetration tests, etc.). It also includes the superposition of all the geophysical techniques carried out, locating the main anomalies recorded in the plan.

Topographic auscultation. The Leica Geosystems RTC360 laser scanner was used in collaboration with Tecnitop, a Spanish company specialising in digitisation and 3D applications for heritage, engineering and industrial metrology. There have been 4 laser scanner monitoring campaigns. For example, in the fourth topography auscultation campaign, a total of 47 measurement stations were carried out, 22 of which were used to carry out detailed topographic auscultation in the embankment that protects Alcalá de Ebro.

This laser takes panoramic images superimposed on a cloud of high-precision points at a speed of 2,000,000 points/second. It has a range of up to 130 m and is accurate to the millimetre. This type of analysis allows us to obtain 3D images composed of point clouds. By processing these images (Cloud Compare software: 3D point cloud editing and processing software), detailed topographies are generated that are used to relocate all existing information from tests and trials carried out. It also helps to identify differential movements that can be deduced from small depressions and crack systems that can be seen both on the surface and on the facades of some houses. The

use of this 3D technology provides a series of advantages over the usual 2D technology, which we list below:

- Greater “as-built” information: The capture of reality data is much more complete than usual acquisitions, which represents an increase in reliability and precision, as well as better visualization than in 2D plans.
- Allows greater access to information: Information is more available, since we can manage the model in 3 dimensions, which allows for excellent structuring of it.
- Provides better use of information: The multiple possibilities of obtaining results provide us with a better design.
- Better capture and post-processing method: Compared with any traditional method, 3D laser scanner technology offers great advantages [6,7].

The data obtained were processed using the Ciclon Register 2023.3 software, uniting the visualisations made in the same model, obtaining an overlap greater than 38% and a precision of 0.7 cm. Plans were obtained at a scale of 1:1000 (general situation with contours every 0.20 m) and at a scale of 1500 (detailed with contours every 0.02 m).

- New geophysical and verification surveys will be conducted in the identified areas, extending the work area to assess whether the consolidation carried out will transfer any potential effects to other adjacent areas within the nearby environment. In the affected area and its surroundings, we consider that the combination of electrical tomography in the 3D mode and the georadar of the UltraGPR type constitutes the geophysical tools with the greatest capacity to detect subsoil areas affected by dissolution processes of halite layers [3,8]:
 - Electrical tomography. The campaign carried out includes an electrical tomography profile and ultra-GPR profiles (mainly on the wheel). The geophysical prospection campaign was carried out by the company IGT (International Geophysical Technology, S.L.) in November 2021. The tomographic profile was 150 m long, consisting of 16 electrodes spaced 5.5 m apart, and reached a depth of approximately 30 m.
 - UltraGPR type georadar. The UGPR-1 profile, carried out along the banks of the Ebro River, was made.

During the injection process, the volume and pressure achieved at each stage of the manoeuvre (relative depth) are shown. The distribution of these columns is presented in Figure 5. Figure 6 shows the monitor showing the number of injections (24), the relative depth (at −20 m), and the total volume injected (373.2 L), with the pressures reaching up to 20.4 bar.

The characteristics of the mortar were rigorously checked using the European Standard: EN 12350-2:2019—Testing fresh concrete. Part 2: Slump test [9]. Specifically, its dosage is to control its density and viscosity, with the intention that it remain in the environment of the application itself, creating semi-columnar structures (Figure 7).

The injected materials correspond to low-mobility mortars, as they are suitable for the treatment of karst soils. They are composed of a mixture of cement as an inorganic binder, aggregates of controlled granulometry and chemical additives.

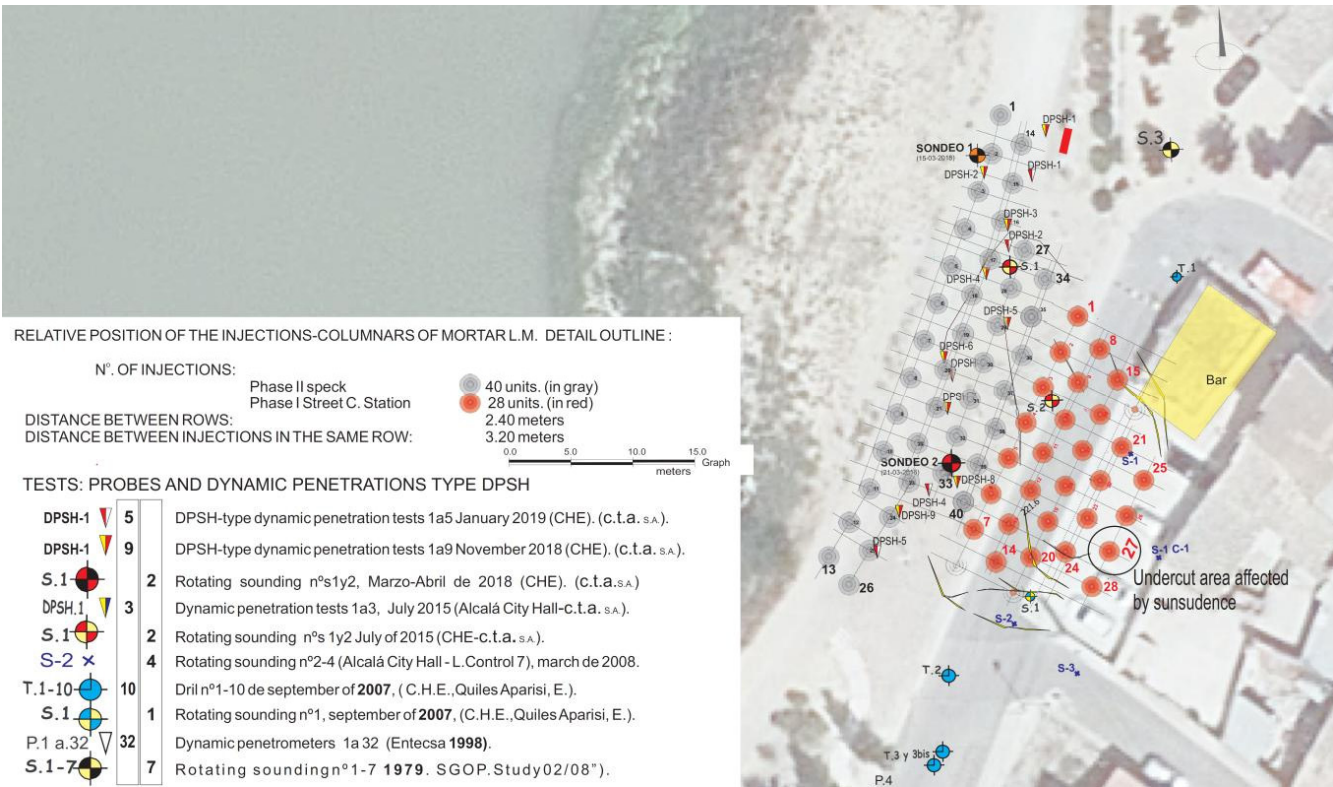


Figure 5. Low-mobility mortar injections and high tensile strength geogrids execution: Low mobility mortar Injections layout (in red, injections conducted in December 2016; in grey, injections were conducted in December 2018). The only injection that failed (no. 27) is noted; modified from [2].

