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Comprehensive Sinkhole Mitigation: A Case Study and Application of Compaction Grouting in Karstic Environments in the State of Tennessee, USA

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ABSTRACT

Sinkholes pose significant risks to infrastructure, requiring detailed investigation and effective repair strategies. This paper details a case study of a persistent sinkhole along a driveway in Nashville, Tennessee, which has caused repeated pavement subsidence despite multiple repairs. The investigation included site visits, drilling operations, soil and rock analysis, and groundwater assessment. Three mitigation approaches were evaluated including conventional inverted rock filter repair, constructing a land bridge, and compaction grouting. After considering technical, situational, and cost factors, compaction grouting was chosen as the optimal solution. The paper outlines the compaction grouting repair strategy, including methodology, materials, and construction specifications. The findings aim to enhance design standards and construction practices for sinkhole repairs in Tennessee and similar geotechnical regions.

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1. Introduction and literature review on sinkhole remediation methods and case studies

Sinkholes pose significant challenges to infrastructure, safety, and environmental stability in regions susceptible to subsidence. These natural phenomena, often triggered by geological factors or human activities, necessitate effective remediation and repair strategies to mitigate their impact [1] to [5]. Repairing sinkholes requires careful planning, engineering expertise, and innovative solutions tailored to each unique case. Sinkholes occur when underground voids collapse, leading to sudden depressions on the surface. They can vary in size from small cavities to large craters, causing substantial damage to buildings, roads, and other structures. The occurrence of sinkholes is often unpredictable and can be triggered by factors such as heavy rainfall, changes in groundwater levels, or human activities like mining and construction [6]. Over the years, extensive research has been conducted to develop methodologies for addressing sinkhole occurrences, ranging from preventive measures to post-collapse interventions [7] to [49]. This literature review examines several case studies on sinkhole

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repairs, highlighting different approaches, challenges faced, and lessons learned, and aims to provide an overview of the current state of knowledge regarding sinkhole remediation and repair techniques. Development in karst-prone geologies poses significant risks, necessitating careful attention during site preparation to mitigate potential hazards. Key considerations include ensuring positive drainage to prevent water ponding, capturing surface runoff in stormwater systems, and vigilant observation for incipient sinkholes during construction [45] to [49]. Given the inherent risks associated with karst formations, it is imperative to involve geotechnical engineers in site assessments and grading operations to detect and remediate karst features promptly [20]. Several approaches exist for mitigating the risks of sinkholes in karst areas. These approaches encompass both preventive measures and reactive strategies. Preventive measures aim to minimize the occurrence of sinkholes by assessing and managing the geological hazards associated with karst terrain [28]. This may involve comprehensive geological surveys, monitoring of groundwater levels, land-use planning regulations, and the implementation of engineering practices that consider the unique characteristics of karst landscapes [34]. Reactive strategies, on the other hand, focus on addressing sinkhole formation after it has occurred. These strategies encompass a range of techniques aimed at stabilizing sinkholes, repairing damaged infrastructure, and restoring affected areas. Reactive measures often involve a combination of geotechnical engineering, structural reinforcement, and ecological restoration to mitigate the impacts of sinkholes on the surrounding environment [1] to [3].

The choice of mitigation techniques and sinkhole repair strategies depends on various factors, including the size and severity of the sinkhole, the geological conditions of the site, and the socio-economic considerations of the affected community [1] to [3], [45] to [49]. Furthermore, the effectiveness of these strategies may vary depending on local environmental factors and the availability of resources. Recent advancements in technology and scientific understanding have led to the development of innovative approaches for karst mitigation and sinkhole repair. These include the use of geophysical surveys, remote sensing techniques, and advanced modeling tools to assess and monitor karst hazards accurately [8]. Additionally, the integration of nature-based solutions, such as bioengineering and ecological restoration, offers sustainable approaches to mitigating the impacts of sinkholes while enhancing ecosystem resilience. Despite these advancements, challenges remain in effectively managing karst hazards and mitigating the risks associated with sinkholes. Limited resources, inadequate infrastructure, and competing land-use priorities often constrain the implementation of comprehensive mitigation measures in karst regions [45]. Furthermore, the dynamic nature of karst landscapes presents ongoing challenges in assessing and managing geological hazards effectively. Karst mitigation techniques could be performed by some methods such as avoidance strategies, inverted rock filter, and cap and permeation grouting.

Preventing sinkhole formation is crucial in minimizing their potential hazards. Comprehensive geological surveys, monitoring of ground conditions, and land use planning are essential components of preventive strategies. Early detection techniques such as ground-penetrating radar (GPR), electrical resistivity imaging (ERI), and LiDAR have proven effective in identifying potential sinkhole locations. Moreover, proper management of groundwater resources through controlled extraction and recharge programs can help stabilize subsurface conditions and reduce the likelihood of sinkhole formation. Avoidance remains one of the most cost-effective strategies for mitigating karst-related risks. This involves situating developments away from areas prone to karst activity, minimizing exposure to potential hazards. Critical structures should be located in areas with minimal karst features, and detention/retention ponds should be positioned outside karst-prone zones. Furthermore, measures such as lining ponds with geomembranes can help prevent water infiltration into subsurface voids, reducing the risk of sinkhole formation triggered by fluctuating water levels.

