The Sealing of a Massive Water Flow through Karstic Limestone

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Abstract

This paper describes the design and construction of a multi-material grout curtain to cut off a major inflow through karstic features from a river to a nearby limestone quarry. A total of over 16,700 yd^3 (12,800 m^3) of slurry, Low Mobility Grouts, and hot bitumen were injected to depths of over 200 feet (60 m) along a 1500-foot (460-m) long curtain in several phases. The value of real time monitoring of all relevant hydrogeological as well as grouting parameters during the execution of such works is clearly demonstrated. This is believed to be the largest project of its type undertaken to date in North America.

1. Introduction

A large operational dolomitic limestone quarry is situated in West Virginia less than 1500 feet (460 m) from the Shenandoah River (Figure 1). In April 1997, a major sudden inflow developed into the southwest corner of the quarry pit following production blasting activities and several abnormally severe precipitation events that caused flooding of the river and nearby sinkhole formation. The initial magnitude of the flow, estimated at over 35,000 gpm (132,500 L/min) was far greater than the capacity of the existing pit pumping facilities. Prior to the incident, total flows from all sources into the pit were substantially less than 10,000 gpm (37,850 L/min).

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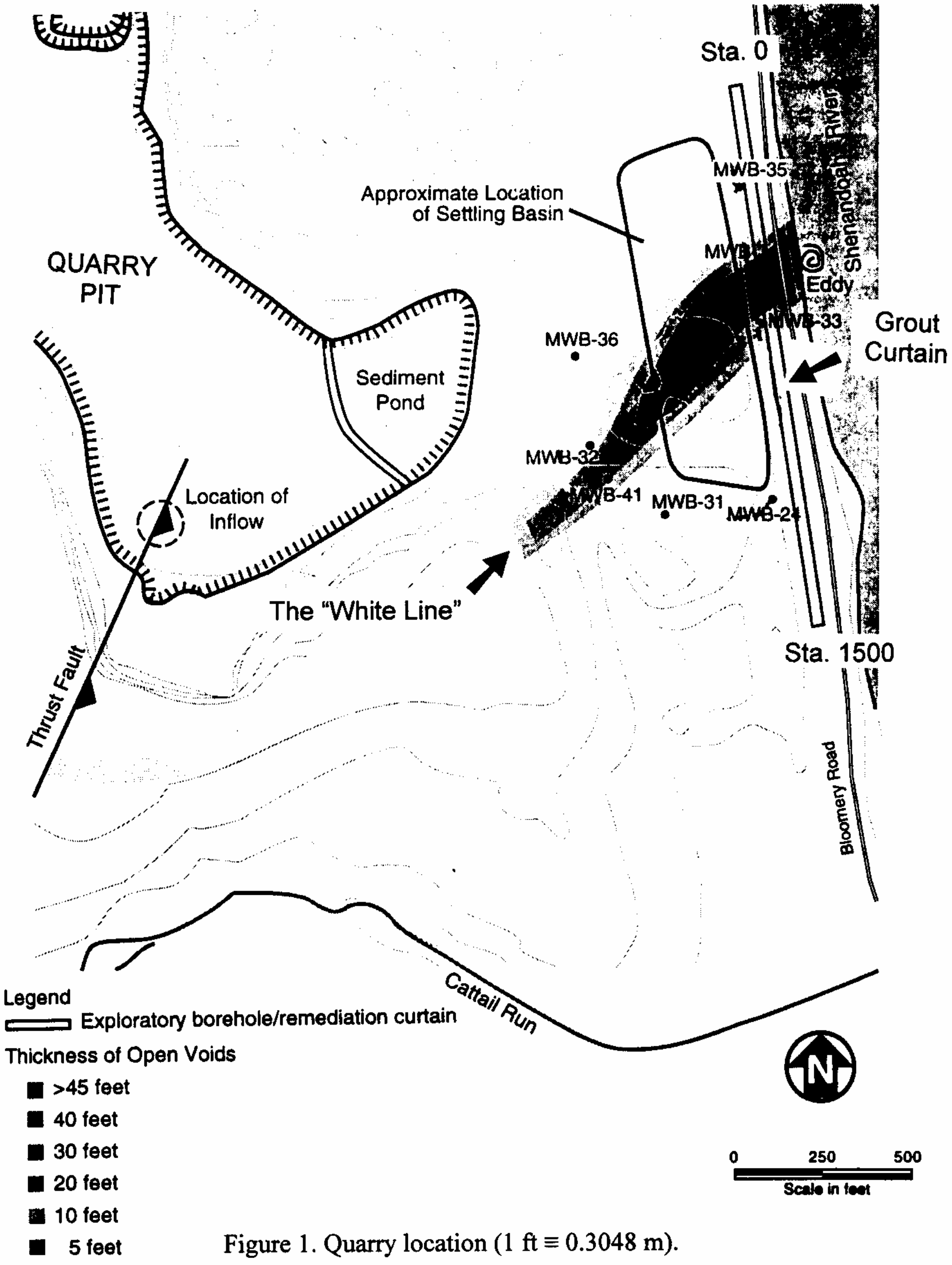