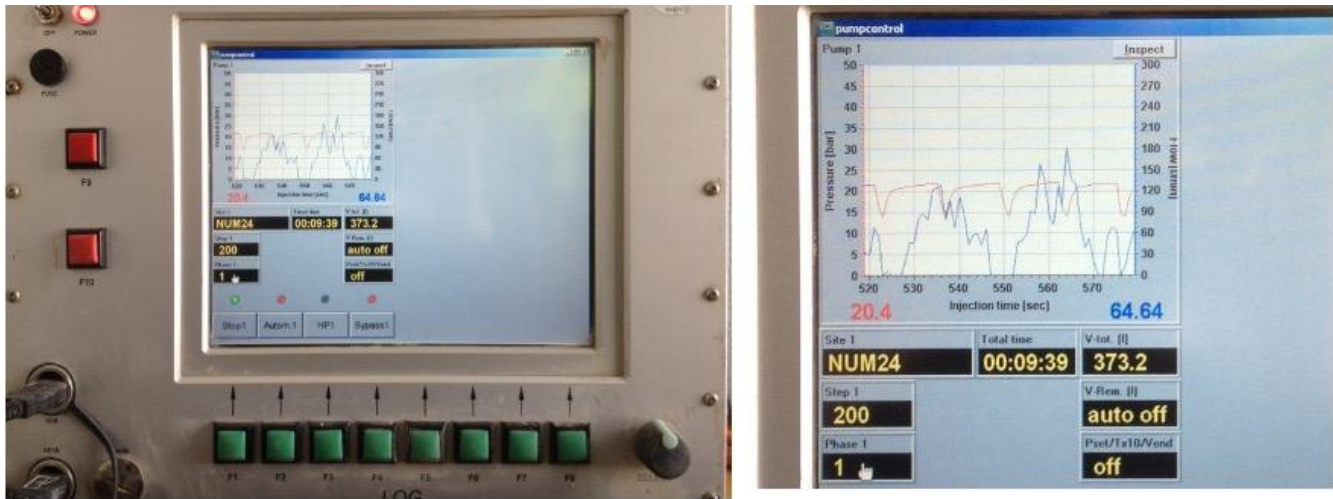


Figure 6. Injection control equipment. The graphs show the mortar admissions (blue line) and injection pressures (red line) during the execution of mortar Column no. 24 at a depth of 20 m. The time of execution (9'39'') and the volume injected (373.2 L) are also shown. The location of this column is shown in Figure 5.



Figure 7. Control of the consistency of the mortar L.M. of Column no. 24. The Abrams cone gives values between 8 and 12 cm. The location of this column is shown in Figure 5.

3. Results

3.1. Results of the Consolidation Procedure of the Undermined Terrain Using “Low Mobility” (L.M.) Mortar Injections

As a reference to the results obtained, in the section of the avenue protection area affected by scour, the admission/injection pressures of those carried out in Column 2 are included (Figure 8). This is probably the most representative of the situation based on the geotechnical model carried out.

For Phase II injections near the embankment (grey spots in Figure 5), an average mortar consumption of up to 250 L per linear metre of drilling (two 0.5 m manoeuvres) was estimated. However, as an example of the variability of the situation, in one case, up to 9000 L were exceptionally recorded (injection no. 13), and in many other cases, there were no recorded injections other than the filling of the borehole itself:

- Consumption has been exceptionally high in the first row (closest to the river). The total injected in the first column was 135,165.85 L in 13 injections of 24 m of relative length, of the order of 433.22 L/m.l.
- In the second row, consumption was moderated by being “protected by the injections of the first column” and by recalibration of the injection procedure. The total injected in the second column was 76,331.50 L in 13 injections of 24 m of relative length, of the order of 244.65 L/m.l.
- In the third row, 46,339.30 L were injected in seven injections of 24 m in relative length, of the order of 275.83 L/m.l.
- In the fourth row, these consumptions were moderated even more as they were confined between the first three columns and the injections carried out in 2015 on the street (very close). The total injected in the fourth row was 33,321.45 L in seven injections of 24 m of relative length, of the order of 198.34 L/m.l.



ADMISSIONS		< 1.500
liters/0,5 m.l.		1.500-2.000
		2.000-3.000
		> 3.000

LEVEL	DEPTH (m)		Press (bars)	SUM	AVERAGE
1	-24,00	-23,50	32	3.667,00	282,08
2	-23,50	-23,00	32	318,45	24,50
3	-23,00	-22,50	32	231,60	17,82
4	-22,50	-22,00	32	405,30	31,18
5	-22,00	-21,50	32	299,15	23,01
6	-21,50	-21,00	29	1.794,90	138,07
7	-21,00	-20,50	28	2.721,30	209,33
8	-20,50	-20,00	27	3.551,20	273,17
9	-20,00	-19,50	26	2.875,70	221,21
10	-19,50	-19,00	26	2.933,60	225,66
11	-19,00	-18,50	28	2.026,50	155,88
12	-18,50	-18,00	27	1.891,40	145,49
13	-18,00	-17,50	26	2.644,10	203,39
14	-17,50	-17,00	25	2.779,20	213,78
15	-17,00	-16,50	25	3.049,40	234,57
16	-16,50	-16,00	26	3.010,80	231,60
17	-16,00	-15,50	24	2.180,90	167,76
18	-15,50	-15,00	24	2.354,60	181,12
19	-15,00	-14,50	24	2.335,30	179,64
20	-14,50	-14,00	24	1.601,90	123,22
21	-14,00	-13,50	24	1.370,30	105,41
22	-13,50	-13,00	24	1.389,60	106,89
23	-13,00	-12,50	24	1.331,70	102,44
24	-12,50	-12,00	24	1.370,30	105,41
25	-12,00	-11,50	24	1.389,60	106,89
26	-11,50	-11,00	24	1.254,50	96,50
27	-11,00	-10,50	24	1.273,80	97,98
28	-10,50	-10,00	23	1.486,10	114,32
29	-10,00	-9,50	24	1.408,90	108,38
30	-9,50	-9,00	21	1.601,90	123,22
31	-9,00	-8,50	21	1.582,60	121,74
32	-8,50	-8,00	19	1.563,30	120,25
33	-8,00	-7,50	21	1.746,65	134,36
34	-7,50	-7,00	21	1.341,35	103,18
35	-7,00	-6,50	19	1.524,70	117,28
36	-6,50	-6,00	22	1.370,30	105,41
37	-6,00	-5,50	21	1.312,40	100,95
38	-5,50	-5,00	23	1.061,50	81,65
39	-5,00	-4,50	23	1.100,10	84,62
40	-4,50	-4,00	23	1.109,75	85,37
41	-4,00	-3,50	22	1.225,55	94,27
42	-3,50	-3,00		1.080,80	83,14
43	-3,00	-2,50		926,40	71,26
44	-2,50	-2,00		1.071,15	82,40
45	-2,00	-1,50		627,25	48,25
46	-1,50	-1,00		868,50	66,81
47	-1,00	-0,50		250,90	19,30
48	-0,50	0,00		19,30	1,48
LEVEL	DEPTH (m)			SUM	AVERAGE
	suma			76.331,50	
	Lit/m.l.				244,65
	Pres med.		25		

Figure 8. Pressure/admission control in Column 2. Admission volumes are recorded at each work level. An average of 13 injections were performed.

