A Sinking Feeling in Happy Valley

Limited Mobility Grouting Arrests Movement of Emergency Room

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Shortly after construction began on a new emergency room addition at the Mount Nittany Medical Center in State College, PA (a.k.a. "Happy Valley"), the existing structure and new construction began to show signs of distress. Floor slabs were cracking to the point of causing tripping hazards to employees and patients, and doors were not functioning properly. The building's façade was separating from the structure, and survey data revealed that the newly constructed spread column footings were 2-3 in. lower than originally constructed just a few months prior.

As can happen with any complicated diagnosis, the first theory explored was that the distress had something to do with the northeast region's moderate seismic event ($M \approx 5.8$) on August 23, 2011. The structural distress also happened to coincide with Hurricane Irene and Tropical Storm Lee events in late August and early September of the same year. Rainfall data in State College for August and September indicated above average rainfall amounts of 1.91 and 3.52 in., respectively.

An investigation quickly focused on the stormwater management adjacent to and within the new construction zone (Figure 1). A local fire company was called to the scene, and several thousand gallons of water were poured on the upper parking lot area. The water contained a green dye to attempt to track the flow after it entered the suspect inlet, but it was quickly revealed that the inlet was not functional, and the lime green water began to flow toward the subsidence area. A test pit was excavated adjacent to one of the footings in the subsidence zone, and a classic erosion channel was revealed, indicative of the region's challenging karst geology (Figure 2).

Emergency Response and Investigation

The first order of business was to assess the risk to the hospital's staff and patients. The construction manager coordinated with hospital staff and the project's geotechnical, structural, and civil engineering team. The structural engineer immediately inspected the structural elements of the existing building and new construction. The civil engineer began a comprehensive survey to determine the zone of subsidence and developed a monitoring program to assess the rate of movement. The geotechnical engineer directed subsurface explorations and laid the plans for remediation.

The team's first recommendation was to repair the inoperable inlet and return the site's stormwater system to functionality. This was a critical path forward for the project, given the extremely damaging effects of concentrated water flows in this sensitive geologic environment. Sinkholes are a common occurrence in Happy Valley, and, unfortunately, they tend to show themselves during construction, when the overburden soils are most vulnerable to erosion into the soluble and cavernous limestone and dolostone bedrock formations that prevail within this region.

The structural assessment did not produce any compelling evidence to suggest that the superstructure had experienced damage requiring immediate structural repair. The civil engineer performed a standard elevation survey throughout the new construction area, and a manometer was used to map the subsidence in the existing emergency room area. Most of the distress to both the existing emergency room and new construction was cosmetic; the greatest risk was from tripping hazards due to the cracked floor slab. The cracks were temporarily repaired to reduce this risk. The survey and manometer results revealed that the subsidence zone was larger than

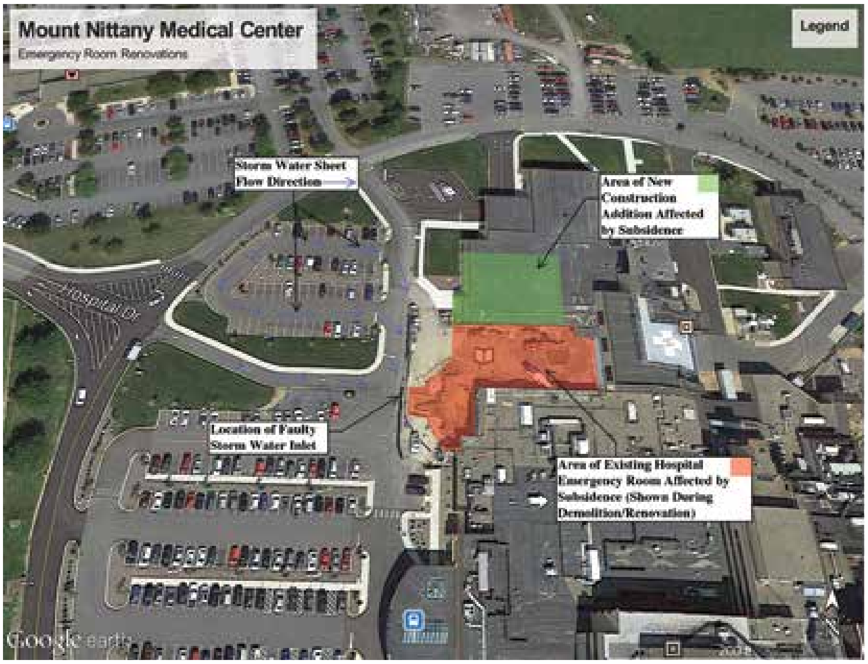

Figure 1. Map of Mount Nittany Medical Center, August 2012. (Image courtesy Google Earth Pro.)

