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[Alberto Gracia](#) ^{*} , [Francisco Javier Torrijo](#) , [Julio Garzón-Roca](#) , [Miguel Pérez-Picallo](#)

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Article

Identification and Mitigation of Subsidence in Karstic Areas with Sustainable Geotechnical Structures: A Case Study in Gallur (Spain)

Alberto Gracia ^{1,*}, Francisco Javier Torrijo ², Julio Garzón-Roca ³ and Miguel Pérez-Picallo ¹

¹ C.T.A. Associated Technical Consultants, S.A.P.; agracia@cta-consultores.com; mperez@cta-consultores.com

² Research Centre for Architecture, Heritage and Management for Sustainable Development (PEGASO), Department of Geotechnical Engineering, Universitat Politècnica de València, Camino de Vera s/n, 46022, Valencia, Spain; fratorec@trr.upv.es

³ Department of Geodynamics, Stratigraphy and Paleontology, Faculty of Geology, Complutense University of Madrid, 28040, Madrid, Spain; julgarzo@ucm.es

* Correspondence: agracia@cta-consultores.com; Tel.: +34-677-48-00-66

Abstract: As in many points in this middle section of the Ebro Valley (Spain), the risks of sinkholes are becoming particularly severe, affecting urban areas and roads, where land subsidence due to karstic processes is frequent. However, knowledge of the area, its geological-geotechnical configuration and the carrying out of specific research studies are allowing solutions to be tested in an attempt to resolve these situations. The present analysis of the seating problems recorded on a section of the access road to the town of Gallur from the east (Camino Real) in the province of Zaragoza (Spain), is a good example. Numerous surface manifestations of the recent activity of subsidence and/or collapse processes have been reproduced throughout the surrounding area. The latter, appearing in the form of craters, undercuts in the ground, sometimes several metres in diameter. The presence of highly karstifiable materials in the area, as indicated by the existence of several pockets of subsidence and collapse dolines, constitutes a serious problem for safety, in this case for traffic and access to the town. For this reason, the road has been closed for several years. The local and provincial administrations have been undertaking studies to try to recognise this type of situation. The detailed definition of the karstification processes, the geomechanical analysis of subsidence and cavity collapse, and the justified technical proposal of the measures to be adopted to control and mitigate the risk, were the objectives of several reports in which possible technical solutions were proposed. Finally, a consolidation solution was proposed based on the injection at depth of columns of mortar with special characteristics, combined with the replacement and reinforcement of the most superficial soil by means of high tensile strength geotextile meshes to mitigate this hazard, it is crucial to identify it, and mitigation techniques must be employed to curb its development

Keywords: hazard; sinkhole mitigation; gypsum karst; Gallur; injections; geogrid; evaporitic rocks

1. Introduction

A sinkhole is a geological hazard characterized by a depression or cavity in the ground. The risk of sinkholes is escalating, particularly in urban areas lacking meticulous planning, where karst depressions are frequently filled and developed. Effectively addressing these risks requires the identification, investigation, prediction, and mitigation of sinkholes [1]. Corrective measures can be implemented to mitigate subsidence processes.

As said, subsidence and sinkholes pose a particularly significant challenge in urban areas situated within karstic regions [2,3]. Such regions are identified by the prevalence of soluble rocks, either be carbonate rocks or evaporitic ones. These areas encompass approximately 20% of the Earth's

ice-free continental surface [4,5]. The dissolution of these soluble strata, forming the rocky substratum, initiates a process of upward subsidence towards the surface, which, in certain instances, results in episodes of collapse [1,7–10]. Sinkholes are more likely to occur and exhibit greater genetic diversity in evaporite rocks compared to carbonate rocks. This is attributed to the higher solubility of the former, such as halite and gypsum. The progression of sinkhole development occurs more rapidly in evaporitic rocks, with gypsum being approximately 100 times more soluble than carbonate rocks, this ratio being even higher for halite. Subsidence damage resulting from the dissolution of such rocks leads to substantial global losses. Consequently, the presence of evaporitic rocks poses significant challenges in built environments [11].

Sinkholes emerge sporadically due to the gravitational movement of the overlying material situated above the soluble rock stratum [10,12,13]. The overlying material typically consists of residual soils, referring to the *in situ* disturbed substrate. The gradual dissolution of soluble rocks at depth, resulting from the infiltration and flow of water, gives rise to the formation of cavities or domes near the interface between residual soils and the soluble rock [10,12–14].

Sinkhole hazards exert a significant economic impact in Spain, as indicated by recent studies focused on identifying and investigating sinkholes in the Iberian Peninsula [10,15–17]. Specifically, the city of Zaragoza in northeastern Spain and its surrounding areas are identified as the highest sinkhole risk area in Europe [18]. The abundance of gypsum serves as the primary origin of these sinkholes, although the interstratal dissolution of halite and glauberite beds also contributes to their development [10,18,19]. In this context, the paper presents a case study in Gallur, a town situated in a high-risk area in Spain (Figure 1). Over the course of several years, the access road to Gallur from the east (Camino Real) experienced disruptions due to the emergence of a sinkhole, impeding access to the town. A preliminary examination of the area uncovered a sinking sinkhole, with its most depressed sector located immediately to the southwest. In this region, a cluster of discharge edges was identified, undermining the mentioned road surface (Figure 2).

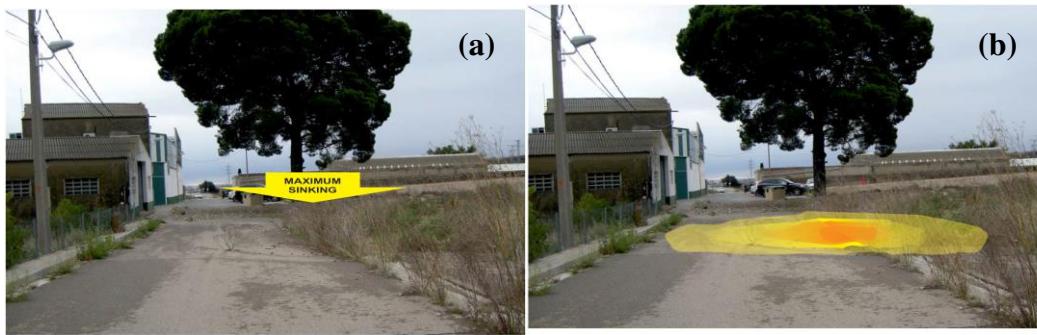


Figure 1. Panoramic image of the apparent subsidence of the road surface of the access to Gallur along the Camino Real (2015). The most depressed area is highlighted in color. This access had remained closed for several years.