Conclusions and relevant aspects for the evaluation of the results of the injection campaign are as follows:

- Admissions are mainly concentrated in the recognised section, between -14.0 m and -21.0 m (between 5 and 7 m), where it is assessed that there is a dissolution-undermining process associated with levels or layers of salts (type glauberite, halite, etc.) that are exceptionally soluble.
- More than half of the registered entries are concentrated in this section, of about 35,000 L of mortar.
- It is confirmed that the resistance to drilling is greater at a depth of -24 m. It is not considered necessary to drill deeper. Based on the developed model, the injections penetrate the apparently undercut rock substrate to a depth of 3–5 m. In this first interval, once the drill-injection pipe is filled, injections of the order of 20 to 30 L per litre are recorded, which is practically equivalent to filling the perforation itself.
- The intakes, between -14.0 and -6.0 m, have average intakes of between 200 and 250 L per litre. Occasionally, however, volumes of up to twice the injected mortar are recorded, which can be interpreted as fill from previous sinkholes and/or collapses associated with the undermined lower level.

- The upper part (from -6 m to the surface) corresponds to the body of the trench, which is made of compacted gravel. In dry terrain, it usually has a capacity of 100–150 L per litre, and in many cases, the capacity is reduced to the volume of the borehole itself. In some cases, however, there is conspicuous over-consumption, which means that the borehole may be close to the surface. In Column 1, in injections 4 and 5, consumption of up to 4 m^3 was recorded at a depth of around -6 m.
- In Column 2, overconsumption was also recorded in injections 15 and 18 with more than 700 L/m.l. less than 2–3 m from the surface. Although these are not volumes associated with large voids, they may be associated with fractures connecting them at greater depths. The same could be interpreted for perforation 29 in line 3 and injection 34 in line 4.

Figure 9 shows the position and relative dimensions of the injections carried out on the geological–geotechnical profile obtained by correlation of surveys and geophysical prospecting techniques. In practically all cases, the solid ground was reached and at least 2–3 m were embedded.

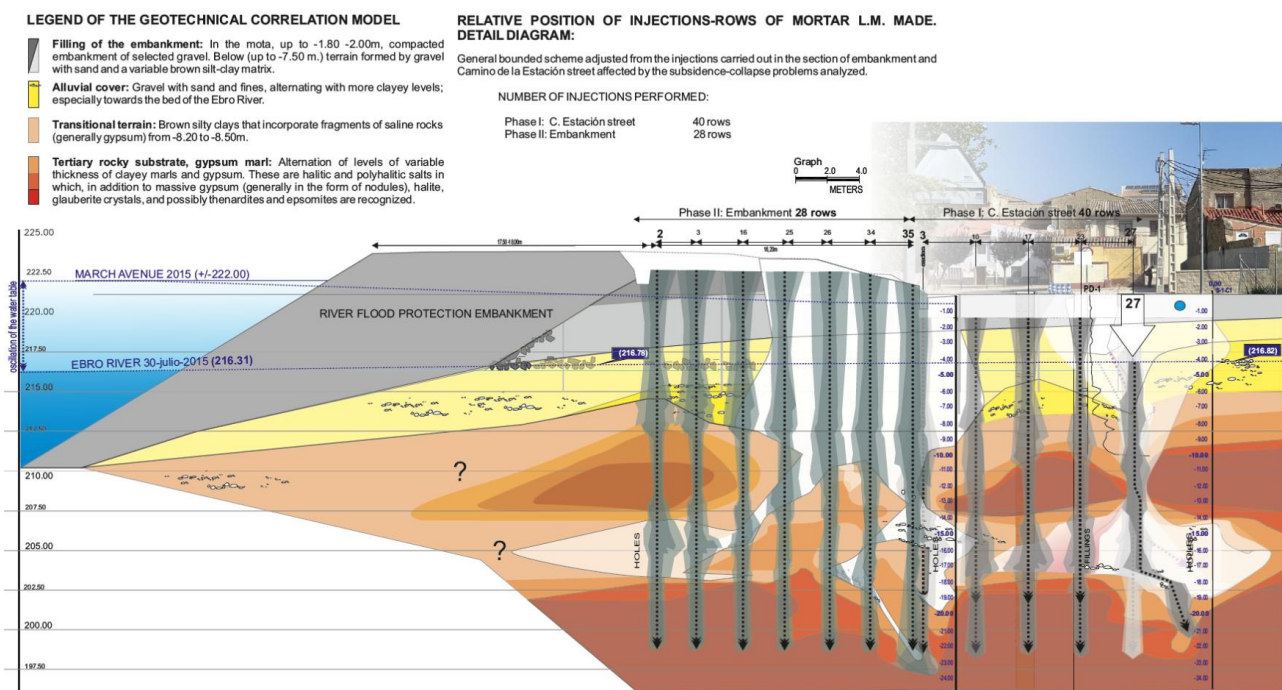


Figure 9. Position of mortar columns L.M. in the geological–geotechnical profile carried out. The only injection that failed (no. 27) is noted. Figures 3, 10 and 11 show their location. Graphical representation of the lateral expansion of the mortar in the columns is a reasonable assumption based on the properties of this type of mortar, which are characterised by “low mobility” and the injected ground. They contain plasticisers and tend not to flow away from the point of application.

The only one that failed, in the farthest column towards the village, was injection no. 27 (see Figures 5 and 9), which was apparently made on an old well filled with all kinds of waste. The problem is shown in the graph.

