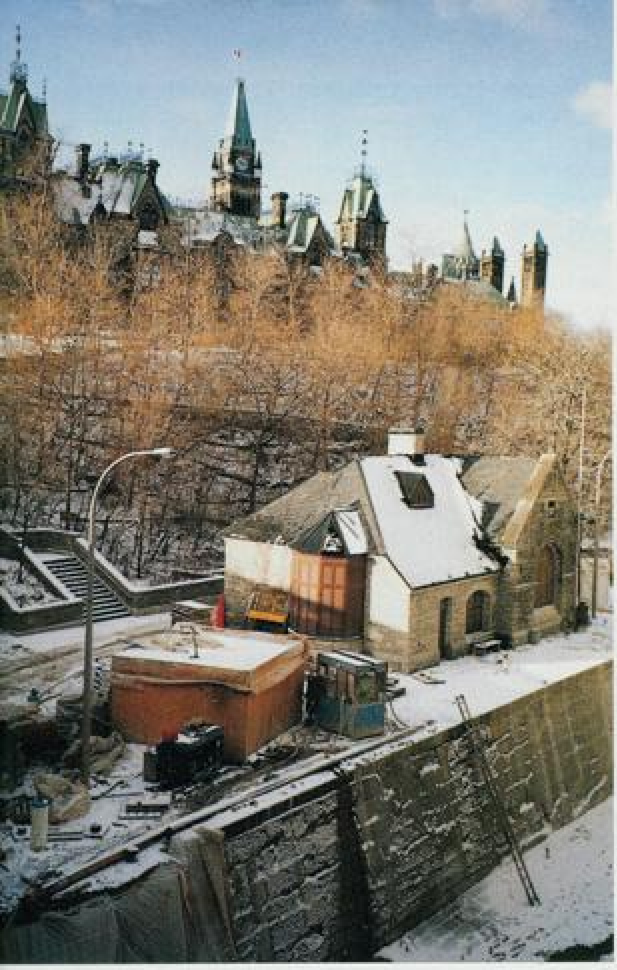


Grouting technology improves structure

Restoration of Rideau Canal Historical Locks

by Luigi Narduzzo and Alex Naudts

North America's historical structures are becoming an endangered species. Professional grouting has proven to be a technically viable and economically attractive engineering technique for the rehabilitation of buildings and structures. Such a state-of-the-art grouting approach was used for the rehabilitation of the historical locks on the Rideau Canal. Grouting reduces permeablity of the structures, increases their structural integrity, and preserves their historical character.

Historical perspective

The authorities in charge of the maintenance of the nearly fifty historical lock structures on the Rideau Canal, located in Ontario, Canada, were first introduced to professional grouting in 1989 during a pilot program implemented at the Kingston Mills Locks at the southern end of the Rideau Canal. The lockwalls and monoliths, built in the mid-1800s, consist of large limestone blocks (each about 0.45 m high x 1.30 m long x 0.90 m deep) with a composite limestone rubble-mortar backwall. The face of the lockwalls and monoliths are lined with facing stones of similar dimensions but only 0.30 m in depth. Over time, navigation operations has led to water washing out fine mortar particles from within the massive walls and floors, creating channels for internal erosion and causing severe deterioration of the lock structures. Often restoration has meant new, look-alike structures would be built, but the tragedy of this approach is that it ruins their historical authenticity as well as their heart.

Since 1989 six locks on the Rideau Canal system have been restored by properly engineered, hands-on supervised grouting programs:

- in 1990-91, Hartwell's Locks 9 and 10, located just west of Carlton University in Ottawa;
- in 1991, Upper Beveridge's Lock 34 on the Tay Canal between Smiths' Falls and Perth, Ontario;
- in 1992-93, Ottawa's Locks 6, 7, and 8, located between Parliament Hill and Chateau Laurier in downtown Ottawa.

These restorations do not take into account routine grouting programs that the maintenance crews have conducted throughout the Rideau Canal system.

A calling from the past

After the construction of a series of locks in about 1840, Colonel By, the designer and chief engineer, recommended to the Ordnance Department that "the pointing of the masonry with Philemon Wright's cement, and the forcing of grout into the structure made of the same cement, wherever the work will take it, should be constantly attended to, during the spring and summer of *each* year." It appears to have been the will of the Colonel that grouting be carried out on a regular basis in order to maintain the structures. Someone eventually forgot about this intent, and the structure eventually deteriorated. Although Colonel By couldn't have foreseen that the grouting industry would evolve into a predictable and reliable engineering technology, he somehow knew that grouting would prevent their deterioration.