Figure 1. Quarry location (1 ft ≡ 0.3048 m).

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The new inflow posed a severe threat to both the current and future viability of the quarry, especially since the owner had to fulfill major aggregate supply contracts. A team of hydrogeologists, geophysicists, geologists, and geotechnical engineers was soon established to determine the source and path of the newly discovered inflow, to define options for remediation, and to design and supervise the construction of the favored option.

A vortex (or eddy) observed previously in the river appeared to be the point source of the flow. Initially, several attempts were made to construct a cofferdam with sandbags on and around the location of the vortex. Such actions resulted in immediate, yet very temporary, reductions of the new inflow to as little as 6,000 gpm (22,700 L/min). In each case, however, the flow conditions were re-established within 8 to 12 hours as a new vortex re-formed, up strike in the riverbed. Of importance in evaluating such attempts was the discovery that the new vortex locations were all situated along an approximately straight line, extending out into the river and corresponding to the regional northeast to southwest strike of the formation. This strike line would later be termed the "White Line" as shown on Figure 1, where it existed on land and would serve as the focus for later remedial measures.

In May 1997, pumping was discontinued, and the quarry water level was allowed to rise. This was done, in part, because the existing pumps were insufficient to maintain dewatering efforts. The partial flooding of the quarry would also assist later remedial operations by reducing the hydraulic gradient between the river and the inflow point. By the time remediation began in October 1997, the quarry water elevation had risen over 130 feet (40 m), to approximate Elevation 260 feet (79 m) above MSL (as compared to a river elevation of between 290 and 300 feet (88 and 91 m)). The total inflow was estimated at 22,000 gpm (83,300 L/min) even at this reduced hydraulic gradient. Dewatering was resumed in early December 1997, part way through remediation, to permit access to certain rock extraction areas in the pit.

2. *Geological Background*

2.1 Regional and Site Geology

The geology of the quarry area consists primarily of Ordovician limestone and dolomite. It is located on the eastern edge of the Valley and Ridge Province of the Appalachian and Mid-Atlantic regions. The geological features of the region strike primarily northeast-southwest and are highly faulted with anticlines and synclines and fracturing of the bedding planes. Similar Palaeozoic geology stretches from New Jersey to Georgia and is observed in many areas to contain karstic features.

The Tomstown Formation was identified as the primary soluble carbonate lithology at the site. It consists of lenses and beds of dolomite and limestone, and is exposed along the banks of the Shenandoah River adjacent to the quarry. Clay-filled karstic features are prominent in the walls of the quarry, while the adjacent property contained many large, deep sinkholes.

The quarry inflow contained large amounts of red and brown sediment. This sediment was particularly evident after the initial flooding of the quarry, when the inflow was visible in the quarry as a plume up to 40 feet (12 m) in diameter. Such sediment washout indicated that the inflow was piping through erodible materials contained in karstic features. This observation again highlighted the Tomstown Formation as containing the most probable inflow conduit.

2.2 Site Investigation Programs

During summer 1997, extensive investigations were conducted to determine the source and extent of the inflow. There was considerable debate about whether the source of the inflow was regional groundwater, Cattail Run (a small tributary of the Shenandoah River running to the south of the pit as shown in Figure 1), or the Shenandoah River itself. Various investigations were conducted, of which the following is a summary:

Extensive geophysical testing was conducted during summer 1997 to help pinpoint the source and path of the inflow. The geophysical investigations included fracture trace analyses, EM surveys, and dipole-dipole resistivity surveys. Anomalies as wide as 100 to 200 feet (30 to 60 m) were discovered, and suggested potential water conduits along the bedding planes, along fractures within the synclinal axis and through the fracture system in the alignment of Cattail Run.