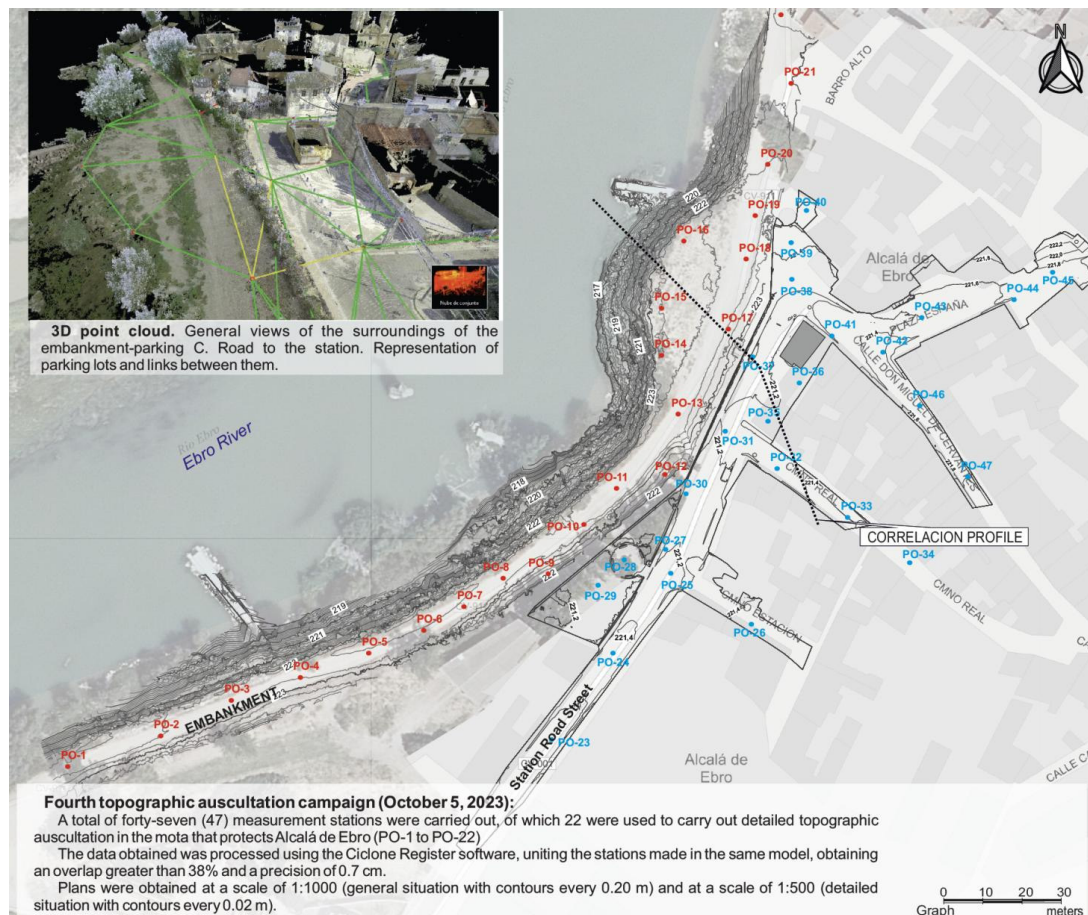


Figure 10. Measuring stations used for topographical auscultation: 24 at the embankment (red colour) and 27 in the village (blue colour). The result of the precision was achieved in September 2024. The correlation profile is shown in Figure 7.

3.2. Control Work on the Consolidation Measures Carried Out. Topographic Auscultation

The fundamental objective of this type of analysis is to obtain a detailed topography of the studied area, obtain a 3D image, and perform a topographic comparison between the different auscultations, thus identifying the differential movements produced in a certain time interval. In this way, it will be possible to focus on the origin of the problem that has led to the deformations recorded [10,11].

A total of 51 stations (Figure 10) have been made for this campaign (24 September 2024), between the town (27 stations) and embankment (24 stations). In this case, a total overlap of 47% and a set error of 0.7 cm were achieved.

Comparing 2021 and 2023, the following is concluded:

- During the 2022 monitoring, a small landslide was detected at the top of the embankment (cross sections 1 to 4, Figure 11). In some places, it may have experienced a slight relative subsidence at the top of the embankment. However, it has not changed significantly since then.
- During the winter of 2021–2022, the embankment was raised as a preventive measure against the Ebro River. At that time, a slight accretion of the crown of the embankment was noted.
- The ruts and other deformations caused by the work on the crown of the embankment continue to be observed.
- The deformations identified in the staircase continue to suffer from slow subsidence. The topographic comparison between the 2021 and 2023 surveys (Figure 11) shows

anomalies on both sides of the staircase. These may in part be due to the presence of vegetation in the 2021 campaign and its absence in 2023. However, towards the north, between PPKK 90 and 100, the anomalies identified tend to merge with those identified in point 1, corresponding to the slip.

- There are no obvious seats in the park area. At this point in the UGPR-1 profile (points 200 to 260 of the longitudinal profiles), an anomaly at greater depths has been identified. There is a possible cavity.
- An evolution of deformations is identified in a. and b. (Figure 12), which are indicated in the detailed topography shown in Figure 11 and which were also recorded by [7].