Sinkhole repair entails restoring affected infrastructure and preventing further subsidence. Excavation and backfilling are commonly employed to fill collapsed sinkholes and rebuild damaged foundations. However, conventional repair methods may be insufficient for large or deep sinkholes, necessitating innovative solutions such as the use of geosynthetic reinforcements or soil stabilization techniques. In karst geologies, surface collapses during construction are a significant concern due to vibrations and water intrusion. The inverted rock filter method offers an economical and practical solution for remediation. This technique involves excavating the collapse area to the sinkhole throat, lining it with geotextile fabric, and filling it with rip-rap stone. The fabric prevents soil erosion while allowing water drainage, and the stone provides structural support. This method is suitable for pavement and slab areas but may require alternative approaches, such as concrete backfill, for collapses beneath foundations. Figure 1a to 1e illustrate sinkhole remediation via inverted rock filter method.

When sinkholes do occur, prompt and effective mitigation measures are necessary to prevent further damage. One common approach is the injection of grout materials into subsurface cavities to fill voids and provide structural support. Various types of grouts, including

a) b) c)

d) e)

Figure 1. a to e) Sinkhole Remediation via Inverted Rock Filter

cement-based, chemical, and foam formulations, have been employed depending on the specific geological conditions and desired outcomes. Ground improvement techniques such as compaction grouting and vibro-compaction have also been utilized to stabilize loose or compressible soils prone to sinkhole development. In some cases, advanced grouting technologies combined with ground improvement methods may offer more durable and cost-effective repair alternatives. Cap and permeation grouting are effective methods for stabilizing subsurface voids and enhancing soil strength. Cap grouting involves injecting low-mobility cement grout into voids to fill them and increase soil density, while permeation grouting uses more viscous grout under low pressure to fill smaller voids. Cap grouting, performed by specialty contractors, creates a grout blanket at the bedrock surface and extends columns of grout to stabilize the soil. Permeation grouting, on the other hand, targets smaller voids to prevent further subsidence. It is advisable to perform cap grouting before permeation grouting to seal off bedrock surfaces from water infiltration. Grouting can also be considered for pavement areas at sinkhole features, with consultation from specialty contractors recommended to determine the extent of the grouting program. Figure 2 shows sinkhole remediation via cap and permeation grouting method.

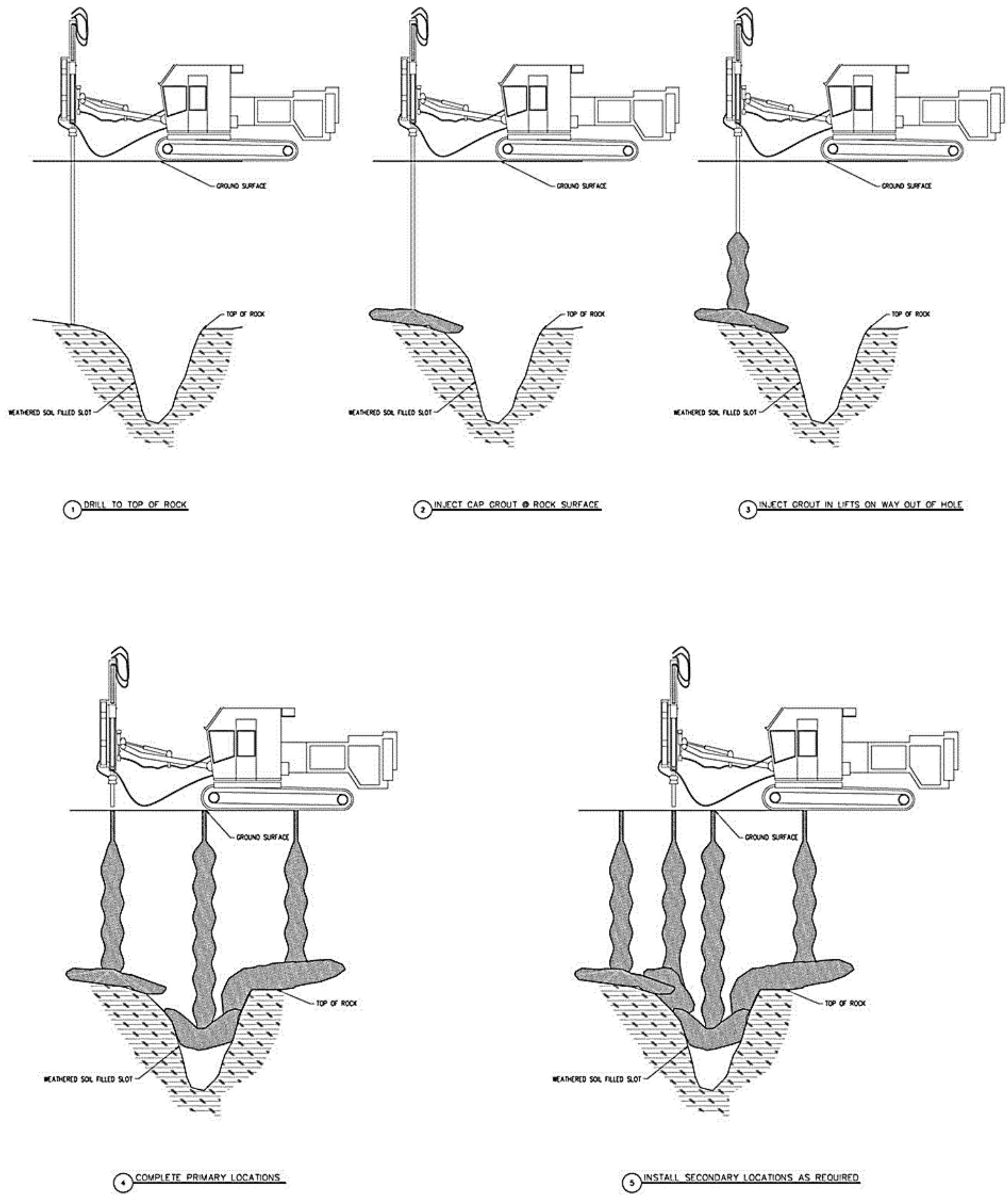

Figure 2. Sinkhole Remediation via Cap and Permeation Grouting

The remediation of sinkholes must also address environmental concerns, particularly regarding groundwater contamination and habitat restoration. Sustainable remediation practices aim to minimize ecosystem disruption and promote long-term environmental resilience. Techniques such as phytoremediation, which utilize plants to uptake contaminants from soil and water, have shown promise in mitigating the environmental impact of sinkhole collapse.

