SUMMARY REPORT FOR KINGSTON MILLS

LOCKS 46, 47, 48 & 49

REHABILITATION PROJECT

KINGSTON, ONTARIO

Prepared for:
Public Works and Government Services Canada

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KINGSTON MILLS LOCKS : 1994-1995 PRESSURE GROUTING PROJECT

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1. OPENING STATEMENT

This report on the pressure grouting of Kingston Mills Locks was requested by Mr. John Mazhar P.Eng. with Public Works Canada.

It is impossible to provide a factual report for the future generation of engineers and/or canal buffs, without explaining the controversial situation between the design team (assisted by the University of Sherbrooke, Quebec) and the Engineer of Record. The intent of this report is to be a truthful document containing the factual information and comments. This report is also a contribution towards a better approach for future rehabilitation projects. It is in the interest of the grouting industry and of the general public that good specifications are created providing a level playing field for the specialist contractors bidding the work, with equitable compensation for good work. Nobody wins, if at the end of a project, the money is spent, the seepage persists and the structural integrity is barely improved.

It is not unusual on projects for the design team to have disagreements with the field engineer. This was the case on this project, induced and further aggravated by the contractor. Problems were however resolved, and resulted in the timely completion of the project, within budget. The quality of the end-product however was debatable.

ECO is only motivated to advance the grouting industry and to improve performance standards. We like to do this by disseminating accurate information, interpreted to the best of our professional ability.

The two last publicly tendered pressure grouting operations at the locks on the Rideau Canal have not lived up to the expectations. It is time to reverse this trend. There is a lot of expertise in numerous fields within P.W.C. and their various advisers. Somehow a combination of practical, academical, and theoretical know-how should be combined to provide better engineering on future pressure grouting projects.

ECO Grouting Specialists Limited have prepared this report without consideration and thereby ask the recipients to refrain from using it for the production of specifications, reports or publication without written consent of the authors. Obviously, such approval shall not unreasonably be withheld.

Luigi Narduzzo, P.Eng.

Alex Naudts, P.Eng.

2. EXECUTIVE SUMMARY

A rehabilitation program involving pressure grouting, vertical and horizontal anchoring, pointing, dewatering, stone replacement, concrete refacing and erosion protection was undertaken at the Kingston Mills site (Locks 46, 47, 48 and 49). The project is located at the southern end of the Rideau Canal, on the Cataraqui River approximately 5 km north of Kingston, Ontario. This work was authorized by Public Works and Government Services Canada (P.W.G.S.C.) and was performed from early November 1994 to May 1995.

The contract was carried out by Atlas Corporation of Concord, Ontario. A specialist grouting contractor (Geotec Contracting Limited) was retained by Atlas Corporation to perform the pressure grouting related works. The pressure grouting operations were restricted to the monoliths, sills and walls of Locks 47, 48 and 49. A unique membrane anchoring system was used in locations where difficult site conditions prevailed.

Prior to the actual pressure grouting operation a testing program involving six holes in the east chamber wall of Lock No. 47 was conducted by a team of researchers from the University of Sherbrooke and P.W.G.S.C. The testing program was executed in the month of November 1994. The intent was to provide valuable information for the pressure grouting operation.

Public Works and Government Services Canada provided the design for this rehabilitation project. The general on-site supervision for the project was provided by Mr. Ben Groves with the Engineering and Maintenance Division of Rideau Canada (first 3 months) and the concluding 3 months of the project was supervised by Mr. David McDonald with P.W.G.S.C. ECO Grouting Specialists Limited were retained by P.W.G.S.C. as the engineers of record, to provide the on-site supervision for the grouting portion of the works.

Ambiguities in the specifications forced P.W.G.S.C. into a number of ad-hoc decisions, not in line or in accordance with industry standards. The grout-filling ratios were 300 % lower than the estimated as a result of the difficult in-situ conditions and low amenability of the cement based grout formulations used, leading to a less than satisfactory outcome. Presently, some locations in the locks are already leaking. The project only partly achieved its goals.

Rehabilitation of any future lock structure by pressure grouting, requires the execution of a properly engineered site investigation prior to tendering. This should be done by experienced, knowledgable grouting specialists willing to put their reputation on the line. Only then can properly engineered specifications be developed taking into account the uniquely different site specific characteristics.

3. INTRODUCTION

Kingston Mills Locks, the gateway to the Rideau Canal has undergone an extensive rehabilitation program during the winter of 1994-1995. The rehabilitation involved pressure grouting, vertical and horizontal anchoring, pointing, dewatering, stone replacement, concrete refacing and erosion protection.

