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Hot Bitumen Grouting at Lonestar Quarry

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ABSTRACT

Although still somewhat obscure and seldom utilized, hot melt grouts have for decades proven useful in stopping high magnitude inflows (Schonian & Naudts, 2003). In 2002, injection of hot bitumen in combination with low mobility and high mobility cement-based grouts succeeded in eliminating a 2205 ℓ /sec (35,000 GPM) inflow into the Lonestar Quarry in Cape Girardeau, Missouri.

By 2002, quarrying at the site had been active for over 100 years and the quarry floor at the locus of the inflow was more than 100 metres lower than prevailing grade. The source of the inflow was the nearby Mississippi River. Two principal inflow pathways were identified, each of them large conduits measuring as great as 6 metres wide x 9 metres high and centered 76 metres and 93 metres below prevailing grade, respectively.

Grouting holes were drilled on a line parallel to the quarry face, transverse to the strike of the inflow path and set back approximately 80 metres from the quarry face. Prior to hot bitumen grouting, several weeks and thousands of tons of cement were consumed attempting, unsuccessfully, to reduce the inflow. Once the program was eventually shifted to hot bitumen grouting, drilling and cement grouting operations were redirected to focus on flushing clean any sediment-filled, inactive features, and filling these with a competent grout in advance of the eventual hot bitumen grouting intervention. Concurrently, an array of new injection wells was drilled consisting of four hot bitumen injection wells, two low mobility cement-based grout injection wells and five high mobility cement-based grout injection wells, all for simultaneous use in a final assault on the inflow. This final assault, with hot bitumen injection playing the key role, succeeded in completely stopping the inflow within just seven hours of the start of grouting.

INTRODUCTION

The Lonestar Quarry in Cape Girardeau, Missouri, is located on a property that also contains a cement plant that ships bulk product direct to market via truck, bulk rail car and Mississippi River barges. During April 2002, a small leak developed and grew rapidly and to such an extent over the next 2 weeks that the quarry began to flood.

An investigative drilling and remedial grouting program was begun in mid May and continued until late July. This work was staged from a conveniently accessible strip of land at prevailing grade, offset 80 metres from the quarry face. During this phase of the work, the leak into the quarry continued unabated and the water level in the quarry continued to rise until, by late July, the quarry floor was flooded by over 35 metres (Figure 1). Drilling and grouting was performed with multiple drill rigs using duplex methods on an investigate-and-remediate, or "search and destroy", basis. As progress was made in delineating the subterranean limits of the inflow – ultimately determined to have as its source the Mississippi River at a point some 1000 metres distant from the quarry – no progress was made in reducing the inflow, despite injection of several thousand cubic metres of low mobility, cement-based grouts. The only ameliorating effect on the flow was the rising elevation of the quarry pond, but allowing total flooding of the quarry was not an option: if the quarry inflow could not be stopped before the water rose above the elevation of the existing crushing infrastructure, all production using existing equipment would cease and an alternate source of limestone would have to be found.

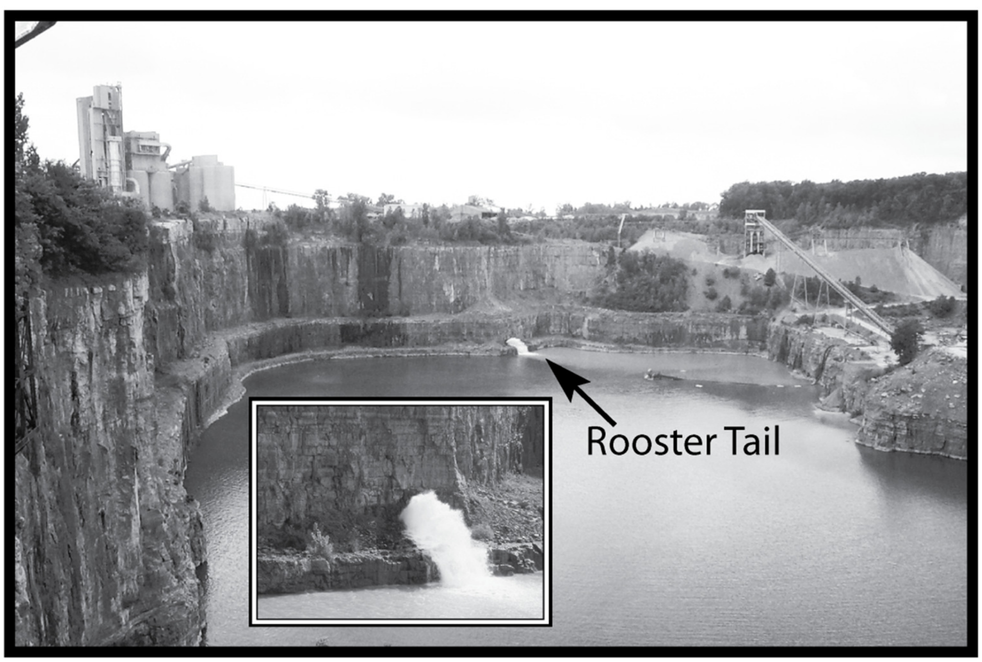

FIG. 1: Photo of the flooded quarry in late July 2002 (close up of rooster tail, inset)

Overburden at the site of the grout curtain ranges in depth from 7 to 16 metres. Due to the highly pinnacled bedrock-to-overburden interface and the high frequency of vertical fractures within the rock mass, much of the drilling work had to be performed with the added step of downstage grouting. Every time a grouting hole encountered a principal inflow pathway, grouting with even the stiffest of cement-based low mobility grout was ineffective due to washout. By late July, with the cost of the emergency work increasing with seemingly no tangible success, the decision to overhaul the direction of the work and change to hot bitumen grouting was made.

