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REMEDIATION OF A SINKHOLE INDUCED BY QUARRYING

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ABSTRACT: On the morning of April 28, 1997, a sinkhole developed beneath a Burlington Northern Santa Fe Railway track. The sinkhole caused the derailment of 22 railroad cars, spilling diesel fuel from the engines that ignited, resulting in a fire and injuries to railroad personnel. Railroad personnel filled the sinkhole with about 500 cubic yards of rock fill, and traffic resumed while a subsurface study was carried out. The study resulted in a grouting program where 40 to 50 cubic yards of grout were injected into the subsurface. In August of 1999, the track subsided again. A second investigation conducted in October 1999, involved a tomographic imaging survey to define weaker zones beneath the track that may have contributed to the August ground movement. A much more extensive grouting program followed this study in April 2000. A total of 2746 cubic feet of neat cement/fly ash grout and 162 cubic feet of sand-cement/fly ash grout were injected into the underlying bedrock. In July of 2000 another and larger subsidence occurred, and a second tomographic imaging survey was conducted. In April of 2002, the sinkhole reactivated and continuing movement occurred over a period of weeks. About this time, a large volume of sand-laden water was reported entering the adjacent quarry. A third grouting program was conducted and involved injection of cement, chemical, and hot asphalt grouts. The grouting appears to have arrested both the subsidence as well as the inflow of water into the quarry.

INTRODUCTION

In the early morning of April 28, 1997, a northbound train traveling into Cape Girardeau, Missouri, derailed on the Burlington Northern Santa Fe's (BNSF) main

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line at Milepost (MP) 134.5. Initial assessments prior to removing any of the derailed railroad cars suspected the cause of the derailment was possibly related to a track or mechanical failure. However, once removal of the railroad cars began, it became apparent that development of a sinkhole beneath the track was the cause of the derailment. Railroad cars buried atop each other were uncovered within the sinkhole. The estimated size of the sinkhole was about 100 feet long and 40 feet deep near the center. Approximately 500 cubic yards of shotrock were used to backfill the sinkhole and level the site prior to relaying the track. A series of investigations and grouting programs were performed at the site over several years to define subsurface conditions and attempt to stabilize the sinkhole. This paper will present this case, the subsurface investigations, remedial actions, and lessons learned.

LOCATION

The BNSF's right-of-way and track are situated within a tract of land that lies between a cement plant and limestone surface quarry in Cape Girardeau, Missouri. The railroad right-of-way is approximately 100-feet wide (50-feet to each side from the centerline of the track). The plant is located immediately to the south and southeast of the BNSF right-of way, while the surface quarry is located about 400 to 500 feet north of the sinkhole. The active quarry had several levels that varied from about 150 to 300 feet below the grade of the track at the time of the 1997 derailment. The shallowest portion closest to the track was at the western end. Subsequent quarrying at the western end over the next 5 years extended this area to a depth of about 280 feet below the ground surface.

INITIAL INVESTIGATION, CONDITIONS, AND GROUTING

Subsurface Investigations and Conditions

The site is located in the flood plain of the Mississippi River with the Mississippi River being about ½ mile to the southeast. The initial site investigation following the derailment included the drilling of four borings to the top of bedrock around the periphery of the sinkhole, three on the northern side of the track and one to the south. No borings were drilled through the sinkhole because large diameter shot rock was used to backfill the sinkhole and the track was open to train traffic.

Soils underlying the site are alluvial in nature, consisting of a cohesive cap overlying sand, which overlies limestone bedrock. The cohesive cap consisted of very soft to medium stiff, lean and fat clay soils that extended to depths of about 28 to 54 feet. The thickness of the cohesive cap tended to increase to the south and southeast across the site. Medium dense, fine to coarse sand underlies the cohesive cap and extends to the top of bedrock. The rock depth tends to increase to the southeast with the depth to rock being between 47 and 63 feet on the northern side of the track and increasing to 92.5 feet along the southern side of the BNSF's right-of-way. Review of previous boring logs for explorations within the plant area shows that the depth to rock reaches 110 to 130 feet further into the plant and closer to the Mississippi River.