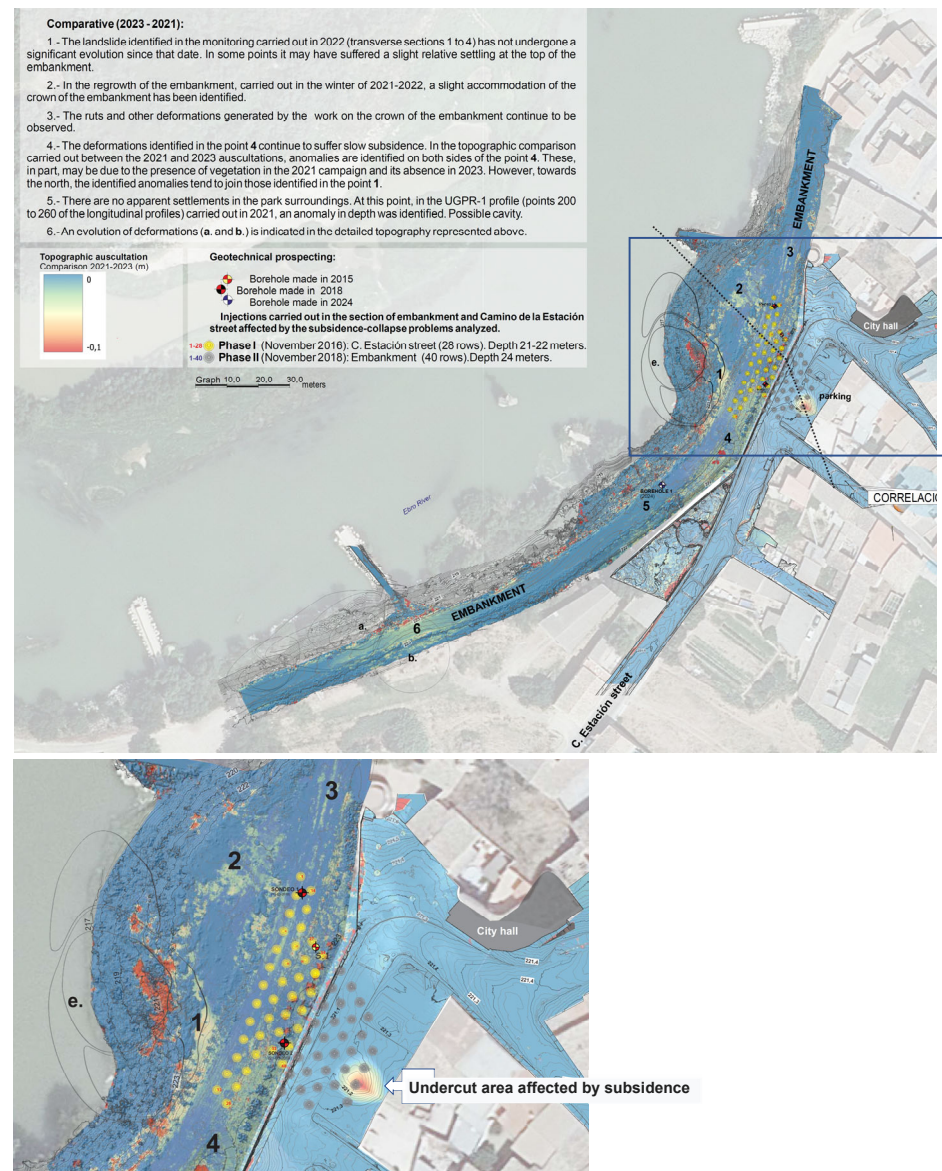


Figure 11. Topographic comparison between the data obtained on 22 November 2021 and 5 November 2023, with the RTC360 laser scanner. (**Top figure**) General situation plan. (**Bottom figure**) Detail of the area in which consolidation measures were carried out using L.M. mortar injections.

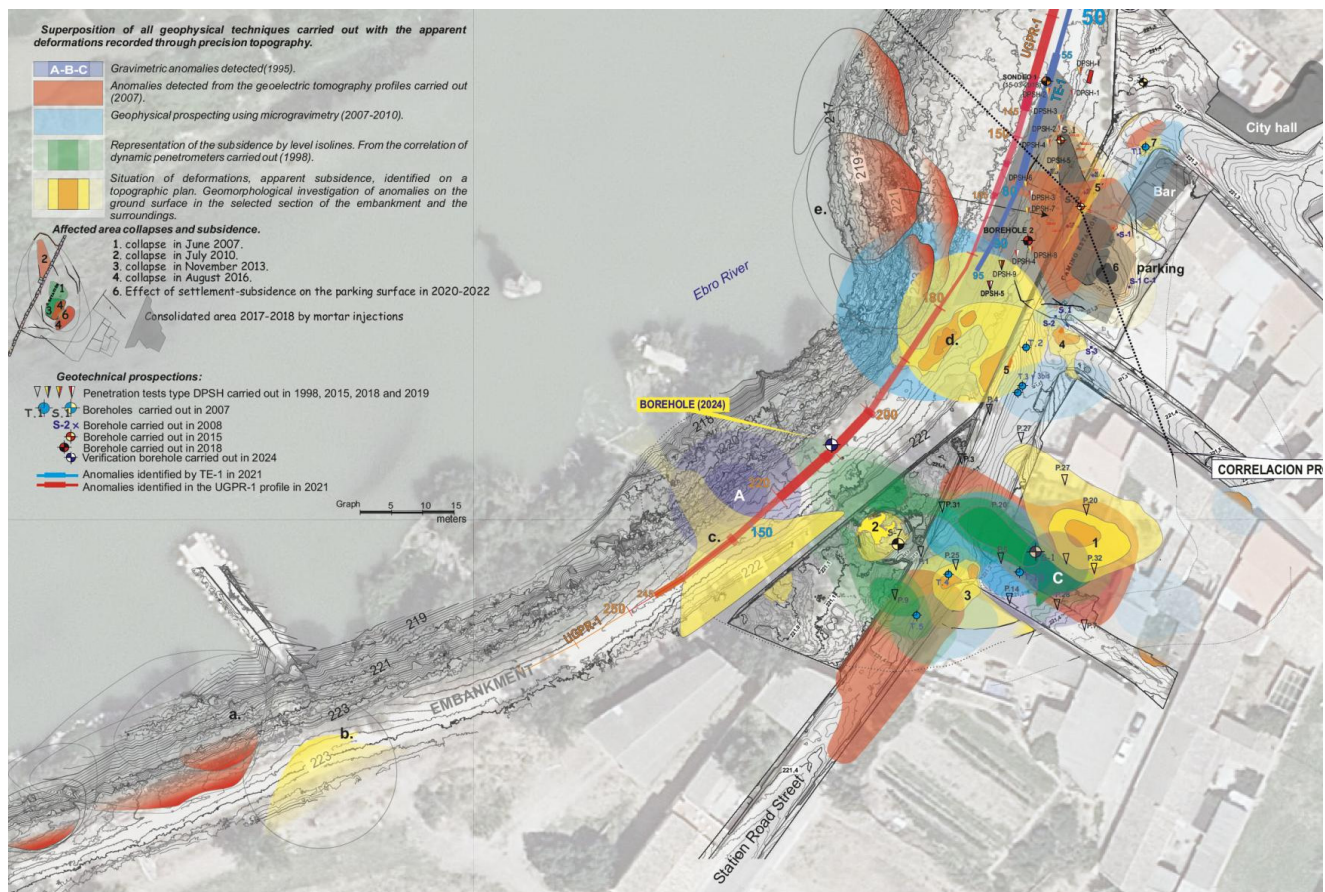


Figure 12. Zoning obtained with the anomalies observed in the detailed topography carried out and the different geophysical prospecting campaigns.

The deformations recorded in the station path are as follows:

- Old sinkhole (1975). Old sinkhole [5].
- Seventy-five deformations of up to 0.9–1.2 cm were observed between November 2021 and October 2023. This differential movement is reflected in the cracks observed in the pavement, as well as in the walls that would make up old structures of houses or corrals. During these years, no significant increase in the size and dimension of these cracks was observed, as the recorded evolution is not very high.
- Deformations in the public park. Between November 2021 and October 2023, minor specific deformations will be detected, generally between 0.5 and 0.8 cm, although they may reach 2.0 cm.
- Concentric contour curves are identified in the topography. This point is related to deformations in structure no. 11 of the station path. This is related to points 1 and 2 and represents the rocky substrate at a depth of 22 m.
- Deformation at the corner of the station path and the royal path, which is related, in depth, to the collapses that occurred previously in the parking lot area.
- Deformations near the embankment. In the area of point 5, in the steps leading up to the embankment next to the park, outside the detailed topography, a series of cracks have been observed, indicating some relative settlement. This is obviously related to the deformation at point 5. According to the topographic comparison carried out, a relative settlement between 0.8 and 1.3 cm occurred in the period 22 November 2021–5 October 2023.
- Parking area. These deformations are related to the collapses that occurred at this point, which were partially treated in 2016–2017 by injecting low-mobility mortar columns.