ECO Grouting Specialists Limited were retained by P.W.G.S.C. as the engineers of record, to provide the on-site supervision of the grouting portion of the works. This summary report has been prepared for Public Works and Government Services Canada elaborating on the factual data collected from the pressure grouting operation and alternate anchoring technology (membrane anchors) used on this difficult and very challenging project.

This report also provides recommendations to Public Works and Government Services Canada on ways to improve on future pressure grouting projects on the Locks of the Rideau Canal, in the pre-bid, award and post-award phases. These recommendations are intended to create a level playing field for the tendering process and to minimize and/or eliminate the aggravating experiences caused by contractors' "claims" which P.W.G.S.C. experienced on the Kingston Mills Project.

This report does not discuss nor contain any of the findings of the experimental-research program (involving a total of six grout holes) that was executed at the start of this contract by the University of Sherbrooke in coordination with a research team from Public Works and Government Services Canada. The latter can be found in appendix 1-A. ECO considers this publication by the University of Sherbrooke, an over simplification and - to some extent - a misrepresentation of the facts. The grout volumes injected in each of the six grout holes during the test program are incorporated in the overall statistical summary of grout takes.

This report also contains abstracts from several world renown authorities on grouting, bringing forth their scientific findings and views, confirming that the use of deflocculator in-conjunction with bentonite enhances penetrability and durability of cement based grouts.

Also in this report appendices are included, containing the grouting field records, X-Y recorder tapes, daily grouting reports, daily quantity reconciliation, as-built drawings, membrane anchor summary, borehole photos and some general photos on different aspects of the pressure grouting and anchor installation.

4. BACKGROUND AND PROJECT SCOPE OF GROUTING WORK IN 1994-1995

The 1994-95 Kingston Mills Locks rehabilitation of Locks 47, 48 and 49 was the fourth documented grouting/rehabilitation operation to be executed on these locks during the last 15 years; the other operations took place in 1979-80, 1989 and 1992-93.

In 1979-80 a rehabilitation project involved the grouting of the east lock chamber walls of locks no. 47, 48 and 49 including all four sills. The total grout volume injected on this project was documented at being 4 (four) cubic metres.

In 1989 a test grouting program work involved both horizontal and vertical grout holes (20 horizontal holes and 6 vertical holes). The work focused on Locks No. 47 and No. 48. No work was done in Lock No. 49 and on any of the Sills. The grouting work was limited to Monolith's No. 3, 4, 5 and 6 as well as the east and west chamber walls of Lock's No. 47 and 48. The total grout volume injected during the 1989 investigation program was 9,050 litres. A report by TROW Consulting Engineers dated January 24, 1990 signed by Messrs. Surrender Aggarwal and Alex Naudts was issued pertaining to this operation.

In 1992-93, a maintenance project covering the east wall of Lock No. 47 (including a small zone in the upstream end of the west wall) and Monoliths No. 6, No. 7 and No. 8 was implemented. The overall total grout volumes injected were approximately 15 cubic metres.

The 1994-1995 rehabilitation project was large in scope and perhaps because of its overall size, it was more technically challenging than the previous ones. The grouting works focused on the following structures:
Monolith's No.'s 1, 2, 3, 4, 5, 6, 7 and 8,
Sill between Monolith's No. 1 and 2 (designated as Sill No. 1),
Sill between Monolith's No. 3 and 4 (designated as Sill No. 2),
Sill between Monolith's No. 5 and 6 (designated as Sill No. 3) and
Sill between Monolith's No. 7 and 8 (designated as Sill No. 4),
East and West Lock Chamber Walls of Lock No. 47,
East and West Lock Chamber Walls of Lock No. 48,
East and West Lock Chamber Walls of Lock No. 49 and the
Wingwalls south of Monolith No.'s 1 and 2.

The installation of vertical and horizontal anchors followed the grouting operations. Vertical anchors (either the Conventional Williams type anchor or Membrane anchors) were drilled and installed at the locations of the grouted holes. In Appendix 4, the locations of the vertical anchors are marked with a cross centred over the grout hole locations. Membrane anchors have the letter "M" marked beside the hole location (Appendix 4 - As Built Drawings: Plan View of Locks Showing Grout hole and Anchor locations)

5. COMMENTS AND CRITIQUES ON THE DESIGN FOR THE PRESSURE GROUTING

The general atmosphere between all parties on this project was tense from the start. The grouting related work comprised over 60% of the value of the contract. Both the general contractor and specialist grouting sub-contractor created a "claim-for-everything" type of project.

