

FINAL REPORT FOR THE GEOTECHNICAL INVESTIGATION OF THE BUSHKILL CREEK SITE

**PALMER TOWNSHIP
NORTHAMPTON COUNTY, PENNSYLVANIA**

Prepared for



**US Army Corps
of Engineers®**

PHILADELPHIA DISTRICT

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TASK ORDER No. 022

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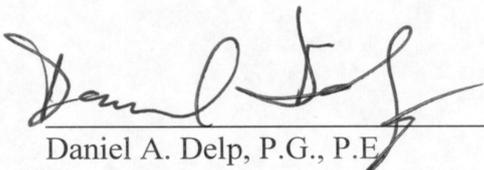
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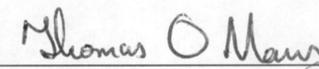
Science Applications International Corporation
916 Springdale Drive
Exton, PA 19341
(610) 594-3630

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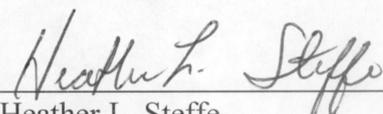
Respectfully submitted,



Daniel A. Delp, P.G., P.E.
Program Manager



Thomas O. Marrs, P.G.
Project Manager



Heather L. Steffe
Project Geophysicist

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LIST OF ACRONYMS

2-D	Two-dimensional
AGI	Advanced Geosciences, Inc.
AMSL	Above Mean Sea Level
bgs	below ground surface
EI	Electrical Imaging
FTP	Field Technical Procedure
SAIC	Science Applications International Corporation
SR	State Route
USACE	United States Army Corps of Engineers
HSA	Hollow-stem Auger

1.0 INTRODUCTION

1.0 INTRODUCTION

This report presents the work performed by Science Applications International Corporation (SAIC) for the United States Army Corps of Engineers (USACE), Philadelphia District, under Contract No. DACW61-00-D-0007, Task Order No. 22. Task Order 22 was comprised of a geotechnical drilling investigation conducted along Bushkill Creek, approximately ½-mile south of Stockertown, Palmer Township, Northampton County, Pennsylvania (Figure 1). The objective of this work was to obtain subsurface characterization data as a check against the geophysical data previously collected at the site by SAIC and presented in the Report for Geophysical Survey of the Bushkill Creek Area, Palmer Township, Northampton County, Pennsylvania, in February 2002.. The geotechnical work (rock coring and air-rotary drilling) conducted for this Task Order delineated the nature of geophysical anomalies identified in work completed under Task Order 15. This study also interprets how these anomalies relate to the presence of karst features in the subsurface. A second data collection objective was to confirm the site conceptual model developed by the geophysical study that presented a picture of the subsurface as an unstable karst environment containing the necessary components for sinkhole development.

The intrusive program described herein includes the completion of two continuously sampled rock core borings and forty pneumatic air-rotary borings. The project work was performed in accordance with the Site Accident Prevention Plan and the site project work plan entitled “Bushkill Creek Site, Palmer Township, Northampton County, Pennsylvania, Geotechnical Investigation”, both prepared by SAIC and attached as Appendix A. Detailed in this report are the task activities, the results of the geotechnical borings, and the comparison of the boring and geophysical study results.

1.1 SITE DESCRIPTION

The subsurface being investigated through this study is described in the literature as unconsolidated material containing sandy and clayey silts with significant amounts of cobbles

and gravel (Pennsylvania Department of Highways, 1969). The thickness of unconsolidated material has been described as occurring between 20 to 25 feet thick (6.1 to 7.6 meters), or greater. The bedrock within the survey is mapped as the Epler Formation (Aaron, 1971, USGS, 1987), a limestone/dolomite sequence susceptible to karst development, with bedrock pinnacles posing special problems (Geyer and Wilshusen, 1982). Also mapped in the study area is the Jacksonburg Formation, described as a well bedded silty limestone, not exhibiting pinnacles or karst features according to Geyer and Wilshusen, 1982.