Further information was compiled from exploratory drilling, flowmeter data, TV surveys, vortex pool locations, subsurface temperature anomalies, and sinkhole locations. One of the primary sources of information was a series of existing and new monitoring wells, termed MWB Wells, strategically located throughout the quarry property.

The hydrologists also conducted a study of the ions present in the various bodies of water. Comparison of the geochemical properties of the quarry inflow, Cattail Run, the Shenandoah River and regional groundwater revealed a fingerprint of ions present both in the Shenandoah River and the quarry inflow. The presence of such ions, unique to the Shenandoah River and the inflow, therefore narrowed the possible primary inflow source to the Shenandoah River.

Finally an independent geological consultant contributed further valuable information by mapping the bedrock and joint sets, and summarizing the local geological and structural setting, as it related directly to the problem.

3. Concept of Remediation Design

3.1 Analysis of Geotechnical Data

A review meeting attended by all the investigation specialists arrived at the following major conclusions:

- The likely trend of the flow was along the "White Line" (Figure 1).
- Karstic features of dimension over 50 feet (15 m) could be expected in the worst, central section of the "White Line", referred to subsequently as the "Red Zone".
- The several base water levels during geological history had led to different dissolution paths along the bedding planes and joint sets in the Tomstown Formation giving rise to possibly as many as four superimposed karst developments.
- The uppermost karst was probably 60 to 100 feet (18 to 30.5 m) deep, but the lowest could be as deep as 300 feet (91 m), with the features mainly oriented along the northeast-southwest trending structural fracture traces.
- Investigation of ground water temperature anomalies (i.e., river water hotter than ground water) confirmed the likelihood of flow conduits as deep as 200 feet (61 m). "Cold Karst" features were by definition those which did not appear to be connected hydraulically to the quarry.
- A hydrogeological model was produced, which estimated the total flows in the quarry as resulting from the Shenandoah River (60 to 70%); Precipitation (0 to 10%); Quarry catchment (2 to 10%); Regional aquifer (5 to 15%); Storage losses (5 to 25%); and Cattail Run (3 to 5%).

The width of the "White Line" could not be accurately defined, but was anticipated as being at least 500 feet (152 m) at its most intense with "Cold Karst" extending several hundred feet further on each edge (i.e., north and south). The boundaries of the "White Line" were approximately Sta. 500 to 1000 (Figure 1).

3.2 Ongoing Monitoring Program

Prior to the detailed design and execution of the remediation, it was agreed to "baseline" the hydrogeologic situation as closely as possible. The MWB Wells referred to above comprised deep piezometers located strategically between the river and the quarry. The wells were evaluated regularly for water level, pH, conductivity, and temperature. Such data continued to be monitored during and after the remediation to provide both real time data on the progressive effectiveness of the cut off, and on its long-term efficiency. Later in the remediation process, a new series of 20 shallow monitoring wells (OV Wells) was located about 15 feet (4.5 m) upstream of the cut off, to again help define the short and long term hydraulic impact of the cut off.

3.3 Selection of Cut Off Methodology

The goal of the program, as set by the Owner, was to reduce the total inflow into the quarry to an economically pumpable 8000 gpm (30,300 L/min) with the quarry completely dewatered. Later data would indicate this would require reducing the flow from the river to below 3000 gpm (11,400 L/min)

Three specific remediation options were considered:

1. Identify the specific solution cavities in the river and seal them there.
2. Construct an intercepting cut off at some appropriate location between river and quarry.
3. Treat the problem close to the quarry.

Option 1 was dismissed due to the demonstrated interconnection of the various entry points in the river, and the lengthy process needed to secure construction permits from the State environmental agencies, Corps of Engineers, and so on. This option was also felt not to offer opportunities for a methodical, engineered approach.

Option 3 was also dismissed since it was felt that the flow could bypass a near-quarry curtain and simply enter the quarry by exploiting different routes akin to the deltaic mouth of a major river. It would also be practically impossible to verify the extent and any deficiencies in a cut off. In addition, a cut off close to the quarry could hinder or be damaged by future mining activities.

Option 2 was clearly favored, on logistical, technical, and environmental grounds, and it was decided to locate the cut off on a convenient road side location about 50 feet from the river bank (Figure 1).