Sinkhole repairs present complex challenges requiring interdisciplinary approaches, innovative techniques, and proactive risk management strategies. Case studies from around the world highlight the diverse methods employed to stabilize sinkholes and mitigate associated risks. These include grouting techniques, soil stabilization, structural reinforcement, and ground improvement measures. Lessons learned from these case studies underscore the importance of early detection, rapid response, community engagement, and long-term monitoring in effective sinkhole remediation. Smith et al. (2015) reviewed a massive sinkhole formed in Winter Park, Florida, threatening nearby homes and infrastructure in 2013. This case study utilized a combination of compaction grouting and permeation grouting to fill voids and stabilize the surrounding soil. Monitoring systems were installed to track ground movement and ensure the effectiveness of the repairs. The project highlighted the importance of early detection, rapid response, and collaboration between stakeholders to mitigate sinkhole risks effectively. Garcia et al. reviewed the sinkhole incident in Guatemala City in 2010, which drew international attention due to its sheer size and impact on urban infrastructure. This case study employed a combination of geophysical surveys, soil stabilization techniques, and structural reinforcement to stabilize the sinkhole and prevent further collapse. The project showcased the complexities of urban sinkhole remediation, including logistical constraints, public safety concerns, and socio-economic implications. Lessons learned from this case emphasized the need for interdisciplinary collaboration, community engagement, and long-term monitoring to ensure the effectiveness of sinkhole repairs. Barton et al. reviewed a sinkhole formed beneath the National Corvette Museum in Bowling Green, Kentucky, in 2014, swallowing several rare cars on display. This case study employed a combination of geotechnical investigations, ground improvement techniques, and structural reinforcement to stabilize the sinkhole and restore the museum building. The project required careful coordination between preservation experts, engineers, and museum stakeholders to balance structural integrity with historical preservation goals. The Corvette Museum sinkhole restoration highlighted the importance of adaptive strategies, risk communication, and public outreach in managing sinkhole incidents in sensitive environments.

Wang et al. reviewed a sinkhole formed near a metro construction site in Xi'an, China, in 2018, prompting emergency response efforts to stabilize the area. This case study examined the application of innovative repair techniques, including jet grouting and ground improvement, to mitigate sinkhole risks in urban settings. They employed advanced monitoring systems and numerical modeling to assess ground stability and optimize grouting operations. The project demonstrated the effectiveness of proactive risk management and rapid intervention in preventing sinkhole-related disasters in urbanizing areas. Lessons learned from the Xi'an sinkhole remediation underscored the importance of early warning systems, geotechnical analysis, and contingency planning in mitigating sinkhole hazards. Another case study, performed by O'Connor et al., reviewed one of the most visually striking sinkhole incidents to occur in Guatemala City in 2010, when a massive crater measuring approximately 60 feet in diameter and 300 feet deep suddenly appeared, swallowing buildings and roads. The sinkhole was attributed to a combination of factors, including heavy rainfall, volcanic activity, and inadequate infrastructure maintenance. They faced significant challenges in repairing the sinkhole due to its size and the surrounding unstable soil conditions. Traditional repair methods such as grouting and soil stabilization were deemed impractical due to the scale of the sinkhole. Instead, they opted for a combination of backfilling with compacted soil and reinforced concrete structures to stabilize the sinkhole's edges and restore the affected area. The Guatemala City sinkhole serves as a sobering reminder of the catastrophic consequences of neglecting infrastructure maintenance and geological risk assessment.

In 2015, a sinkhole emerged on Oakwood Drive in Toledo, Ohio, prompting emergency repairs to prevent further subsidence. Investigation revealed that the sinkhole was caused by a leaking stormwater pipe, which eroded the surrounding soil and created a void beneath the road surface. Repair efforts involved excavating the damaged pipe, backfilling the void with compacted soil, and reinforcing the roadbed with concrete. Geotechnical monitoring was implemented to detect any signs of instability and ensure the effectiveness of the repair measures. In Beit She'an, Israel, a massive sinkhole formed due to extensive groundwater extraction for agricultural purposes. A unique solution was employed, involving the injection of expansive polyurethane foam to fill the void and stabilize the surrounding soil. This innovative approach provided rapid and cost-effective repairs, minimizing disruption to the local community and infrastructure. Long-term monitoring indicated the stability of the repaired sinkhole, demonstrating the effectiveness of this unconventional technique. In Ripon, North Yorkshire, UK, a large sinkhole formed in 2016, posing a threat to residential areas and infrastructure. Engineers implemented a multifaceted approach, combining traditional grouting methods with innovative geophysical techniques such as ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) to accurately assess subsurface conditions. This comprehensive approach enabled targeted grouting to fill voids and stabilize the sinkhole effectively. Continuous monitoring following the repair ensured the long-term stability of the site, demonstrating the efficacy of integrating advanced technologies with conventional repair methods.

This paper provides an overview of karst mitigation techniques and sinkhole repair strategies, highlighting recent advancements, challenges, and future directions in the field. By synthesizing existing knowledge and emerging trends, this paper aims to contribute to the development of effective strategies for mitigating the risks associated with sinkholes in karst landscapes. Future research should continue to explore novel repair strategies, enhance predictive modeling capabilities, and promote collaboration between stakeholders to address the ongoing threat of sinkhole hazards.