The investigated area described in this report extends from State Route (SR) 33 bridge (northbound lanes) eastward beyond the SR 2017 Bridge. The area also includes a segment of Bushkill Creek, and the areas along the southern and northern creek banks and floodplain (Figure 1).

Conceptually, the subsurface study area adjacent to and inclusive of Bushkill Creek is an active karst environment. Sinkholes are anticipated to develop at the site in areas where less competent rock is weathered, eroded, and fractured, providing a pathway for the migration of overburden materials and water into the fractured rock. The migration of overburden material deeper into the subsurface, otherwise known as “piping”, can cause soil slumping and collapse of soil at the ground surface. Piping of overburden materials and water infiltrating into the bedrock slowly dissolve the limestone/dolomite bedrock, thereby increasing the opportunity for piping activity to occur. Surface and subsurface water migration through the streambed and banks contributes to piping and dissolution by creating an erosive force that mobilizes the loose, saturated overburden, making it easily transported. Numerous sinkhole features and previously filled collapse features, (sinkholes), were evident during performance of the fieldwork. It was also evident that prior sinkhole repairs at the site have not succeeded in permanently stabilizing these active karst areas.

During the mid 1970s, Bushkill Creek was rerouted due to construction of SR 33. The historical stream channel was located south of the SR33 Bridge and occupied the low-lying flat area along the southern stream bank to the west of the site. Karst features, such as bedrock pinnacles,

sinkholes, and weathered bedrock were described during road and bridge construction activities (Pennsylvania Department of Highways, 1969). Bedrock topographic lows of approximately 60 feet (18.3 meters) below ground surface (bgs) were described within the vicinity of SR 33 northbound lanes by the Pennsylvania Department of Highways (1969).

Accelerated karst feature development has been on going along the Bushkill Creek channel in recent times. Adjacent properties affected by karst development since 1999 include a residence to the south of Bushkill Creek, the farm fields north of Bushkill Creek, and the SR 2017 Bridge (Figure 2). Within the backyard of the residence, a large sinkhole developed with an approximate surface expression of 75 to 100 feet in diameter (22.9 to 30.5 meters). This sinkhole was later backfilled with crushed rock and soil. Sinkholes also developed near the northern abutment of the SR 2017 Bridge and contributed to the collapse of the northern bridge abutment. Additional sinkholes continue to develop along the creek and areas adjacent to the creek. Presently, sinkholes exist within the middle of a farm field to the north of the creek, within SR 2017 north of the creek, northeast of the collapsed bridge, and also adjacent to the overhead power lines parallel to SR 2017.

1.2 PURPOSE AND SCOPE OF WORK

The geotechnical investigation was completed following a geophysical study that used Electrical Imaging (EI) resistivity to identify potential subsurface karst features. The collected data indicated that a more detailed intrusive effort was necessary to verify the geophysical study results. The geotechnical data presented herein were then compared to the previous geophysical study results to provide a more refined representation of the subsurface features for areas along Bushkill Creek. The intrusive investigation described in this report included two core borings and forty air-rotary borings (pneumatic rock borings) located along both sides of the creek. Along the streambanks of Bushkill Creek, the geophysical and geotechnical results were compared and correlated. Where boring information was limited on an EI traverse, it was extrapolated from a nearby location. This report describes the results, correlation, and

limitations of the data comparison. In addition, the work scope included the preparation of an Accident Prevention Plan, Project Work Plan, and a Final Report.

2.0 FIELD ACTIVITIES

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A geotechnical investigation consisting of approximately 2,100 linear feet (633 meters) of drilling along Bushkill Creek was completed by SAIC from May 6-22, 2002. Forty borings were advanced using a pneumatic rock boring drilling unit and two borings were continuously sampled using both hollow stem auger (HSA) and rock coring methods. During drilling, the SAIC geologist overseeing drill activities paid special attention to the stability of ground conditions in the vicinity of the drilling rig due to potential subsidence and ground surface instability.

