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Geotechnical and structural analysis in the remediation of sinkholes: A case study in Alcalá de Ebro (Zaragoza, Spain)

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Abstract

Karst-related subsidence constitutes a major geotechnical hazard in areas underlain by evaporitic formations. The municipality of Alcalá de Ebro (NE Spain) has experienced recurrent sinkhole activity associated with gypsum dissolution, causing damage to roads, buildings and public infrastructure. Previous remediation measures, including aggregate backfilling and resin injections, achieved only partial success and did not prevent further subsidence. This study evaluates the effectiveness of a ground-improvement system based on low-mobility mortar columns combined with geogrid reinforcement.

A numerical model was developed using the finite element method in SAP2000. The model incorporated the stratigraphic profile obtained from geotechnical investigations and reproduced the mechanical behaviour of the untreated ground and the reinforced configuration. Attention was given to the assessment of vertical displacements and settlement reduction under service and ultimate loading conditions.

The results indicate that the proposed solution substantially improves the mechanical response of the ground. Maximum calculated settlements were reduced by approximately 96% compared with untreated conditions. The mortar columns increase ground stiffness and load-bearing capacity, while the geogrid contributes to load redistribution and improved deformation control. The proposed technique therefore represents an effective solution for mitigating sinkhole-related ground deformation in evaporite-karst environments.

Keywords: collapse hazard; sinkhole mitigation; gypsum karst; Alcalá de Ebro; injections; geogrid; evaporitic rocks; finite element analysis

1. Introduction

Karst-related subsidence is one of the most important geotechnical hazards affecting urban and transport infrastructure developed on soluble rock formations. Dissolution processes occurring within evaporitic terrains may generate underground cavities that progressively evolve into sinkholes and ground-settlement phenomena, causing damage to buildings, roads, buried utilities and hydraulic infrastructure. In addition to the direct costs associated with repair and maintenance, these processes may compromise public safety and restrict future urban development (Waltham et al., 2005; Gutiérrez et al., 2008).

Evaporite karst environments are especially prone to ground instability because gypsum exhibits high solubility under natural groundwater circulation conditions. As a result, progressive dissolution may reduce the bearing capacity of the overlying materials and generate differential settlements that are often difficult to predict using conventional site investigation techniques. Numerous studies have documented the occurrence of sinkholes and subsidence in gypsum-bearing terrains, highlighting the need for effective investigation, monitoring and remediation strategies (Cooper et al., 2011; Gutiérrez et al., 2011).

The central sector of the Ebro Valley, in north-eastern Spain, constitutes one of the most extensively studied evaporite-karst regions in Europe. Active dissolution of Tertiary gypsum deposits has generated widespread subsidence problems affecting urban areas, transport infrastructure and agricultural land. Recent investigations based on geomorphological surveys and Differential Interferometric Synthetic Aperture Radar (DInSAR) have confirmed the continued activity of sinkhole-related deformation throughout the region (Galve et al., 2015a; Galve et al., 2015b).



Figure 1

Within this geological setting, the municipality of Alcalá de Ebro, located approximately 40 km north-west of Zaragoza (Figure 1), has experienced recurrent subsidence episodes over recent decades. A significant proportion of these deformation processes have been concentrated along Estación Street (Figure 2), where settlements have affected roads, residential properties and municipal services. Previous investigations indicate that the instability is closely linked to

groundwater circulation through gypsum-bearing formations, which promotes dissolution processes and progressive loss of support within the subsurface (Gracia et al., 2025).



Figure 2

Several remediation measures have been implemented in the municipality, including aggregate backfilling, resin injections and localized stabilization works. Although these interventions have reduced deformation in some areas, recurring settlement demonstrates that the underlying hydrogeological and geotechnical mechanisms have not been fully controlled. Consequently, there is a need for improvement techniques capable of increasing ground stiffness, improving load transfer and reducing long-term differential settlements.

Ground-improvement systems based on rigid or semi-rigid inclusions are widely used in problematic ground conditions because of their ability to reduce compressibility and enhance bearing capacity. Likewise, geosynthetic reinforcement can improve stress redistribution and settlement control by promoting interaction between the inclusions and the surrounding soil. The combined use of columns and geogrids has demonstrated satisfactory performance in a variety of ground-improvement applications (Priebe, 1995; Gniel & Bouazza, 2007; Schaefer et al., 2017). However, their effectiveness in sinkhole-prone evaporite-karst environments remains less extensively documented.

