Multifaceted Approach for Evaluating and Treating Sinkhole Activity beneath Highways – Case Study: SR 0422 in Southeastern Pennsylvania

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ABSTRACT

In the overnight hours between September 30th and October 1st, 2010, several sinkholes developed along a heavily-traveled section of SR 0422 in southeast Pennsylvania. In conjunction with PENNDOT’s geotechnical engineers, Gannett Fleming developed a sinkhole investigation program to identify the likely sources of the sinkhole activity amid the busy highway environment. The sinkhole investigation program consisted of a multifaceted approach incorporating three different geophysical survey methods; test borings within the travel lanes, shoulders, and median; a comprehensive review of available geologic data, including previous test borings performed adjacent to the investigation area; a visual pavement condition assessment; and visual and survey monitoring of the ongoing sinkhole and subsidence related activities across the site.

The geology of the project site is characterized by a variable bedrock surface consisting of pinnacles, solution cavities, fracture zones, and a localized thrust fault. Using a comprehensive investigation approach allowed for the analysis and consolidation of a large amount of data leading to a more detailed interpretation of the subsurface conditions. Based on the findings, a limited mobility grout program was designed and implemented to address the subsidence features at the site and mitigate future sinkhole activity.

Several logistical challenges were encountered during the investigation and subsequent construction phase of the project, including maintenance of traffic, limited work zone areas, and time constraints. Sinkhole activity in the carbonate belt of southeastern Pennsylvania is not unfamiliar to engineers and geologists, however, when sinkholes occur in a heavily-traveled highway corridor, they present unique challenges for investigation and remediation.
INTRODUCTION
Following an exceptional rainfall event in the overnight hours of September 30th, 2010 several sinkholes appeared along a heavily-traveled section of State Route (SR) 422 in Tredyffrin Township, Chester County, Pennsylvania. A total of seven sinkholes of various sizes were noted within the median and shoulders of the roadway and on an adjacent property west of the site. This section of 422, located between First Avenue and the Pennsylvania Turnpike (Turnpike) overpass, is four lanes (two in each direction) and carries more than 98,000 vehicles per day serving suburban communities of the Philadelphia metropolitan area.

After emergency repairs, the Pennsylvania Department of Transportation’s (PENNDOT) Engineering District 6-0 requested Gannet Fleming develop a program to identify the limits and potential sources of the sinkhole activity and provide recommendations for remediation. A multifaceted approach to the investigation was employed, including a review of available geologic data and historic test borings performed in the area, geophysical surveys, test borings, a visual survey of existing pavement conditions, settlement monitoring, and routine observation of the ongoing sinkhole related activities on the site. Based on the findings of the sinkhole investigation, a program of limited mobility grouting (LMG) was conceived and implemented to address the subsidence features at the site and help prevent future sinkhole activity. Due to the high volume of traffic on 422, all investigation and construction activities were to take place while maintaining two lanes of traffic in both directions, which required both night and weekend work.

INITIAL EMERGENCY SINKHOLE AND HIGHWAY REPAIRS
The appearance of the sinkholes resulted in emergency closure of the eastbound right travel lane. At some locations, sinkholes along the shoulder extended beneath the adjacent lane by several feet causing subsidence of the roadway. The pavement section in this segment of 422 is ten inches of reinforced concrete overlain by two inches of bituminous asphalt. Fortunately, the reinforced concrete pavement (RCP) section was able to span the sinkhole cavities until the lane could be closed and the voids backfilled, thereby preventing collapse of the roadway and potential traffic accidents.

Utilizing the lane closure to protect traffic, PENNDOT crews performed emergency backfilling of the sinkholes with concrete. The roadway was subsequently reopened to traffic, but over the next two weeks, additional settlement and sagging of the pavement was observed at three locations in the eastbound lanes manifesting as longitudinal pavement sags. PENNDOT responded by initiating emergency limited mobility grouting via their on-call surface treatment contractor. This emergency grouting, conducted at night using lane closures and restricted work hours, focused only on the immediate areas where subsidence was present. Due to the limited work hours available and the need to reopen the roadway at the end of each work shift, the grout holes were limited to a maximum depth of 20 feet. Three grout holes, arranged in a longitudinal fashion at a spacing of 10 feet, were used to treat each sag area. The holes were placed roughly in the center of each affected travel lane, in an attempt to provide additional support to the overlying RCP slab. A total of 18 holes were grouted over a period of five nights in mid-October, with a total LMG injection volume of 204 cubic yards.