2.1 PREPARATORY ACTIVITIES

On April 30, 2002, prior to the mobilization of drilling equipment, SAIC and USACE located and staked the proposed boring locations previously plotted on a project planning map by USACE. During the staking of boring locations, SAIC and USACE relocated certain borings to provide safe access to the boring location by the drill rig.

Initially, SAIC used a Global Positioning System (GPS) to locate borings BKK-1, BKK-18, and BKK-36. From these locations, additional borings were positioned every 25 feet (approximately) to the east of these borings and parallel to Bushkill Creek. Some locations were shifted slightly to avoid large trees and obvious sinkhole activity. A wooden stake with a white painted circle and the boring number denoted a boring location approved by USACE. The USACE Philadelphia District secured agreements from the local residents to access their property where necessary to conduct the subsurface investigation. In addition, SAIC notified each resident of the drilling schedule prior to accessing his or her property. No state or local permits were required for this work. Pennsylvania One Call was notified prior to drilling, as required by law.

2.2 DRILLING ACTIVITIES

SAIC contracted Eichelbergers Well Drilling, Inc., of Mechanicsburg, Pennsylvania, to perform the drilling of the rock borings, rock cores, and subsequent boring abandonment activities. An SAIC geologist supervised the drilling and recorded the type of rock penetrated, the presence of voids or seams in the rock, drill bit drops, loss of circulation of the drilling air or water, the drill bit penetration rate, and the amount of grout required to abandon each borehole. This information was used to create a complete geologic description of each boring as shown in Appendix B.

Approximately seventy-five linear feet of continuous sampling using HSA and rock coring methods were performed on May 6 and 7, 2002, at boring locations BKB-1 and BKB-2 (Figure 2). The rock cores were collected, described, and archived according to procedures outlined in the Drilling Work Plan dated April 24, 2002 prepared by SAIC. Per Work Plan protocol, drilling at BKB-1 and BKB-2 was advanced to the top of rock using a 4.25-inch inside diameter (ID) HSA. Two-inch diameter split-spoons were used to retrieve the unconsolidated overburden material. The SAIC geologist recorded the number of blows by a standard 140-pound hammer used to drive the two-inch spoons through each six-inch interval of overburden penetrated. This information, along with the complete drilling record, was documented on USACE Form 1836 (Appendix C). Samples of materials retrieved from the borehole were placed in airtight jars retained by the USACE. Once rock was encountered using the HSA rig, a 2-inch, NX diamond tipped core barrel was used to core 15 feet into rock. The rock cores were archived by the USACE.

The Unified Soil Classification (USC) scheme was used to describe the overburden as predominately silt with gravel at the Bushkill Creek site. Bedrock was encountered at 20 feet bgs at BKB-1 and 25.5 feet bgs at BKB-2. Fifteen feet of light bluish-gray calcitic dolomite was described in rock cores collected from each location.

After reaching the target depth of rock coring, the drilling tools were withdrawn. Borehole abandonment using grout and hole plug then proceeded according to the Drilling Work Plan. A high-solids benseal bentonite grout was mixed with a mechanical mixer and pumped through a tremie pipe into each boring from the bottom of the borehole to the surface. Sufficient pressure was used to circulate the grout to the surface. Grout was pumped into each borehole until the grout volume reached 1.3 times the calculated boring volume. Existing fluids in the borehole displaced by the grout discharged to the ground surface, away from Bushkill Creek. Subsequent settlement of the grout surface was re-filled with bentonite hole plug until flush with the top of the borehole.

Rock borings using an air-rotary pneumatic drill unit were completed at locations BKK-1 through BKK-40 (Figure 2). A total of approximately 2,000 feet of lineal rock boring air-rotary drilling was completed at forty locations along Bushkill Creek. The rock boring provides information about rock type, fracture/void locations, rock quality, and overburden thickness and characteristics. This information was obtained by the examination of drilling cuttings generated from each bore hole, penetration rates of the drill bit, and drill bit drops where occurring.