Contrary to rebuilding, professional grouting leaves the original structure unchanged. It is used to fill existing pores, cracks, joints, voids, and channels in the masonry structures with durable material of low hydraulic conductivity, thereby minimizing the damage of freeze/thaw action to the lock structure and improving its structural integrity.

The results

The restoration operations demonstrated that properly repointed locks can be grouted to obtain a final hydraulic conductivity comparable to concrete (10^{-8} m/sec). Typically, seven to eight percent of the masonry structure volume has been filled with cement-based suspension grouts as the result of the grouting program. The potential of preserving these functional historical structures by means of professional grouting technology has proven itself as an economically attractive alternative to other repair methods.

Difference with the past

Grouting attempts on the various lock structures during the sixties, seventies, and early eighties were unsuccessful, or provided only limited and temporary improvement, because of the outdated methods used. The use of inadequate materials was one contributing factor to the less-than-satisfactory results. Only balanced, stable cement-based suspension grouts (either regular or microfine) should be used in structural repair grouting.

The terms "stable" or "unstable" refer to decantation by gravity of particles from the suspension grout. If more than five percent bleed water is formed, the suspension is considered unstable. A stable grout refers to a suspension grout in which the bleeding has been limited to less than five percent (often by just using bentonite) without any further consideration given to the impact on cohesion, viscosity, or durability. Balanced stable grouts are suspension grouts with several additives, providing the desired rheologic characteristics for the circumstances.

In the past, the suspension grouts were simply classified as "thick" and "thin." Sand also was used in the mixes. Pump-as-you-feel approaches resulted in erratic grout takes and even a lock wall occasionally being pushed out of position. These factors sometimes lessened the confidence in grouting technology as a valuable restoration technique, and led to the conclusion that grouting doesn't work.