The nature of the ground (containing incipient, potentially erodible karstic material) and the anticipated length and depth of a cut off, suggested initially either a diaphragm wall or a wall comprising large diameter overlapping piles (Bruce and Dugnani, 1996.). However, studies revealed that both were practically impossible, financially prohibitive, and overly time consuming. The decision was therefore taken to construct a grout curtain as the cut off, designed to both treat cold karstic features and permeate fissured rock in a preemptive fashion, and to create a permanent "plug" to the water inflow in the "Red Zone" as the active solution.

Immediately, installation began of vertical "exploratory holes" drilled in two parallel rows, 10 feet (3 m) apart along the proposed grout curtain location. The holes in each row were 20 feet (6 m) apart and staggered to provide therefore one hole every 10 feet (3 m). These holes were drilled initially for investigation and later used for grouting. The geological and hydrogeological data from these holes were interpreted to confirm the lateral and vertical boundaries of the treatment and the respective locations of the "cold" and "hot" karsts. Soon it was established that the curtain would conceptually extend laterally for at least 1100 feet (335 m) and vertically as much as 220 feet (67 m) to ensure continuity with relatively competent, impermeable bedrock below and beyond the karsts enclosed within the "White Line".

3.4 Selection of Grouting Concepts

The main challenges facing the construction of a successful grout curtain were: the very high velocity and rate of the flow, potentially through multiple conduits; many of the karstic features were mud-filled, creating the possibility for erosion, piping, and so "blow out" after curtain placement when the hydraulic gradient acting across it began increasing; and the possibility of grout migration "upstream", into the river.

Several grouting related technologies were therefore studied to provide the curtain, in part or in whole jet grouting; polyurethane injection; Low Mobility Grouting ("compaction" grouting); hot bitumen injection; accelerated cement based slurries; use of the MPSP system; and geotextile grout-filled bags. Each technique was assessed based on technical feasibility, likelihood of successful treatment of the inflow in both short and long terms, and cost, given the very severe geological and hydrogeological regimes to be accommodated. In summary, it was determined to first treat the "Cold Karst" zones with Low Mobility Grout (LMG) and slurry grouts via the MPSP system (Bruce and Gallavresi, 1988) using slurry grouts; and then treat the "Hot Karst", i.e., the zones were water flowed, with hot bitumen from the downstream row of holes, backed up by slurry grouts simultaneously injected from the upstream row via the MPSP locations.

The use of grout-filled geotextile fabric bags (Bruce and Bell, 1983) was considered to be potentially valuable for dealing with specific local features. The use of Low Mobility Grout (LMG) for karstic remediation is well known (e.g., Byle, 1997; Cadden et al., 2000) as are the details of slurry grouting. However, the following discussion relates to the less well-known technologies of hot bitumen and MPSP.

Hot bitumen grouting involves the injection of roofing grade bitumen when heated to a liquid state (over 200°C). Hot bitumen is ideal for high velocity water flow conditions, because as the fluid bitumen comes in contact with the colder, flowing water, it is rapidly cooled and so forms a very viscous mass with a semi-rigid skin. If the volume of water flow is large, the bitumen cools relatively quickly and forms a plug directly where the inflow is greatest. Although it is ideal for stopping flowing water, in-place hot bitumen grout remains slightly visco-plastic in a hardened state and is therefore susceptible to creep, and potentially, therefore to extrusion. Moreover, bitumen tends to shrink by as much as 10% as it cools and hardens, and so may permit residual flow paths around the edges of the plugs. Bitumen must therefore be injected simultaneously with cement-based slurries, which travel to these flow path areas to jointly create a permanent plug. Due to the relatively low cost associated with bitumen materials (approximately 35 times lower than polyurethane grout), and its suitability for treating high magnitude flows, bitumen was chosen as a primary technology for the construction of the grout curtain in high flow conditions. Such concepts are not new but have reached new prominence in fast flow applications in recent years (Bruce et al., 1998).

The MPSP (multiple packer sleeve pipe) system is applicable to highly variable collapsible and fractured formations such as encountered here. Geotextile bags are attached around plastic or steel sleeve pipes at specific locations. The bags are then inflated with cementitious grout after the pipes are placed in drill holes, and so act as packers that divide the annulus surrounding the sleeve pipe into specific sections or zones. In this manner, highly fractured or voided zones can be isolated from more competent zones. The formation grouting is conducted by means of a packer placed at successively higher levels within the sleeve pipe. The MPSP system was originally designed for permitting controlled treatment of badly fissured, unstable rock masses.