Groundwater Conditions

The stage of the Mississippi River and dewatering of the adjacent quarry control the groundwater regime at the site and create a groundwater gradient toward the quarry. Higher river stages result in higher groundwater flow rates toward the quarry. Piezometers installed to measure piezometric conditions in the clay and underlying sand measured groundwater at depths of about 11.5 feet in the clay and 20 to 23.5 feet in the sand following completion of the investigation in 1997.

Plant and quarry personnel interviewed following the derailment indicated that water flow into the quarry was occurring in a portion of the quarry that was about 150 feet below the ground surface. This area was at the southwestern end of the quarry. The rate of water inflow had increased during high Mississippi River stages preceding the sinkhole development.

1997 Grouting Program

A contractor for the BNSF conducted the first grouting program at the site in July 1997. Grouting at the contact between the alluvial sands and the bedrock surface occurred from the northern side of the track through a series of inclined holes. The purpose of the grouting was to fill voids and joints in the bedrock surface beneath the track and to stabilize the underlying sands to mitigate the potential for their future infiltration into joints. Twelve grout holes drilled parallel to the track, over a length of about 100 feet, and were inclined at approximately 20 degrees from vertical to encounter the top of rock directly below the track.

No observable voids were present in the underlying soil. Most of the grouting efforts were concentrated on an area beneath the track that encountered ballast at deep depths underlain by a deep clay layer. Ballast extended to depths as deep as 30 to 35 feet below the ground surface with clay underlying the area to a depth of 45 feet. The depth to bedrock was about 67 feet in this area compared to depths of 56 to 59 feet in the adjoining grout holes. Grout takes in this area generally ranged from about 3 to 7 cubic yards per hole. A total of 40 to 50 cubic yards of cement, flyash, and sand grout were injected into the subsurface soils during this grouting program.

TOMOGRAPHIC IMAGING SURVEYS AND 2000 GROUTING PROGRAM

1999 Tomographic Imaging Survey

In August 1999, a second reported subsidence event occurred at the same location as the train derailment. The track dropped about 1 to 3 inches over a length of about 40 feet and circular cracks with a diameter of about 40 to 45 feet occurred in the ground surface adjacent to the track movement. This event initiated additional studies at the site, which included a tomographic imaging survey.

NSA Engineering performed the tomographic imaging survey to define weaker zones beneath the track that may have contributed to the August ground movement. The tomographic imaging survey required drilling four additional borings and casing the borings with 4-inch diameter, Schedule 40 polyvinyl chloride (PVC) pipe. Borings were extended to a depth of 123 feet, through the overburden soils and into the underlying bedrock. The tomographic imaging survey, performed in the PVC cased holes, consisted of placing a signal generator (airgun) to propagate a signal and a string of hydrophones in the casings to record the velocity of the generated waves.

NSA Engineering produced a three dimensional image of the subsurface conditions between the borings and below the track to a depth of 100 feet. The survey identified the location of a weak zone, 40 to 50 feet below the track that was about 30 feet long and 20 feet wide. A weaker or softer zone was also present below the bedrock surface at depths of 60 to 80 feet beneath the ground surface. Previously grouted zones between about 15 to 30 feet and 40 to 60 feet beneath the railroad track were also identified in areas.

2000 Grouting Program

A more extensive grouting program was carried performed April 2000 following completion of the additional studies. The objective of the grouting program was to fill pathways in the underlying bedrock that carried water and sand to the quarry. To achieve this objective, the contractor constructed a 100-foot deep, 140-foot long grout curtain about 40 feet north and parallel to the centerline of the track. The grout curtain was located immediately adjacent to the area of the subsidence observed in 1999. The grouting program included the following: drilling of grout holes, water testing of holes, performance of a dye test, and grouting.

Drilling

Drilling of grout holes occurred in two phases. The first phase grout holes were spaced at 20 feet on center with the secondary holes drilled between the first phase holes to provide an overall spacing of about 10 feet on center. Drilling of grout holes included installing and grouting a 5-inch diameter, steel pipe into the bedrock surface, then extending the holes into the bedrock to a depth of about 100 feet using pneumatic percussion techniques. Conditions encountered during drilling included about 30 feet of clay overlying fine to coarse sand with limestone bedrock encountered at depths of about 49 to 58 feet. Grout holes drilled at the southern end of the grout curtain encountered weathered zones in the bedrock between depths of about 52 and 90 feet that varied from about 2 to 10 feet in thickness.