The objective of this study is to evaluate the performance of a ground-improvement system consisting of low-mobility mortar columns combined with a geogrid reinforcement layer for the remediation of sinkhole-related deformation in Alcalá de Ebro. Numerical modelling was performed using SAP2000 to compare the behaviour of untreated and reinforced ground conditions. Particular attention was devoted to the evaluation of vertical displacements and settlement reduction in order to assess the suitability of the proposed solution for mitigating subsidence in evaporite-karst terrains.

2. Methods

2.1 Study Area and Geotechnical Characterisation

The study was conducted in the municipality of Alcalá de Ebro, Zaragoza (Spain), focusing on Estación Street, one of the sectors most affected by recurrent subsidence phenomena. Previous geotechnical investigations identified a heterogeneous subsurface profile composed of anthropogenic fills, alluvial deposits and a marl-gypsum substratum affected by dissolution

processes. The geotechnical profile was simplified into three principal geotechnical units in order to facilitate numerical modelling while preserving the fundamental mechanical characteristics of the ground.

The upper unit (NG1) consists of anthropogenic fills and contaminated alluvial deposits extending to approximately 4.0 m depth. This unit includes gravels, clayey silts, clays and remnants of previous structures. Beneath NG1 lies Geotechnical Unit NG2, composed predominantly of clayey and sandy materials with gravel interbeds. This stratum extends to approximately 9.0 m depth and constitutes the principal load-transfer layer above the evaporitic substratum.

The deepest material corresponds to Geotechnical Unit NG3, consisting of marl and gypsum deposits. Due to the different engineering properties of its constituent materials, this unit was subdivided into NG3a, dominated by clayey materials, and NG3b, characterised by nodular gypsum interbedded with clays. This subdivision allowed a more realistic representation of the stiffness contrast between the different geological materials and their influence on the overall deformational behaviour of the ground.

The representative geotechnical parameters assigned to the numerical model are summarised in Table 1. The adopted values were obtained from the available geotechnical investigations and subsequently adjusted to provide a realistic representation of the mechanical response of the different strata. Particular attention was given to the stiffness contrast between the superficial anthropogenic deposits and the underlying marl-gypsum substratum, as this contrast plays a significant role in the deformational behaviour of the study area.

2.2 Numerical Modelling Approach

The proposed solution consists of low-mobility mortar columns installed within the affected area and a geogrid reinforcement layer located above the column heads (Figure 3).

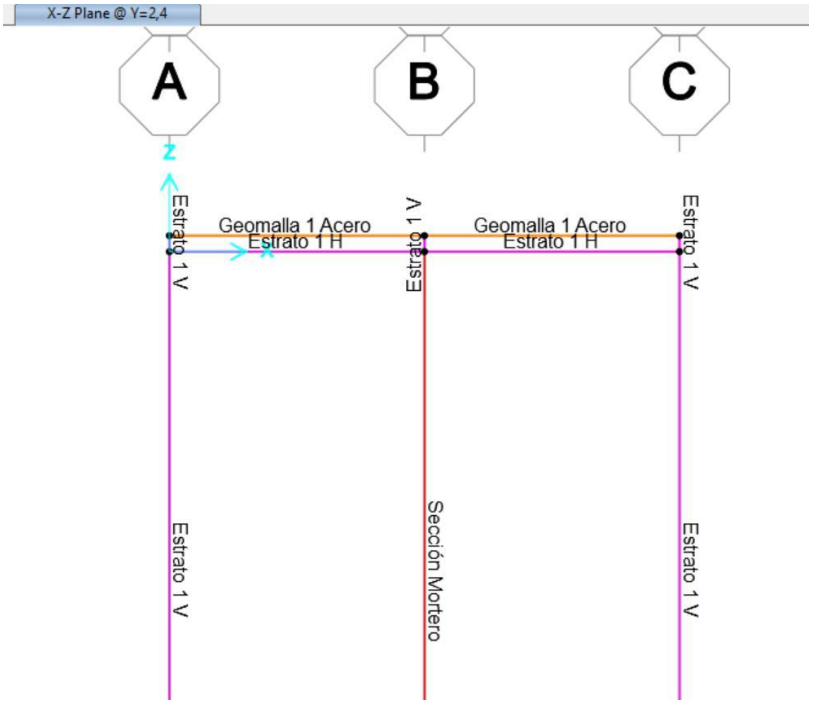


Figure 3

Column-supported systems are widely used to increase stiffness, improve bearing capacity and reduce settlements in weak or unstable ground conditions (Priebe, 1995; Kirsch & Bell, 2012).