As a final general point, the grout injection strategy adopted involved conceptually channeling the inflow into the “Hot Zone” in the center of the curtain. Therefore, the LMG and slurry grouting processes progressed simultaneously from the north and south ends of the curtain inwards, and were also conducted in the underlying “Cold Karst” all along the curtain, prior to then conducting the bitumen operation in the “Hot Zone,” to hopefully stop the concentrated flow.

4. Evolution of the Remediation Program

During the execution of the cut off, new geological data were continuously generated through the analysis of the drilling, grouting, and piezometer well data. In particular, the time-related performance of the curtain at its various stages of completion could be assessed and future directions of the program dictated. The successive phases of the work are summarized in Table 1. It is important to note that the need for, and nature of, each successive phase of treatment reflected a decision based on the consensus of all the stakeholders: owner, consultant, and contractor. For example, the bitumen injected in Phases II through V was used to seal especially large remnant flow paths discovered while conducting LMG or slurry operations. In contrast, the bitumen operations in Phases I and VI were conceived from the beginning as an integral part of the treatment program.

5. *Aspects of Construction*

5.1 Drilling

Throughout the evolution of the project, numerous overburden/karst drilling systems were used together with various drilling rigs. Drilling to depths in excess of 50 feet (15 m) in karstic limestone invariably poses drilling problems, to which the keys are flexibility of response, appropriate methods and equipment, and experienced drillers. Systems ranged from pre-drilling with a down-the-hole hammer and driving 6-inch (152-mm) diameter temporary steel casings, through rotary drilling with end of casing flush, to rotary-percussive duplex drilling (Centrex system). The Centrex system, when powered by a rotary percussive diesel hydraulic track rig proved by far the most effective to depths in excess of 140 feet (43 m).

5.2 Grouting

5.2.1 Materials Mix Design and Delivery Systems

The LMG developed by Phase IV proved relatively inexpensive to produce and had optimal washout resistance and good pressure filtration characteristics (Table 2). A similar intensity of bench and field testing through a succession of mixes, finally produced the suite of slurry grouts shown in Table 3.

Table 2: Final Low Mobility Grout (LMG) Mix Design

INGREDIENT	QUANTITY
Water	Approx. 50 gal (190 L)
Cement	350 lb. (160 kg)
Flyash	350 lb. (160 kg)
Sand	2100 lb. (950 kg)
Antiwashout agent: UW450	100 fl oz. (3 L)
Polypropylene Fiber	3 lb. (1.4 kg)
Maximum Slump	<2 in (50 mm)

Table 3: Mix Designations.

INGREDIENT	**A0**	**A1**	**A2**	**A3**	**A4**
Water (gal/L)	82/310	106/401	103/390	105/397	102/386
Bentonite* (gal/L)	68/257	20/76	26/98	26/98	25/95
Cement (lbs/kg)	729/331	856/389	878/399	895/406	866/393
Flyash (lbs/kg)	638/290	749/340	768/349	783/355	866/393
UW450 (fl. oz./ml)	19/562	22/651	22/651	23/680	22/651
Dispersant 2000B (fl. oz./ml)	62/1833	73/2159	74/2188	76/2247	73/2159
Marsh Time (sec)	55	80 - ∞	120 - ∞	∞	∞
Bleed %	0	5 – 6	2 – 5	2	2
Specific gravity	1.53	1.55	1.6	1.63	1.64

* 8% Bentonite Slurry (prehydrated 24 hours)

The quarry produced the LMG at its batch plant and it was trucked in 9 yd^3 (7 m^3) loads to the curtain. The grout was then injected with modified concrete

pumps through 3-inch (76-mm) injection lines to steel casings as they were withdrawn from maximum depth.

Slurry grouts were also prepared in the batch plant and were delivered by truck to agitation tanks which fed centrifugal and moyno pumps. The MPSP system comprised 3-inch-diameter (76-mm) PVC pipes with grouted geotextile bags at 25- to 30-foot (7- to 9-m) vertical intervals. As for the LMG, all major slurry grout injection parameters were recorded and displayed in real time.