Piezometric levels and Water Testing

Several grout holes had large water takes during water testing conducted prior to grouting. These holes were generally within a 20-foot long area, located north of the center of subsidence and near the center of the grout curtain. Water takes in these holes ranged from about 80 gallons per minute (gpm) to greater than 150 gpm.

The piezometric levels in the overburden soils measured before the start of grouting ranged from a depth of about 27 to 31.5 feet below the ground surface.

Piezometric levels measured in the bedrock following grouting of the conductor casing and extension of the holes into bedrock varied from about 26 to 63 feet in holes of measurable water takes. The deepest piezometric level in the bedrock was located in the center of the 20-foot long zone near the middle of the grout curtain, which was where large water takes occurred. Short-term piezometric levels were not obtained from holes where the bedrock was tight and little or no water takes occurred.

Following an initial grouting of the bedrock, the piezometric level rose to a depth of 28.5 feet in the grout hole where the greatest drawdown in the piezometric level occurred. A second water test performed after the initial bedrock grouting measured water takes in the range of 110 gallons per minute. Table 1 presents Piezometric data and data from the water tests.

Dye testing

Fluorescence dye was added to the water pumped during the water test in the hole where the largest water take and the greatest drawn down in the groundwater table occurred. About 13,000 gallons of water were pumped at a rate of about 150 gpm into the hole in the center of the 20-foot long zone. Dye was observed seeping from a rock bench along the western end of the quarry. This was the same area where previous water inflow occurred. The bench was about 225 feet below the ground surface. No measurements regarding the volume of inflow occurred since access to the quarry by representatives for the BNSF was not attained until completion of the grouting program.

Grouting Program

A total of 3,525 cubic feet of grout was injected into the ground during the grouting program. This material was comprised of about 134,780 pounds of cement, 90,000 pounds of flyash, and 12,750 pounds of sand.

Grout takes for grouting conductor casing into the top of rock generally ranged between 25 and 30 cubic feet. One hole near the south end required about 128 cubic feet of grout to stabilize conditions just below and around the conductor casing. Highly weathered rock with clay and sand were encountered just below the bottom of casing elevation.

Deep grouting of the bedrock was conducted on holes determined from the water test to have significant hydraulic conductivity. A total of 2,746 cubic feet of neat cement/flyash grout and 162 cubic feet of sand-cement/flyash grout were injected into the underlying bedrock. The largest grout takes were generally in three holes immediately north of the area where track movement and ground cracks occurred. These holes were located near the center of the grout curtain. About 2,018 cubic feet of grout were injected into these three holes in phases with the largest grout volume being injected into the hole that was previously determined to have direct

TABLE 1. Piezometric and Water Test Data

Hole Location (1)	Date Measured (2)	Piezometric Level (feet) (3)	Water Take (gpm) (4)	Comments (4)
1+00	4/5/00	N/A	< 1	
1+10	4/12/00	N/A	5	
1+20	4/5/00	N/A	< 1	
1+30	4/10/00	N/A	< 1	
1+40	4/5/00	N/A	< 1	
1+50	4/7/00	31.5		Level in overburden soil prior to grouting casing into rock.
	4/11/00	Not measured	80	
1+60	4/5/00	63	> 150	Dye test performed.
	4/10/00	28.5	110	Retested after initial grouting of bedrock.
1+70	4/11/00	26	> 150	Hole drilled to 95 ft. with sand blow-in to 83 ft.
	4/12/00	N/A	6	Tested after hole stabilized with grout and hole completed to 100 ft. depth.
1+80	4/6/00	N/A	< 1	
1+90	4/11/00	Not measured	60	
2+05	4/6/00	26	> 15	Hole drilled to 63 ft.
	4/12/00	N/A	5	Retested after 4 inch casing installed to stabilized hole to a depth of 64.3 ft. and hole completed to 100 ft.
2+12.5	4/13/00	N/A	< 1	
2+20	4/6/00	29.5	60	Hole drilled to 65 ft.
	4/11/00	N/A	<1	Retested after zone from 55 to 65 ft. was stabilized and hole completed to 100 ft.
2+30	4/11/00	N/A	< 1	
2+40	4/6/00	N/A	< 1	
Water tests performed in completed holes (total depth of 100 feet) unless noted				

contact with the adjacent quarry. About 926 cubic feet of grout was injected into this hole, and grout colored water was observed in the quarry during the grouting process, emanating from the same area as the dye water inflow. This grout hole still had a relatively high conductivity after the initial grouting of the bedrock as well as the adjacent holes to the east and west that additional grouting took place in this area. An additional 256 cubic feet of grout were injected in the center hole and 836 cubic yards in the adjacent holes to the east and west. Several of the grout holes near the center of the grout curtain were hydraulically linked, as grout was circulated between holes. No large discernable weathered or fractured zones were observed in the grout hole that was determined to have the greatest conductivity with the quarry.