The paper illustrates the approach to mitigating this phenomenon by employing various techniques, contingent on factors such as the size of the sinkhole, the objectives sought, and the affected elements. In addition, this work demonstrates sustainable and innovative remediation and mitigation measures for this phenomenon, showing how, even in areas of high karst risk, roads can be made highly safe from this phenomenon.

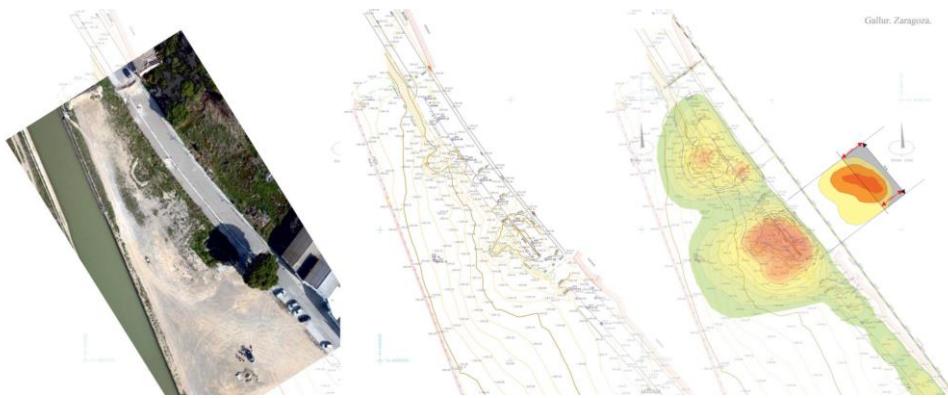


Figure 2. Topography on aerial photography (year 2015). The area affected by land subsidence is marked in colour. The layout of the contour lines shows the subsidence edges and defined areas affected by structural changes.

2. Materials and Methods

2.1. Geographical and geological framework

Gallur is located in the central-western sector of the Ebro Basin, in the province of Zaragoza (Figure 3a,b). The climate is continental, with an average annual temperature between 14 and 15 °C and rainfall of less than 400 mm/year. The temperature fluctuations are strong, with maximum values close to 45 °C and minimum ones below -15 °C.

Geologically, the town is situated on Quaternary materials characterized by variable thickness and compactness, overlaying a Tertiary rocky substratum with a loamy-gypsiferous composition (Figure 3c). The materials that make up the Tertiary sedimentary column have a rhythmic vertical arrangement. In general, these rhythms show two well-defined members or sections: a basal one of a fundamentally terrigenous character, and an upper one of a carbonate and/or evaporitic constitution.

The Quaternary formations overlying the Miocene substratum outcrop extensively throughout the sector. They are arranged in various terrace levels associated with the Ebro, as well as different glacial deposits, colluvium and valley bottoms. Different types of deformations can be distinguished, which fall into four genetic groups: karstic, diapiric, tectonic and hydroplastic. Karst deformations are observed as siniform structures, normal faults and flexures, internal unconformities and so on, and they are the result of the solubilisation of evaporitic materials under Quaternary deposits. In many cases, these morphologies are fossilised by later deposits. At present, their functionality is recognised by the generation of dolines which affect alluvial terraces in the 30 m and 55 m and Neogene terraces, causing spectacular collapses.

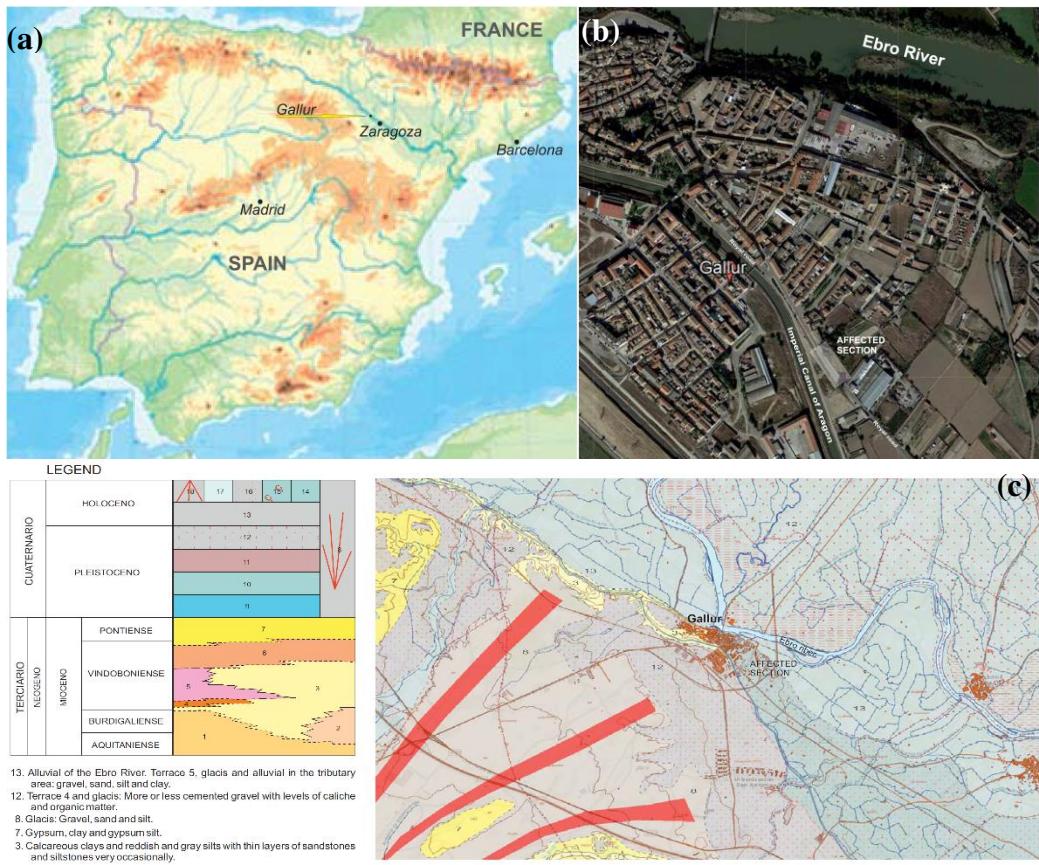


Figure 3. Geographical and geological framework: (a) Location of Gallur in the Iberian Peninsula; (b) Aerial view of the area under study (source: google maps); (c) Geological map of Alcalá de Ebro and its surroundings (source [6]).