The bitumen monitoring and injection plant was specially developed by the contractor for this project. Hot bitumen was supplied in 19 yd^3 (14.5 m^3) tanker trucks and pumped to a heated reservoir tank. The material was then drawn through the containerized control/pumping plant where pump rates were controlled and all relevant injection data were displayed and recorded. The bitumen was pumped through insulated and heat traced field pipeline to the curtain injection points – specially developed steel “stingers” placed in the ground in a fashion not dissimilar to the slurry grout MPSPs. Prior to injecting the bitumen in any one hole, the field piping and stingers were flushed with hot oil (vegetable) to raise the temperature to a level that would prevent the bitumen prematurely plugging the lines prior to reaching the discharge ports in the ground. Throughout the operation, modifications to this basic approach were continuously made to enhance control, responsiveness, and effectiveness leading to, for example, the development of special “stingers" which could allow simultaneous injection of both bitumen and slurry into the same hole concurrently, and enhanced pumping rates.

5.2.2 Procedures

Best industry practice procedures were used for injecting and controlling the LMG and the slurry grouts. For the former, upstage end of casing injection was conducted in appropriate stages to preset stage refusal pressure criteria, although injection in nearer surface horizons in Phase IV, did lead to occasional surface heave. The slurry grouting was conducted via double packers placed into the MPSPs, with each stage being brought to proper refusal by varying the mix rheology, rate of injection and pressure. Routine QA/QC tests were conducted on all mixes, and all injection parameters were continuously recorded and analyzed. Bitumen operations were conducted in very carefully coordinated lateral and vertical patterns, with as many as four holes being "active" at any one time. Total injection rates for the bitumen often averaged 33 yd^3/hr (25 m^3/hr) depending on the ground response.

Criteria for terminating bitumen injection on any one hole included

- The refusal of the adjacent upstream slurry grout holes.
- Attaining the theoretical volumes required to achieve the desired bitumen travel.
- The travel observed by monitoring temperatures in adjacent MPSPs with a well monitoring probe.
- The travel observed from leaks to or connection with surface.
- The data from the downstream monitoring wells. The pH and groundwater elevation readings in these wells were especially important sources of data.

6. Quantities

The quantities of drilling and grouting conducted in each phase are summarized in Table 4.

7. Impact of the Grouting Program on Quarry Inflow Characteristics

Throughout each phase of treatment, the following parameters were recorded and evaluated as a basis for real time direction of the grouting program, and as a guide to the design of the next phase:

- Ground water elevation, temperature and pH of downstream wells MWB-32, MWB-33, and MWB-34 through MWB-41 (Figure 1): these were found to have shown direct response to precipitation and river flow conditions. Other wells were not hydraulically connected and so provided "regional"/background data.
- Quarry water elevation and drawdown rates (and so a calculated total quarry inflow rate, due to flow from the river).

- Groundwater elevation, temperature and pH of upstream OV Wells (from Phase IV onwards).
- Visual observation of the river "eddy" and the pit "boil".

Table 4. Quantities of drilling and grouting conducted in each phase.

PHASE	**DATES**	**SLURRY GROUT**		**LOW MOBILITY GROUT**		**BITUMEN**	
		Holes	**Volume (m^3)**	**Holes**	**Volume (m^3)**	**Holes**	**Volume (m^3)**
I (Cold)	10/31 to 12/21/97	30	207	6	61	-	-
I (Hot)	12/14 to 12/21/97	22	1652	-	-	23	1270
II	1/9/98 to 2/24/98	51	1968	-	-	1	138
III	2/25 to 3/21/98	12	667	-	-	2	184
IV	4/14 to 5/23/98	1	24	120	1436	2	115
V	6/11 to 7/18/98	9	146	21	151	8	254
VI (Cement)	8/20 to 11/1/98	26	484	-	-	-	-
VI-A	11/1 to 11/23/98	11	417	-	-	15	1580
VI-B	12/16 to 12/19/98	11	900	-	-	7	1183
Totals	**10/31/97 to 12/19/98**	**173**	**6465**	**147**	**1649**	**58**	**4724**

A direct and successful intervention by grouting was detected by significant and quick changes in the piezometer data. Space prevents these data being described in detail: it may be reiterated however, that especially during the grouting operations, the assessment of these data in real time played a vital role in the tactical and strategic direction of the work in the field, when integrated with the relevant drilling and grouting data. Table 5 provides data on the clearest measure of success – the river inflow into the quarry itself.