In addition to the grout volume used near the center of the curtain, a large volume of grout was injected into the ground at the south end of the grout curtain to stabilize ground conditions between a depth of 55 and 65 feet. About 760 cubic feet of neat cement/flyash grout was injected to stabilize the highly weathered rock with clay and sand encountered between a depth of 55 and 65 feet. Stabilization of these materials allowed advancement of the hole to the desired depth.

Grouting halted when the minimum planned grouting program was completed. Representatives for the BNSF and the grouting contractor had no way of evaluating the effectiveness of the grouting program since the owner of the quarry did not allow access to the quarry during or just prior to the grouting and there was no timetable to obtain access. As a safety precaution, monitoring systems were installed at the site to detect track and ground movement. One system consisted of a series of sensors installed along the western shoulder to detect ground movements, while the second system installed on the bottom of ties detected ballast movement. Both systems were connected into the existing track signal system.

Observations in the Quarry

Access to the quarry by personnel representing the BNSF finally came about 1 to 2 weeks following termination of the grouting program. The area observed was along the western wall of the quarry where dyed water and grout entered the quarry during the grouting program. This area was about 225 feet below grade and in the same general area where water inflow was observed during a previous visit to the quarry in 1997, although at a lower elevation due to quarry operations since 1997. Water flowed upward through pre-split holes and a crack in the bedrock formed from a blast. The total flow from the holes appeared to be on the order of about 20 to 25 gpm with the majority of the flow (about 15 gpm) emanating from one of the pre-split holes. Very fine sand was present on the bedrock surface around the pre-split hole where the majority of water flow was emanating

2000 Tomographic Imaging Survey

A second tomographic imaging survey conducted in October 2000, followed a third subsidence of the track in July 2000. In July 2000, the ground surface subsided 8 to 10 feet beneath the track and encompassed a circular area that was about 60 to 65 feet in diameter. The location of the subsidence was the same general area as previous subsidence occurrences.

NSA Engineering performed the tomographic imaging survey using the previously established PVC casings and several of the ungrouted holes from the 2000 grouting program. The seismic survey revealed that the upper 50 feet of material overlying the site had relatively slow velocities similar to what is expected for fill, clay or sandy clay. Velocities began to increase below a depth of 50 feet. The velocity over the majority of the area indicated significantly more competent ground and was within the range of limestone below a depth of 70 feet the

A near-vertical anomaly was observed by the survey at a depth of 65 feet. The feature had an approximately east-west orientation and a velocity less than the surrounding material. The feature continued as a lower velocity feature to a depth of 75 feet and transitions to a material with a higher velocity than the surrounding ground at a depth of 90 feet. A second near-vertical anomaly appeared below a depth of 90 feet. The second anomaly had an approximately north-south orientation, was nearly perpendicular to, and intersected the east-west anomaly near the center of the survey area. This feature also had a higher velocity than the surrounding ground. NSA Engineering's interpretation was that these anomalies might be an indication of a joint or void where the bottom portion was grout-filled, and the top portion was still open. The presence of the anomaly oriented in the north-south direction matched observations in the quarry, where a north-south oriented joint was visible in the quarry wall near the location of water inflow.

Options for dealing with the sinkhole were presented to the BNSF following completion of the tomographic imaging survey. These included continued monitoring since ground movement detection systems were operating at the site, additional deep grouting of the bedrock, and construction of a bridge. The BNSF elected to continue to monitor the situation because of costs and/or risk and uncertainties in the other options.

2002 EVENTS

In April of 2002, the sinkhole reactivated and remained active for a period of weeks. The initial subsidence occurred at the same location as previous movements and encompassed an area about 65 to 70 feet in diameter. About 12 to 15 feet of subsidence occurred near the center of the sinkhole, which was directly below the track. About this time, a large volume of sand-laden water was reported entering the adjacent limestone quarry.