SITE GEOLOGY
To obtain a better understanding of the geologic conditions influencing the project area, a desktop study of geological publications and existing test borings was undertaken. The site lies
within the Piedmont Lowland section of the Piedmont physiographic province and is underlain by Ordovician and Cambrian-age dolomite and brecciated dolomite bedrock of the Ledger Formation (1). These geologic features trace their origins to a time of relative geologic quiescence more than 500 million years ago, when waters of the Iapetus Ocean were moving inland depositing shallow-marine carbonate sediments along the continental margin of Laurentia. Subsequent lithification of these sediments is responsible for the carbonate belt that extends across southeastern Pennsylvania today.

Along the southern boundary of the project site, in the area of the Turnpike overpass, the Ledger Formation carbonates meet the Triassic-age sandstone of the Stockton Formation at an unconformable contact and several faults have been mapped in the vicinity of this contact. The Pennsylvania Geological Survey’s (PAGS) Map 61 (Valley Forge quadrangle) shows a localized unnamed thrust fault striking northeast along the boundary of the unconformity (2), evidence of which was not encountered during the subsurface investigation. A review was also performed of boring logs and data, obtained from the Pennsylvania Turnpike Commission (PTC), associated with the proposed widening of the Turnpike overpass.

The Ledger Formation dolomite at the project site is characterized by karst features such as irregular bedrock surfaces, pinnacles, extensive interconnected fractures and solution cavities. Water transport in the rocks of this formation is dominated by secondary porosity (i.e., through fractures, joints, bedding planes, and solution features), which can be quite significant. The geological combination of karst features and disturbed geomaterials associated with disrupted zones along faults makes this area prone to hazards associated with sinkhole activity, including the potential for significant damage to buildings and infrastructure.

SUBSURFACE INVESTIGATION PROGRAM
Gannett Fleming personnel performed initial reconnaissance of the site concurrently with the emergency LMG repairs and used the surface indicators for subsidence to identify the affected
area and plan the extent of the subsurface investigation. Ultimately, the subsurface investigation encompassed a 580-foot section of 422, with an area of approximately 65,000 ft², extending from the end of the First Avenue onramp (in the eastbound travel direction) to the Turnpike overpass. The investigation field work, performed between October 21st and November 22nd, 2010, (with subsequent site monitoring activities continuing through February 2011) included geophysical investigations, test borings, observation and documentation of on-going sinkhole-related activities, and review of available documents related to previous sinkhole activities on the site.

Geophysical Investigation

The geophysical investigation, performed by Quantum Geophysics, a division of Gannett Fleming, utilized a three-method approach, including multi-channel analysis of surface waves (MASW), microgravity, and ground penetrating radar (GPR). The geophysical investigation was performed in advance of any test borings in order to identify geologic anomalies or indications of potential voids that could be targeted with the borings, thereby maximizing their value.

Due to the vibration sensitivity of the microgravity and MASW equipment, geophysical surveys were conducted during off-peak nighttime hours from 9:00 PM to 5:00 AM. This also limited impacts of lane closures on motorists. MASW and microgravity methods were used to survey the extents of the project area (shoulders, travel lanes, and median), while GPR was exclusively used to survey the travel lanes to identify near-surface voids masked by the reinforced concrete pavement. PENNDOT Maintenance personnel supported the investigation by providing temporary lane closures and traffic control patterns.

The geophysical surveys revealed various types of anomalies within the limits of the site. Microgravity data collected using a 10-foot by 10-foot grid pattern revealed six relatively linear low gravity anomalies suggesting significant fracturing of the underlying bedrock. A sizeable low gravity anomaly was observed in the data, with a planimetric area of approximately 4,000 square feet, covering the eastbound outer shoulder, travel lanes, inner shoulder and a portion of the median, with a general east-west trend (4). The anomaly may be a signature of the localized thrust fault shown on the PAGS Map 61. While the microgravity data indicates the planimetric projection of the gravity anomalies, it cannot be used to directly determine the depth or other characteristics of the features related to the anomalies. However, general trends of high or low gravity readings are typically indicative of relative changes in the top of bedrock surface and competency of the intact rock, with higher gravity readings indicating shallower intact bedrock, and lower readings indicating areas of significant weathering or a deeper rock surface.