Three months later the upstream piezometers had remained constant, the differential head was 135 feet (41 m) and the total flow from all sources was about 3000 gpm (11,400 L/min), confirming the existence of an efficient, durable curtain, even in such challenging conditions. The quarry was enjoying full production. Since then, the differential head has been increased to about 140 feet (43 m), and the flow remains minimal from the river. It can be estimated from the flow/head data in Table 5 that although flow rates of over 20,000 gpm (75,700 L/min) reestablished themselves soon after each of the first six phases of grouting, this flow rate was measured at ever increasing hydraulic heads. Thus, although residual flow rates remained high until the last phase of treatment, the

Table 5. Summary of inflow calculated as coming from the River.

Phase	**Flow from River (gpm)**		**Differential Head (ft)**		**Notes**
	At Start	**At End**	**At Start**	**At End**	
I	Approx. 40,000 reducing to 22,000	1,000	70 reducing to 30	30	Flow increased after treatment due to massive surface and subsurface clay erosion
		Rising back to 15,000 within 2 weeks of treatment ending		35	
II	Approx. 22,000	14,000		45	Erosion continuing
III	Approx. 20,000	15,000		60	Erosion continuing and flow redirected
IV	Approx. 20,000	2,000 to 3,000		90	Temporary success followed by “blow out”
		Rising to 17,000 in 48 hrs		95	
V	Approx. 25,000	9,000 to 10,000		110	Erosion in curtain between Sta. 650 and 800
VI-A	Approx. 20,000	15,000		115	Major flow path still undetected
VI-B	Approx. 18,000	Effectively zero		122	Major void found 100 ft down at Sta. 668 (took 400 m^3 grout)

1 gpm ≡ 3.785 L/min; 1 ft ≡ 0.3048 m

actual permeability of the overall karstic system was being, despite internal erosion, systematically reduced, thus allowing the quarry to lower the water level in the pit and so continue with production activities, pending the final sealing.

8. Final Remarks

This case history clearly illustrates many important features, but three are particularly noteworthy. Firstly, from the technical viewpoint, it is an illustration of how contemporary grouting technology can be used, if correctly designed, implemented, analyzed, and controlled, to provide a successful result in even the most adverse conditions. Secondly, however, is the message that all sources of information must be studied before and during such an operation in order to gain the best possible "picture" of what is really happening in the ground and the incremental changes actually brought about the grouting itself and changes in the hydrogeological regime. Thirdly, and perhaps most importantly, this project illustrated the need for all stakeholders to partner fully and openly, and to provide mutual support at all times and in all aspects. In such circumstances, patience and trust are vital ingredients to successful teamwork in arduous and stressful conditions.

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Keywords

Grouting, karst, remediation, hot bitumen, quarry, low mobility grouts, slurry grouts, curtain.

Table 1. Summary of work performed in each phase.

Phase	Purpose	Materials Involved	Stations Involved*	Notes
I I (Cold Karst)	Sealing of karst not conducting water	Slurry, and Low Mobility GroutH	500 to 1100	To over 200 feet depth
I (Hot Karst)	Sealing of flow through hydraulically-conducting karst	Slurry and bitumen	580 to 1040	
II	Southerly extension of "Cold Karst" treatment	Slurry, plus one bitumen hole (Sta. 1140)	1110 to 1590	
III	Reinforcement of "Hot Zone" to greater depths	Ten slurry, plus two bitumen holes (Sta. 870 and 830)	625 to 873	To 250 feet depth
IV	Treatment of overburden and weathered rock above previously treated rock mass	Low Mobility Grout, plus bitumen in two holes (Sta. 775 and 788)	526 to 1200	To maximum depth of 50 feet, especially from Sta. 760 to 820
V	Attempt to finally seal major new path	Low Mobility Grout, and slurry, plus bitumen (eight holes)	730 to 880	To maximum depth of 100 feet. Focus on Sta. 805 to 865, and 730 to 795
VI (Cement)	Permeation grouting to reinforce curtain followed by bitumen in remnant paths	Slurry	738 to 856	To maximum depth of 120 feet
VI-A		Slurry and bitumen	650 to 860	
VI-B		Slurry and bitumen	640 to 785	To maximum depth of 140 feet

*Stations are measured in feet from the northern extent of the curtain holes and running south (Figure 1) (1 ft ≡ 0.3048 m).

HLow Mobility Grout is referred to in the text as LMG.w