- Station Road Street and Don Miguel Cervantes Street. A small deformation has been identified next to the bar, and another larger one, which seems to indicate differential settlement towards the embankment. A concentric depression has been identified around point 7, right at the junction of the two streets. From 22 November 2021 to 5 October 2023, a subsidence of the order of 1 cm was measured around the maximum deformation. This point is in a manhole of the sewerage or supply network, although it seems to be moving to a lesser extent towards the sewer to the north.

On the other hand, the following were found in the embankment:

- Small deformations of the embankment towards the open side facing the Ebro, apparently due to slow movements of the slope caused by the undermining of the river.
- Deformation of the slope inwards, towards the town, with up to 15–20 cm maximum subsidence towards the slope edge.
- Deformations on top of the hill next to the park. This topographic subsidence would correlate with certain anomalies noted in previous studies.
- Apparent collapse in the embankment that projects towards the access “ramp”. This was taken from the road. At this point, new cracks have been observed (in the concrete of the access staircase), which mark possible deformations or differential settlements and correlate well with the slight subsidence indicated in point 5, identified just below, on the pavement itself.
- Signs of sliding towards the free face of the slope towards the river. The possible origin may be related to the scour processes of the river that are currently eroding this margin or settlements caused by a deeper scour related to the karst activity of the specific area.

3.3. New Geophysical and Verification Surveys in the Identified Areas

The most relevant results obtained are detailed below:

- Electrical tomography. The IGT report indicates that the most significant part of a surface layer of approximately 5 m thickness, corresponding to the body of the ditch and possible detrital alluvium, is the resistivity level interpreted as gypsum (Figure 10), located at a depth of 10–12 m. This resistivity level is abruptly interrupted between 45 and 85 m, where a moderately conductive anomaly is defined, interpreted as a karstified zone in the gypsum. This resistivity level is abruptly interrupted between 45 and 85 m, where a moderately conductive anomaly, interpreted as a karstified zone in the gypsum materials, is defined and extends below to a depth of 30 m.
- UltraGPR type georadar. The UGPR-1 profile reveals the existence of an anomalous zone with considerable lateral and depth extension. Its clearest manifestation can be seen between 120 and 220 m from a depth of 35 m, but it is interesting to note that the anomaly extends to shallower levels towards the north, corresponding to the anomaly defined in the electrical tomography measurements, as can be seen from the results of both measurements (Figure 11).

The TE1 electrical tomography profile correlates with the UGPR-1 section measured along the Ebro River embankment. This georadar profile also shows the existence of an anomalous zone with considerable lateral extent and depth. It is reasonable to interpret this anomaly as being because of a strongly karstified or altered area of the subsoil, since there is no evidence of possible interference in the georadar records by elements on the ground.

Its most obvious manifestation is between 120 and 220 m from a depth of 35 m, but it is interesting to note that the anomaly extends to more shallow levels towards the north, corresponding to the anomaly defined by the electrical tomography measurements, as can be seen from the results of both measurements (Figure 13).

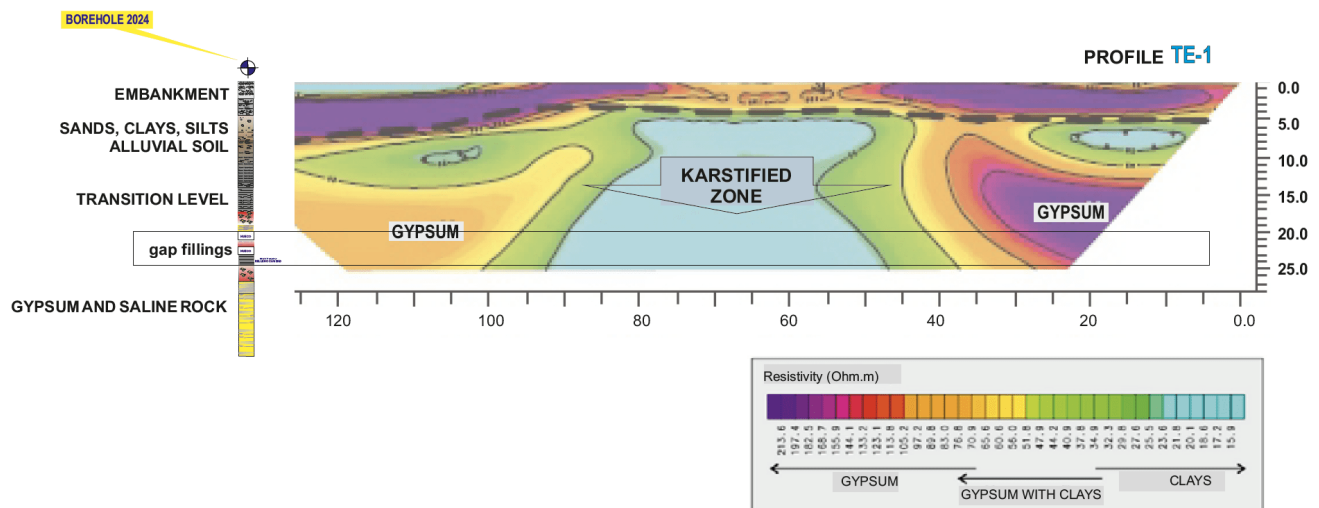


Figure 13. TE 1 electrical tomography profile. Profile localization is shown in Figure 9.

The TE1 electrical tomography profile correlates with the UGPR-1 section measured along the Ebro River protection embankment (Figure 14). This georadar profile also shows the existence of an anomalous zone with considerable lateral extent and depth. It is reasonable to interpret this anomaly as being because of a strongly karstified or altered area of the subsoil, since there is no evidence of possible interference in the georadar records by elements on the ground.

Its most obvious manifestation is observed between 100–165 m and 180–245 m. The first section, especially in its central part (between 129 and 145 m), clearly coincides with the anomalies recorded in the electrical tomography survey. The projection of the disturbance can even be seen towards the surface. In the same sense, it coincides with the projection towards the river (to the north) of the area where subsidence has been recorded in recent years on Station path and the parking area.

The consolidation work of the injected section using mortar columns by L.M. does not appear to be manifested in either of the two methods used.

A second section in which a latent development situation could be assessed, and which could pose an obvious threat, is recorded between 180 m and 245 m. In this case, the anomaly is located at a relative depth between −30 and −45 m. There is an apparent projection to the surface to the south.

As in the previous case, this could be interpreted as a reflection in continuity towards the embankment, in the direction of the river, with the area of arrival to Alcalá from the south, where the first recorded sinkings (that we know of) were located in the 1970s and 1980s of the last century. Also, some manifestations are now recorded as apparent subsidence on the surface. Both sections seem to converge at a depth in what is interpreted as a strongly karstified area that would be located at depths below the order of 40–70 m.