The MASW data, taken in lines parallel to the roadway, revealed fifteen different low shear wave velocity ($V_s$) anomalies, located at depths estimated between 30 to 50 feet below the ground surface. The majority of the $V_s$ anomalies appeared to be within the bedrock stratum, indicating areas of potential voids, soil-filled features or zones of highly fractured rock. The microgravity data and MASW data both revealed a relatively abrupt increase in the depth to bedrock in the southeastern portion of the site, approaching the Turnpike overpass (3).

The GPR survey data collected showed several areas with signs of soil raveling or piping within the upper four feet of the ground surface, along with areas of potential voids at the base of the pavement. In addition, the GPR data identified three linear trench-like features within the roadway thought to have been the site of previous roadway repairs (4).
FIGURE 2 Geophysical data summary plan (4).

Test Boring Program
Utilizing the results of the geophysical investigation, test boring locations were selected to target areas of interest, including several anomalies, and to provide additional subsurface data across the site to supplement planning of a sinkhole remediation program. A total of twelve test borings were performed, including one in the eastbound outside traffic lane (centered in the largest microgravity anomaly), five on the outside shoulders, three on the inside shoulders, and three in the median. The borings were advanced to depths ranging from 15 to 91 feet below grade, with the final depth determined by top of rock elevation, rock quality and whether or not any solution features were encountered within the rock mass. A temporary lane closure was required to drill the boring in the travel lane during the restricted daytime working hours of 9:00 AM to 2:00 PM due to the heavy traffic volume. Test borings on the shoulders utilized temporary shoulder closures to minimize traffic impacts.

Typically, the test borings encountered loose to dense silty sand (SM) and clayey sand (SC) residual overburden soils containing various amounts of gravel (rock fragments). Test borings in the eastbound outside shoulder and travel lane, near the original sinkhole activity, encountered very loose soils and low soil sample recovery within a zone of up to 13 feet above top of bedrock. In general, the overburden soils are underlain by light gray Ledger Formation dolomite, with localized brecciation. Half the test borings encountered significant voids and zones of very loose soil within the bedrock stratum, with the affected anomalous zones ranging from 13 to 32 feet in the vertical dimension within a particular boring.

In general, the boring logs obtained from the PTC proved consistent with the conditions observed in the test borings (4). Specifically, the depth to bedrock is highly variable and is considerably deeper along the southern edge of the site, near the Turnpike overpass.
Obtaining representative groundwater readings during the test boring program was difficult. To facilitate 24-hour groundwater readings in the borings, attempts were made to insert a small-diameter PVC conduit down each hole at the completion of drilling. Caving conditions in several of the borings made it impractical to insert conduit to the bottom of the hole. Where a groundwater level reading was obtained at the completion of the boring, it was unclear if the observed water level was influenced by the drill water circulated during rock coring. Two of the test boring logs obtained from the PTC provided long-term groundwater readings, and along with available well data in the area, suggest a groundwater table of 50 feet or more below the ground surface, which is consistent with regional groundwater levels. The deep groundwater table, which falls well below the top of rock elevation at several locations throughout the site, allows infiltrating water to transport soil into solution features within the underlying rock mass, leading to an increased risk of subsidence and sinkhole formation.
Site Surveying and Routine Monitoring

Surface indicators of impending sinkhole activity, such as shallow closed depressions, or settlement cracking of soils, pavements or structures, can be very subtle initially and may grow or show signs of movement over time, prior to the onset of a collapse. To help identify any developing or ongoing hazardous subsidence conditions, Gannett Fleming personnel visually monitored and documented anomalous surface features at the site from the beginning of the sinkhole investigation through completion of remediation activities.

To provide a quantitative evaluation of potential subsidence areas, a total of 50 settlement monitoring locations were established and surveyed every two weeks to look for indications of ongoing settlement. In the photograph below (see Figure 4), three settlement monitoring locations, indicated by the wooden survey stakes, can be seen adjacent to an active subsidence area in the median of the highway. Where survey results indicated possible settlement activity, an additional field reconnaissance was performed by personnel familiar with the site to see if any visual indicators of additional ground movement could be observed.

During the subsurface investigation and preceding primary construction activities, site observations identified two locations within the median exhibiting signs of continuing subsidence. The settlement progressed at these locations to the point surface repair methods were required, which consisted of overexcavating to competent soil strata and backfilling with flowable fill. This was an interim treatment measure to stabilize the areas until a permanent solution could be designed and implemented.