2.2. Geotechnical investigation and geotechnical profile

As a starting point, and based on data from previous works [21], boreholes and geophysical research of the existing detailed topography were located (Figure 2). The ground conditions facilitated the creation of a correlation model for the terrain, which was used to set the size and to delineate potential ground consolidation solutions (Figure 4).

In the correlation conducted (Figure 5), two reference (guide) levels were obtained, serving to establish the relative decreases recorded in the subsidence zone affected by the sinkholes in this particular case. Level two (2), made up of coarse gravels with sand, showed a relative drop of around 3-4 metres in the sounding. Reference level 4 also showed a relative drop of another 4-5 metres, so that the accumulated result would be in the order of 7 to 9 metres. The thickness of level 3 reached more than 10 metres in the area that registers the subsidence process, while in the part where apparently that did not occur, the thickness was between 5 and 6.5 metres. One can interpret that the gravels with sands that form this defined level are very dense-compact ($N_{SPT} > 50$ /Rejection) in boreholes 1 and 2, and much looser, not very compact, in the borehole performed in the sinkhole, where the resistance to penetration ($N_{SPT} = 5-14$) is significantly lower.

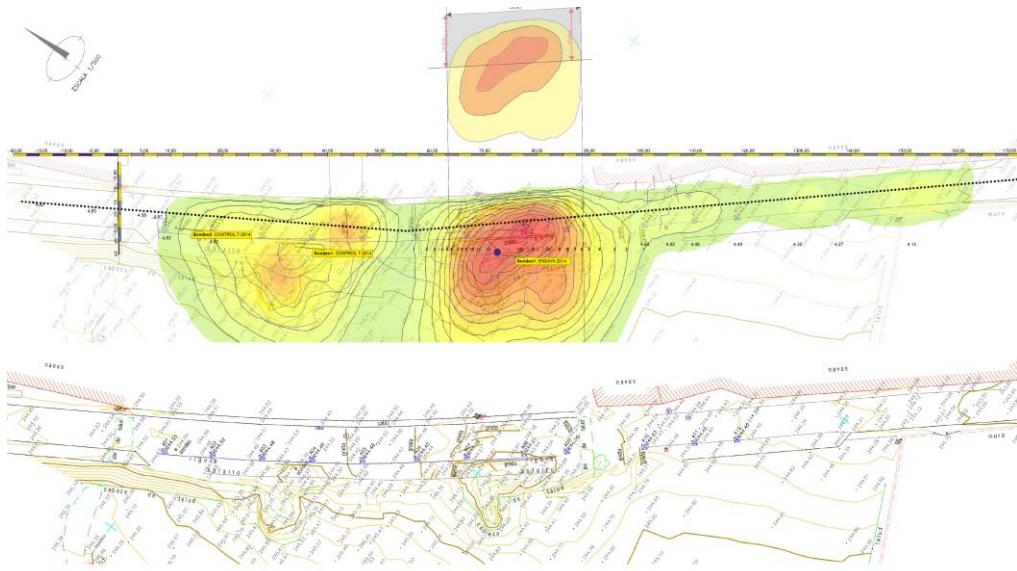


Figure 4. Situation plan with positioning of the subsidence model defined based on the existing data.

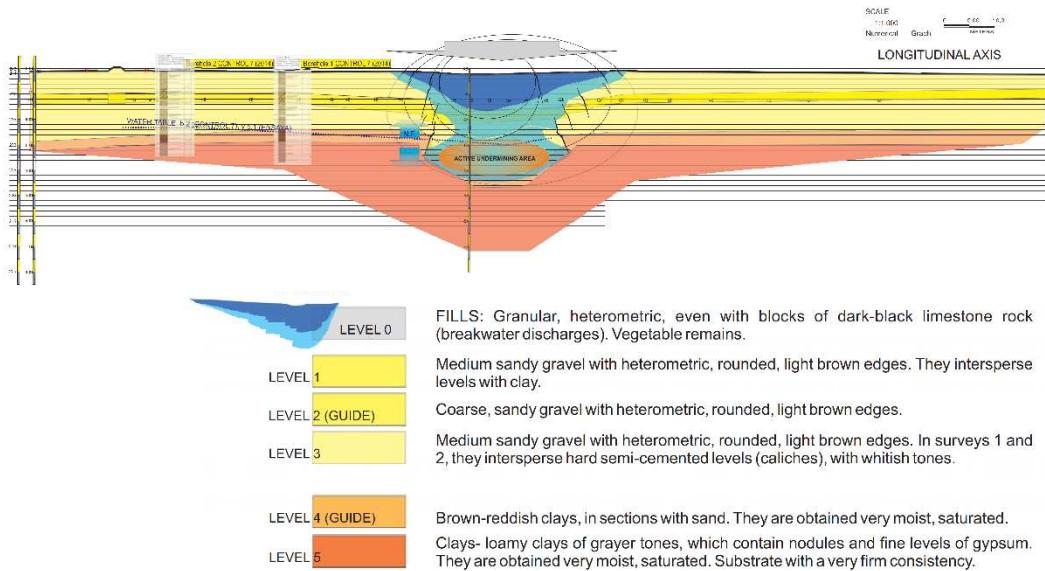


Figure 5. Longitudinal geological-geotechnical profile established based on the existing data.

3. Results and Discussion

3.1. Analysis and interpretation of the dynamics involved in the formation and evolution of doline

In the investigation located in the center of the area with the highest magnitude of surface settlement, no hollows were found. Beyond the level of brown clays (level 4), there were clays and claystones that constitute an apparently altered, but reasonably continuous and fairly firm substrate (level 5).

Thus, the materials that form the rocky substrate (levels 4 and 5) on which the alluvial gravels that form the current terrace of the river Ebro (levels 1, 2 and 3) were deposited, are particularly susceptible to erosion. Their clayey-loamy, loamy-clayey nature and the frequent gypsum content (e.g. nodules, veins and strata) make them easily undermined in conditions in which favourable factors combine. The possibility of fractures in the rocky substratum and its relative slope towards the river, facilitates, in certain areas, the generation of concentrated flows (within the water table) where, taking advantage of this greater permeability, strong internal scour processes are generated

which evolve into hollows or cavities which finally come to the surface in the form of chasms or sinkholes.