Certain rock borings were completed using a rubber-tired Schram air rotary drilling rig. This rig completed twenty-one accessible borings on both sides of the creek between May 6 and May 10, 2002. The Schram rig used a six-inch diameter air rotary percussion hammer to drill from the surface to a depth of 50 feet bgs. Temporary casing was used at some boring locations to prevent the borehole walls from collapsing during drilling. The borings were logged using USACE form 1836 located in Appendix B of this report. Some borings were not accessible with the Schram rubber tired rig and, therefore, the Schram rig was replaced with a crawler-mounted, all-terrain air rotary rig on May 13, 2002. The crawler-mounted rig completed the remaining borings. The same drilling protocols were used for both drilling units. Borehole abandonment procedures were performed as described above for the rock core borings.

2.3 SURVEYING

Following the drilling efforts within this study area along Bushkill Creek, Keystone Consulting Engineers of Allentown, Pennsylvania, surveyed the final boring locations. The surveyors provided boring locations and elevations using State Plane Coordinate System, Pennsylvania South, NAD 83 in US Feet. Surveyed locations are shown on Figure 2, and the survey data is presented in Table 1.

3.0 RESULT OF DRILLING ACTIVITIES

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The results of drilling activities within this study area along Bushkill Creek support surface observations that this area is undergoing aggressive karst development. The study area is experiencing shallow sinkhole development (less than 20 feet bgs), soil piping, and soil slumping. These features are the direct result of the shallow bedrock and overburden characteristics identified during the drilling effort that indicate the piping of overburden soil into voids, fractures, and cavities in the bedrock causing the formation of sinkholes at the ground surface.

3.1 ROCK CORING

Coring results obtained at locations BKB-1 and BKB-2 from the top 15 feet of bedrock indicate a light, bluish-gray calcitic dolomite containing small fractures and weathered near the top of the bedrock surface. A small silt-filled void approximately 1.5 feet thick was encountered in BKB-1 at 21 feet bgs. In addition, two small silt-filled seams were logged within BKB-2 at 26.2 feet and 32.1 feet bgs. Despite the active sinkhole located adjacent to BKB-2, only small voids and fractures were identified within the core collected from this location. Although larger voids were not identified within the core, the cores do suggest that this rock is highly weathered. BKB-2 core may represent pinnacles of more competent rock, which forms the “throat” or edge of a sinkhole.

3.2 ROCK BORINGS

Figure 2 provides a plan view of the distribution of boring locations along Bushkill Creek within the study area. Data from the rock borings indicate that the overburden soil is a mix of sand, gravel, and silty sand, saturated and very soft in some locations. Rock boring data also indicates that the overburden thickness is highly variable, ranging from 15 feet to 48 feet thick across the site and that areas of soft, weak rock exist approximately 30 to 45 feet bgs throughout most of the study area. The large variation in overburden thickness suggests pinnacle development, indicative of karst bedrock. Pinnacle formation can be characterized by localized areas of

competent rock directly adjacent to weathered, less competent rock. This terrain often contains zones of very soft overburden, soil piping, and potential sinkholes in areas between pinnacles. Soft, weak rock (less competent) can develop voids or weathered zones that contribute to pinnacle development and the piping of the overburden material. A summary of the voids encountered and the depth to the top of rock are noted in Table 2.

Not all areas of the subsurface along Bushkill Creek contain soft, weak rock. Areas of more competent rock were also identified using the geotechnical boring information. Changes between rock characteristics appear abrupt and represent typical subsurface changes within a karst terrain, where significant subsurface characteristic changes occur within several feet. Generally, zones of less competent rock can be observed trending approximately southwest-northeast (N 60 E), east-west, and north-south.