Movements and subsidence continued for several weeks, unlike previous events where only minor movements occurred for a brief time following a subsidence. The track remained open to train traffic, and temporary closures of the track occurred to allow for aligning and resurfacing of the track. The size of the sinkhole grew to about 120 feet in diameter and began to encroach upon adjacent structures within the cement plant. This increase in size of the sinkhole and the growing volume of water infiltration into the quarry began to affect the operations of the quarry and plant, and raised their level of concern.

Access to the quarry by BNSF official and personnel representing the BNSF came about 1 to 2 weeks following the April subsidence. A large inflow of sand-laden water was occurring in the quarry about 250 to 280 feet below the ground surface. Estimates of the inflow rate at the time of our observations 1 to 2 weeks following the appearance of the sinkhole were in the range of 1,500 gpm. This rate quickly rose to about 5,000 gpm by late April and was in the range of 32,000 gpm by mid July. Flooding on the Mississippi River in May and June complicated matters. The river level reached about 47 feet above flood stage and was in portions of the plant.

The owners of the quarry began formulating plans to slow or stop the inflow of water into the quarry. Their ideas included construction of a bulkhead in the quarry at the point of inflow, grouting at the sinkhole, underpinning of the affected structures, and construction of a grout curtain. The quarry initiated a grouting program that concentrated on pressure grouting at the location of the sinkhole. Pressure grouting was conducted at the interface between the sand and bedrock. At the same time, construction of a bulkhead occurred in the quarry at the point of inflow. Abandonment of both of these alternatives occurred because they were not successful at slowing the inflow into the quarry. The quarry's focus then turned to construction of a grout curtain. A second sinkhole developed in the plant area, about 1,200 feet south of sinkhole, and along the same general line as the observed north-south oriented joint in the quarry. In the mean time, the BNSF monitored the situation and formulated contingencies. One contingency discussed was construction of a bridge across the sinkhole.

Installation of a grout curtain initially occurred in an area immediately atop and behind the point of inflow into the quarry. This location was abandoned for a site closer to the sinkhole. A 350-foot deep, nearly 200-foot long grout curtain was constructed about 75 to 100 feet north of the railroad track. Piezometric levels measured in the bedrock at the grout curtain were at depths of 170 to 180 feet below the ground surface at the time of the highest inflow into the quarry. The groundwater table in the overburden soils at the sinkhole was also drawn down to near the top of rock.

Sand, cement, and flyash grout was initially injected to seal fractured zones and voids in the bedrock. Except for a nearly 20-foot length near the center of the grout curtain, the sand, cement, and flyash grout appeared to be beneficial at sealing fractured zones and voids. However, the groundwater velocities in fractured zones and voids encountered at depths of 240 to 260 feet below the ground surface were too high in the approximately 20-foot long zone near the center of the curtain that alternative grouting methods were required.

In August 2002, molten asphalt was injected near the center of the grout curtain to seal off the fractured zones and voids encountered at depths of 240 to 260 feet below the ground surface. Water flow into the quarry visibly reduced within a short time following the start of grouting.

CONCLUSIONS AND LESSONS LEARNED

The level of groundwater inflow near the western end of the quarry followed with the excavation depth in this area. The depth of inflow was close to the same level as the quarry. This was treated as a maintenance issue by the quarry. Deepening of the quarry and high river stages increased the hydraulic gradient toward the quarry and the potential for large inflows of water.

From the start, grouting of the sinkhole by the BNSF had measures of uncertainty. The uncertainty arose from the fact that deep grouting was required and without cooperation from the quarry, there was no way to verify that the grouting was beneficial at slowing inflow into the quarry. Control of where the grout migrated to was also a concern.

A previous derailment near the cement plant was attributed to the cement plant and created an adverse relationship at the time of the 1997 derailment and sinkhole. This relationship continued until the quarry's level of concern grew because of the effects the water inflow and sinkhole began to have on their operations in 2002. Better communications between the two parties early in the process may have created a more constructive grouting program by the BNSF because there would have been ways to measure its success.

The latest grouting appears to have arrested both the subsidence as well as the inflow of water into the quarry. Time will tell whether this is a long-term repair or if the groundwater finds a new path into the quarry.