HOT BITUMEN GROUTING – DESIGN PRINCIPLE AND INJECTION TECHNIQUE

Hot bitumen grouting is a specific form of the generic category known as hot melt grouting. The bitumen is injected at 200° C to 225° C, at which temperature it is highly fluid. Unlike cement-based or water-reactive chemical grouts, the curing mechanism for hot melts is NOT driven by a time-dependent chemical reaction, but rather is thermally driven, independent of time. In the case of injection of grout into a subterranean chamber or conduit through which water is flowing, where there is simply not sufficient time for conventional grouts to gel before being diluted and/or washed away, a hot melt undergoes an instantaneous reaction due to the dramatic heat exchange that occurs upon contact with the flow. In the first moments of injection, the hot grout is indeed washed downstream, but it is not diluted; the viscosity of the grout increases dramatically as its temperature decreases, causing the grout to gum up, providing the onus for some of it to adhere to the sides of the inflow pathway (Figure 2). As more and more grout is injected, a bulb of grout forms around the injection point and, in combination with the grout adhering to the sides of the pathway, begins to block the inflow passage. Inside this bulb, as more hot bitumen is continuously injected and the heat exchange slows, an insulated core forms that is both hot and pliable. Meanwhile, at the outwards extent of the bulb, where the thermal gradient remains extreme as fresh inflow passes by, the grout becomes brittle

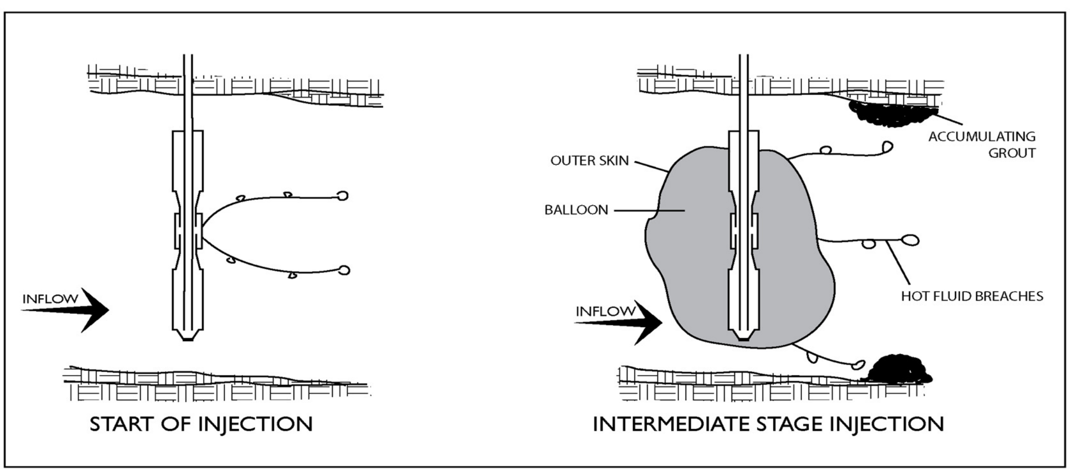

FIG. 2: Hot bitumen grouting principle, illustrated

and sticky. As the bulb grows, the outer crust is progressively and repeatedly breached by gushes of hot grout and the instantaneous curing mechanism – and its benefits – occurs again and again: more and more grout sticks to the sides of the inflow pathway under increasingly constricted flow conditions.

Recognizing that hot bitumen shrinks as it cools, cement-based grouts are injected via wells upstream and downstream of the hot bitumen wells to help stiffen the bitumen and to compensate for the shrinkage. Hot bitumen injection continues uninterrupted (possibly for several hours) even after a plug is formed and the inflow is eliminated, to ensure that hot, fluid grout is available in situ for flowing into any breaches of the newly placed plug attributable to the rapidly rising differential gradient across the grout curtain and the increased erosive power of the inflow in the early stages of plug formation. Similarly, cement grout injection upstream of the curtain also continues uninterrupted, sometimes for days, to fortify the hot bitumen plug, to compensate for ongoing bitumen shrinkage, and to fill to the greatest extent possible all the previously eroded (but now static) voids and conduits.

The greatest operational obstacle to success is establishing the initial flow of hot bitumen in situ. The attributes of hot bitumen that so strongly favour it as a hot melt grout also make it difficult to establish this initial flow. Since the injection typically requires small diameter casing, it is very easy to inadvertently "freeze" the grout in the delivery tubing before it exits into the target zone. To this end, maintaining a suitably high grout temperature prior to injection into the inflow is crucial. Freeze-preventing measures are engineered into the delivery system, and can include down-hole pre-heating and other special insulating measures to provide the greatest chance of success prior to establishment of hot bitumen grout flow.