Based on previous experiences [1,7-10,22,23] the following scheme can be applied (Figure 6):

1. In the area of oscillation of the water table and in the contact between the deposit of granular material (gravels and sands) and the clay-marl substratum (with gypsum), there is an anomalous differential concentration of a sub-valve flow in the direction of the river Ebro.
2. A higher velocity flow is generated in this area and, consequently, a greater dragging capacity (scour) of both the fines in the granular deposit and those displaced due to the alteration of the substratum.
3. For this reason, the gravels of level 3, in the zone of contact with the clayey substrate, have a low fines content, which results in a higher relative permeability and abnormally low strength.
4. Hence, the process can be likened to a large hourglass with lateral expansion, favoring the preferential flow line toward the base level of the entire aquifer system, situated in the direction of the Ebro river.

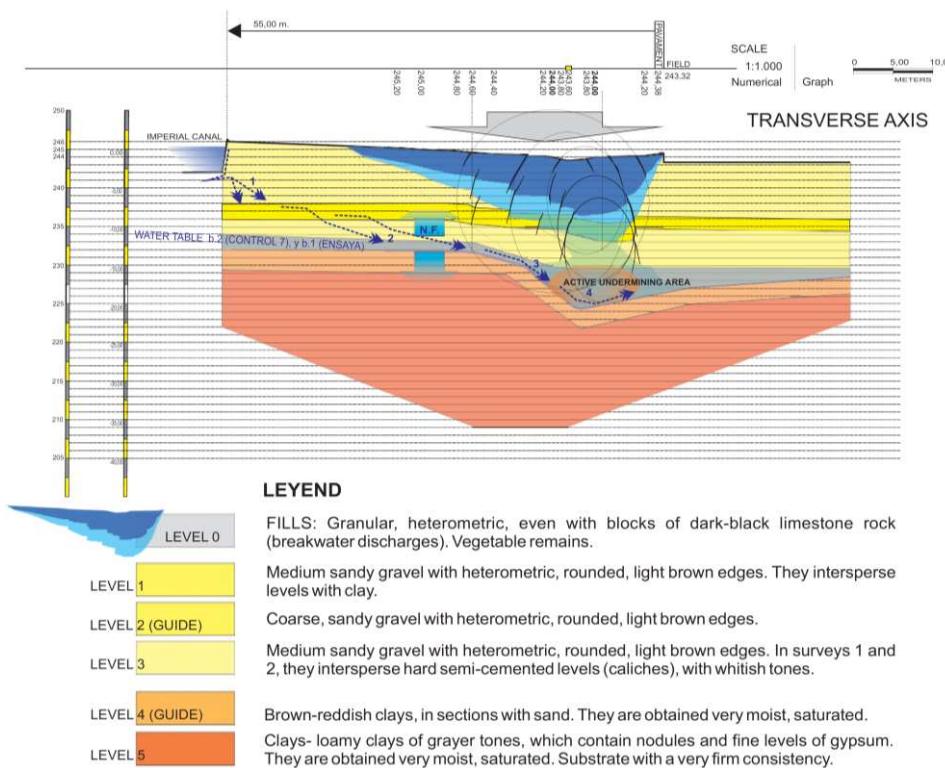


Figure 6. Geological-geotechnical cross-sectional profile established based on previous existing data.

3.2. Proposed solution

3.2.1. Approach to the Solution

From a perspective taken from a transversal axis of the road (Figure 6) and based on the surface morphology of the terrain, an interpretation of the situation can be made which leads to a model in which the following aspects can be assessed:

- There is no nearby catchment basin that could justify a process of this magnitude. The unusual influx of water into the system might be attributed to the nearby Canal Imperial de Aragón. In recent history, it is widely known that repairs were necessary on a section located immediately to the west, merely 30-40 meters away. The same issue that prompted the aforementioned repair could have influenced the emergence of the new subsidence observed in this access area to Gallur.

- These inputs have been infiltrating for a long time through the gravel deposit that makes up the soil in the area. The infiltrated flow was incorporated into a system of high relative porosity (levels 1 and 2), taking advantage of levels where the proportion of fines is lower (level 3), incorporating itself into the phreatic. The natural, preferential direction of this flow is in the direction of the river Ebro, towards the west.
- Taking into account the correlation among the boreholes surveyed, it is conceivable that there was a reduction in the relief corresponding to the Tertiary substratum. In this relative difference in elevation, there is a shift in the speed of the phreatic flow, which also integrates infiltrated contributions from the nearby channel, likely accumulating over the years. This contact gives rise to a flow with higher velocity and, consequently, an enhanced capacity for dragging (scour) of both fines from the granular deposit itself and those displaced due to the alteration of the substratum.
- Even though the issue of filtrations from the canal was addressed at the time, the process retains a certain inertia that promotes the emergence of sinkholes long after the required repairs to the canal were completed. It is crucial to ensure that the canal does not persist in leaking within this environment.

Based on all the aspects analyzed and on the basis of the interpreted geological and geotechnical model, the most suitable solution was assessed. The following arguments were considered:

1. The process of subsidence in this particular area is immediately related to the problems of filtrations that occurred from the Canal Imperial de Aragón from the section that was replaced by an artificial canal-aqueduct that apparently ceased to provide these filtrations, which, nevertheless, could have been acting for a long time.
2. The model, developed using data from the geophysical campaign and borehole surveys, interprets that the ongoing scour process, which led to the land sinking, primarily took place at the interface between the gravelly sands of the alluvial deposit and the loamy clays with gypsum in the underlying substratum.
3. Although there is a possibility that the process of scour and creep may affect levels or strata located within the rocky substratum, at greater depths, in order to be able to deal with the problem, once the origin of the problem was apparently resolved, acting on the soil of the first levels (on the gravels with sands of the alluvial terrace deposit) is considered appropriate. This would involve filling the voids in the area of the street layout and compacting the soil, to recover as much bearing capacity as possible.

Finally, the solution adopted consisted of consolidating the ground in the section where the settlements were located by injecting low-mobility mortar in the center of the sunken area (Figure 7), and the construction of an embankment reinforced with high tensile strength geogrids along the entire section of the affected street.