2. Practical case study

2.1. Project Description

The sinkhole is situated on Whispering Hills Drive just north of Bonerwood Drive in Nashville, Tennessee. Whispering Hills Drive is a two-lane asphalt roadway, approximately 30 feet wide, sloping gently downward to the north-northeast. Subsidence, spanning the width of the travel lanes, is visibly apparent along a segment of approximately 50 feet in length. Additionally, an isolated dropout of approximately 6 feet in diameter is observed in the east (northbound) lane of the roadway. Within the affected area, there reportedly exists a 36-inch diameter water main and a 12-inch diameter water line. A storm drain traverses through the pavement subsidence area, located along the eastern end of the pavement. A stone-lined ditch is situated on the western side of the roadway.

This problematic area has been a persistent issue for several years. Personnel from Metro Public Works recall visiting the site in the late 1990s, observing isolated dropouts and subsidence related to soil piping. It appears that conventional sinkhole repair methods involving excavation of overburden and placement of rock fill have been implemented on multiple occasions since then. The most recent repair of the pavement settlement area, reportedly conducted about four months ago, involved the removal of asphalt pavement and undercutting of the soft subgrade soils to an unspecified depth. The undercut area was subsequently backfilled with crushed rock fill, topped with a thick layer of asphalt pavement. However, noticeable and measurable subsidence, along with a significant dropout, occurred shortly after the repair efforts, prompting the initiation of the current exploration and study to investigate and mitigate the issue. The affected section of the road has been closed to traffic since the latter part of May 2009. The site location map and the approximate location of dropout within the roadway are depicted in figures 3a and 3b respectively. Figures 4a to 4k also illustrate the existing site situations and dropouts and subsidence along the driveway on the site.

a) b)

Figure 3. a) Site location, and b) the approximate location of dropout within the roadway

a) b)

c) d)

e) f)

Figure 4. Continued on the next page

g)

h)

i)

j)

k)

Figure 4. a to k) the existing site situations and dropouts within the roadway

2.2. Field Exploration and Laboratory Testing

The subsurface exploration comprised two distinct phases. The initial phase, conducted from April 24 to 28, 2009, involved the drilling of seven borings in the vicinity of the sinkhole area. These borings delved to depths ranging between approximately 17 and 48½ feet below existing grade. Subsequently, the second phase occurred from June 8 to 9, 2009, during which an additional five borings were drilled to augment the subsurface data. The locations of these borings were determined by Terracon personnel and were positioned relative to the features delineated in Figure 3. Both truck-mounted rotary drill rigs and ATV rigs equipped with hollow stem augers were utilized to advance the boreholes. Soil sampling was conducted using the split barrel sampling procedure, whereby the standard penetration resistance value (N) was determined based on the number of blows required to advance a standard 2-inch O.D. split barrel sampler the final 12 inches of an 18-inch penetration, using a 140-pound hammer with a free fall of 30 inches. This value facilitated estimates of in situ relative density for cohesionless soils and the consistency of cohesive soils. The depths of sampling, penetration distances, and standard penetration resistance values were meticulously documented on the boring logs, with the samples subsequently sealed and transported to the laboratory for comprehensive testing and classification. Field logs detailing the visual classifications of encountered materials and the driller's interpretation of subsurface conditions between samples were meticulously prepared. Final boring logs represented an amalgamation of field observations and laboratory analyses, with modifications made based on the latter. Figure 5 illustrates locations of the performed borings within the roadway and Figure 6 shows cross section of pavement and location of some borings within the existing dropout.

All boreholes were extended until auger refusal was encountered, typically occurring at depths ranging from approximately 7½ to 48½ feet below existing grade. For seven of the twelve borings, refusal materials were penetrated using a diamond bit affixed to the outer barrel of a double core barrel. The inner barrel collected cored material while the outer barrel, rotating at high speeds, facilitated rock cutting. Upon completion of each drilling operation, the barrel was retrieved, and the core samples were boxed and logged. Subsequent rock classification by an engineer involved determining the "percent recovery" and the rock quality designation (RQD), with the former representing the ratio of retrieved sample length to drilled length, and the latter providing an indication of in-situ rock quality based on the length of intact core segments.