At many boring locations, weak zones within the rock contain numerous small fractures and some larger fractures and voids. Borings that encountered soft and weak rock that were drilled near Bushkill Creek often established communication with the creek during drilling. For example, during drilling of BKK-13, air bubbles were observed within the creek that indicates that the compressed air used to turn the drill bit was traveling along cracks and fractures from the borehole to the creek. Similar drilling conditions indicating unstable subsurface conditions include the need for temporary casing to prevent the borehole sidewalls from collapse, and the use of large volumes of grout and hole plug to abandon the borings. Table 3 outlines notable conditions encountered during drilling.

4.0 INTEGRATION OF GEOTECHNICAL AND GEOPHYSICAL RESULTS

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4.1 BACKGROUND GEOPHYSICAL INFORMATION

A geophysical survey was completed within this study area during Fall 2001. The survey utilized Electrical Imaging (EI) methods, also known as electrical resistivity, to identify possible subsurface fractures/voids, less competent rock, or saturated areas that may contribute to the piping of overburden material and, thus, sinkhole development along Bushkill Creek. The EI survey was completed as a “screening tool” to provide subsurface information that would ultimately be used in a potential geotechnical sinkhole mitigation and stream restoration design.

The EI survey provided a two-dimensional image of the subsurface along Bushkill Creek at specific traverse line locations. Following the completion of the survey, a report was provided to USACE describing the methods, procedures, results, and the two-dimensional EI profiles. This report has been included as Appendix D of this report.

The EI results indicated that the study area along Bushkill Creek exhibited distinct electrical conditions and contrasts. The electrical contrasts along the creek were presented as areas of low resistivity and areas of higher resistivity. Low resistivity areas within the EI profiles were consistent with conductive materials, while higher resistivity materials were consistent with less conductive materials. Within this type of geologic setting, conductive material is attributed to increased silt/clay content (due to increased weathering of limestone/dolomite rock), increased saturation, and voids/fractures (either filled with water or silt/clay). These types of conditions are generally consistent with soft, weak (less competent) rock and saturated, loose overburden. Less conductive material within this geologic setting can be attributed to decreased saturation, increased sand and gravel content, less fracturing/void development, generally more competent rock and/or dry overburden.

The resistivity profiles obtained along Bushkill Creek indicate that significant areas along and within the creek exhibit low resistivity (more conductive material). This low resistivity ranges

from approximately 10 to 50 feet bgs, but appears ubiquitous between 30 and 50 feet bgs. EI traverse numbers 3 and 7 along the southern streambank (Figure 3) indicate that the subsurface resistivities may also be highly variable. Potential voids/fractures were identified on each EI profile where abrupt vertical changes were observed within the EI data or extremely low resistivity was identified.

4.2 COMPARISON OF THE GEOPHYSICAL AND GEOTECHNICAL RESULTS

Comparison of the geophysical results with rock core and rock boring information allowed calibration of the geophysical data interpretation. The top of rock, type of overburden, amount of saturation, significant notable fractures/voids, and drilling conditions for each boring were compared to the resistivity signature for the nearest EI traverse. A good correlation was assigned if two or more of the previously stated conditions correlated to the modeled resistivity profile. For example, if the boring log indicated the overburden was saturated and that soft, weak rock existed at 32 feet bgs and the corresponding EI traverse identified low resistivity at this depth, then a good correlation exists because both data sets (boring information and EI results) indicate saturated conditions and less competent rock.

Conversely, if the boring log did not indicate conditions that correlated to the modeled resistivity value, a poor correlation was assigned. A “moderate” designation was used for only one major condition correlated between the data sets. In most instances, EI traverses that were more than 25 to 30 feet away from the boring were not considered for comparison. Due to the geologic setting, extreme subsurface changes could occur within short lateral distances and depths making correlation unreliable. Borings that were not proximate to EI traverses were assigned “NA” or not applicable. This analysis is summarized in Table 4. The “good” correlation ranking is plotted pictorially (with red dots) on Figure 3 and suggests that “pockets” of good correlation exist throughout the study area. For the most part, good correlation exists in areas where mostly soft rock and unstable drilling conditions were found in the subsurface.