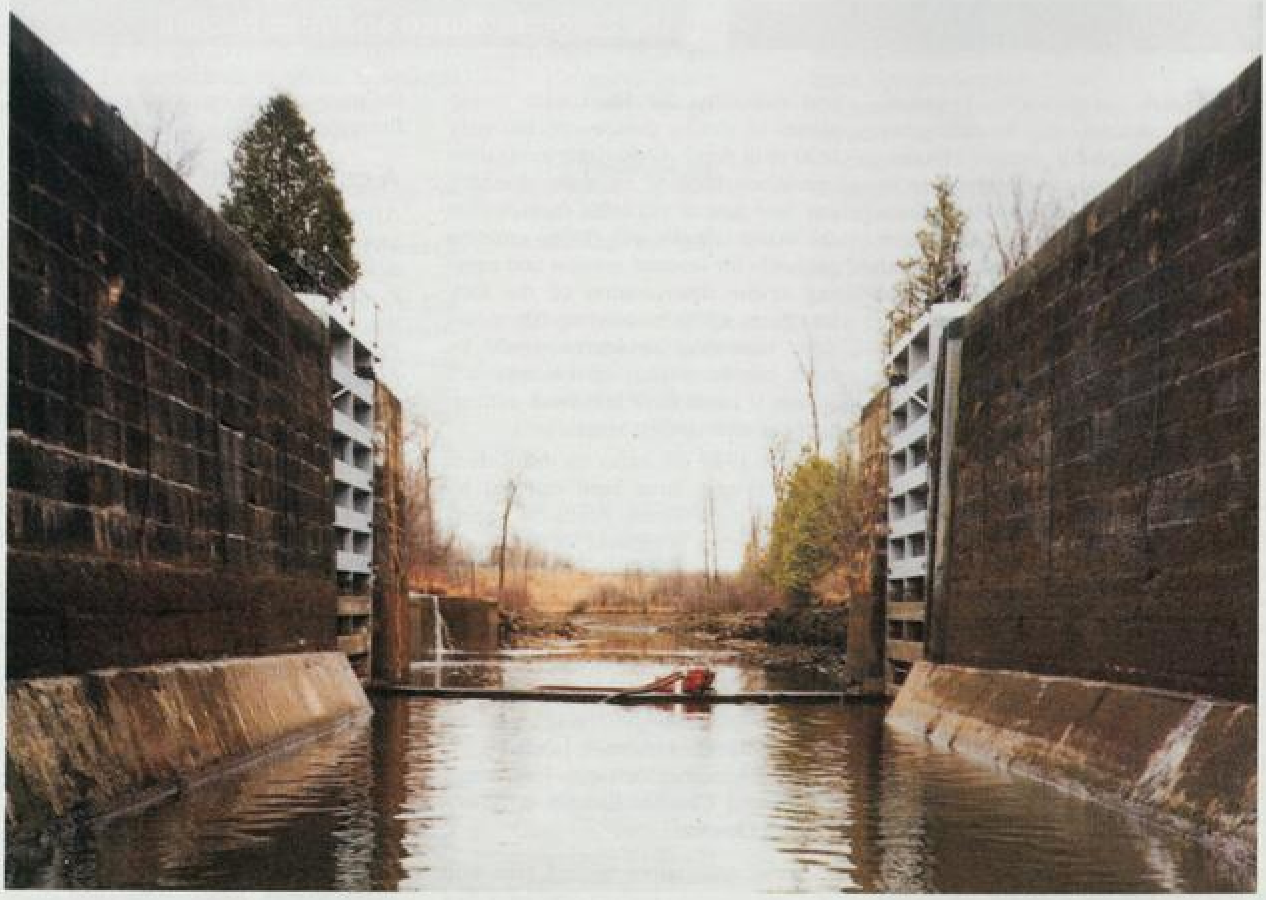
Professional grouting

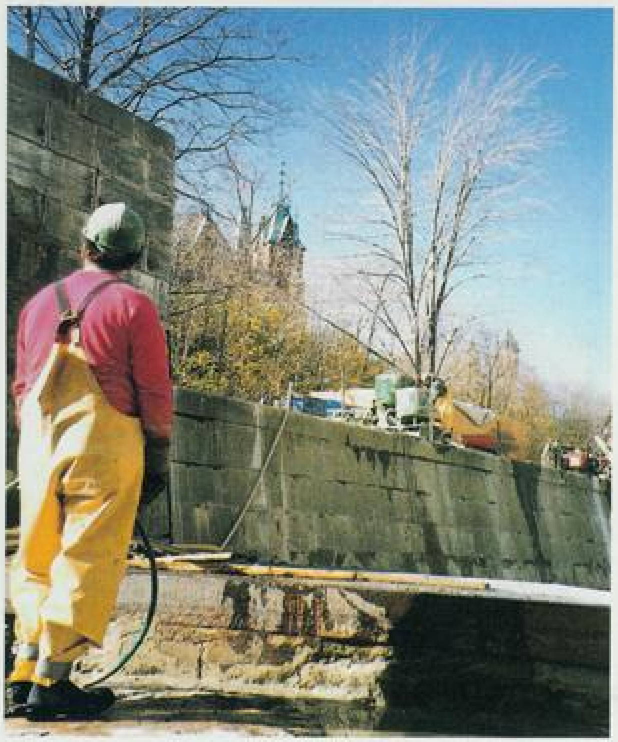
The execution of a well-engineered structural grouting program on the locks involved:

- drilling of deep grout holes;
- MPSP grout pipe installation;
- flushing of the grout holes;
- barrier bag grouting;
- permeability (Lugeon) testing;
- grouting with a variety of suitable cement-based suspension grouts designed to suit the specific conditions.

Drilling

Drilling is done with either a rotary air percussion, or a rotary diamond drill. Both methods have been used on the lock restoration projects. For speed and economy, primary holes are typically drilled with rotary percussion drilling methods to enable the installation of the grout pipes. Secondary and





One of the eight Ottawa locks, near Parliament Hill.

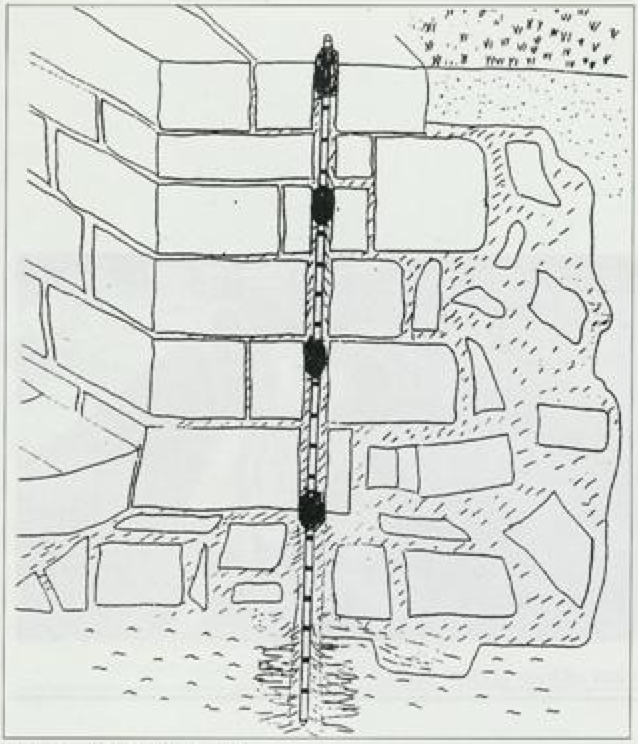


Fig. 1 — MPSP system.

tertiary holes are typically cored by rotary diamond drilling.