FIGURE 4 Evidence of ongoing sinkhole activity at a location of previous surface repairs.
Visual Pavement Condition Assessment
In addition to settlement monitoring, a visual inventory of the existing pavement conditions was taken and evidence of past surface repair features that may have been related to previous sinkhole activity was documented.

The pavement condition assessment identified one area of significant pavement distress where abnormal slab settlement was present. This area was treated during the emergency LMG work, but continued to experience additional settlement prior to implementing the final treatment program. The depression, located eastbound approaching the Turnpike overpass (4), was readily apparent as vehicles passed over the area. In addition, the GPR survey identified that a portion of this area had been previously been excavated and repaired, possibly in response to a subsidence condition. Other areas of pavement distress were noted; however, they did not necessarily appear to be related to the subsidence activity at the site, but rather could have been a result of the advanced age of the pavement system in this segment of the roadway.

SINKHOLE TREATMENT PROGRAM
Based on the findings of the sinkhole investigation, a limited mobility grouting program was recommended to remediate the effects of the recent sinkhole activity to help prevent future sinkhole activity. Other ground improvement and structural support options were considered to stabilize the roadway and treat the subsidence features within the project area. However, none of the other options considered offered the relative economy of a grouting program while effecting a long-term solution. Other benefits realized are minimizing disturbance to the existing roadway, allowing for maintenance of traffic through the work zone, and treating the source of the ongoing sinkhole activity. The grouting program was developed with the following objectives in mind:

- fill voids in the bedrock into which significant amounts of overburden soils could migrate;
- choke off major openings, or “throats”, in the top of the rock mass through which soil could readily pass;
- fill voids and densify loose zones in the overburden soils caused by previous or incipient sinkholes; and
- create in-situ “columns” of grout in the overburden, which while not directly supporting the roadway, would allow for some arching of soil loading onto the grout columns and provide some densification of the overburden soils.

Limited mobility grout is a stiff, low-slump material, typically with a soil-cement composition designed to remain in a coherent mass and travel only a limited distance from the point of injection. When injecting LMG in a rock mass, the grout characteristics limit the size of fractures into which the grout can penetrate and the distance the grout can migrate in smaller solution features. Because solution features in carbonate bedrock can be interconnected over large distances, this helps prevent excessive grout takes that could occur with fluid grouts. The viscous nature of the grout also limits lateral migration of the grout during injection in soil overburden materials, allowing for controlled placement of the grout and reducing the risk of hydraulic fracturing of the soil mass, which can result in ground surface heave and weakening of the overlying soil mass.
The limits of the grouting program were selected as described above and encompassed the known subsidence features as well as areas of interest identified by the investigation. Areas of interest included: voids in the rock mass, fracture features, a potential fault, zones of loose overburden soils, and low gravity anomalies. The MASW and test boring data proved particularly valuable in establishing the minimum and maximum target treatment depths. Given the objectives of the grouting program, it was important for the grout holes to extend into bedrock to cut off the underlying solution features from the overburden soils. A minimum rock penetration of 10 feet was utilized, however, where voids or soil zones were encountered in the rock mass, grout holes were extended deeper in an effort to find the bottom of the anomaly, allowing a firm support zone from which the grout injection could commence upward. In the area of the large gravity anomaly, test boring and MASW data suggested that the problem areas would be encountered deeper within the rock mass and the 10-foot penetration might not be sufficient. To remedy this situation, a group of grout holes in this area was identified in which the contractor would be required to advance a minimum of 20 feet into the underlying bedrock. Based on the results of the subsurface investigation data, contract specifications were used to inform the contractor that grout holes of 80 feet or more in depth could be required so appropriate drilling and grouting equipment and casing would be selected for the work.

In addition, design of the grouting program needed to consider the overall cost and duration of the construction efforts, general sequencing of the grout holes, potential impacts to onsite structures and underground utilities, traffic staging requirements limiting the available work zones at any given time, and potential environmental impacts. The as-designed LMG program included a total of 425 primary grout hole locations on a grid pattern of 10 feet by 10 feet over the area of interest, with provisions to add intermediate secondary and tertiary holes where particularly large grout takes were encountered. The 10-foot grid spacing was selected as a balance between obtaining effective treatment of the soil mass between adjacent grout holes and maintaining a cost-effective grouting program.

Recommendations were also provided for the following: verification of the grouting program via test borings and geophysics; pavement repairs; and drainage and grading improvements. The latter included regrading of the grass median to direct stormwater runoff to a lowered inlet and installation of a geomembrane liner in the median swale to inhibit infiltration of surface water.