CHARACTERIZATION OF THE LONESTAR INFLOW

The geology of the region is heavily karstic (Orndorff et al, 2001). The overburden-to-bedrock interface is highly pinnacled, and the rock mass proper contains innumerable solution cavities of varying sizes, extending to upwards of several metres in breadth and depth. Such cavities are often completely full of sediments or diagenically derived infill, and large networks of cavities, interconnected due to the prevalence of vertical fractures, are not uncommon. Prior to the inflow at Lonestar Quarry, the interconnected system of cavities and voids that would eventually transmit the inflow waters into the quarry were filled with sediment and groundwater, but were absent of any appreciable flow. The deeper quarry excavation was taken, the higher the hydraulic gradient (and consequently the higher the state of potential energy) across this sediment-filled void network.

At least two locations of inflow discharge into the quarry were known: the larger of the two, quickly obscured from view beneath the growing quarry pond, discharged at an elevation coincident with the floor of the quarry at 100 metres below prevailing grade, while the smaller of the two came to be known as "the rooster tail" (Figure 1). Via conversion of key drilling and grouting data such as large rod drops or runaway grout takes, and via study of published geological mappings of the area, it was determined that the entirety of the inflow was bound within two strata, both dipping at 6^{o} (from river to quarry), with their uppermost limits (at the grout curtain) at 70.1

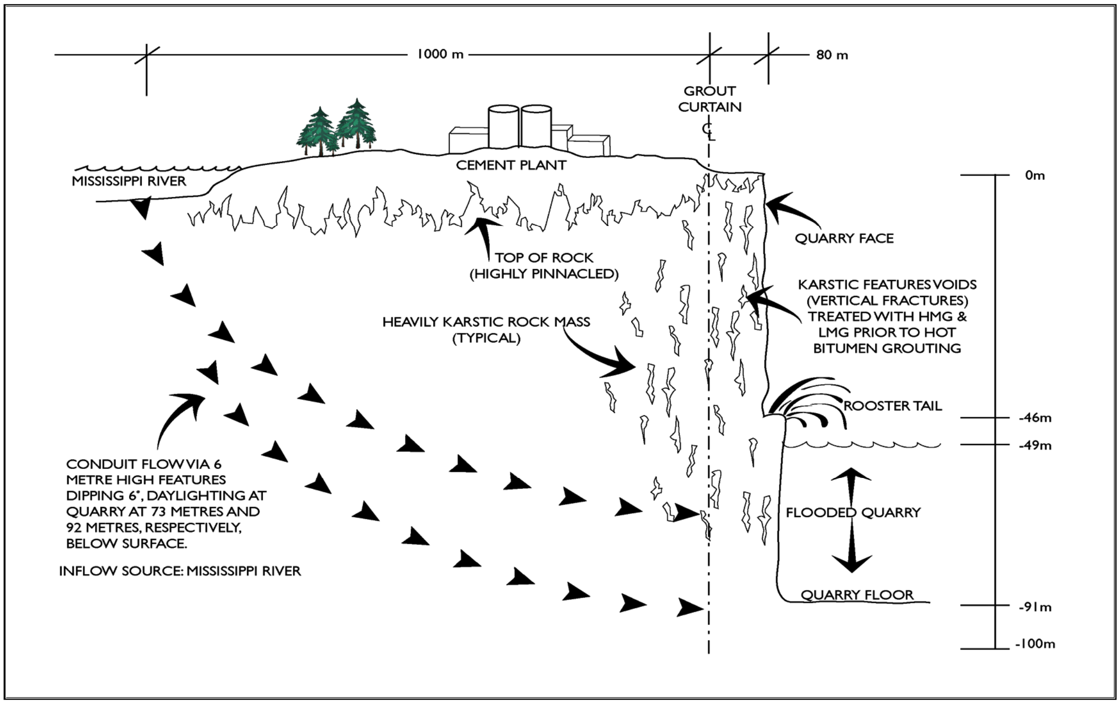

FIG. 3: Illustrated characterisation of the Lonestar Quarry inflow

metres and 88.5 metres below ground surface, respectively (Figure 3). Modeling of the rate of rise of the quarry pond compared with the rate of pump discharge enabled the inflow to be estimated at 2205 ℓ/sec. Finally, from the inflow's thermal signature – water from the Mississippi River is several degrees warmer than the prevailing static groundwater regime – the Lonestar inflow was diagnosed as being wholly attributable to conduit flow (as opposed to diffuse flow). Once this was recognized, the drilling and grouting focus undertaken up to that point in time was abandoned in favour of hot bitumen injection.

HOT BITUMEN GROUTING – THE LONESTAR QUARRY PRESCRIPTION

Once the decision was made to switch to hot bitumen grouting, the established, cement-based, investigate-and-remediate drilling and grouting focus was immediately replaced with a methodical approach consisting of 1) drilling and grouting to flush and fill any and all features not connected to the inflow, 2) drilling to construct LMG (low mobility cement-based grout), HMG (high mobility cement-based grout) and hot bitumen injection wells for simultaneous use in eventually creating the plug starting on "Grouting Day", and 3) Grouting Day itself, during which the plug would first be created via injection of hot bitumen, LMG and HMG, then fortified by injecting HMG upstream of the plug.

Pre-treatment of the Overburden and Rock Mass

Systematic drilling and grouting of the overburden and rock mass was performed with the purpose of consolidating the formation. This aspect of the program was undertaken with the knowledge that simply creating a plug could prove only temporary if no effort was made to first tighten the formation to prevent future piping or flow around the plug. This was perhaps the greatest lesson of past hot bitumen interventions in similar terrain (Bruce et al, 2001): if the surrounding rock mass is left untreated before constructing a plug, the intervention is susceptible to future failure, not from failure of the plug itself, but from the water finding alternative pathways around the plug. The tightening of the formation also reduced the operational risks of sinkhole formation and hot bitumen escaping to surface; sealing flows in karst is susceptible to formation of sinkholes due to erosion and rearrangement of the inflow induced by grouting.