Mortar columns act as preferential load-transfer elements, reducing stresses transmitted to the surrounding soil. In addition, the geogrid functions as a load transfer platform, promoting stress redistribution and reducing differential settlements (Gniel & Bouazza, 2007; Schaefer et al., 2017).

The reinforcement arrangement adopted in this study consists of 32 columns spaced at approximately 3.60 m, combined with a FORTRAC 2000 M SP geogrid.

The performance of the proposed remediation system was evaluated using the finite-element software SAP2000. Numerical modelling was selected because it provides a practical framework for assessing the interaction between the ground and the improvement system while allowing comparison of alternative reinforcement configurations (Han & Gabr, 2002; Potts & Zdravkovic, 1999). Two numerical models were developed:

- Untreated ground condition, representing the existing geological profile.
- Improved ground condition, incorporating mortar columns and geogrid reinforcement.

The comparison between these two scenarios enabled direct assessment of the effectiveness of the proposed solution in reducing settlement and modifying the stiffness of the treated ground.

Given that SAP2000 is primarily intended for structural analysis, the ground was represented through an equivalent structural model. The different geotechnical layers were idealised using beam elements with equivalent elastic properties derived from the available geotechnical information. This approach provides a simplified but representative approximation of the deformational response of the ground under the loading conditions considered.

Table 2 summarises the principal mechanical properties assigned to the mortar columns and geogrid. These parameters were incorporated into the finite-element model in order to reproduce the stiffness contribution of the mortar inclusions and the load-transfer function of the geogrid reinforcement layer.

2.3 Boundary Conditions and Ground Representation

The interaction between the modelled strata and the underlying natural ground was represented through discrete elastic springs located at the base of the numerical model. These springs were used to simulate the vertical deformability of the foundations and were characterised by an equivalent coefficient of subgrade reaction.

The coefficient of subgrade reaction was estimated from the deformation modulus obtained during the geotechnical investigations. The resulting stiffness values were introduced as elastic support conditions within SAP2000. The adopted approach assumes linear elastic behaviour and is considered appropriate for evaluating comparative settlement performance between untreated and reinforced ground conditions (Bowles, 1996; Das, 2016).

Model dimensions were selected following preliminary sensitivity analyses to ensure representative behaviour while maintaining computational efficiency. The final numerical domain measured 2.40 m × 3.20 m and included the complete stratigraphic sequence identified during the geotechnical investigation.

2.4 Ground Improvement System

The proposed remediation solution combines low-mobility mortar columns with a geogrid load-transfer platform (Figure 4). Mortar columns were selected because of their ability to increase stiffness, improve bearing capacity and reduce the compressibility of weak or unstable ground (Priebe, 1995; Kirsch & Bell, 2012).