The drill hole may have to be cased to full depth when the holes intersect crumbly or caving masonry within the lock walls. Water-retaining structures, especially when surrounded by a limestone formation, contain unwanted deposits of calcite, and after drilling, cuttings of limestone and mortar. These cuttings have to be removed before grouting.

Multiple packer sleeve pipes

In the past the drilling and grouting operations often could not be separated. Grouting was executed by stage-up or stage-down methods. In the stage-up method the grout hole is drilled to the final depth; then grouting is begun at the lowest point, working its way up toward the surface. This method was predominantly used in stable rock formations. The stage-down method was used in unstable (crumbly or caving) rock formations. It involved drilling ahead of the grouting. The grout hole was drilled to a certain depth (depending on the amount of caving within the hole), then grouted. Later the drilling was advanced through the grouted section, and a new stage was then grouted. This continued until the target depth was reached.

In order to separate the drilling from the grouting operation, Multiple Packer Sleeve Pipes (MPSP) were developed. The system was developed for drilling and grouting in caving (unstable) rock formations. Fig. 1 is a pictorial representation of an MPSP system as it has been installed in the lock chamber walls on the various projects. An MPSP pipe is a modified sleeve pipe consisting of a plastic pipe with perforations every 0.33 or 0.50 m along the pipe. The perforations are protected by rubber sleeves acting as one-way valves during grouting. In order to isolate the grout hole into separate zones, concentric geotextile barrier bags are strapped over a number of the rubber sleeves in the sleeve pipe. The barrier bags are firmly attached, uninflated, to the sleeve pipe with clips above and below the rubber sleeve selected as the barrier. They typically are 0.40 to 0.60 m long. After the hole is drilled, the MPSP is installed in the cased hole. This operation allows the separation of the drilling operation from the grouting.

Flushing

After the MPSP pipe is installed, a flushing operation is executed to remove drill cuttings, soil, and organic material accumulated in the joints and fissures of the structure over the many years of locking operations. An air-lifting technique is typically used. With this technique the borehole is flushed using water and air, allowing the water, debris, and air to come to the collar of the hole (the barrier bags are not yet inflated). Acid flushing of the borehole produces dramatic results, cleaning fractures, joints, and the surface of the limestone itself. This flushing enables larger amounts of grout to penetrate the structure, and improves the grout's bond to the surfaces of joints, crevices, and stones.

Barrier bag grouting

The geotextile barrier bags attached to the MPSP grout pipes are inflated via a double packer positioned at the sleeved port covered by the bag using a high viscosity cement and bentonite-based suspension grout. The barrier bags are grouted from the bottom up, and divide the borehole into zones (typically 1.5 to 2.5 m long). Once the barrier bags are inflated, the hole remains accessible, allowing for water testing and subsequent grouting of the various zones with the most appropriate grouts.

View of lock under repair.

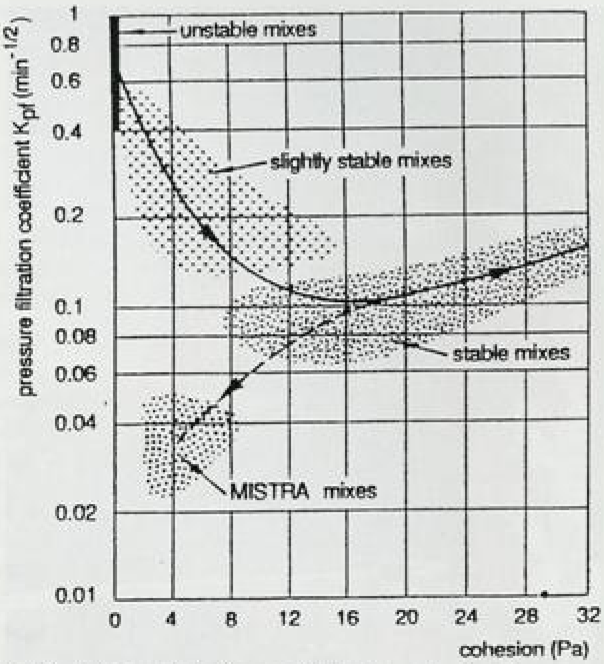


Fig. 2 — Pressure filtration coefficient vs. cohesion.[2]