The degree of correlation between the data sets relies on the following factors:

1. Site geologic setting – Karst environments are characterized by significant and abrupt subsurface changes within relatively short distances and depths. This condition results in subsurface characteristics that can vary significantly between the boring and EI traverse locations making good correlation between the data sets unlikely if the boring location does not fall directly on the EI traverse line. Extrapolation of the boring information onto the EI traverse is acceptable for presentation purposes; however, any interpretations derived from the extrapolated boring data should be reviewed with caution.
2. Boring Data Limitations- Data obtained from a single point (boring) within the study area provides only a small discrete sample of the subsurface. The data contained in a single boring may not be representative of the subsurface environment surrounding that particular point. This variability could easily explain correlation differences between the data sets.
3. EI Data Limitations – The EI method tends to “generalize” or “smooth” abrupt changes within the subsurface. For example, a bedrock pinnacle may be apparent on the EI profile, but it will appear smoother and much less abrupt. The electrical contrasts within the subsurface may also contribute to amounts of variability within the EI data. For example, mud-filled or water-filled fractures are electrically similar with regard to resistivity and, therefore, are not easily discernible within the EI data set. These EI data limitations result in potential differences between the EI and boring data interpretations.

Although the correlation between EI and drilling data is affected by these factors, a comparison of EI and drilling data produced at the Bushkill Creek Site are shown on Figures 4 through 11. Figures 4 through 11 present selected geophysical data (2001 geophysical report – Appendix D) and boring data obtained along Bushkill Creek. Figures 4, 6, 8, and 10 plot the boring information, including boring identifier, distance from EI traverse, top of rock, total depth, and presence of fractured rock onto the adjacent EI profile. Using the criteria described in the

preceding paragraphs, a correlation was made between the boring data and the EI profile. This correlation information is presented on Figures 5, 7, 9, and 11.

EI and boring information along the southern streambank of Bushkill Creek are presented in Figures 4, 5, 6, and 7. The northwestern portion of EI traverse 3 (Figure 4) was within close proximity to borings BKK-1, rock core BKB-1, BKK-2, BKK-3, BKK-4, and BKK-5. The top of rock information obtained from these borings indicates a depth to rock ranging from 17 to 20.5 feet bgs. The overburden was described as partially saturated loose sand, silt, and gravel. A 5-foot thick saturated, weathered interval above the bedrock was usually encountered. The borings identified fractured rock in some places. The EI information within the vicinity of these borings correlated well with respect to top of rock. High resistivity anomalies L3H, L3I, and L3F appear to correlate with the loose sand, silt, gravel overburden (anomalies L3H and L3I), and competent rock (L3F). Anomaly L3D correlates well with the weathered, saturated material described approximately 15 feet bgs. Fractures identified within BKK-1 and BKK-5 appear to correlate well with the EI vertical discontinuities at 110 feet and 222 feet inline distance, respectively. Fractures described within boring BKK-3 did not appear to correlate with the EI results.

Top of rock information from borings BKK-10 and BKK-11 does not appear to correlate well with the EI results. The bedrock topographic low and weathered, saturated material correlates well with the low resistivity results (anomaly L3B) at 350 feet inline distance. The top of rock information described at BKK-7 does not correlate well with the EI results. This poor correlation is most likely related to the strong low resistivity anomaly at BKK-10 and BKK-11, causing a false high conductivity at BKK-7. Areas of good correlation are outlined on Figure 5.