The general technical approach at Kingston Mills was to apply more or less the same methodology applied in similar projects completed over the last 5 years (i.e. Hartwells Locks, Ottawa Locks, Upper Beveridges Locks). The recommendations made by ECO after the grouting of Ottawa Locks were not utilized. A departure was made from past projects (all of which were designed by P.W.G.S.C.) whereby the mix design for microfine cement based formulations did not contain any bentonite, nor silicafume but higher percentages of deflocculator than on past projects. The regular cement based formulations did contain silicafume and deflocculator but no bentonite nor other additives. The refusal criteria were not outlined either.

The structures grouted in this program appeared to have acquired distinctly different characteristics from what was encountered and documented five years earlier during the 1989 pilot test grouting program. Other grouting operations (i.e. project in 1992-93) performed since the 1989 pilot program, only partly explain the change in the permeability of the structure but only in those areas that were grouted on both occasions.

In ECO's opinion, the consultants advising P.W.G.S.C. in the design phase treated the grouting of clean fissured granitic rock as encountered in the Pinawa Test program, (Atomic Energy of Canada) the same way as the grouting of partly deteriorated mortar (with reference to Papers by Doug Keil and Maria Onoffrei pertaining to this project). Moreover the injectability of deteriorated mortar was simplified or trivialised by grouting a small column of sand, obtained from below the coping stones.

The specifications contained several ambiguities pertaining to the unconfined compressive strengths and sedimentation values for the range of grout mix designs. The values for unconfined compressive strength and sedimentation did not jive with the strength requirements.

On each lock grouting operation something new is to be learned about these historical engineering marvels, unfortunately, for this project P.W.G.S.C. did not improve on what was learned by painstakingly monitoring the previous grouting operations on the locks and many other similar structural grouting projects. A "tight" and fair specification can be produced whereby all possibilities, technical aspects and procedures of the work are covered and clearly outlined. As a very minimum, a qualified grouting consulting firm such as ECO should review the specifications prior to tendering, to create a fair bidding process and a level playing field.

The supervisory staff and grouting consultant on this project were under formidable stress because of ambiguities in the specifications and the directions given by the P.W.C./University of Sherbrooke research team which were often conflicting and contradictory to established practice in the industry and contrary to the (well documented) opinion of the grouting consultant of record and the methodology established and adopted by P.W.C. on similar Locks. The decisions and directions unfortunately produced an end product with debatable qualities. The long term impact of the selection of the formulations may never be known. Further in this report, quotes from world renown grouting authorities have been presented to show that small percentages of *bentonite improves the grouts strength and durability.*

6. ANALYSIS OF THE FACTUAL DATA

The tables 1 to 20 contain a wall by wall, monolith by monolith, sill by sill break-down of the total grout volumes injected in each phase (i.e. primary phase, secondary phase, tertiary phase, etc..) the filling ratios achieved from each phase and the overall filling ratio from the combined phases.

From the above tables, the overall filling ratio (taking into account all 20 structures, and allowing for 10 % overall grout wastage) is 1.82 %. Compared to the 7.5 % filling ratio as obtained in Hartwells Locks and the approximately 8 % filling ratio at Kingston Mills Locks in the 1989 test program. Ottawa Locks had an absolute filling ratio of approximately 1.3 %.

6.1 Grouting of the Sills

The absolute filling ratio for the four sills ranged from 0.73% for Sill No. 2 to 4.26% for Sill No. 1. Sill No. 3 had a filling ratio of 3.49% and Sill No. 4 had a filling ratio of 2.27%.

The major problem encountered with the Sill grouting operations was grout leakage along mortar joints, the sluice recess, and the Lock floor/gate sill interface.

At Sill No. 2 there was also the problem of ground/formation water migration via the breast wall. The constant hydraulic gradient towards the face of the breast wall made the pointing operation of the joints difficult. The difficulties encountered with the pointing were carried over to the grouting. Extensive grout leakage resulted in the premature termination of the grouting operation on Sill No. 2, in turn explaining the low filling ratio.

In general, all four sills displayed a unique trend in reduction rates during the grouting (reduction in grout take between primary and secondary grout holes).

Sill No. 4 was the most successful grouting operation of the 4 sills grouted, where there was almost a 3 fold reduction in grout take from the primary to secondary holes.

For Sill No. 2, (as described above) the grouting was prematurely terminated due to grout leaks, hence a reduction rate is not a true reflection of what transpired for the grouting of this Sill. Additionally, the drilling/grouting sequence on this sill was altered to accommodate the contractor in meeting an already delayed completion date. The primary and secondary holes on the upper sill were drilled and hence grouted at the same time.