Drilling of Injection Wells & Piezometers

In parallel with formation treatment, drilling of new injection wells was undertaken with primary focus on directly intersecting the conduit flow in order to most advantageously locate the hot bitumen injection and LMG injection wells.

The eventual injection well array – all holes were drilled plumb and packed off a minimum of 6 metres into sound rock – is depicted schematically in Figure 4. The arrangement of the array was not predetermined at the outset of drilling, but rather

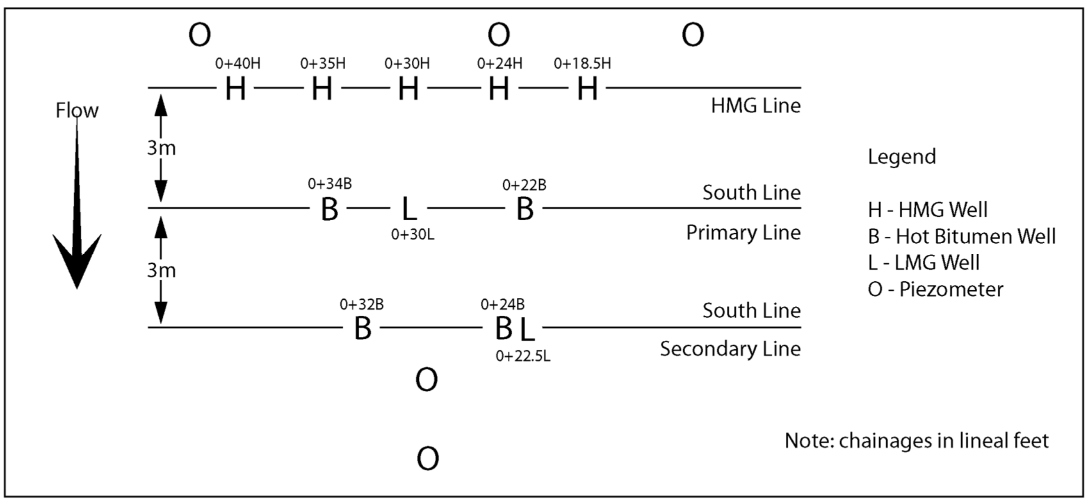

FIG. 4: Schematic plan view of "hot" piezometers and grout injection wells

evolved as the worst of the inflow pathways were confirmed or newly discovered during this new phase of drilling. The LMG injection wells – located on the same basis as the hot bitumen wells: where the worst inflow-connected voids were encountered during drilling – were positioned immediately downstream or adjacent to the hot bitumen wells. Of the six total hot bitumen and LMG wells, three were constructed within re-reamed holes where previous episodes of cement-based grouting had been conducted without achieving refusal. After the position of the fourth and final hot bitumen injection well was established, a grid of HMG injection wells (5 total) was drilled, offset approximately 3 metres upstream from the nearest hot bitumen injection well.

The final task of this drilling phase in preparation for grouting day was to increase the grouting team's ability to evaluate the response of the inflow during and after hot bitumen injection by complementing the 3 confirmed existing "hot" (connected to the inflow) piezometers with 2 additional installations. The final array of piezometers connected to the inflow consisted of 3 downstream and 2 upstream of the grout curtain.

Fabrication and Installation of the Hot Bitumen Injection Wells

The piping assemblies inserted into the hot bitumen injection wells are represented schematically in Figure 5. Each injection assembly was comprised of two principle segments: an insulated, non-sleeved segment that extended from ground surface to the top of the injection zone, and a sleeved segment with sleeved injection ports