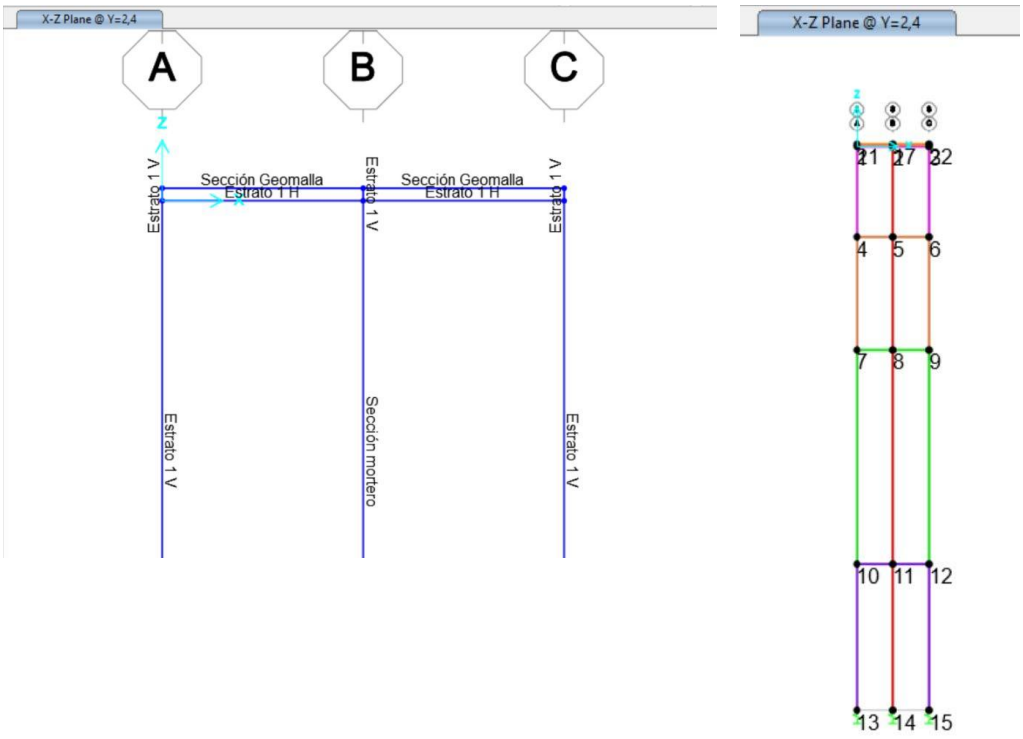


Figure 4

Based on preliminary calculations and numerical simulations, a total of 32 mortar columns were distributed along the affected section of Camino Estación Street in a staggered arrangement. The spacing and configuration of the columns were defined to optimise settlement reduction while maintaining practical constructability.

A FORTRAC 2000 M SP geogrid was installed above the column heads. The geogrid acts as a load-transfer platform that redistributes stresses between adjacent columns and limits differential settlements. Unlike pile-supported systems, no rigid connection exists between the geogrid and the mortar columns. Load transfer therefore occurs through interaction with the surrounding soil and through deformation compatibility between the different components of the reinforcement system (Gniel & Bouazza, 2007; Schaefer et al., 2017).

2.5 Loading Conditions and Assessment Criteria

The numerical analyses were performed under serviceability and ultimate limit state loading conditions. Permanent and variable loads were combined in accordance with the requirements of Eurocode 0. Vertical displacement was adopted as the principal performance indicator because settlement control constitutes the primary objective of the remediation system.

The effectiveness of the proposed solution was evaluated by comparing the maximum vertical displacements obtained in the untreated and reinforced models. Additional consideration was given to the distribution of displacements throughout the profile in order to assess the influence of the reinforcement system on differential settlement and overall ground behaviour.

The resulting displacement patterns provided the basis for evaluating the effectiveness of the mortar-column and geogrid system and for determining its suitability as a remediation technique for sinkhole-prone evaporite-karst environments.

3 Results and Discussion

3.1 Behaviour of the Untreated Ground

The analysis of the untreated ground provided a reference condition against which the effectiveness of the proposed intervention could be assessed. Under the imposed service load, the numerical model predicted relatively large vertical displacements within the upper geotechnical units, reflecting the limited stiffness of the anthropogenic fills and alluvial deposits that characterise the shallow part of the profile.

The maximum settlement obtained for the untreated configuration reached approximately 80 mm under serviceability conditions (Figure 5). When the ultimate limit state (ULS) load combination was applied, the calculated maximum displacement increased to approximately 120 mm (Figure 6). These results indicate that the existing ground conditions are unable to adequately control deformation and are consistent with the recurrent settlement problems historically observed in the study area.

The largest deformations were concentrated within Geotechnical Units NG1 and NG2, where the relatively low stiffness of the materials resulted in significant stress redistribution and vertical strain development. The presence of the underlying marl-gypsum formation further contributes to the complexity of the deformational response due to the potential influence of dissolution processes and progressive loss of support.