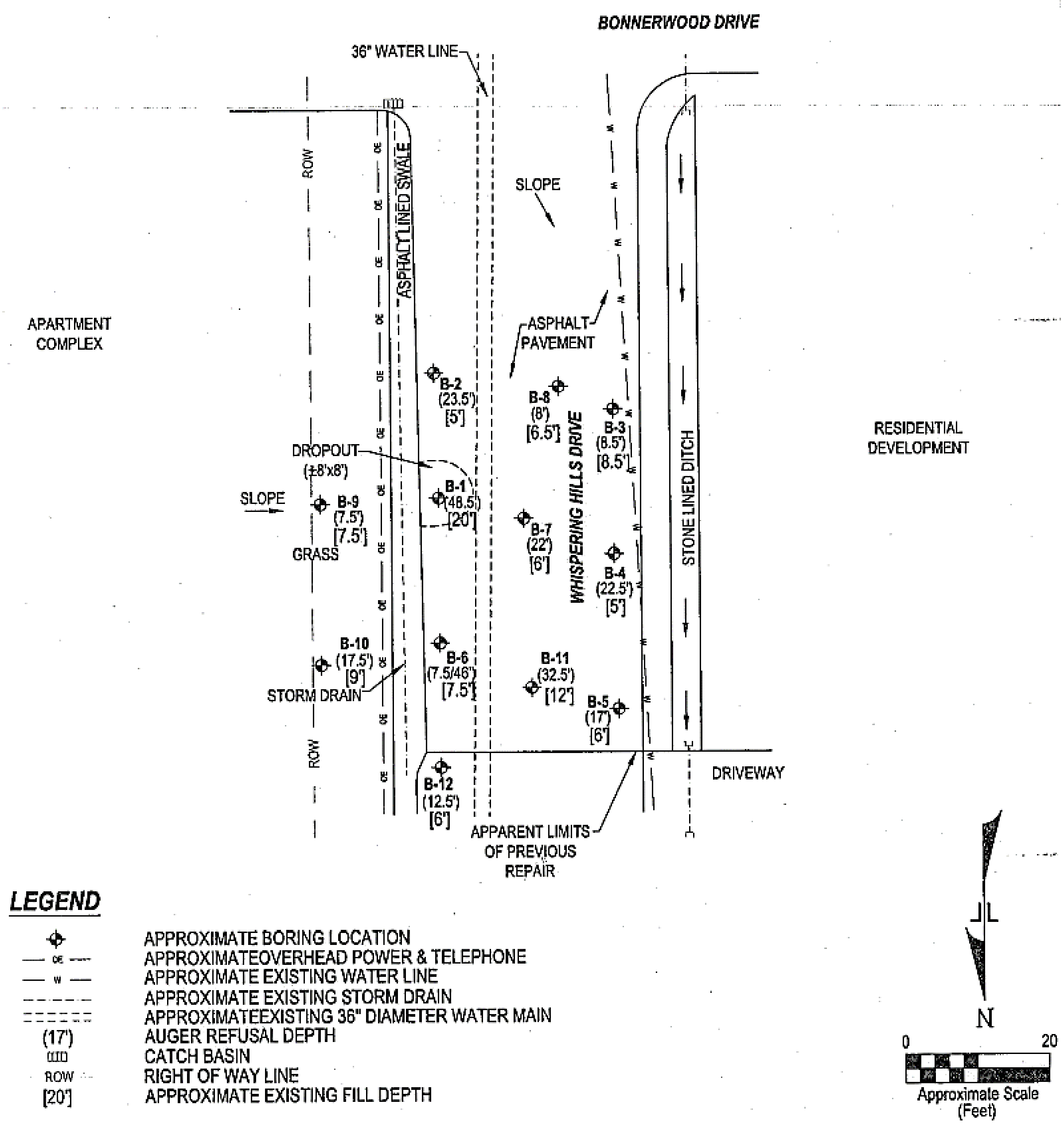

Figure 5. Locations of the borings within the roadway

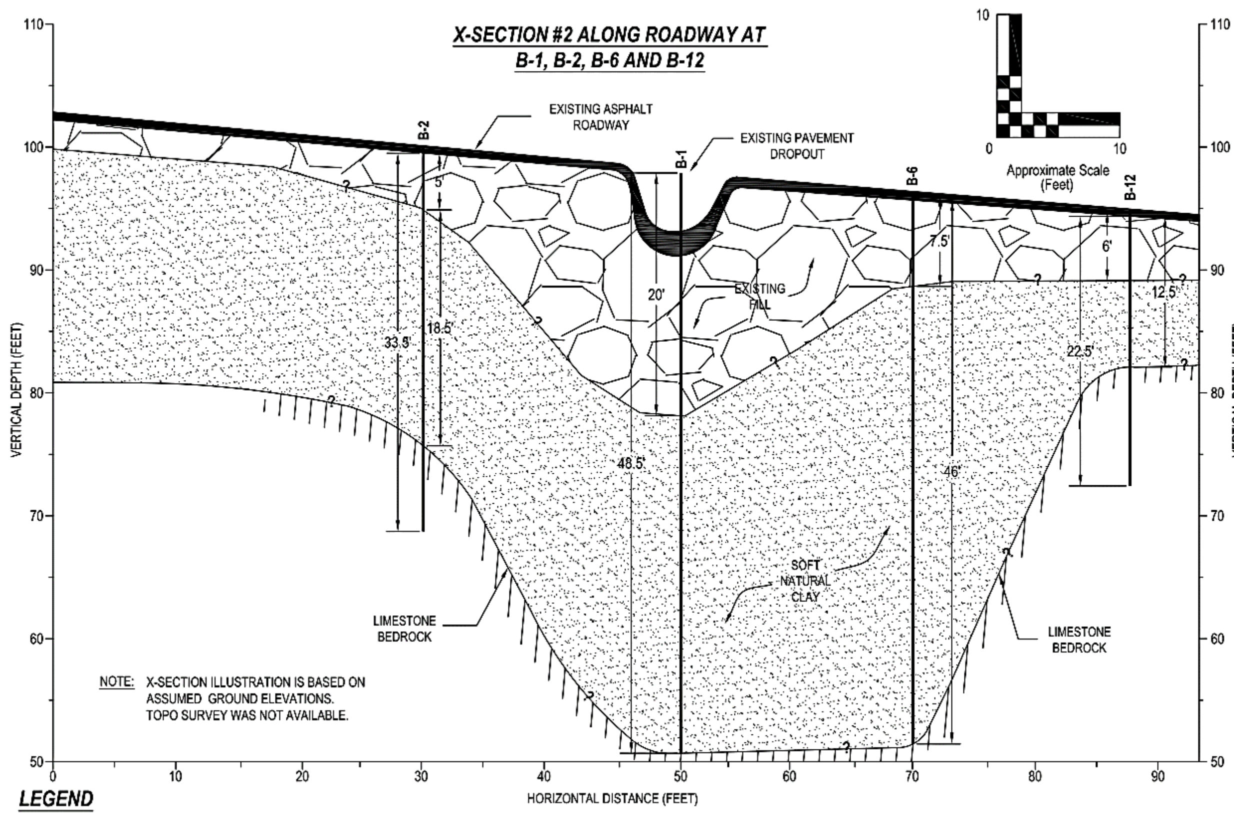

Figure 6. Cross section of pavement and location of some borings within the existing dropout