Figure 2. Test pit within subsidence zone of existing construction area. (Photo courtesy of CMT Laboratories, Inc.)

originally identified by visual inspection, and access to this zone with geotechnical drilling equipment was limited.

A geophysical exploration company was added to the team and recommended the use of a microgravity survey. Microgravity was selected as the most applicable geophysical method to image the subsurface for density contrasts that would best indicate the presence of subsurface anomalies. The microgravity testing was conducted in two phases. Phase I was conducted immediately prior to the test boring work and stabilization efforts. Phase II was conducted after stabilization efforts were coming to a close.

Phase I consisted of 195 differential microgravity measurements that were collected during mid-January, 2011. The results showed areas of low gravitational response, indicative of anomalies associated with voids or cavities that corresponded with the zone of greatest subsidence within the new construction area. The survey also showed an abrupt increase in gravitational response toward the existing emergency room area. These data highlighted the significant geologic differentiation typical within karst areas.

Five borings were then drilled within the new construction area. The borings revealed an extremely irregular bedrock surface profile, with the top of rock varying between 15 and 45 ft below the site within a horizontal distance of approximately 25 ft. Moisture contents in excess of the liquid limit in the residuum indicated a highly mobile condition. Split-barrel sampling produced N_{70} values consistently below 5 blows/ft within 20 ft of the bedrock surface. The quality of the dolostone of the Nittany Formation was very poor, with rock core recovery values rarely exceeding 50 percent and non-existent to single-digit Rock Quality Designation (RQD) values. Voids and soil seams were a common occurrence in the bedrock, which gives the overburden a perfect avenue of escape, should it be mobilized with excessive water migration.

Figure 3. **Drill rig within subsidence zone of existing construction area with Beaver Stadium in background. (Photo courtesy of Alexander Building Construction.)**

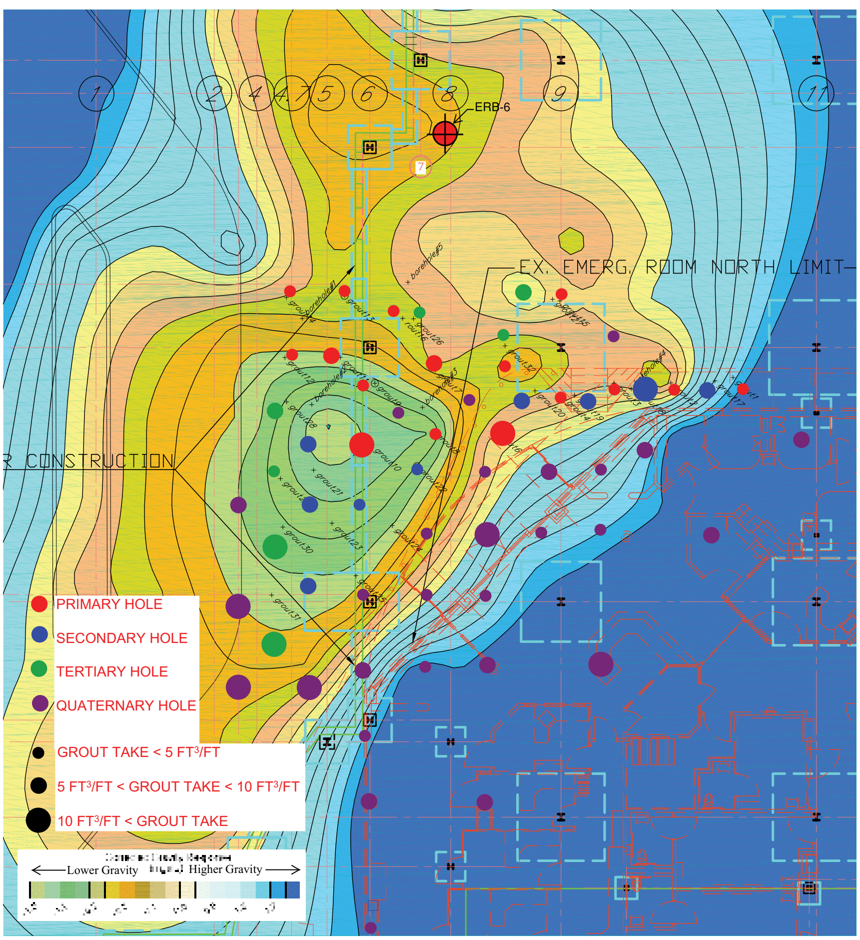

Figure 4. **Microgravity contour image with grout injection data. (Image courtesy of THG Geophysics, Ltd.)**