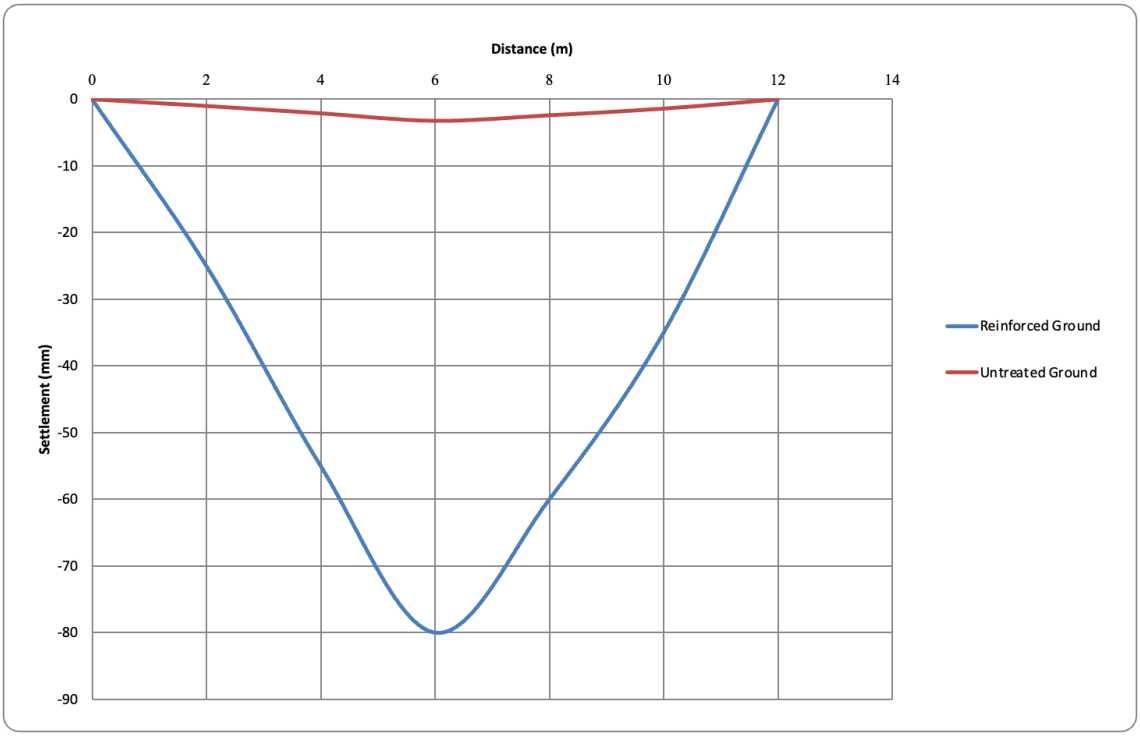


Figure 5

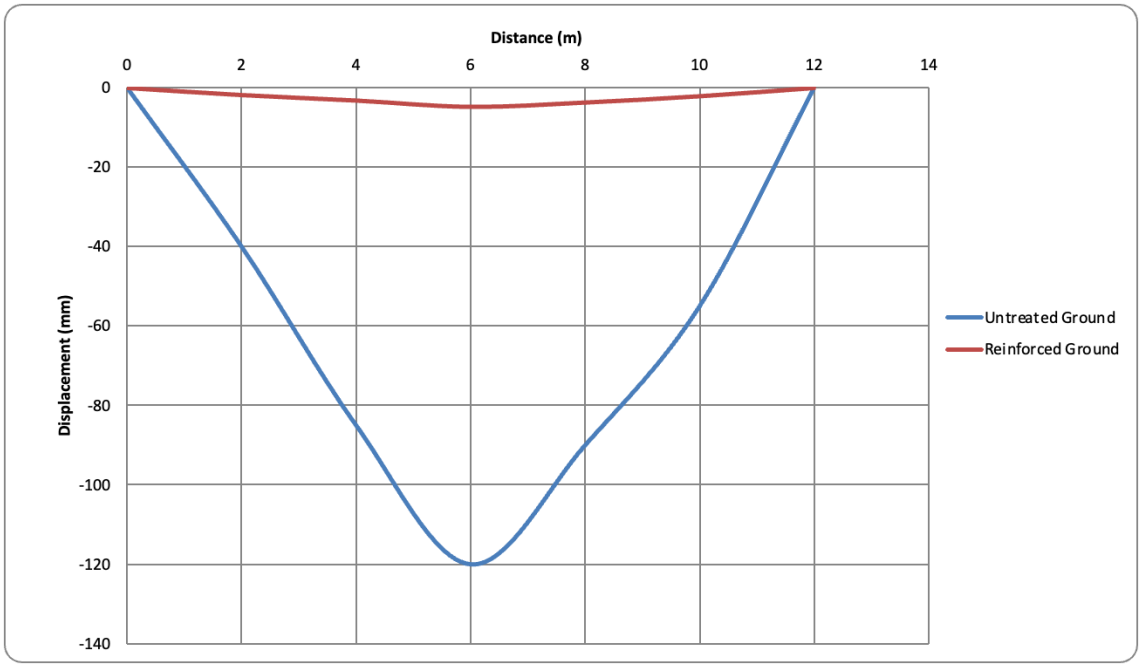


Figure 6

3.2 Behaviour of the Reinforced Ground

The incorporation of the mortar columns and geogrid produced a substantial modification of the mechanical behaviour of the system. The mortar columns acted as stiff inclusions that transferred a significant proportion of the applied load to deeper and more competent strata, thereby reducing