Sill No. 1 had a slight increase in grout take, from the primary to secondary holes. Two thirds of Lock No. 49 is constructed on clay (floating structure) including the sill. The primary and secondary grouting operations could be viewed as independent operations. The grouting was squeezing the clay below the sill from some holes (a separation was noted between the bottom of the sill structure and clay founding base in all of the holes drilled). This grout squeezing phenomena in the clay was the main reason for the higher grout takes in comparison to the other sills.

The grouting of Sill No. 3 was not straight forward. The results of the primary hole grouting (grout takes) were dismal at best. The grout take from the primary to secondary hole grouting increased by a factor of 26.75. The average grout take (per hole) of the primary holes was only 19 litres. The average grout take (per hole) of the secondary holes was 508.3 litres. It should be noted that these six primary holes formed part of a series of 21 boreholes that were the first holes in which the barrier bags were grouted on this project. The secondary hole grouting operation had to be prematurely terminated because of the uncontrollable leakage through mortar joints, fine fissures in the stones, and the sluice recess. The tertiary hole grouting indicated an increase in grout take over the secondary holes substantiating the need for additional holes. The tertiary hole grouting was terminated prematurely because of persistent and extensive grout leakage. The reduction rate from tertiary holes to quaternary holes was 2.2. Two cracks were observed (during the quaternary grouting stage) running parallel to the sluice recess causing the termination of the grouting operation. A set of three quinary holes were used in an effort to repair any damage caused during the quaternary grouting operation. The grouting of final holes was very crudely and unprofessionally executed by the grouting contractor. Not even 2 minutes into the operation, a stone was lifted. The grout crew did not even notify the site engineer (occupied with the drilling and anchoring operations) that they had started the grouting operation. Grouting in this sill was terminated. At the conclusion of the project, the contractor was requested to pressure wash the entire area and perform flow grouting as required on any locations where stone movement occurred, to repair the damage.

6.2 Grouting of the Lock Chamber Walls

The absolute grout filling ratio of the 6 chamber walls was 2.52%. The individual filling ratios for each wall ranged from a low of 0.56% to 4.10%. In summary they were as follows:
Lock No. 47 East Chamber wall: 2.00%
Lock No. 47 West Chamber wall: 4.10%
Lock No. 48 East Chamber wall: 2.02%
Lock No. 48 West Chamber wall: 2.57%
Lock No. 49 East Chamber wall: 3.84%
Lock No. 49 West Chamber wall: 0.56%

These numbers are in a sharp contrast with the 7.5% - 10% filling ratio as obtained in the Kingston Mills Locks test grouting program in 1989, Hartwells Locks in 1990 and Old Slys Lock in 1995.

Only on two occasions a reduction in grout take from the primary to secondary hole grout phases was noted. This occurred for Lock No. 47 East wall and Lock No. 48 East wall, with a reduction rate of 1.52 and 3.26 respectively. The remaining 4 walls each had an increase in grout take from the primary to secondary hole grouting phase. These increases were: 2.99, 8.04, 1.55 and 3.43 for Lock No.47 West Wall, Lock No. 48 West Wall, Lock No. 49 West Wall and Lock No. 49 East Wall respectively. These numbers provide strong evidence that the spacing of the grout holes was too wide for the selected formulations by the designers. Tertiary holes were utilized for all walls with the exception of the west wall of Lock No. 49 where the site conditions did not warrant tertiary holes (i.e. the west side was buried in mud and would have made "proper" grout hole preparations impossible).

Reduction rates from the secondary grouting phase to the tertiary grouting phase were:
3.37 - Lock No. 47 West Wall
7.64 - Lock No. 47 East Wall
4.75 - Lock No. 48 West Wall
15.7 - Lock No. 48 East Wall
2.04 - Lock No. 47 West Wall

These numbers suggest - with some exception for the East wall of Lock No. 48, that further grouting (using horizontal holes) is warranted.

6.3 Grouting of the Monoliths

The absolute filling ratios for the eight monolith structures was 1.05%. The filling ratios for each monolith were:
0.33% - Monolith No. 1
0.78% - Monolith No. 2
1.01% - Monolith No. 3
2.02% - Monolith No. 4
0.60% - Monolith No. 5
2.33% - Monolith No. 6
0.37% - Monolith No. 7
1.03% - Monolith No. 8

Based on the results of the 1989 pilot grouting program on Locks 47 and 48, the above takes are low. The degree of improvement to the structural integrity of the monoliths as a result of the pressure grouting program is debatable.
The following reduction rates were encountered from the primary to secondary grouting phase:
Monolith No. 2 - 4.62
Monolith No. 4 - 1.05
Monolith No. 6 - 3.02
Monolith No. 7 - 2.39
Monolith No. 8 - 2.81

The following increase in grout takes were encountered from the primary to secondary grouting phase:

Monolith No. 1 - 2.66
Monolith No. 3 - 1.14
Monolith No. 5 - 17.67

Tertiary holes were utilized on Monolith No. 5 only. The reduction rate from the secondary to tertiary hole grouting phase was 1.86.