Laboratory testing encompassed water content tests and Atterberg Limits tests on representative soil samples. These tests, coupled with field penetration data, facilitated assessments of soil strength in-situ, volume change potential, and soil classification, with results documented on the boring logs. Classification and descriptions of rock core samples adhered to established guidelines and were primarily based on visual and tactile assessments, although petrographic analysis of thin sections could potentially reveal additional rock types. Percent recovery and RQD calculations for these samples were documented at their respective depths on the boring logs.

3. Subsurface Conditions

3.1. Geology

A comprehensive review of available geological data reveals that the site is underlain by the Hermitage Formation from the Ordovician Period. This formation comprises four distinct facies (sections), including the granular phosphatic limestone facies at the uppermost level, followed by the Coquina and laminated argillaceous limestone facies in the middle, and the Curdsville Limestone at the base. The granular phosphatic limestone facies is identified by its medium light gray to brownish-gray coloration, medium bedding, and crossbedding, along with brown phosphatic pallets. The Coquina facies exhibits a medium gray to brownish-gray hue, medium bedding, and contains disseminated silt and shale partings. The laminated argillaceous facies consists of medium to dark gray, very fine-grained limestone with numerous thin shale partings. The Curdsville Limestone, on the other hand, is characterized by a medium to dark gray coloration, fine to medium grain size, thin bedding, and thin shale partings. These facies undergo weathering processes resulting in a transition to pale to dark yellowish-brown silty, sandy clay material, akin to the conditions observed beneath the fill in our boreholes.

The subject property is located within a region characterized by karst-prone geology. Any development in such topography carries inherent risks of future internal soil erosion and ground subsidence, potentially impacting the stability of pavements and buried utilities. Presently, the state of the art in geotechnical engineering does not facilitate accurate prediction of the location and probability of karst-related subsidence. The subsidence of the existing pavement, along with associated dropout within the

Table 1. depths of fill and auger refusal encountered at each boring locations

Boring	Approximate fill depth (ft)	Approx. depth to refusal (ft)	Boring	Approximate fill depth (ft)	Approx. depth to refusal (ft)
B-1	20	48 ½	B-7	6	22
B-2	5	23 ½ *	B-8	6 ½	8 *
B-3	8 ½	8 ½ *	B-9	7 ½	7 ½ *
B-4	5	22 ½ *	B-10	9	17 ½
B-5	6	17	B-11	12	32 ½
B-6 **	7 ½	46 *	B-12	6	12 ½ *

* Boring where rock coring was performed

** Initial auger refusal occurred at a depth of about 7½ feet on weathered limestone rock

roadway, is seemingly linked to karst-related soil piping, and is typified as a sinkhole occurrence.

3.2. Soil and Rock Conditions

The subsurface conditions inferred from the borehole investigations can be summarized as follows: Borings B-1 through B-8, B-11, and B-12 were conducted within the asphalt pavement area, revealing a layer of asphalt ranging from 0.3 to 2 feet in thickness. Borings B-9 and B-10, located off the pavement at the right-of-way limits east of the roadway, encountered approximately 0.4 to 0.6 feet of topsoil. Beneath the surface cover, the boreholes generally penetrated 5 to 20 feet of fill material overlying natural lean to fat clay and/or limestone bedrock. Boring B-1, situated within the pavement dropout area, revealed a deeper fill of about 20 feet, primarily comprised of crushed rock with or without clay. The fill material appeared to be uniformly graded with minimal fines, with variations noted such as the presence of soil and rock at B-3 and large limestone fragments, possibly shot rock, at B-9 and B-10. The depths of fill and auger refusal encountered at each boring location are summarized in Table 1.

Natural clay was encountered beneath the fill layer, extending to auger refusal on limestone bedrock at depths ranging from 8 to 48½ feet below the existing grade. A void of approximately 1 foot was observed between the bottom of the asphalt and the surface of the crushed rock at Boring B-4. The fill material exhibited a variable relative density, ranging from very loose to medium dense, with standard penetration resistance (N) values typically ranging from 0 to 23 blows per foot (bpf). It is noted that higher N-values may be inflated due to the presence of large limestone fragments and do not accurately represent the true relative density of the fill. The natural clay beneath the existing fill generally displayed a very soft to medium stiff consistency, with most N-values ranging from 0 to 6 bpf, except for borings B-4 and B-12 where stiff clays were encountered down to the bedrock. This softening of soil is indicative of karst activity and suggests soil piping at these locations.

All boreholes were extended to auger refusal on apparent limestone bedrock, with depths ranging from about 7½ to 48½ feet below the existing grade. Deeper refusal depths, ranging from 46 to 48½ feet below grade, were observed at B-1 and B-6. Rock core sampling was performed at selected boring locations (B-2 through B-4, B-6, B-8, B-9, and B-12) to further investigate the materials encountered at auger refusal. The sampled bedrock materials primarily consisted of light to medium gray, thin to very thin bedded limestone with weathered shaly seams. Core recovery ranged from 30 to 100 percent, with poorer recovery noted at B-9 and B-12. The quality of the cores obtained was generally assessed as very poor to fair based on the Rock Quality Designation (RQD) values, typically ranging from 0 to 75 percent. At Boring B-6, initial auger refusal was encountered at approximately 7½ feet below grade on weathered limestone, which extended to a depth of about 14 feet below grade. Below this depth, the core barrel encountered minimal resistance down to approximately 46 feet below grade, with no recovery of subsurface material due to an apparent clay-filled slot resulting from solution weathering, a common feature in the Hermitage Limestone formation present at the site. At Boring B-9, the sampled bedrock material comprised moderately to highly weathered limestone with voids and crevices filled with concrete grout. Additionally, a 3-inch thick asphalt piece was encountered during coring at approximately 12 feet below grade, indicating the possibility of prior compaction grouting to fill voids within the rock mass.