the stresses acting within the compressible superficial materials.

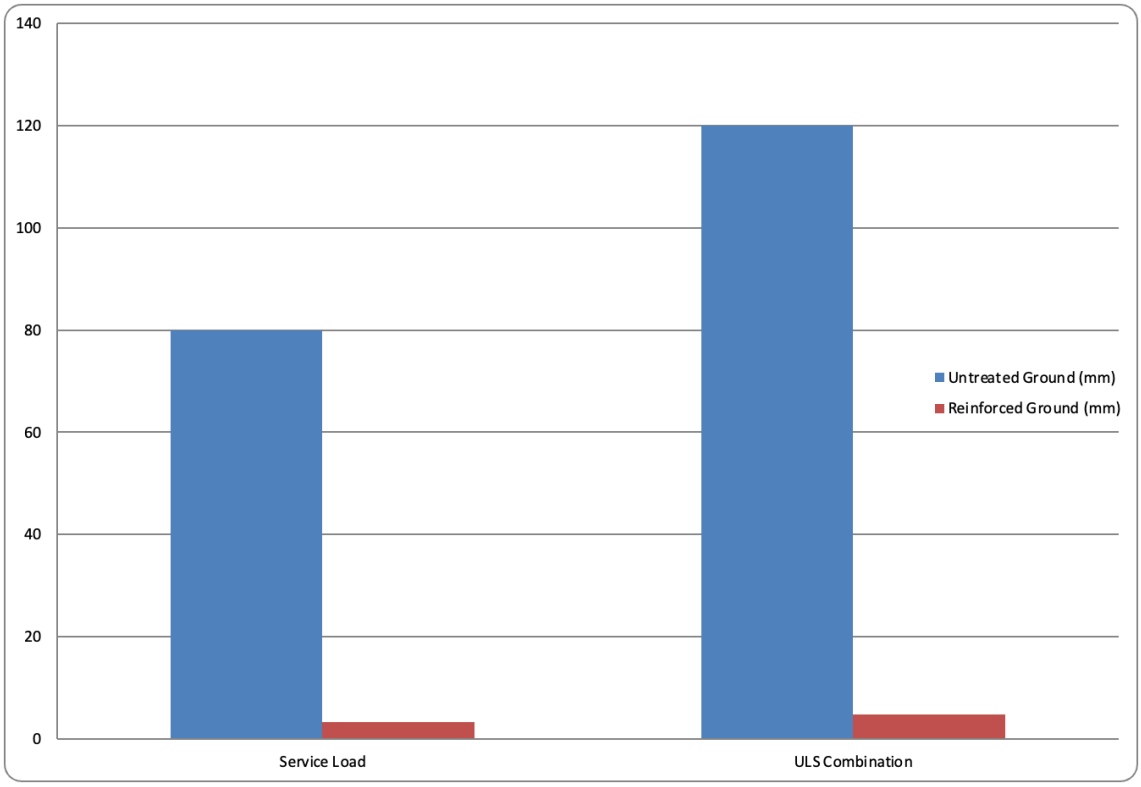


Figure 7

Simultaneously, the geogrid provided additional load-transfer capacity by redistributing stresses between adjacent columns and promoting a more uniform deformation pattern across the treated area. This interaction reduced differential settlements and improved the overall stiffness of the reinforced ground.