Subsurface Stabilization with Limited Mobility Grouting

A *Building Subsidence Report* was submitted to the hospital with the recommendation for immediate stabilization efforts using limited mobility grouting (LMG). The project's team of engineers endorsed the recommendation, and the hospital quickly engaged a geotechnical construction contractor, experienced in LMG, to perform the work.

A total of 16 primary injection holes were chosen based on the test boring, geophysical, and settlement data gathered during the investigation. Duplex drilling was specified so that the casing would follow the down-the-hole hammer to prevent hole collapse in the highly unstable ground. The holes extended in depth until a minimum of 10 ft of solid bedrock was encountered, which was verified utilizing a down-hole camera. Grout refusal criteria took into account pressure (400 psi max.), heave (1/4 in. ground surface heave or any detectable movement of the structure), and grout take (100 ft^3/2-ft stage). This work had to be performed in tight spaces within an existing construction zone and adjacent to an active emergency room. The contractor deployed a low-clearance specialty drill rig with adjustable tracks to allow for access to tight areas (Figure 3).

Primary hole depths ranged between 30 and 105 ft below ground surface, revealing the craggy condition of the dolostone. Grouting operations got off to a rocky start due to the high sand content of the grout delivered to the site. The original mix design had a water:cement ratio of 0.53 and included 2,334 lbs/cy of well-graded, coarse to medium (PennDOT Type A) sand. The adjusted mix had a water:cement ratio of 0.38 and 2,210 lbs/cy of Type A sand. The adjusted mix design proved to have the proper rheological properties for this application.

Grout-take data quickly identified the highly variable nature of the stabilization efforts. One 105-ft primary