Figure 7. (a) Damage to an adjacent building is evident, highlighting points where deformations (cracks) are most pronounced, along with their indicated direction. (b) View of the street affected by the subsidence where the maximum subsidence is marked.

3.2.2. Adopted solution

Injection works

The injection works were carried out according to the following procedure:

1. Installation on site and restoration of pavements. Trench excavation, up to -3.00 m, of the area (section of street) in which the consolidation injections were subsequently carried out. In point (a) of Figure 8 the specific area is included in plan view.

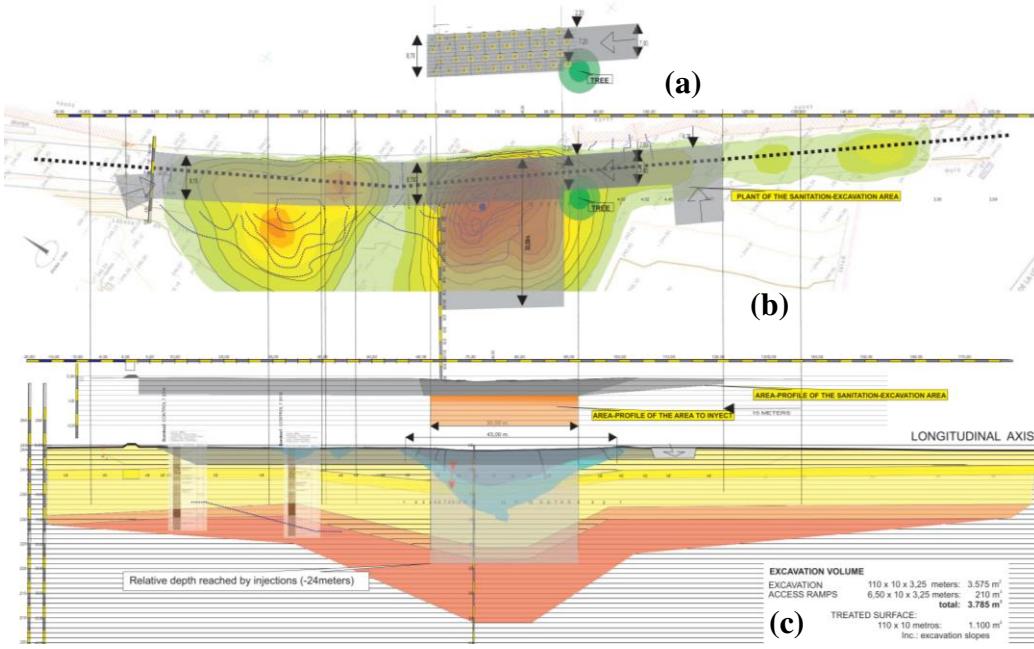


Figure 8. Location in plan view and profile of the consolidation works. (a) Initial excavation (in plan view) to carry out the consolidation mortar injections. (b) Excavation in the second phase, for the rehabilitation and placement of a reinforced-compacted embankment using high tensile strength geogrids. The relative depth reached by the B.M. mortar injections is included in the diagram that serves as a geotechnical model.

2. Access and staking out of the injection equipment campaign (Figure 9), a test section was carried out to define the spacing of the injections and to evaluate the injection pressures. DPSH tests were carried out to verify the situation.

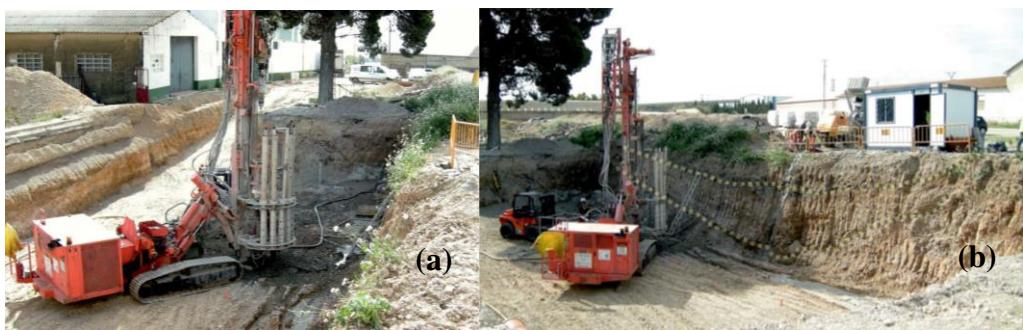


Figure 9. (a) Drilling equipment located in the excavation (at -3.00 m). (b) Excavation slope with the apparent arrangement of the ground levels in the shape of a trough, indicating the point of maximum subsidence.

3. Execution of low mobility mortar injections (compaction grouting), in the excavation made (Figure 10), at -3.00 m from the current street level. Maximum planned consumption of 150 l/m, including drilling into the ground. The mortar was injected at a pressure up to 20 bar and with an Abrams cone value of less than 8 to 12 cm. The pumping speed was limited to less than 60 l/m in order to produce infiltration-displacement of the soil without breaking its structure.