As a result of the pavement assessment, it was recommended that the bituminous overlay be milled off to expose the location of the longitudinal and transverse RCP joints prior to commencing the LMG program. The milling allowed for grout hole locations to be field adjusted to avoid problems associated with grouting too close to the edges of the pavement slabs, such as weakening the edge of the slab or causing differential movements between slabs leading to joint distress.

Along with the recommendations above, it was necessary for Gannett Fleming to prepare a construction cost estimate as part of the construction procurement process. The combination of MASW and test boring data significantly aided this process by providing a rational basis for estimation of average grout hole depths. The total grout injection volume was more difficult to estimate. Data was utilized from previous LMG projects at SR 309 and nearby SR 202, as well as grouting projects performed for private clients of Gannett Fleming, to estimate typical takes in the different strata encountered at the site. These estimated takes were then combined with the estimate of average hole depth and associated average rock depth to estimate the total grout...
injection required for the project. The final estimate incorporated an allowance for secondary and tertiary holes.

Role of Geophysics in Planning the Grouting Treatment Program

As found for this project, geophysical methods are useful when performing a subsurface investigation and planning an LMG treatment program in karst. However, the designer must keep in mind the limitations of any one geophysical method to get the most benefit from their investigation. Knowing the limitations of individual methods, multiple methods can be combined to create a more complete picture of the subsurface conditions and challenges that exist.

Test borings are a fundamental informational tool for the design of geotechnical solutions but are limited to providing reliable information only at the boring points, and thus represent a small percentage of the subsurface variability present at the project site. In a karst environment, where highly variable subsurface conditions are common, test borings provide a very limited picture of what is going on at a site. Geophysical surveys allow more complete spatial coverage of the site, while test borings are used as a calibration tool for data interpretation.

In this particular project each geophysical method contributed a unique aspect to the project. Microgravity provided grid coverage of the entire investigation area, allowing identification of anomalous features within the bedrock mass. A significant drawback of the method is the inability to determine the depth of the features of interest. MASW was utilized to gather longitudinal profile data of the site. The data was then processed in 2-D panels which showed the variation of top of rock. Due to considerations of cost and practicality, survey lines were performed at no closer than 10-foot spacing, meaning no direct data was available to interpret conditions between lines. Additionally, for reasons unknown, high-quality MASW data could not be obtained in all sections of each survey line. It is possible that the presence of LMG and concrete masses in the ground from previous sinkhole repair efforts interfered with the collection and processing of the data. Lastly, GPR was used to determine if there were any open voids directly beneath the pavement section that were being bridged by the RCP slabs. GPR is limited to relatively shallow penetration depths and is therefore not normally used for large-scale sinkhole investigations; however, it proved useful in a niche role in this case.

CONSTRUCTION PHASE

As a result of ongoing surface subsidence during the investigation phase, PENNDOT assigned emergency status to the project which allowed construction of the project to be bid and let under an accelerated procurement process. The bid period of the project was reduced from the five-week period normally allowed for PENNDOT projects to one week. The successful bidder was general contractor J.D. Eckman, Inc. (JDE) of Atglen, Pennsylvania, who teamed with specialty subcontractor Structural Preservation Systems (SPS), now known as STRUCTURAL, of Hawthorne, NJ, to perform the LMG grouting work.

Staging of Traffic Control and Resulting Impacts on the LMG Program

Maintaining four lanes of traffic (two in each direction) through the work zone during the execution of the LMG program was particularly challenging for the construction team. As part of the project design, a traffic control plan was developed to maintain traffic through the work zone and protect the traveling public as well as construction personnel within the work zone. The plan included three separate stages of traffic control patterns, with each stage customized to
allow for logical partitioning of grouting work in the travel lanes and shoulders. Traffic control patterns were implemented in both the eastbound and westbound directions of the highway concurrently, allowing LMG crews to work on both sides of the highway at the same time thereby expediting the grouting operations. The traffic control patterns, which encompassed the work zone and staging areas, along with lane shift tapers, covered more than 1,700 linear feet of the 422 corridor.

By shifting traffic lanes onto either the inner or outer shoulders through the work zone, both lanes of traffic could be maintained in each direction; however, the resulting work areas available within these traffic control patterns were long linear zones that presented a challenge for design and construction of the grouting program. Within the confines of the work areas provided by the traffic control, typically only one or two rows of grout holes were available to the contractor at a given time in each direction. As a result, the contractor was forced to progress much of the grouting in a linear fashion, making it a challenge to move equipment within a work area.