EI traverse 7 (Figure 6) along the southern streambank of Bushkill Creek was compared to borings BKK-6, BKK-12, BKK-13, and BKK-14. Borings BKK-6 and BKK-13 suggest that low resistivity anomalies L7D and L7C are consistent with fractured, saturated rock and weathered, saturated material, respectively. Borings along EI traverse 7 indicate that saturated conditions and unstable drilling conditions exist along the southern streambank. The EI results depict

generally lower resistivity, suggesting saturated conditions; however, the EI results did not correlate well to top of rock or other specific fracture zones. Figure 7 depicts the zone with good correlation. The remainder of the borings have only moderate correlation.

Within the streambed, EI traverses 2 and 6 were compared to borings BKK-21 through BKK-25. Only one boring (BKK-21) was compared to EI traverse 2 results (Figures 8 and 9). EI results appear to correlate well to the top of rock (16 feet bgs) and overburden described within boring BKK-21. Significant fractures were not observed within this boring. EI traverse 6 results indicate very low resistivity and suggest saturated, weathered material (Figure 10). The boring results (BKK-22 through BKK-25) indicate a bedrock topographic low with weathered, saturated overburden. Unstable or difficult drilling conditions were noted at some borings. Although poor correlation is observed between the borings and EI results with respect to the top of rock, the overall low resistivity values modeled indicated saturated, weathered, and broken rock. This correlates well with the bedrock topographic low and the overall borehole conditions. Low resistivity anomalies L6A and L6D also appear to correlate well with the boring information. Correlation is depicted in Figure 11.

A summary of the EI and boring data comparison yielded the following:

1. Both data sets indicate that the subsurface bedrock contains zones of less competent bedrock and that the size and location of these zones are variable across the study area.
2. The boring data identified fewer large (more than 1 foot), open voids than suggested by the EI data; however, the boring data reinforced the EI interpretation that several significant zones of increased fracturing and weathering exist within the bedrock throughout the site. For example, both data sets characterized the bedrock in the study area next to Bushkill Creek as especially weathered and soft at depths between 20 to 50 feet bgs.

3. Both EI and boring data sets confirm the hypothesized mechanism for sinkhole development along Bushkill Creek as weathered, less competent, fractured rock serving as the conduit for the “piping” of overburden soil, resulting in collapse of the ground surface. In addition, saturated conditions identified by both investigations confirm the mechanism for soil movement into these cracks and fractures in the less competent rock.

4. Large, cavern-type voids within the rock were not identified by either the geophysical or geotechnical investigations.

5.0 SUMMARY

5.0 SUMMARY

The rock boring and core information generally supported the site conceptual model generated by interpretation of the EI data that characterizes the study area as underlain by a large region of fractured, less competent, soft bedrock overlain by unstable, saturated soil. The correlation between the physical data collected by the boring program and the electrical resistivity data collected by the EI surveys was more consistent in areas where the borings were within 10 feet of the EI traverses and the subsurface showed strong variation in resistivity. In general, data from each investigation consistently characterized the subsurface along Bushkill Creek as undergoing accelerated karst development, probably due to surface water infiltrating through the stream bed and banks of Bushkill Creek into the bedrock below.

Both data sets indicate that the dolomite bedrock beneath the site is extremely susceptible to development of karst features. Surface expressions of sinkholes are evident on both sides of the creek and in the nearby farm fields. Both the EI and boring programs identified the same areas of concentrated fractures and saturated zones of broken or weak rock, generally at depths between 25 and 50 feet below grade. Variation in the topography of the bedrock indicated that bedrock pinnacle development exists. All of these features are found in classic karst terrain.

The boring log data generally confirms the EI information regarding the location and thickness of saturated overburden and depth to top of bedrock. The resistivity contrasts identified in the EI surveys implied that there was a potential for large voids in the subsurface. Although a void was penetrated at BKK-12, the borings often encountered broken or unstable weakened rock, rather than large voids.

The overburden penetrated by the rock borings, HSA, and described on the boring logs is consistent with the clays, sands and gravels previously identified by EI methods. The overburden was generally saturated near the creek, overburden thickness varied greatly across the site, and overburden thickness changed abruptly over small distances, further supporting a karst subsurface model.