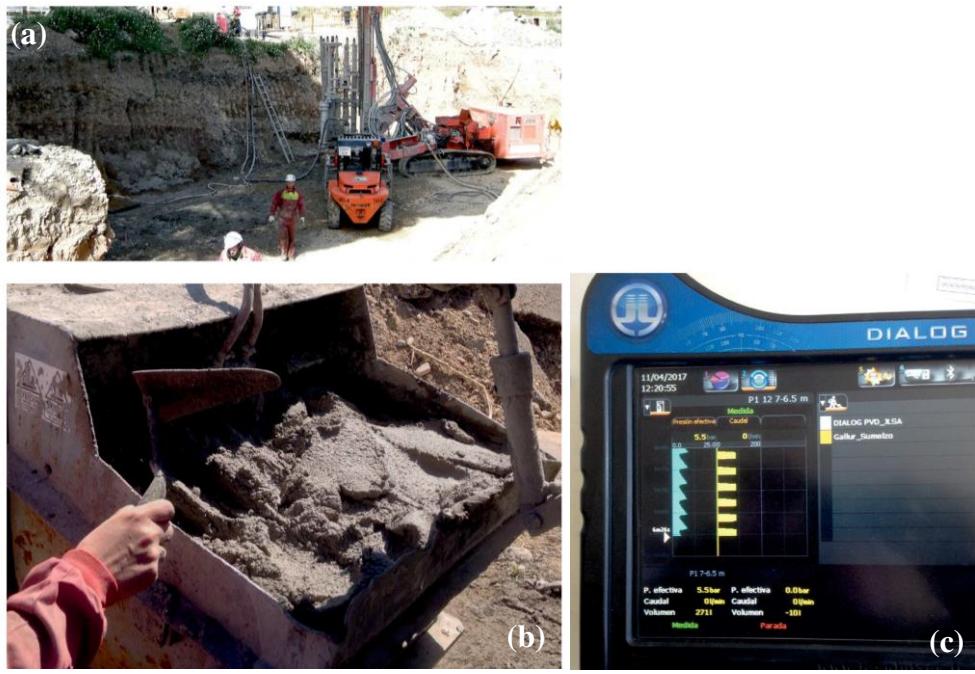


Figure 10. (a) Drilling equipment located in the excavation made at -3.00 m from the original street surface; (b) Appearance (texture and consistency) of the injection mortar in the injection pump hopper; (c) Injection control equipment: Injection in the interval between -7.00 and -6.50m; Effective pressure at that time 5.5 bar; mortar intake volume, after 6.26 minutes: 271 l.

The work was carried out in the arrangement shown in Figure 11, and to previously determined depths at each injection point, initially assessed to be -21.00 m deep from the excavation grade, at -3.00 m from the current street.

In order to improve the information on the ground situation at depth, 7 of the 38 injections of 29 m were extended to -27 m (Tables 1 and 2).

Table 1. General conditions for drilling. Number 1 to 38 (4/04/2017 to 13/06/2017).

Open circuit pressure	2 a 5 bars
Density mortar	1,9kgr/liter
Water content	18-20%
Maximun planned volume (l/m.l.)	150 l/ml*
Efective pressure (bars)	10 – 15 bars**

* If a minimun pressure of 10-15 bars. ** Above pressure of open circuit pressure.

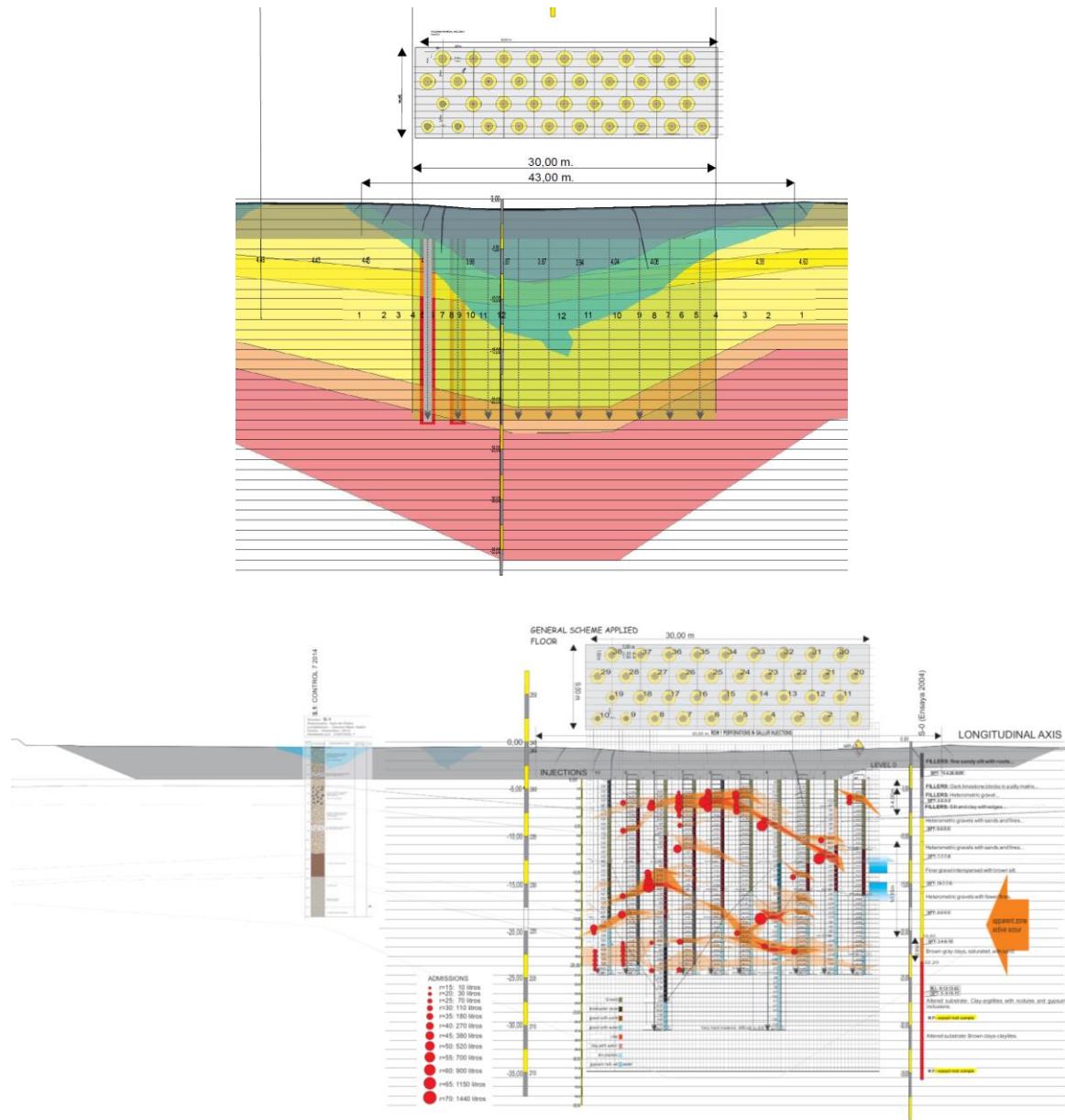


Figure 11. Profile showing the arrangement of the injections in the section with the highest apparent subsidence-subsidence at the surface, where the correlation model showed the largest deformations.

Construction of a reinforced backfill

In the area where the settlements reflected a greater subsidence, a deeper treatment was carried out (Figure 12) consisting of a 3 m soil remediation, injections, a bidirectional reinforcement (two uniaxial layers) and subsequent reconstruction by means of reinforced fill and a lighter treatment on both sides of this area of greater deformation (following the route of the road).

Table 2. Drilling data performed.