LMG work typically progresses from the periphery of a planned treatment area towards the center; however, this approach could not be utilized under these circumstances. In general an attempt was made to grout the holes in a given line by progressing from either end towards the middle but this was not always possible due to the challenges of positioning the drill rigs, pumps and grout trucks within the linear work areas, particularly when more than one crew was working concurrently on a line of holes. Because the use of an onsite batch plant would have been impractical under the circumstances, all grout was provided from a local ready-mix concrete plant.

**Limited Mobility Grouting Program**

The final limited mobility grouting program consisted of drilling and grouting a total of 605 production holes, including 436 primary holes, 161 secondary holes and 8 tertiary holes, with total grout injection of more than 85,000 cubic feet of grout. The production grouting work was performed over a period of 17 weeks between February and June of 2011. SPS provided between one and four full-time crews during the course of the LMG work, while Gannett Fleming provided full-time inspection of the grouting operation.

Production drilling was controlled using a set of termination criteria established during the design phase of the project. The criteria established limits for drilling depths under the various subsurface conditions anticipated across the site. In general, an attempt was made to terminate holes in a competent rock stratum, however this was not possible at all locations. Where competent rock was not encountered, maximum drilling depths were limited to no more than 100 feet below ground surface. Only 2.5 percent of all grout holes ended up reaching 100 feet, and less than 11 percent reached depths of 70 feet or more. Average drilling depths were much shallower at only 45 feet, correlating very well with the design estimates based on the geophysical and test boring data. Twenty-four percent of the grout holes were terminated at 30 feet or less below ground surface, serving as another indicator of the large variation in top of rock encountered within the project limits.

The grout mix selected by SPS consisted of water, Portland cement, Class F fly ash, clean sand, and admixtures including a combination water reducing agent and retarder, and an air entraining agent. Over the course of the project the grout slump averaged 1-3/4 inches and 28-day compressive strengths typically ranged between 3,000 and 6,000 psi, or higher in some cases, well in excess of the required strength of 400 psi.
Grouting was performed using a bottom-up, or upstage, approach with injection intervals, or stages, of two feet. A maximum injection rate of two cubic feet per minute was selected, except where large anomalies were encountered in the rock mass when a maximum injection rate of four cubic feet per minute was permitted. The intent of limiting the grout injection rate was to prevent uncontrolled lateral and vertical movement of the grout which could lead to hydraulic fracturing of the overburden soils and increased potential for heave at the ground surface. Grout injection stage termination criteria were also established in the design phase, providing specific limits for injection pressures, volume cutoffs, combinations of intermediate pressures and volumes, surface heave and structural movement. More conservative stage termination criteria were utilized when grouting adjacent to structures and subsurface utilities, because damage to these facilities could not be tolerated.

Once grouting of primary hole locations was completed in a particular area, grouting and drilling log data for each hole were reviewed to determine where secondary and tertiary hole locations should be added. For each line of grout holes, a conditionally-formatted (color-coded) summary spreadsheet was prepared showing the grout takes for each stage. The summary spreadsheet was updated daily so timely recommendations for secondary and tertiary holes could be provided to PENNDOT for review, and subsequently passed on to the contractor once approved. Conditionally formatting the large body of data into an easily readable summary table made it manageable for the design engineers and reviewers to quickly evaluate grouting progress and supply the contractor with updated recommendations in a timely manner.

In general, secondary holes were added where the following grout take conditions were encountered in an adjacent primary hole(s):

- a single stage with a take of 50 cubic feet or more,
- two consecutive stages with a combined take of 60 cubic feet or more,
- any series of five stages with three or more stages exceeding 25 cubic feet each.

Depths of secondary grout holes were tailored using information from the drilling logs for nearby holes and depths of the exceptional grout takes in adjacent holes. The need for tertiary holes was evaluated on a case-by-case basis given the available drilling and grouting data. A total of 161 secondary grout holes were incorporated into the project, while only 8 tertiary holes were required. The total number of added secondary and tertiary grout holes represented just under 30 percent of the total number of production holes grouted, correlating very well with the design estimates used to develop anticipated construction costs. In a few instances, additional primary holes were added when high grout takes were encountered at the perimeter of the treatment area to confirm a significant subsurface anomaly was not left partially untreated.