3.3. Groundwater Conditions

The borings were meticulously monitored during and immediately after drilling to assess the presence and depth of groundwater. Upon completion of the boring process, groundwater was observed in borings B-1, B-3, B-4, and B-8, with depths ranging from approximately 5 to 28 feet below the existing grade. These observations offer a preliminary insight into the groundwater conditions prevailing on the site at the time of drilling. However, owing to the low permeability of the cohesive soils encountered in the borings, more extensive monitoring over the long term, possibly through cased holes or piezometers, would be necessary for a comprehensive and precise evaluation of groundwater conditions. It is essential to recognize that fluctuations in groundwater levels may arise due to seasonal variations in rainfall, runoff, and other factors that may not have been evident during the initial boring operations.

4. Evaluations and Recommendations

Based on subsurface data and our professional experience, the pavement distress and dropout are attributed to active soil piping and ground subsidence, likely associated with an apparent sinkhole. Previous repair efforts have been largely superficial and insufficient to halt the ongoing soil piping at significant depths.

Initially, a conventional inverted rock filter sinkhole repair method was contemplated for this project. However, optimal execution of such a repair would necessitate the rock fill to extend down to the bedrock. The excavation required to reach the bedrock is anticipated to be considerable, possibly extending beyond the road right-of-way into adjacent private properties. Consequently, temporary shoring of excavation sidewalls may be necessary due to space constraints. Furthermore, this approach would mandate the relocation of all buried utilities within the excavation area. Considering the substantial depth of excavation, reaching up to 48½ feet below grade, along with the potential need for temporary shoring, this sinkhole repair option is deemed impractical and cost-ineffective.

Alternatively, the project team explored a structural solution involving the construction of a land bridge spanning the affected area. Extensive research and review were conducted regarding the costs and logistical challenges associated with this approach. However, it was concluded that the construction of a land bridge would be prohibitively expensive and time-consuming, with the design and construction phases spanning several months. The adverse impacts on both cost and schedule were deemed unacceptable, leading to the abandonment of this approach.

Based on our extensive experience, research, and consultations with specialty contractors, a compaction grouting program, sometimes referred to as cap grouting, emerges as a viable and practical solution for enhancing subgrade conditions and mitigating ground subsidence. Compaction grouting entails the precise injection of low-slump grout in a grid pattern to displace soft soils, fill voids above the bedrock surface, and establish a grouted matrix aimed at solidifying and stabilizing the affected area. The primary objective of the initial grouting phase is to create a grout blanket or cap across the bedrock surface, sealing voids without filling those within the bedrock itself. This targeted grouting strategy involves placing grout bulbs at the bedrock surface to prevent further loss of overburden into bedrock voids and crevices, while also reducing voids within the overburden above. As the lower reaches of the target area are grouted, casings are gradually withdrawn, and grout is injected at predetermined intervals. This incremental approach effectively reduces voids within the overburden, contributing to the solidification of the zone. Subsequent rounds of grouting, if necessary, will be determined based on the outcomes of the primary injection cycle. The grouting operations are expected to extend up to near the invert of the existing 36-inch diameter water line, reaching a depth of approximately 8 feet below the road surface. Typically, such specialized work is undertaken by a dedicated grouting contractor.

Following the completion of grouting operations, the near-surface subgrades in the affected area will undergo undercutting and replacement with engineered fill, followed by repaving. The engineered fill will primarily comprise granular materials such as well-graded crushed mineral aggregate, conforming to TDOT Section 903.05 (Type A, Grading D), and/or approved clean shot rock. The granular fill will be placed in maximum 10-inch thick loose lifts, with each layer compacted to at least 95% of the material’s standard Proctor maximum dry density. The upper 12 inches of fill subgrade will be compacted to at least 100% of the same standard. Graded solid rock fill shall comprise well-graded, durable shot rock with a maximum fragment size of 18 inches, with 20 to 30 percent passing the No. 4 sieve and no more than 5 percent passing the No. 200 sieve. The fragments should exhibit roughly equidimensional shapes, with thin, slabby, or shaly material deemed unacceptable. The material's performance under five iterations of the sodium sulfate soundness test (AASHTO T-104) should yield a weighted percentage of loss not exceeding 12%. It is not recommended to mix shot rock with natural clayey soils. Placement and compaction of uniform fill materials will aid in densification and testing during construction. Graded solid rock material must be approved by the engineer before use on the project. Shot rock fill should be compacted in lifts not exceeding 2 feet using a D-8 class Dozer (10-ton class vibratory roller) or equivalent equipment. Undercut material is expected to comprise open-graded crushed rock with minimal or no fines, large limestone fragments, and soil-rock mixture.