Order	Date	Nº drilling.	Meters	Liters registered	Kg mortar	Liter/m.l.	Pallets
1.00	42,829.00	3.00	21.00	2,542.12	4,830.03	121.05	2.76
2.00	42,830.00	5.00	21.00	2,542.13	4,830.05	121.05	2.76
3.00	42,836.00	7.00	21.00	3,094.73	5,879.99	147.37	3.36
4.00	42,837.00	9.00	21.00	2,586.22	4,913.82	123.15	2.81

	5.00	42,843.00	1.00	21.00	1,789.30	3,399.67	85.20	1.94
	6.00	42,844.00	6.00	21.00	3,912.65	7,434.04	186.32	4.25
	7.00	42,845.00	10.00	21.00	2,155.29	4,095.05	102.63	2.34
	8.00	42,846.00	2.00	21.00	1,293.12	2,456.93	61.58	1.40
	9.00	42,870.00	8.00	27.00	4,156.00	7,896.40	153.93	4.51
	10.00	42,879.00	4.00	27.00	3,920.54	7,449.03	145.21	4.26
Line 2 (9 uds.)	11.00	42,851.00	11.00	21.00	1,724.11	3,275.81	82.10	1.87
	12.00	42,859.00	19.00	21.00	2,155.21	4,094.90	102.63	2.34
	13.00	42,860.00	17.00	21.00	4,404.69	8,368.91	209.75	4.78
	14.00	42,864.00	18.00	21.00	2,251.00	4,276.90	107.19	2.44
	15.00	42,878.00	12.00	21.00	1,756.68	3,337.69	83.65	1.91
	16.00	42,880.00	16.00	27.00	3,507.41	6,664.08	129.90	3.81
	17.00	42,881.00	13.00	21.00	1,708.60	3,246.35	81.36	1.86
	18.00	42,885.00	14.00	27.00	3,400.79	6,461.50	125.96	3.69
	19.00	42,894.00	15.00	21.00	3,883.94	7,379.49	184.95	4.22
	20.00	42,865.00	29.00	21.00	1,457.00	2,768.30	69.38	1.58
Line 3 (10 uds.)	21.00	42,866.00	26.00	21.00	2,507.00	4,763.30	119.38	2.72
	22.00	42,867.00	28.00	21.00	1,740.00	3,306.00	82.86	1.89
	23.00	42,870.00	25.00	21.00	4,271.48	8,115.81	203.40	4.64
	24.00	42,871.00	27.00	21.00	1,830.00	3,477.00	87.14	1.99
	25.00	42,874.00	20.00	21.00	1,643.00	3,121.70	78.24	1.78
	26.00	42,886.00	22.00	27.00	2,873.73	5,460.09	106.43	3.12
	27.00	42,888.00	21.00	21.00	1,547.38	2,940.02	73.68	1.68
	28.00	42,891.00	24.00	27.00	2,260.50	4,294.95	83.72	2.45
	29.00	42,893.00	23.00	21.00	1,454.93	2,764.37	69.28	1.58
	30.00	42,857.00	38.00	21.00	1,293.22	2,457.12	61.58	1.40
Line 4	31.00	42,857.00	36.00	21.00	2,155.26	4,094.99	102.63	2.34
	32.00	42,863.00	37.00	21.00	1,551.32	2,947.51	73.87	1.68
	33.00	42,884.00	35.00	21.00	1,919.48	3,647.01	91.40	2.08
	34.00	42,892.00	32.00	27.00	2,873.76	5,460.14	106.44	3.12
	35.00	42,894.00	31.00	21.00	2,291.25	4,353.38	109.11	2.49
	36.00	42,895.00	33.00	21.00	2,832.66	5,382.05	134.89	3.08
	37.00	42,898.00	34.00	21.00	1,519.43	2,886.92	72.35	1.65
	38.00	42,899.00	30.00	21.00	2,157.00	4,098.30	102.71	2.34
	Total			840.00	92,962.93	176,629.57	110.67	100.93