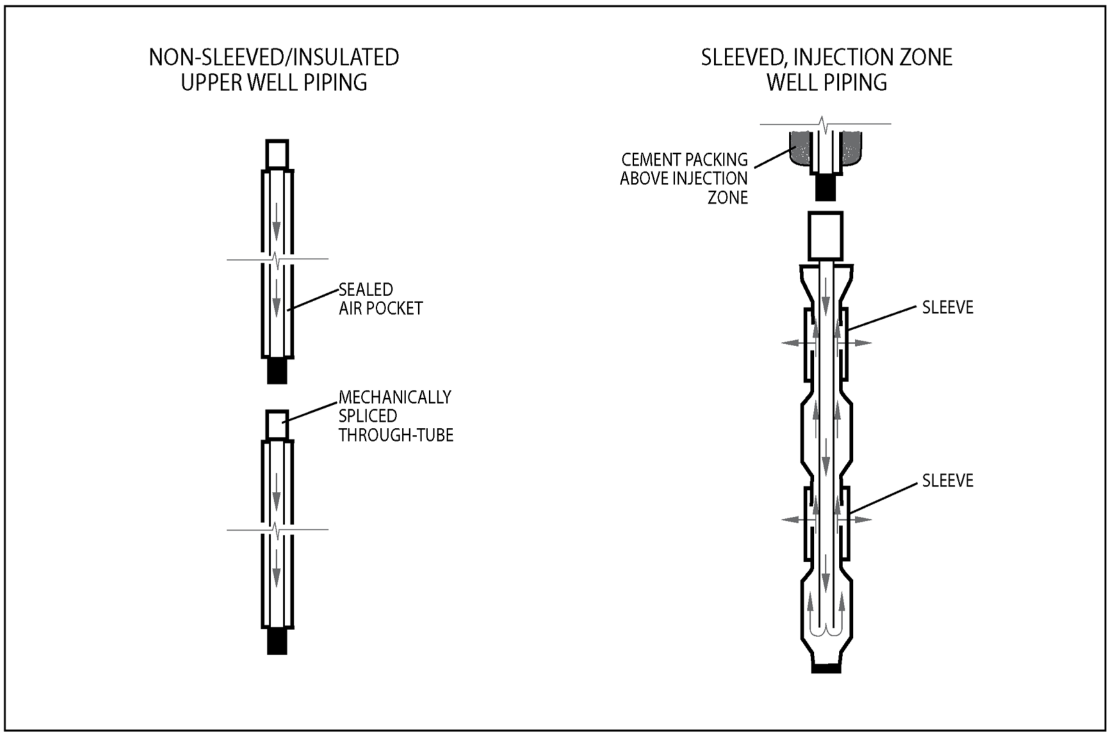

FIG. 5: Schematic representation of hot bitumen injection piping assembly

spaced strategically over the length of the assembly throughout the injection zone. Each well's injection zone was tailored to the information obtained during drilling, but for the most part the wells' injection zones extended from 60 metres to 105 metres below grade. The non-sleeved extent of the piping assembly was of double-concentric steel pipe construction, with 6 metre long "pods" of 61mm through-pipe surrounded by 115mm outer pipe, with a sealed layer of air between them to insulate the through-pipe. The sleeved extent of the piping assembly consisted of injection ports, each covered by a rubber sleeve to allow grout to be forced out of the pipe while not allowing ground water in to the pipe prior to commencement of grouting. A key design requirement of the double-concentric construction is that before the hot bitumen can flow outwards, it must first travel all the way to the bottom of the well and then back upwards to the injection sleeves. This way, the hot bitumen flowing through the piping assembly acts to heat the injection assembly at all times. This design evolved directly from first generation, monotube injection assemblies that contained a key shortcoming in that, if the upper sleeves were located in open features then the majority of hot bitumen was injected through these sleeves, allowing the lower sleeves to freeze before any bitumen could be injected, resulting in potentially groutable features that were never grouted.

Construction of these assemblies required two steps: shop fabrication and field assembly. Shop fabrication involved preparation of the double-concentric sleeved and non-sleeved components of the assemblies in 6 metre segments and included negative air pressure testing as a proxy for the stresses acting on the sleeves at depth. In the field, down-hole fabrication involved mechanical splicing of the 61mm through-pipe and butt weld splicing of the outer shell layer throughout the injection zone. As a final quality control undertaking, every hot bitumen well was checked daily after its installation to ensure there was no fouling of the pipe assemblies via groundwater ingress past any of the sleeves.

Hot Bitumen Grout Plant

The hot bitumen injection plant arrived on site self-contained within a standard 6.0m x 2.5m x 2.5m shipping container. The container's contents included:

- three positive-displacement Viking gear pumps powered by 25 HP electric motors for injecting the hot bitumen, each pump capable of injecting as many as 20 m^3 of grout per hour, and each outfitted with a spring-loaded safety valve set to bypass at 830 kPa (120 psi) discharge pressure
- three variable-frequency drives – one for each hot bitumen injection pump – that allowed pinpoint control of hot bitumen injection rates
- a control room with computer readouts of temperature, discharge pressure, instantaneous flow rate and totalized flow for each hot bitumen injection pump
- a heat-traced network of hard-plumbed piping and valves engineered for crossover capability and flexible suction options, and complete with 2 discharge headers individually instrumented to transmit and display temperature and pressure
- several dozen steel-braided flex hoses (50mm, 65mm and 75mm diameter), spiral-wound gaskets, gate valves, stainless steel camlock fittings, Class 2000 couplers and elbows, and other field piping accoutrements

Accompanying the self contained plant were a 350 ℓ capacity, electric immersion tank for heating and storing hot vegetable oil for use in priming the hot bitumen wells immediately prior to hot bitumen injection, and a direct-fire-heated, 28m^3 capacity hot bitumen reservoir. The plant, wired for 600VAC electric power, was powered by a portable 225 kW diesel generator set.

Delivery Logistics

The hot bitumen grout used at the Lonestar Quarry intervention was Type III (per ASTM D312), or roofing asphalt (flash point 274°C; softening point 90°C). This material is less susceptible to long term extrusion and creep than its more common cousin, Type II, or road grade asphalt. Important to the consideration of its use as a grout for the Lonestar Quarry intervention was that Type III bitumen is commonly

only manufactured during limited runs and the closest bitumen refinery to the project was in St. Louis, a 150 minute journey by truck during non-peak driving times. Exhaustive preparations were necessary to ensure an adequate supply of hot bitumen grout for both the start and the progress of grouting, and for good reason: if the operation ran out of grout in mid operation, this would certainly eliminate any chance of creating a plug. In order to ensure an adequate supply:

- Hot bitumen was supplied direct to site from the refinery in St. Louis via a fleet of $21m^3$ capacity tanker trucks
- On-call haulers were arranged in the event that the duration of hot bitumen injection extended beyond 16 hours
- A supply agreement was negotiated that compensated both the refinery and the hauler for any load put on the road that was delayed or ultimately turned back unneeded
- A direct-fire heated reservoir was used to create a buffer between real-time fluctuations between delivery rates and consumption
- Professional asphalt handlers were employed at the site of the grouting to transfer loads from incoming trucks to the on-site hot bitumen reservoir
- Grouting day was scheduled for a Saturday with back up day Sunday to miss peak traffic and to mobilize a suitably large fleet of trucks from those that would otherwise be busy hauling road asphalt or serving the conventional roofing asphalt market
- The first few trucks of hot bitumen were ordered at the hottest that the refinery could put out to provide a hedge against the highest risk time of injection – at the very start

In addition to these supplier-related preparations, at the operations level offside shifts were established to allow for injection on a continuous, 24-hour basis, for several consecutive days if necessary.

Safety Considerations

On top of the usual hazards associated with a pressure grouting operation, hot bitumen grouting poses additional, extreme hazards. Aside from the obvious dangers of working with extremely hot material, there are all the hazards associated with subsiding ground and sinkholes, as well as ground heave and surface eruptions of hot bitumen.

So great was the onus on safety that all grouting site personnel – whether members of the hot bitumen injection team or not – were subjected to rigorous training, consisting of both classroom study and on-site rehearsal of both normal operating procedures and contingency plans. A project manual was created to assist learning in the days leading up to hot bitumen injection. For the team of workers and technicians that had direct roles in the hot bitumen injection operation, specific and rigorous training was completed before any such individual could earn “Hot Zone” clearance. A Hot Zone perimeter was delineated on site and only authorized personnel were allowed entry. Each Hot Zone worker was outfitted with fire-retardant coveralls, temperature resistant gloves, safety glasses and full face shield. Numerous dunk tanks filled with ice water were stationed within steps of the hot bitumen injection wells and the hot bitumen reservoir for use in the event of a splash or immersion mishap.

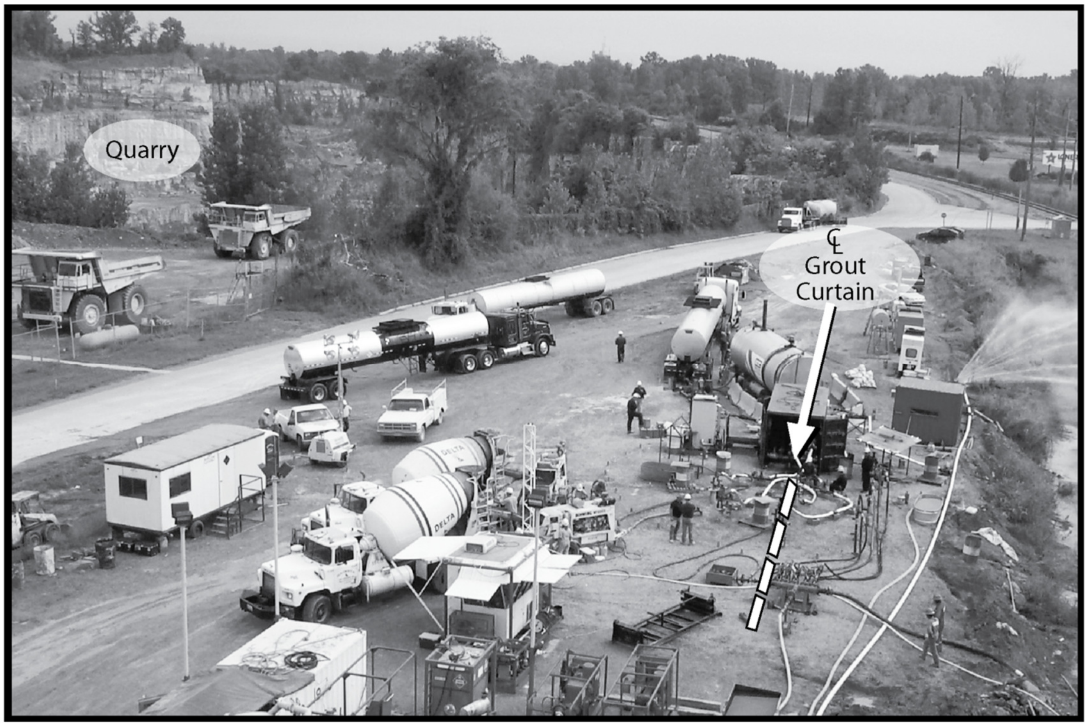

FIG. 6: Project site on Grouting Day

GROUTING DAY

Grouting Day – August 24, 2002 – saw the culmination of four weeks' intense preparation and coordination. Figure 6 shows the site moments prior to the commencement of grouting. Despite having made preparations to grout for more than 72 straight hours if necessary, the inflow was completely stopped a mere 7 hours after the first drops of hot bitumen were injected.

Collection and Reporting of Information from the Field

A command center was installed on site to receive real time reports from all stations and to track, in real time, the progress of grouting and its effects on the inflow. All grout-related data were relayed to the command centre verbally. As for readings of remote field data, numerous such stations were inspected and reported hourly by radio to the command centre by a team of roving technicians who took depth and pH readings from all 5 hot piezometers, took precision survey readings of the quarry pond surface elevation, and visited the rooster tail to observe its color, take its pH, and estimate changes in its magnitude.