Under serviceability loading conditions, the maximum calculated settlement decreased from approximately 80 mm to 3.23 mm. This reduction corresponds to a decrease of approximately 96.0% relative to the untreated condition. Similarly, under the governing ULS load combination, the maximum calculated displacement decreased from approximately 120 mm to 4.80 mm, representing a reduction of approximately 96.0% (Table 3 and Figures 5 to 7).

The results demonstrate a clear improvement in performance following implementation of the proposed reinforcement system. In both loading scenarios, settlements were reduced to values that would generally be considered acceptable for urban infrastructure and roadway applications.

3.3 Discussion of Ground-Improvement Mechanisms

The significant reduction in calculated settlements is primarily attributable to the increase in equivalent ground stiffness provided by the mortar columns. These inclusions function as preferential load-transfer elements, reducing the proportion of vertical stress carried by the weaker superficial deposits. Similar behaviour has been reported for column-supported ground-improvement systems used in soft soils and highly compressible ground conditions (Priebe, 1995; Filz et al., 2019).

The geogrid contributes through a different but complementary mechanism. Rather than increasing stiffness directly, it acts as a load-transfer platform that redistributes stresses between adjacent columns and limits localised deformation. This behaviour improves interaction between the reinforcement elements and the surrounding soil, leading to more uniform settlement patterns and reducing the likelihood of differential movements (Gniel & Bouazza, 2007; Schaefer et al., 2017).

The results obtained in the present study are also consistent with previous investigations carried out within the evaporite-karst environments of the Ebro Valley, where reinforcement measures aimed at increasing ground stiffness have demonstrated positive effects on the control of deformation and subsidence-related damage (Galve et al., 2015a; Gracia et al., 2025).

Although the numerical model is based on linear-elastic assumptions and therefore does not explicitly reproduce all the hydrogeological and geochemical processes associated with gypsum dissolution, it provides a useful engineering tool for evaluating the relative effectiveness of alternative remediation strategies. The substantial reduction in predicted settlements indicates that the combined mortar-column and geogrid system can significantly improve the serviceability performance of sinkhole-affected ground.

Overall, the numerical analyses suggest that the proposed solution represents a technically viable remediation strategy for urban areas affected by evaporite-karst subsidence. The combination of increased stiffness, improved load transfer and reduced differential settlement provides a robust basis for mitigating future ground deformation and enhancing the long-term performance of infrastructure constructed over unstable gypsum-bearing formations.

4. Conclusions

This study evaluated the effectiveness of a ground-improvement system based on low-mobility mortar columns combined with geogrid reinforcement for the remediation of sinkhole-related

ground deformation in Alcalá de Ebro (Zaragoza, Spain). The assessment was performed through finite-element modelling using SAP2000, comparing untreated and reinforced ground conditions under representative serviceability and ultimate loading scenarios.

The main conclusions derived from the research are as follows:

1. The numerical model provided a satisfactory representation of the geotechnical behaviour of the study area, allowing the influence of the proposed reinforcement system on settlement development to be assessed. The adopted stratigraphic simplification and elastic modelling approach proved suitable for comparing untreated and improved ground conditions.
2. The incorporation of low-mobility mortar columns significantly increased the stiffness of the ground, reducing the magnitude of vertical deformations and improving load transfer towards deeper and more competent strata. The columns acted as stiff inclusions that effectively limited the compressibility of the upper geotechnical units.
3. The geogrid reinforcement contributed to the redistribution of stresses and the control of differential settlements. Although not rigidly connected to the mortar columns, the geogrid functioned as a load-transfer platform, promoting interaction between the reinforcement elements and the surrounding soil.
4. Substantial reductions in settlement were obtained in all analysed scenarios. Under serviceability loading conditions, the maximum predicted settlement decreased from approximately 80 mm in the untreated ground to 3.23 mm after reinforcement. Similarly, under the governing ultimate limit state (ULS) load combination, settlement decreased from approximately 120 mm to 4.80 mm. In both cases, the calculated reduction was close to 96%.
5. The combined reinforcement system demonstrated a significant improvement in the overall deformational response of the ground. In addition to reducing maximum settlements, the proposed solution produced a more uniform displacement distribution, decreasing the risk of differential movements that could affect surface infrastructure.
6. The proposed methodology represents a technically viable remediation strategy for sinkhole-prone areas developed over evaporite-karst formations. Although the numerical model is based on simplified assumptions and linear-elastic behaviour, the results indicate that the combined use of mortar columns and geogrid reinforcement can substantially improve ground performance and reduce the impact of subsidence-related damage.