Eleven primary grout holes were added as a result of this approach.

Due to construction impacts on the traveling public and potential hazards associated with sinkhole activity, the project was under a strict construction schedule. The contractor and subcontractors faced daily challenges associated with working in a high traffic area with a limited work zone and compressed time schedule. Inclement weather interspersed throughout the timeline, including significant snowfalls at the start of the project, resulted in less-than-ideal working conditions that hampered grouting efforts. Effectively managing these conditions was a major contributor to reaching the timely conclusion of the project.

Estimated total drilling and grouting quantities, which served as the basis for the contract bid process, compared favorably with the total quantities used on the project. Total grout hole
drilling quantities were within less than 1 percent of the estimate, while grout injection quantities were within 15 percent.

FIGURE 5 Grouting and traffic control arrangement during weekend lane closure.

Quality Control

Full-time inspection of all LMG activities was implemented to establish and maintain quality control, to assure compliance with the specifications, and maintain detailed records of the grouting operations. The inspectors maintained drilling records for each hole, identifying strata changes and taking special note of zones with voids or very loose materials to be targeted during the grout injection, and were also responsible for determining the termination depth for each hole based on the depth and condition of rock encountered. During the grout injection, inspectors recorded the volume and the range of injection pressures for each stage, injection rate, stage termination criteria (pressure surge, volume cutoff, etc.), slump, and start and stop times, along with any unusual occurrences that might affect the work. The inspection staff for the drilling and grouting operations were geotechnical engineers or geologists familiar with the site conditions and objectives of the grouting program. This was a contributing factor in providing a successful oversight and quality control effort.

Special attention was paid to monitoring ground movements during the course of the grout injection, with the goal of minimizing ground surface heave and associated impacts to the highway infrastructure. In general, no injection of grout under pressure was allowed within eight feet of the ground surface. Survey laser targets equipped with alarm features were used to
establish real-time monitoring at various locations near each active injection site. Additionally, vertical “tell-tale” indicators were installed at regular intervals above a 42-inch diameter concrete lock-joint pipe water main traversing the site. The tell-tales allowed for direct monitoring of movements at the pipe, preventing a situation where pipe movements might be masked by the overlying soils.

Additional quality control measures included regular testing of the grout slump, daily calibration of the grout pump stroke volumes, confirming grout hole layout and spacing, pre- and post-grouting verification test borings and careful documentation of all pay quantities associated with the LMG program. Prior to allowing grout to be injected, the slump of each ready-mix batch delivered to the site was tested. On rare occasions when the grout slump came up low (between ½ and 1 inch), the concrete truck driver was allowed to add a small amount of water to the batch to increase slump and aid pumpability of the mix. If the slump exceeded the maximum allowable of 3 inches, the grout batch was automatically rejected. Consistency of the grout was also monitored during placement of each batch to make sure no issues arose if the truck was onsite for more than approximately four hours (the contractor utilized a set-retarding admixture to extend the working time of the grout).

CONCLUSIONS
To date, several months after completion of the grouting program and associated pavement repair work, the site appears to be performing well with no obvious visual indicators of active subsidence, even after the region experienced record monthly precipitation levels during August and September, 2011, including the remnants of Hurricane Irene, which dumped more than five inches of rain on the region.

Several factors contributed to the successful implementation of the limited mobility grouting program.

1. A combination of methods were utilized during the investigation phase of the project, allowing subsurface factors contributing to subsidence to be clearly identified and targeted for treatment. The investigation included a test boring program, multiple geophysical methods, review and analysis of geologic resources including historic test boring and groundwater well data, and reconnaissance and regular visual monitoring of the site.

2. Drilling termination criteria were implemented, based on the objectives of the grouting treatment program, to limit the overall drilling and grouting depths required while targeting specific areas of concern. This helped control the total project cost and schedule.

3. Comprehensive limited mobility grouting criteria were employed, including continuous evaluation of grout injection rates, monitoring of grout takes and pressure behavior for each stage of each hole, and monitoring for ground and structural movements.

4. Primary grout hole parameters were reviewed and evaluated daily to determine the need for secondary and tertiary grout holes, with the goal of providing consistent grouting treatment throughout the project area.

Meeting the investigation, design, and construction challenges was facilitated through constant communication between Gannett Fleming, PENNDOT, and the Contractors, along with detailed attention to documentation and implementation of field activities.
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