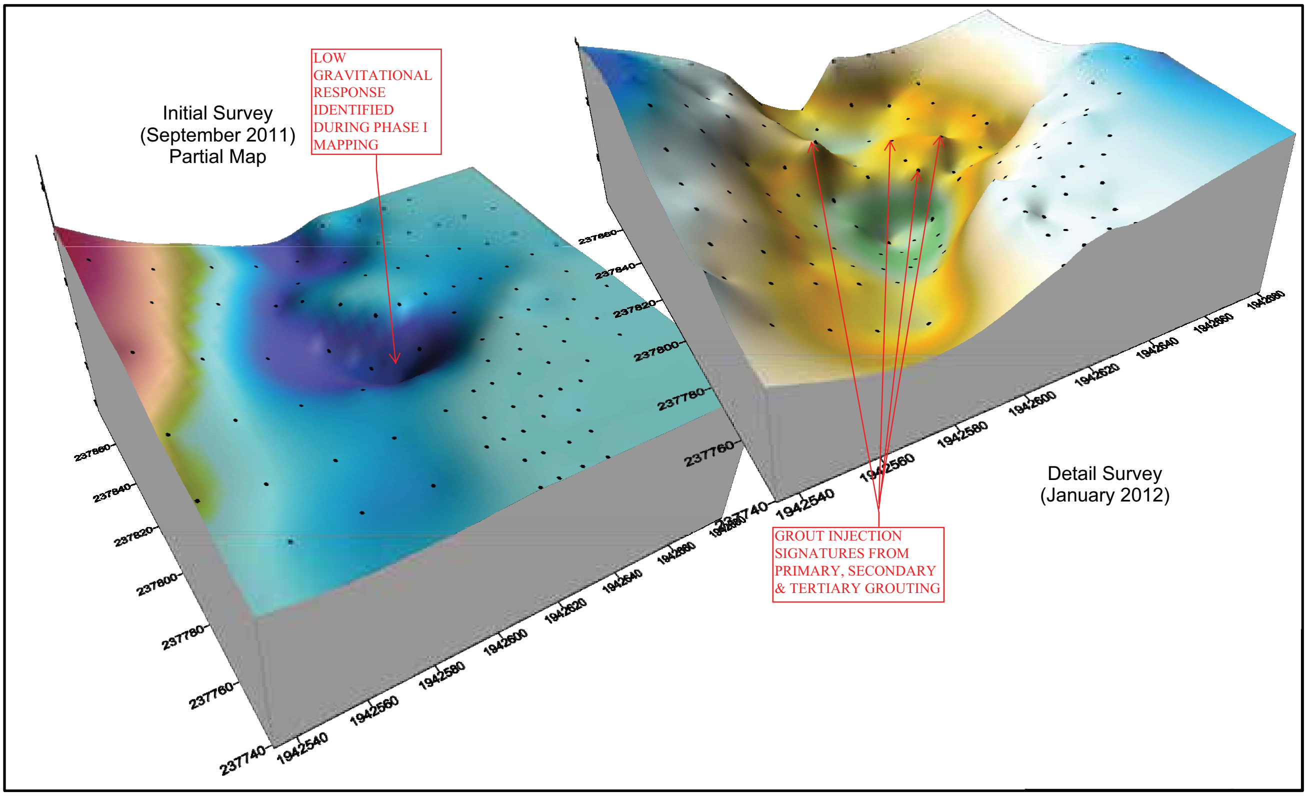

Figure 5. 3D microgravity images prior to ground improvement and following tertiary grouting phase. (Image courtesy of THG Geophysics, Ltd.)

hole accepted 206 ft³ of grout, while an adjacent 101-ft hole, less than 10 ft away, accepted a healthy 1,820 ft³. The average grout take for the primary injection phase was 7.18 ft³/ft. The data from the drilling and grouting of the *primary* injection holes was utilized to specify nine *secondary* holes within the existing construction area. Drilling depths within the *secondary* injection phase ranged between 54 and 105 ft, and grout takes averaged 7.29 ft³/ft. Subsequently, seven *tertiary* holes were added in the same general area, with depths ranging between 53 and 100 ft and grout-take volume averages dropping to 6.71 ft³/ft.

Reassessment and a Final Path Ahead

Upon completion of the *tertiary* grouting, the geophysical surveyor was asked to return to the site to complete the Phase II microgravity survey, which consisted of 130 differential microgravity measurements. The Phase II survey focused on the zone of greatest subsidence within the new construction area and just outside of the existing emergency room entrance. Figure 4 shows the 2-D gravitational contour mapping, along with the grout hole locations. The lowest gravitational response was recorded in the vicinity of the newly constructed column M-6, which is also the area that accepted the largest amount of grout.

3-D gravitational contour mapping of the Phase I and Phase II areas was also performed. Figure 5 shows the broad range 3-D mapping performed in September of 2011 and the focused mapping of January 2012. Note that the 3-D Phase II mapping was able to show the peaks associated with the grouting efforts.

The settlement readings before and immediately after the *primary*, *secondary*, and *tertiary* grouting phases is shown on Figure 6. This information shows that the combination of the newly repaired stormwater management system and subsurface grouting operations were able to successfully arrest the movement of the structure.

After planned demolition operations within the existing emergency room were completed, 28 *quaternary* LMG holes were added to the stabilization program. Hole depths ranged between 41 and 134 ft, and grout-take volumes continued to be impressive, but fell to an average of 6.34 ft³/ft.

A final review by the project team took into consideration the structural response to the stormwater control and LMG stabilization efforts and decided that additional grouting was not necessary. A total of 1,123 cy of grout was injected during the stabilization efforts. Repairs were performed on the portions of the new construction that had experienced subsidence, and construction of a conventional shallow spread footing foundation system throughout the renovated portion of the former emergency room area continued as planned.

Keys to Success and Lessons Learned

Teamwork and a careful response to the problem sum up the approach to tackling this potentially catastrophic incident. The project team placed the