- A verification survey in the area was indicated by geophysical anomalies. Due to the presence of these anomalies at greater depths, it was particularly interesting to carry out deep surveys to contrast the information obtained. For this reason, survey one was carried out (10 July 2024), reaching a depth of 35 m (Figure 15).

Below the surface level of the 4.20 m-thick embankment fill, a predominantly sandy and silty layer is identified, with occasional boulders and gravel ridges. Towards the surface, the matrix is brown; however, at greater depths it becomes dark brown due to its higher apparent organic content. The consistency of this level is very low, with N15 SPT hits ranging from 4 to 7. These values correlate very well laterally with the graphs extracted from the dynamic penetration tests carried out in 1998.

Below, between -13.40 and -14.60 , a transition terrain to the rocky substrate has been identified, composed of blackish clays, much plastic and of very low consistency. It is possible that this is a rocky substrate that has been greatly altered by the presence and continuous circulation of water.

Joint interpretation of the results of the resistivity section and that of the Georadar, obtained on embankment (2021)

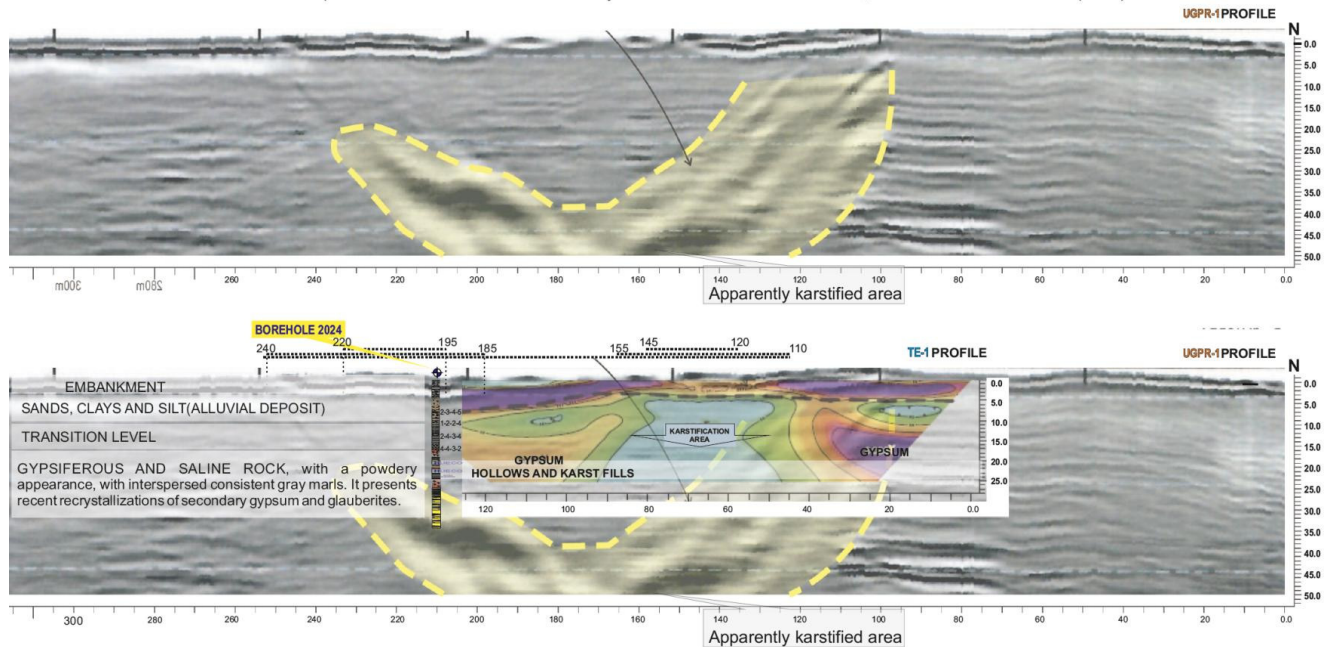


Figure 14. Combination of electrical tomography in 3D mode and the UltraGPR type georadar (top images) and the appearance of the materials obtained in the S1 survey (bottom images).

From -14.60 m, there are gypsum and marl layers with very different degrees of alteration. It should be noted that what is generally defined as “gypsum rock” is, in fact, halite and polyhalite salts in which, in addition to massive gypsum (generally in the form of nodules), halite, crystals of glauberite and possibly thenardite and epsomite can be seen.

This substrate is altered in the area closest to the contact with the alluvial cover, which is affected by variations in the water table, especially in the area closest to the bed of the Ebro River. The infiltration of water to deeper levels, through fissures or more altered levels, can give rise to karst processes. As a result, internal dissolution–undermining processes are generated, which favour the formation of caves or sinkholes.