Lugeon testing

Before grouting begins, the permeability of the various zones has to be determined. This is done with the Lugeon test. A Lugeon is a measure of permeability, used in the grouting industry, and defined by the following equation:

$$1 \text{ Lugeon } (Lu) = \frac{\text{flow (l/min)}}{\text{l /min}} \times \frac{1 \text{ m}}{\text{Length of zone}} \times \frac{10 \text{ bar}}{\text{Effective pressure (bar)}}$$

The data (flows and pressures) are recorded with state-of-the-art monitoring devices (X-Y recorders), and the hydraulic conductivities are meticulously computed for each zone. The selection of the grout formulations is done as a function of the Lugeon values encountered. The X-Y recorder provides real-time monitoring of the water testing operation: a continuous display and printout of flow and pressure as a function of time. It is very important to understand the regime of the formation. Therefore, a combined Lugeon test, a series of simple Lugeon tests in a particular test zone, is performed in a number of boreholes.

Grouting

After Lugeon values are calculated, a trend analysis of the permeability tests through the various phases of the grouting operation is conducted. Based on the initial hydraulic conductivity a grout formulation is selected to start the grouting of a particular zone or hole with a given permeability. The response of the formation to the selected grout formulation has to be evaluated immediately after being introduced into the crack system. Grouting is a kind of continuous permeability test, whereby the Newtonian test fluid (water) is replaced by a Binghamian fluid with a given apparent viscosity.

The apparent Lugeon value, Lu_{gr}, of the formation is a measure of its hydraulic conductivity, whereby the suspension grout acts as the testing fluid. The apparent viscosity of the suspension grout has to be factored in while calculating the apparent Lugeon value. For practical purposes, the multiplying factor is the marsh viscosity of the grout divided by 28 seconds (marsh viscosity of water). For the calculation of the effective pressure, the head losses through the system for the given flow have to be accounted for. The only way to monitor the apparent Lugeon values is with the help of a pressure-flow recorder (X-Y recorder) providing continuous printout. The apparent Lugeon value of the formation should be evaluated on a continuous basis during the grouting operation.

Since water also permeates in fissures and pores not accessible to a particulate grout, it is expected that the initial grout take be less than what can be derived from the Lugeon value, Lu_{wa}, established during the permeablilty test. The amenability coefficient, A_c, of a particular grout injected in a given formation is defined as $A_c = Lu_{gr} / Lu_{wa}$, where Lu_{gr} refers to the initial stages of the grouting operation. The amenability is a measure of the suitability for a given suspension grout to permeate fissures and apertures in the grout zone. The amenability coefficient signals immediately if a particular formulation is suitable for the grout zone. Even a microfine-based suspension grout can provide a less-than-satisfactory amenability.

At this point the decision has to be made if it is necessary to resort to appropriate solution grouts to achieve the design targets. During the grouting operation the X-Y graph immediately informs the grouting engineer about the mode of the grouting operation and the suitability of the formulation for the formation at that particular stage of the operation. The pressure-flow data allows the engineer to calculate the reduction rate in the apparent Lugeon value and compare it with the desired rate, which in turn dictates the changes in the formulation for the next batches.

A suspension grout should be characterized by its pressure filtration resistance coefficient, K_{pf}, its solid coneach of the injectable tubes with a five percent phosphoric acid solution to dissolve the calcium salts built up inside the injectable tubes and cold joints. After flushing with the acid solution the tubes are flushed with water. The tubes are then grouted with a flexible two-component hydrophobic polyurethane elastomer.

Final thoughts

The use of professional grouting technology on the rehabilitation of the historical lock structures on the Rideau Canal has proven to be technically feasible and economical. It is mandatory that proper investigation be performed prior to embarking on a professional grouting program, focusing on the most suitable preparatory work on the grout holes to optimize amenability ratios for cement-based suspension grouts. Furthermore, the investigation must determine grout-hole spacing and filling ratio in order to estimate costs.

Professional grouting has evolved into an applied science, providing predictable results in restoring integrity to historical structures. Exchanging information is important to preventing the repetition of design and execution errors and achieving technically better solutions in the future. It is the responsibility of our generation to preserve the character of historical structures so future generations can enjoy them.

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Selected for reader interest by the editors.

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