Commencement of Injection

Grouting commenced with the injection of a slug of hot oil down Well B1, at 08:55 hours local time. This slug was followed moments later by hot bitumen, and it was quickly apparent that the hot bitumen successfully traveled all the way to the bottom of the 100 metre deep well before returning up the outside of the through-pipe and out past the sleeves to enter the inflow torrent.

As soon as it was confirmed that hot bitumen was flowing through and out of Well B1, LMG injection commenced on L2. As could reasonably be expected considering the proximity of the two wells, L2 refused after only 37 minutes and 7 m^3 of LMG injection. In some respects, it could be considered surprising that this well, that had previously consumed several hundreds of cubic metres of LMG without any suggestion of ever being able to meet refusal, could refuse so quickly. However, it is easier to picture the refusal of L2 when one considers the effect of the hot bitumen (still hotter than 200^{o} C in situ) on the LMG after the two were undoubtedly forcibly mixed together at the location of LMG injection.

Once successful hot bitumen flow was confirmed at the second well, B2, HMG injection was commenced and shortly thereafter all HMG wells were on line.

Response of the Inflow to Grouting

The totalized grout injection volumes and their effect on the inflow are plotted against time on Figure 7. Just 2 hours after the start of grouting, a prominent response was evident from the piezometer network. Although the rooster tail magnitude appeared more or less unchanged, the color of its turbid water had turned gray from cement washout and there were small (10 cm) streamers of bitumen afloat in the pond. By 4 hours after the start of grouting, the rooster tail was noticeably smaller and the response of the piezometers was unmistakably representative of the plug beginning to form: groundwater in the hot piezometers downstream of the curtain began to drop sharply while the inflow-connected groundwater regime upstream begin to rise sharply. By the time hot bitumen grouting had been underway for 7

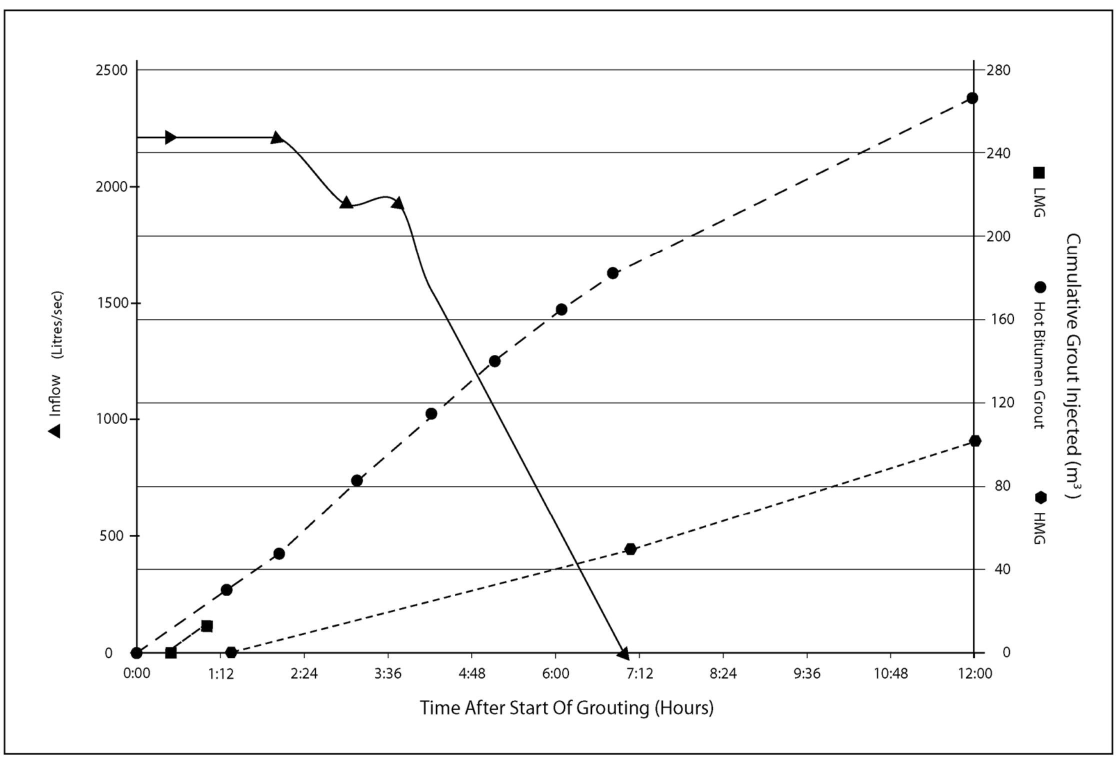

FIG. 7: Change in inflow magnitude in response to grouting progress

hours, the various field reports all corroborated the news that the plug had been successfully constructed and the inflow, for the immediate time being at least, had been completely eliminated.

Continuation of Grout Curtain Construction after Formation of the Plug

Despite the welcome news that the inflow had been completely stopped, hot bitumen injection and HMG injection continued unabated, as planned, for several more hours. In the case of hot bitumen injection, the motivation for continuing was to make absolutely certain not to lose the ability to intervene should the rising driving head on the upstream "face" of the grout curtain find a means of circumventing the plug and re-establishing the inflow. In the case of HMG injection, there would be no more opportune time to inject as much grout as possible into the residual flow channels upstream of the newly formed plug, considering that the bitumen would continue to shrink for several days to come.