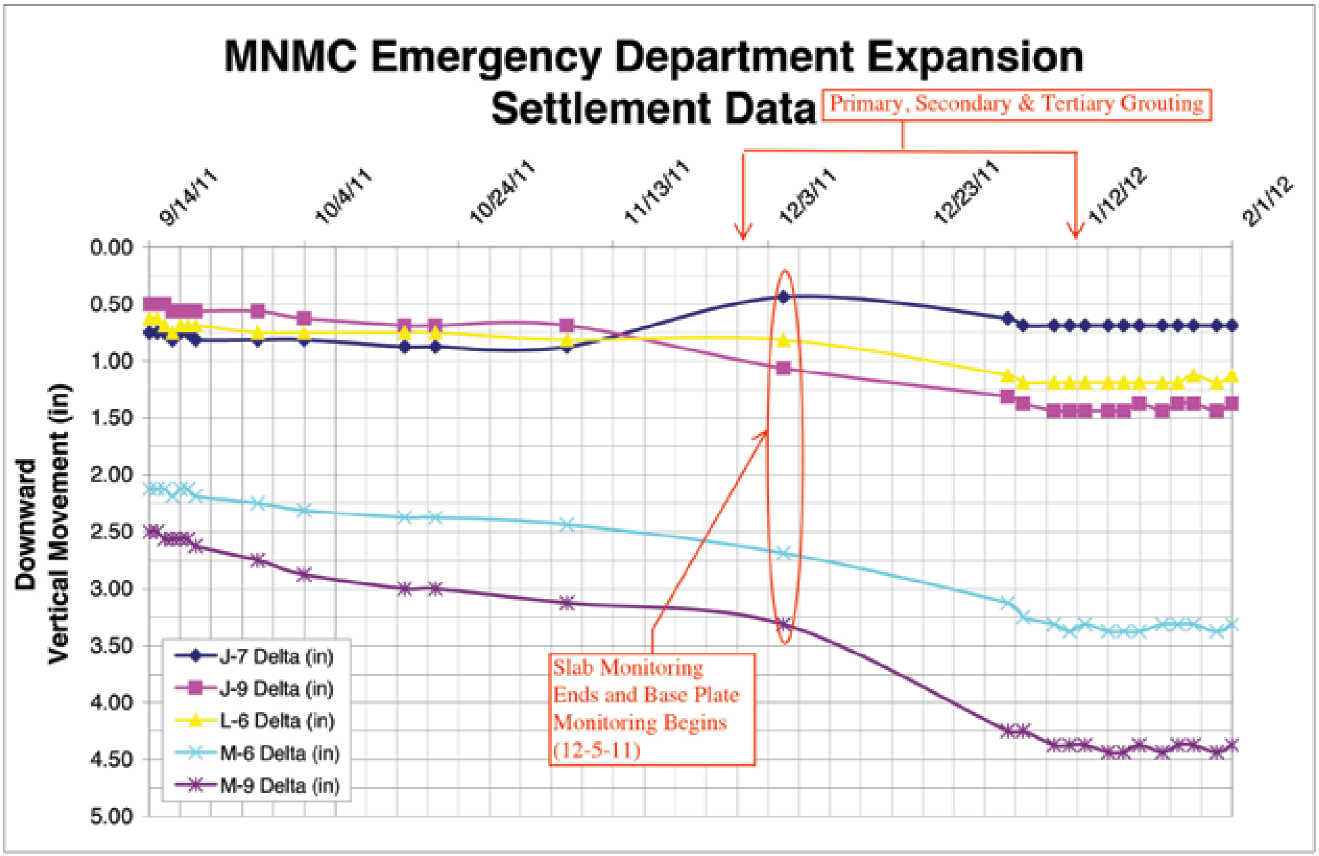

Figure 6. New construction column settlement data during and after ground improvement.

safety of the hospital's patients and staff first and foremost. Open communication of the issues was critical for cooperation throughout the investigation and repair processes. Even though initial forensic conjecture pointed to seismic activity as the potential cause for the sudden subsidence, the project team's experienced members refocused on the above-average rainfall during this period, realizing how water infiltration can dramatically alter the stability of ground in a karstic environment. The hospital's engineering department quickly coordinated the stormwater simulation test that revealed the faulty stormwater inlet. The test boring and geophysical investigations corroborated the theory of excessive stormwater infiltration into the construction zone.

It was extremely important for the team to understand the risks of using LMG in such a sensitive environment. Time was obviously critical, and the drilling and grouting methodology had to be precise and effective. Specifically, open-hole drilling was not permitted because of the extremely poor quality of the dolostone bedrock, meaning there could be no time wasted in dealing with collapsed holes and lost casing. The grout mix was also a critical element to the success of the stabilization efforts. The grout had to be thick enough to prevent hydro-fracturing of the very unstable residual soils, but also mobile enough to be pumped through 100+ ft of casing.

Finally, a focused effort was required during grouting operations to prevent potentially serious structural distress and life-threatening risks to patients and hospital staff. This risk was minimized by using multiple laser survey points on the ground surface adjacent to the grout injection hole and on points outside and inside of the existing emergency room.

Since the project concluded in 2013, the hospital has continued to expand to meet the growing needs of the residents of Happy Valley. The team assembled for the emergency room expansion continues to work together on new and exciting projects at the hospital. The lessons learned during the challenges of 2011 and 2012 continue to shape the approach of the team in this sensitive karst environment. GS

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