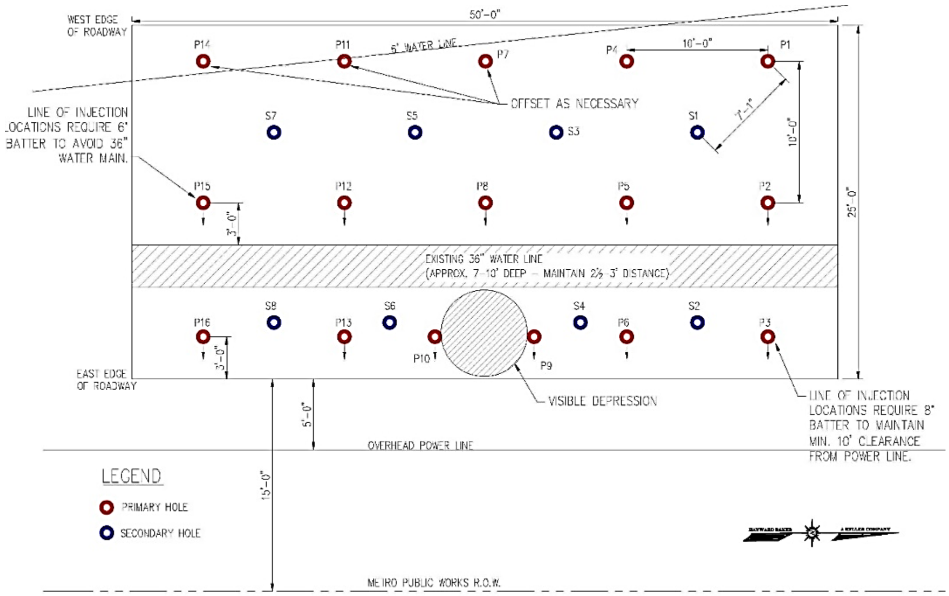

Figure 7. Primary hole and secondary hole locations of the studied site

Reuse of this material is not recommended; it should be hauled off-site.

We recommended that the new engineered fill be properly benching with the existing subgrade to establish a positive bond between the new fill and the existing soils. Finish pavement grades should be properly sloped to ensure positive drainage, thereby reducing water ponding on the pavement and infiltration into the underlying subgrade. Based on our discussions, we understand that the Owner agrees with the compaction grouting repair option and has authorized the project team to prepare bid documents accordingly. In compliance with their request, we have previously prepared and forwarded a permit for the work as required by the regulatory division of the state of Tennessee.

The compaction grouting program has been determined to be a viable treatment plan for the problem area, based on our discussions. Our experience indicates that compaction or cap grouting has effectively addressed sinkhole/karst-related ground subsidence in the past. The objective of the current work is to provide a permanent repair to the current problems in the affected road segment. This was discussed with the Owner and nearby residents in a project-related public meeting, and communicated to the regulatory agency. The intent of the grouting is to inject sufficient low slump material into the subsurface to create a solidified but porous mass, forming a plug over the bedrock voids to support the road subgrade for many years. It's important to note that the work is not intended to fill every bedrock void within the upper weathered bedrock profile at the problem area. Instead, an associated goal is to permit the continued passage of groundwater through the zone. The aim of this objective is to reduce potential negative impacts of groundwater movement in peripheral areas where such movement had not previously occurred. However, it's crucial for the Owner and nearby residents to understand that this targeted remedy is not a widespread treatment expected to address or reduce the risk of sinkholes on adjacent public right of way or nearby properties. Figure 7 shows proposed primary hole and secondary hole locations of the studied site. Sinkhole formation risk is inherent in this geologic setting, as adamantly stated in the public meeting, and local risk cannot be entirely eliminated. Future sinkhole occurrences in this neighborhood cannot be predicted but should not be totally unexpected. Any future sinkhole incidents should be addressed on a case-by-case basis, and any such occurrence would be considered coincidental to the currently proposed repair work.

5. Conclusions

In conclusion, the comprehensive investigation detailed in this paper sheds light on the complexities surrounding sinkhole occurrences and their remediation, as exemplified by the persistent sinkhole along Whispering Hills Drive in Nashville, Tennessee. The interdisciplinary approach employed, combining geotechnical expertise, geological analysis, and engineering solutions, underscores the multifaceted nature of sinkhole mitigation. Through meticulous field exploration and laboratory testing, the geological and subsurface conditions were thoroughly characterized, revealing the presence of karst-prone geology and variable soil and rock compositions. Evaluation of potential repair strategies highlighted the limitations of conventional methods and led to the selection of a compaction grouting program as the most viable solution. This approach, involving precise injection of low-slump grout to stabilize the affected area, offers a practical and cost-effective means of addressing soil piping and ground subsidence. The proposed repair strategy, detailed with specifications for material selection and construction methodologies, aims to provide a long-lasting solution to the persistent sinkhole issue. The recommendations put forth emphasize the importance of proactive risk management and continued monitoring to address potential future sinkhole occurrences. While the selected repair strategy targets the specific problem area, it is essential to recognize the inherent risks associated with sinkhole formation in karstic landscapes. Stakeholders must remain vigilant and prepared to address any future incidents on a case-by-case basis. Continued research and collaboration among stakeholders are essential to further enhance the effectiveness and sustainability of sinkhole remediation efforts. The findings presented in this paper underscore the significance of proactive risk management and adaptive strategies in addressing sinkhole hazards. While the selected compaction grouting program offers a promising solution for the current problem area, it is essential to acknowledge the inherent risks associated with sinkhole formation in karstic landscapes. Continued research, monitoring, and community engagement are imperative in enhancing our understanding of sinkhole dynamics and developing resilient infrastructure systems capable of withstanding such geological challenges. Ultimately, the lessons learned from this study contribute to the advancement of design standards and construction practices for sinkhole repairs, fostering safer and more sustainable development in karstic areas and beyond.

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7. Conflict of interest

The authors declare that they have no conflict of interest.

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