As had been feared, but not wholly unexpected, the continuation of hot bitumen injection long after elimination of the inflow – even at the drastically reduced rate of just more than 1 m^3 per hour – gave rise to two separate surface eruptions. Small geysers of steam preceded the slow, lava like flow of bitumen at surface. The loader and operator that had been on standby all day waiting for such a scenario took action and quickly constructed berms to contain the spills. These spills, envisioned during safety scenario planning, were managed through the early night hours until 18 hours after start of grouting when all further hot bitumen injection was ceased. The total injected volume of hot bitumen grout (through all four wells) was 283 m^3.

HMG injection continued through the night and into the next morning until, at 28 hours after the start of hot bitumen grouting, the last HMG well refused after a total injected volume of 212 m^3.

Table 1 details, in chronological order, notable events and key grouting milestones achieved over the duration of Grouting Day.

CONCLUSIONS

The total elimination of a 2205 ℓ/sec inflow that had heretofore stymied the best conventional grouting efforts for months was achieved in just 7 hours after injecting 185 m^3 of hot bitumen in conjunction with 61 m^3 of cement based grouts.

The success of this hot bitumen grouting intervention can be attributed to several factors, key amongst these:

- By the time the hot bitumen grouting took place, the inflow pathways were very well characterized and the surrounding ground above, beside and below the conduit flow had been methodically flushed clean and fortified, so ensuring avoidance of any post-plug blowout.
- A commercially equitable arrangement was reached with a major hot bitumen manufacturer and a reputable delivery subcontractor, so ensuring an adequate supply of hot bitumen.
- The drilling works at this site were undertaken using properly outfitted duplex drill rigs, key to the successful drilling of hot bitumen injection wells to the

TABLE 1: Operational chronology of notable and key events on Grouting Day

Hours after start of grouting	Event / Comments
-2:00	Arrival of first 2 trucks of hot bitumen; transfer 1.5 truckloads into reservoir
-0:30	One last safety talk for all dayshift Hot Zone personnel
-0:08	Prime surface piping by discharging hot bitumen into open-top 200 ℓ drums
-0:05	Commence hot oil injection at B1
0:00	Commence injection of hot bitumen at B1
0:09	Commence hot oil injection at B2
0:13	Commence hot bitumen injection at B2
0:15	Commence low mobility grouting at L1
0:30	10m3 injected to date at B1
0:38	Commence low mobility grout injection at L2
0:52	Refusal on L1 – 7 m^3 total injected
0:57	Refusal on L2 – 4 m^3 total injected; Low mobility grouting operation demobilized from site
0:58	Bitumen streamers and cement washout showing up at rooster tail; no decrease in rooster tail flow
1:00	19.2 m^3 hot bitumen injected to date on B1; 8.7 m^3 injected to date on B2
1:01	Hot bitumen injection commenced at B4 – no hot oil slug used
1:05	First set of hourly piezometer readings showing some flutter on opposite sides of grout curtain
1:22	Commencement of high mobility grout on all upstream H-series wells
2:00	Hot bitumen injected totals to date: B1 = 25.8 m^3; B2 = 15.4 m^3; B4 = 7.9 m^3
2:05	2nd set of hourly piezometer readings show marked fluctuations – some blockage of flow taking place
3:00	Total hot bitumen injected to date at 3 wells = 84.2 m^3
3:10	3rd set of hourly piezometer readings show distinct signs of plug formation – inflow drastically reduced
4:00	Total hot bitumen injected to date on 3 wells: 117.5 m^3
5:00	Total hot bitumen injected to date at all wells: 145.1 m^3
5:05	Field inspection report: strong piezometer response, rooster tail reduced to ¼ flow of cement-rich water
6:00	Total hot bitumen injected to date at all wells: 165.3 m^3
7:00	Total hot bitumen injected to date at all wells: 184.5 m^3
7:10	**Field reporting confirms inflow reduced to zero; rooster tail flow zero, head in quarry dropping at 50mm per hour; downstream piezometers mimicking quarry pond**
7:10	High mobility grout injected to date on all wells: 50 m^3
11:20	Hot bitumen leak to surface at B2 – direct connection, injection ceased after 64.4 m^3 total injected on B2
13:00	Hot bitumen injection commenced on B3
14:30	Leak to surface at B4 – injection ceased after 68.0 m^3 total injected on B4
16:41	Hot bitumen injection ceased at B1 after total 144.0 m^3 total injected on B1
17:51	Final drops of hot bitumen injected – total injected on all wells 282.7 m^3
28:00	High mobility grout injection ceased – total injected 212 m^3

full depth (105 metres) necessary through highly karstified rock with numerous vertical fractures and high, open void systems.

- The hot bitumen specialist practitioners were able to parlay their collective past experience with high magnitude inflow grouting in similar terrain into success at this project with very little time consuming trial and error.
- Design and implementation of a second generation down-hole hot bitumen injection piping arrangement enabled the successful injection of bitumen 100 metres below ground surface.
- The strong focus on pre-job planning and implementation of thorough safety measures helped to ensure that this undertaking, replete with extreme hazards to worker safety, was completed without incident.

This project demonstrates the potential usefulness of otherwise extreme specialty grouting techniques for overcoming seemingly insurmountable subterranean inflows.

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