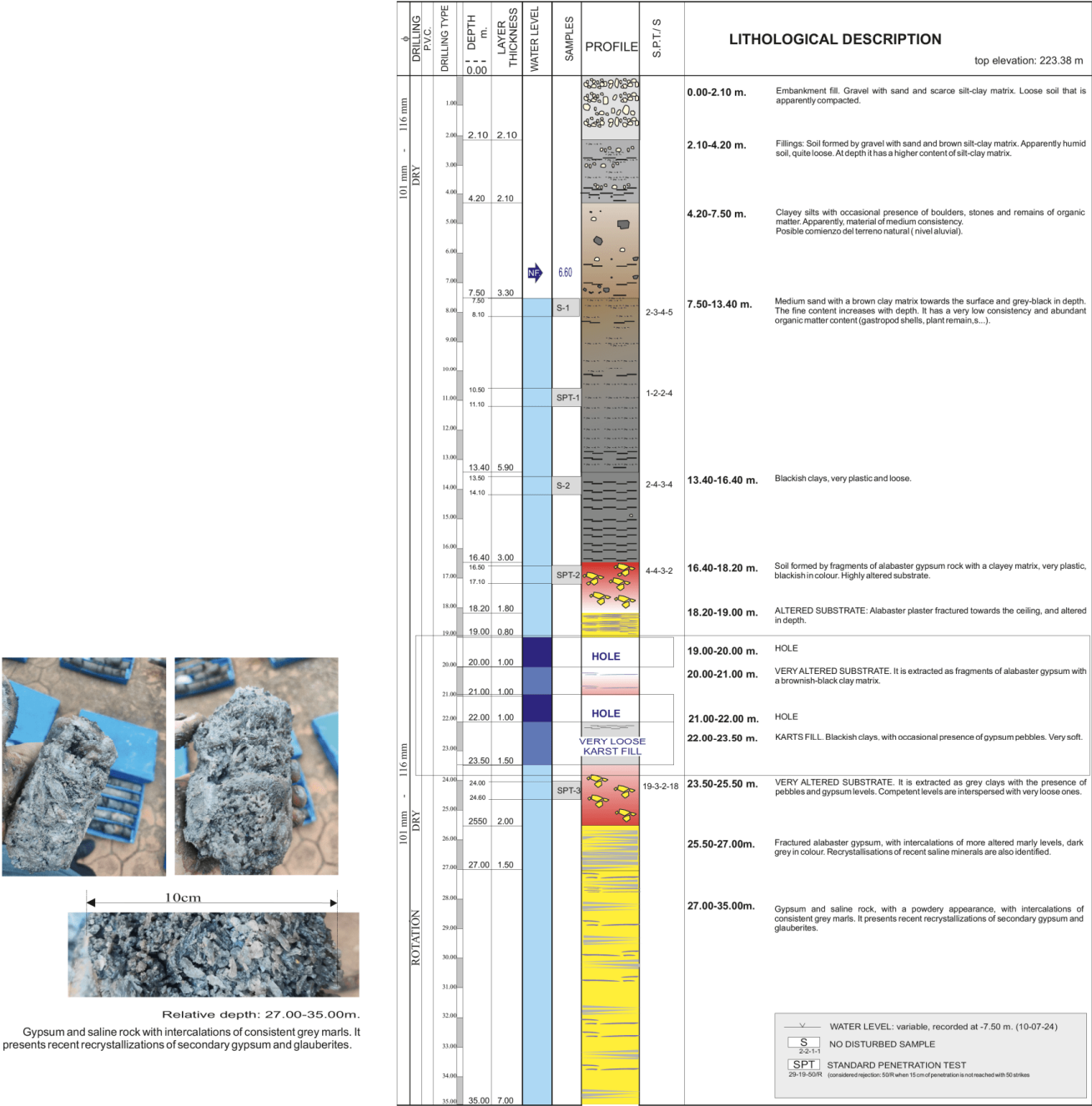


Figure 15. Rotation survey with continuous core extraction located in an area with apparent anomalies recorded through geophysical prospecting. The borehole is shown in Figure 12, which confirms the data from the geophysical surveys carried out.

In this case, the S-1 survey (2024) identified a sinkhole between 19.00 and 20.00 m deep and between −21.00 and −22.00 m deep, with a clay fill between −22.00 and −23.50 m deep. Practically on the same topographic level, the S-7 survey carried out by the SGOP in 1979 identified a gap of 80 cm (between −17.30 and −18.10 m), below which, according to our understanding, the excavations would have filled the cavity.

4. Discussion and Conclusions

The land consolidation work carried out in the areas most affected by the subsidence and collapse problems is proving effective. The result confirms the good performance (in the last 6–8 years) of the treated areas (on the protection zone and on the access road to

Alcalá), except at one point, located towards the border to the east, where, unfortunately, the injection campaign was not sufficiently completed. Additional work will be carried out soon using the same method.

The geomorphological analysis of the land surface, by processing the information obtained using a laser scanner (RTC360, Leica Geosystems), makes it possible to obtain a topographic plan of the highest precision. The interest of this detailed topographic base is to enable the following:

- It provides a base from which to incorporate all the information collected in previous studies. The areas where the collapses have occurred are also included. It has made it possible to locate all the tests and surveys carried out, the geophysical anomalies of various types identified, the drilling campaigns, dynamic penetration tests, pits, etc.
- The areas of land consolidation work have also been more accurately located, specifically, of the two low-mobility mortar injection campaigns. The first is on the station road and the second is on the river protection embankment.
- It has been possible to identify areas of apparent relative sinking or subsidence. The formation of points or small areas of closed or semi-closed contours in this environment can indicate the situation of a deformation process on the surface, related to the situation of sunken areas, in the process of subsidence and/or at risk of collapse. New studies and research have focused on these points. In a survey carried out during the last research campaign, undermined levels and holes were again detected at a depth very similar to that recognised in previous phases of work.
- Using the first measurements as a reference, new measurements using this method will allow us to assess whether the process has stopped and/or whether it is still ongoing, and even its rate of development.

The differential analysis of the measurements carried out has made it possible to draw up a synthesis plan in which the obvious aspects of the surface can be related to the deep surveys and investigations carried out by surveying and geophysics. It was also possible to compare the effectiveness of the land consolidation measures carried out almost 6–8 years ago. In this sense, the area was treated with the injection of L.M. mortar. A very high level of stability was recorded in the area, which had been experiencing subsidence and collapse problems for years. Only on one edge of the treated area (parking area on the road to the station), where the injections carried out may not have been sufficient, is there a noticeable subsidence, which is an indication of the stability achieved. It is planned to intensify the consolidation work at this point.

At present, no significant subsidence problems have been observed in the embankment and its immediate surroundings, despite the voids identified at depth in the 2024 S-1 survey, especially considering that the ground is very loose up to -18.20 m and that a hole was identified at -19.00 m. It is possible that if this apparent dissolution–undermining process continues, it could be reflected on the surface in the form of slow subsidence (sinkhole) or, less likely, collapse.

For this reason, to effectively detect and, if necessary, anticipate any subsidence or collapse issues affecting the embankment, it is recommended that at least a topographical survey of the ditch and its immediate surroundings be conducted.

Author Contributions: Conceptualization, A.G. (Alberto Gracia), F.J.T. and A.B.; methodology, A.G. (Alberto Gracia) and A.G. (Alberto García); software, A.G. (Alberto Gracia) and A.G. (Alberto García); validation, A.G. (Alberto Gracia), F.J.T. and A.B.; formal analysis, A.G. (Alberto Gracia), A.G. (Alberto García) and A.B.; investigation, A.G. (Alberto Gracia), A.G. (Alberto García) and A.B.; resources, A.G. (Alberto Gracia) and A.G. (Alberto García); data curation, A.G. (Alberto García) and A.B.; writing—original draft preparation, A.G. (Alberto Gracia); writing—review and editing, F.J.T.,

A.B. and A.G. (Alberto García); visualization, F.J.T., A.B. and A.G. (Alberto García); supervision, A.B. and F.J.T.; project administration, F.J.T. All authors have read and agreed to the published version of the manuscript.

Funding: Funded with Aid for First Research Projects (PAID-06-24), Vice-rectorate for Research of the Universitat Politècnica de València (UPV).

Data Availability Statement: The data may be available on request from the first author but not publicly available due to being private.

Acknowledgments: We would like to thank the City Hall of Alcalá village for providing permissions and logistic support during the measurement campaigns. Thanks are also given to the Environmental Management Area of the Ebro Hydrographic Confederation (CHE). We are also grateful to Jesús Rico and Miguel Ángel Pérez-Picallo (CTA Associated Technical Consultants, S.A.P.) for his collaboration in the geotechnical reports.

Conflicts of Interest: The authors declare no conflicts of interest.

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