Data from the geophysical investigation also indicated that a greater thickness of overburden does not imply surface stability. Areas of thick overburden were generally saturated and unstable, requiring supplemental casing to provide borehole stability during drilling. These thick areas of overburden are present along zones of weakness in the bedrock, where bedrock has weathered to a greater depth than the surrounding rock. Under these conditions, it is not realistic to expect saturated overburden soils to bridge or stabilize over weakened or fractured bedrock. Therefore, sinkholes would be more prone to occur in areas of thicker overburden for those reasons.

Eddies and whirlpools were visible within Bushkill Creek indicating that surface water is percolating into the bed and banks of the stream. The collapse of the Penn DOT bridge abutment was caused by stream water entering the subsurface and piping the foundation material (soil) from beneath the bridge. Borings BKK-13, BKK-24, BKK-29, BKK-37, and BKK-38 established communication with the stream as indicated by air bubbles in the stream during air-rotary drilling. These conditions imply that the stream is contributing water to the subsurface, providing the mechanism for accelerated subsurface piping of soil and subsequent sinkhole formation at the ground surface adjacent to the stream.

6.0 CONCLUSIONS AND RECOMMENDATIONS

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As previously described in this report, the mechanism for accelerated karst development and sinkhole formation in the study area is the infiltration of surface water through the bed and banks of Bushkill Creek into the bedrock below. This infiltrating water causes the piping of soils and subsequent sinkhole formation at the ground surface in the vicinity of the stream. In order to prevent this infiltration, mitigation activities that consider sealing the stream bottom or otherwise preventing the infiltrating water from piping or removing overburden soils would be required.

Because of the highly unstable condition of the study area, the stability of any mitigation action would be very difficult to provide, and impossible to guarantee. Provided below are two possible mitigation concepts and numerous site constraints for each technique that would potentially prevent its success:

1. **Stream bottom and bank lining** – This technique would involve using a lining material such as polyethylene, poly-vinyl chloride, or concrete to line the stream bottom and banks, theoretically preventing surface water from infiltrating to bedrock. Two factors that make this technique potentially ineffective are the potential failure of the foundation supporting the liner and the inability to control stream water from entering the subsurface upstream of the liner terminus. This water would in effect “short-circuit” the mitigation effort and potentially travel through the subsurface to the study area, causing continued piping of soil and eventual sinkhole redevelopment.
2. **Cut-off wall installation** – This technique involves injecting a high-density grout to form a subsurface wall that effectively “cuts-off” or prevents the stream water from migrating laterally from the stream into the subsurface beneath the study area. Theoretically, the grout wall would be constructed to prevent the water from reaching sensitive areas such as residences, etc. Data collected during drilling indicated communication of bedrock with the stream at fairly great distances from

the stream. “Short-circuiting” of water around the wall (depending on depth of cutoff wall) is likely due to the interconnected and fractured nature of the bedrock, causing piping and subsequent unacceptable sinkhole redevelopment unless large volumes of grout are used to close these pathways. Drilling along the creek banks has also shown a rapidly changing depth to bedrock, making wall anchoring difficult.

Other considerations for any mitigation scheme includes construction issues associated with the Penn DOT right-of-way, active sinkhole development during construction, and the cost/risk relationship associated with the predicted mitigation of this area.

In summary, the variability and instability of the karst environment beneath the study area makes it impossible to predict or reasonably guarantee the success of any mitigation technology at this site. Although short-term successes may be realized, successful long-term mitigation is unlikely where a reasonably priced mitigation scheme was implemented. Mitigation schemes that may have greater long-term success will likely be at a greater cost, and the effectiveness over the duration of time is impossible to gauge. Without mitigation, the site conditions along and beneath Bushkill Creek, including the presence of weathered dolomite, saturated, fractured, and weak bedrock and loose, saturated overburden, will continue to provide the mechanism for further karst development.

7.0 REFERENCES

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