Overall, the findings suggest that the proposed reinforcement system offers an effective engineering solution for mitigating settlement problems in urban areas affected by gypsum dissolution and karst-related subsidence. Future research should focus on long-term monitoring of treated areas and on the incorporation of hydrogeological and dissolution processes into more advanced numerical models to further improve the prediction of sinkhole development and ground behaviour.

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7. Author Contributions

Conceptualization, A.B., F.J.T. and P.B..; methodology, A.B. and A.G.; software, A.B.; validation, A.G., F.J.T. and P.B.; formal analysis, A.B., A.G., and F.J.T.; investigation, A.B., A.G. and F.J.T.; resources, A.B. and P.B.; data curation, A.B. and A.G..; writing—original draft preparation, A.B.; writing—review and editing, A.B., A.G., F.J.T. and P.B.; visualization, F.J.T., A.G., and P.B.; supervision, F.J.T. and P.B.; project administration, F.J.T. All authors have read and agreed to the published version of the manuscript.

8. Data Availability Statement

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

9. Conflicts of Interest

The authors declare no conflicts of interest.

10. Figure legends

Figure 1 - Location map of Alcalá de Ebro

Figure 2 - Sinkhole on Estación Street (Alcalá de Ebro)

Figure 3 - SAP2000 numerical model

Figure 4 - Simplified numerical representation of the mortar-column and geogrid reinforcement system adopted in the analyses.

Figure 5 - Settlement profiles calculated under service loading conditions for untreated and reinforced ground. The proposed reinforcement system significantly reduces both the magnitude and spatial extent of the predicted settlements.

Figure 6 - Comparison of vertical displacement profiles obtained for untreated and reinforced ground under ultimate loading conditions. The reinforcement system significantly reduces the magnitude of deformation and improves the overall stiffness of the ground.

Figure 7 - Summary of the maximum settlements calculated for untreated and reinforced ground conditions under serviceability and ultimate limit state loading. The proposed reinforcement system reduced settlements by approximately 96% in both loading scenarios.

11. Tables

Table 1. Representative geotechnical parameters adopted for numerical modelling. Where:γ = unit weight; E = Young's modulus; ν = Poisson's ratio; k = coefficient of subgrade reaction

Geotechnical Unit	Material Description	γ (kN/m³)	E (MPa)	ν (-)	k (kN/m³)
NG1a	Anthropogenic fills, gravels, silts and concrete remnants	19	15	0.35	12,000
NG1b	Clayey silts and brown clays	18	12	0.38	10,000
NG2	Clays, sands and gravelly interbeds	20	25	0.33	18,000
NG3a	Marl and clay deposits	21	45	0.30	30,000
NG3b	Nodular gypsum with clay interbeds	22	80	0.28	55,000

Table 2. Mechanical properties of the ground-improvement materials adopted in the numerical model

Material	Property	Value
Low-mobility mortar	Compressible strength (28 days)	5–8 MPa
Low-mobility mortar	Young's modulus	5,000 MPa
Low-mobility mortar	Unit weight	22 kN/m³
FORTRAC 2000 M SP geogrid	Tensile strength	≥ 2,000 kN/m
FORTRAC 2000 M SP geogrid	Design strain	≤ 6%
FORTRAC 2000 M SP geogrid	Aperture size	30 × 30 mm

FORTRAC 2000 M SP geogrid	Unit weight	605 g/m²

Table 3. Comparison of settlements obtained from the numerical analyses

Loading condition	**Untreated ground (mm)**	**Reinforced ground (mm)**	**Reduction (%)**
Service load	80.0	3.23	96.0
ULS combination	120.0	4.80	96.0