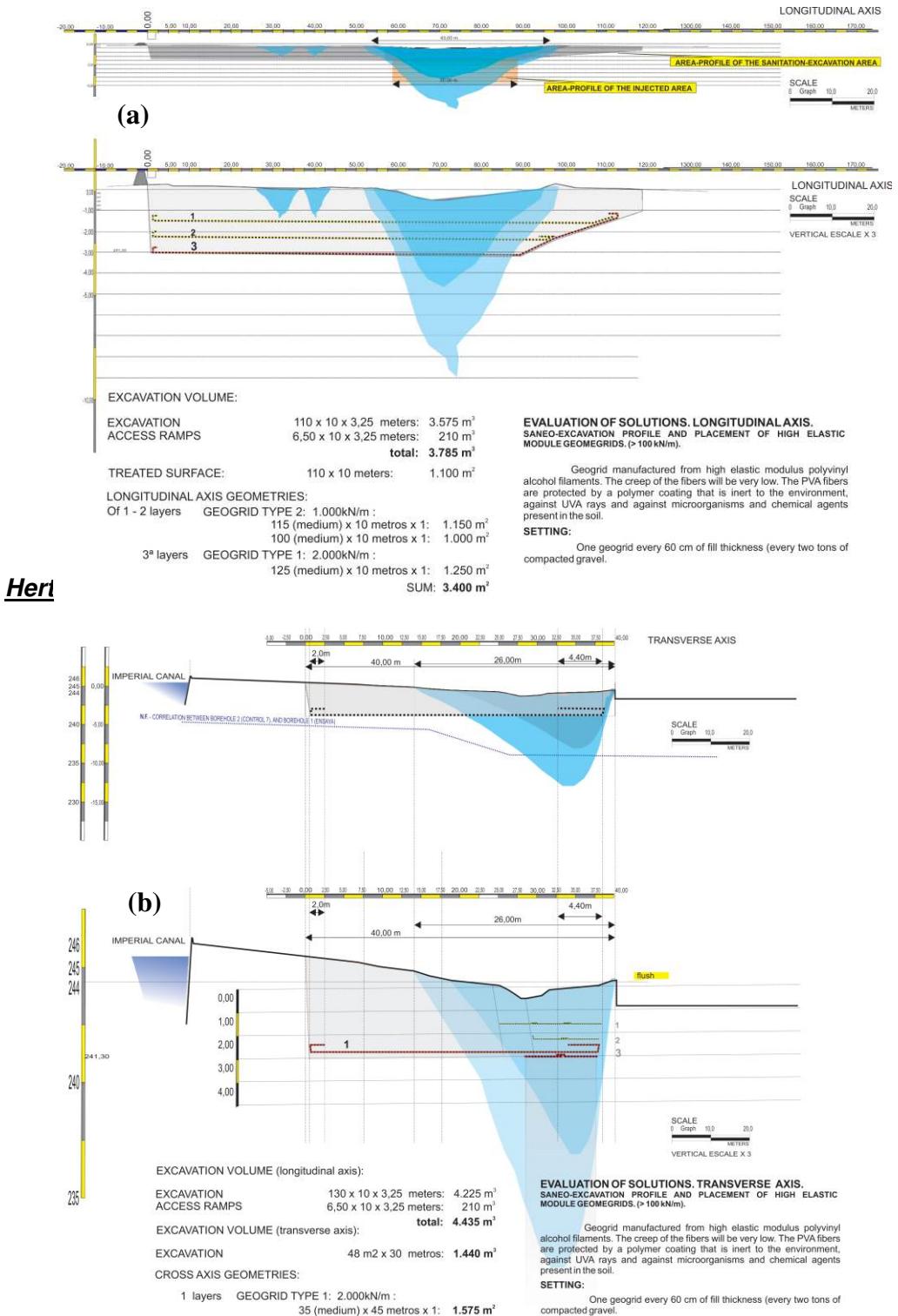


Figure 12. Profile of the reinforced backfill solution: (a) Longitudinal profile; (b) Transverse profile. A series of photographs showing this treatment are attached in Figure 13.

From a geometrical point of view, for this treatment the voids between injections were considered voids of a certain diameter, using of one or more layers of geogrid to bridge them. These geogrids can bridge the differential settlements that occur, anchoring themselves in fixed areas. The solution adopted was based on this concept. In the case of a generalised settlement in the backfill, where no fixed points existed, the geogrid simply descended solidarity with the backfill. Therefore, the design was made on the assumption that the area of differential settlement had a defined direction.

The tensile and deformational characteristics of the geogrid was set based on the thickness of the drainage (3 m) and the diameter of the possible cavity (space between injections), which was considered 2 m.

As $H/D < 1$ (being H the infill thickness and D the diameter), the British standard [24] was used, although considering the method established by Giroud [25], usually used when $H/D > 1$. This distinction is due to the fact that the British standard [24] does not consider the arch effect produced in the infill for H/D ratios > 1 , so if the design is carried out with this standard, the results obtained are exaggeratedly on the side of safety. On the other hand, for $H/D < 1$, as the effect of the discharge arc does not occur, this standard gives solutions that are in line with reality. The method of Giroud [25] takes into account the effect of the unloading arch, which substantially reduces the vertical pressure that the geogrid must bridge, which for H/D ratios > 1 is quite close to reality.

In terms of acceptable surface deformation, following the indications of the British standard [24] for the case of secondary roads, this was set at 2%. It is of great importance in this type of application to use materials whose raw material has a low nominal deformation, for this reason Polyvinyl Alcohol (PVA) was chosen, which has a nominal deformation $< 6\%$.



Figure 13. Photographs showing part of the reinforced backfill solution shown in Figure 12: (a) and (b) Longitudinal profile area; (c), (d) and (e) Transverse profile area. Figure (c) shows in detail a karstic cavity detected during the treatment.

The characteristics of the geogrids used were:

- Positioned at the base of the excavation (at -3.00 m; layer 5): GEOMALLA woven geotextile based on polypropylene, type FORTRAC (HUESKER brand), made of PVA and with a combined modulus of 2,000 kN/m.
- Positioned in 60 cm intervals (layers 1 to 4): GEOMALLA woven geotextile based on polypropylene, type FORTRAC (HUESKER brand), made of PVA and with a combined modulus of 1,000 kN/m.

As for the installation of the geogrid, once the clean-up was performed, the geogrid was laid out on a surface, as smooth as possible and without elements that could damage it, in parallel rolls with a minimum overlap of 0.5 m between them.

As the bridging of the voids was unidirectional, if the length of the action was greater than the length of the rolls, an overlap corresponding to the anchor length plus the void to be bridged plus the anchor length was carried out. Therefore, the action zone was extended by the anchorage length on each side to ensure the anchorage of the geogrid determined in each zone.

A layer of about 15 - 20 cm was placed between the two lines of uniaxial layers placed for subsidence bridging at the bottom of the excavation (one in the longitudinal direction and one in the transverse direction).

Finally, the construction of the backfill was carried out with selected granular material, spread, moistened and compacted in 20-30 cm thick layers (compaction degree 95% of the modified proctor), up to -3,00 m. (Figure 14).



Figure 14. (a) Construction of the backfill with granular material; (b) Final state of the area after treatment and asphalting.

4. Conclusions

The modeling of this type of situation, in which the ground sinks and the possible apparent causes may be related to processes that develop at very variable depths, requires an investigation that includes different points of view.

The study of the background is particularly interesting. The story of many neighbors about events that occurred in previous times often resolves the origin or possible origin of the process in question. In the case of Gallur, there were already known problems of subsidence that affected a house located at the specific point where this work is focused and a section of the Canal Imperial de Aragón, which is in the vicinity. Previous geotechnical studies already existed in which the problem was analyzed and included soundings and other types of tests and investigations, mainly geophysics.

Based on the geomorphological analysis of the ground surface, it was already possible to recognize the subsidence that affected mainly one of the main access roads (Camino Real) to the town of Gallur. The detailed topography of the area and its immediate surroundings allowed to point out the extent and location of the depocenters of a main subsidence and at least two of lesser magnitude.

Using the rotary borings with continuous core drilling, carried out in previous campaigns, a geological and geotechnical model was elaborated, adjusted fundamentally to the access road indicated. It was possible to evaluate the layers of the recharge ground, the situation of the rocky substratum and the local water table. It was possible to appreciate the disposition of the different levels or strata in the form of a basin, pointing out the apparent subsidence process affecting the terrain and reflected on the surface.

Based on all the existing data, it has been possible to propose sustainable, novel and efficient solutions that allow to continue using the infrastructure in a safe way and that can be useful to alleviate similar problems in other types of situations similar to the one studied in this work.

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