6.4 Grouting of the Wingwalls

The absolute filling ratio of the wingwalls was 1.06%.
The wingwall south of Monolith No. 1 had a filling ratio of 0.04% and the wingwall south of Monolith No. 2 had a filling ratio of 2.07%. Both wingwalls were grouted in one phase (i.e. all primary and secondary holes were drilled at the same time and grouted in one phase). The low takes, and hence low filling ratio of the wingwall south of Monolith No. 1 is likely due to the similar site conditions as found on the west wall of Lock No. 49. The holes were "buried" in mud making the borehole preparation an almost impossible task.

6.5 Observations at coping stone elevation & grout travel paths to facing stones

It was observed during the removal of several coping stones in need of replacement (east chamber wall of Lock No. 48 - downstream portion, Monolith No. 4 and Monolith No. 6) that there was an abundance of ungroutable debris including clayey silts, organics (black top soil) and plant and tree roots. If these conditions persist throughout the lock structure it would not be surprising to observe continued deterioration of the structure in the future.

Furthermore, throughout the grouting operations, it was observed time after time, that a preferential travel path for the grout was to the surface. Even when grouting the lower zones of a borehole, grout travel was more often than not observed to make its way to the surface, before showing up else-where. The future grouting of any Locks should consider these observations, and devise a means of treating these situations (some of which are discussed in the recommendations). In the future, the condition of the upper elevation of the coping stones should be monitored on an on-going basis by Rideau Canal maintenance and operating crews.

7. CHRONOLOGY OF EVENTS

The following summarizes the events that took place after the contract award:
7.1) Mobilization of the contractor to the site
7.2) Initial drilling and borehole preparations for grouting
7.3) Initial period (seven days) of grouting
7.4) Technical meetings to try and resolve the site problems
7.5) Consensus trial measures, methods and procedures
7.6) Final decisions/directions on how to proceed with the remainder of the contract.

7.1) Mobilization of the contractor to the site:

The contractor started the mobilization of his equipment during the first week of November.

The University of Sherbrooke also mobilized on site in early November along with a drilling and grouting contractor (EDM) from Quebec, to conduct a six hole testing program on the east wall of Lock No. 47.

7.2) Initial drilling, borehole preparation and water testing prior to grouting

The first activity (regarding the grouting portion of the work) was the drilling of the grout holes. The grouting operations commenced at Lock No. 47 and progressed down to the wingwalls south of Monolith #1 and #2. The drilling on this project started out with a single drill rig (a Diamec 232). A second drill unit (skid mounted) was brought into operation 6 weeks after the start-up date. A third drilling unit (track mounted) was brought in shortly thereafter.

The vertical and horizontal anchoring followed behind the grouting operations, except in the case of the west chamber wall of Lock No. 48, where the vertical anchors were installed in-conjunction with the tertiary hole drilling and grouting operations.

The technical challenges were evident from the onset, when the results of the full Lugeon water test signalled a "red-flag".

As described in professional grouting literature, the Lugeon water test is an important tool to the engineer in selecting what grout and what formulations are to be used for a particular horizon or structure. The full Lugeon water test is a more informative test allowing the engineer to detect and interpret the flow regimes, and their evolution from which the borehole preparation, size of apertures and grout formulations for optimum penetration can be derived. On this particular project, each of the full Lugeon water tests that were conducted consistently demonstrated a "mud filling" phenomena was occurring within the formation regardless of the zone tested. That means that the (clean) water picked up particles along the travel path through the porous mortar matrix and through cracks, gradually turning into an unstable suspension grout, leading to a gradual reduction in apparent permeability of the structure.

7.3) Initial period (seven days) of grouting

The results from the initial grouting activities set off the alarm. By comparing the actual filling ratios obtained in the field to the expected/anticipated filling ratios upon which the estimated quantities (an estimated value chosen, based on similar projects from the past and the 1989 Kingston Mills Lock testing program) were based upon, it was evident that something was not

right. The filling ratio is the ratio of: the amount of grout effectively installed to the theoretical volume of masonry being grouted.
ECO is of the opinion that the inflation of the barrier bags on the MPSP pipes was suspect.

7.4) Technical meetings to resolve the site problems

Three technical meetings were held between the grouting consultant of record, the University of Sherbrooke/P.W.G.S.C. research team, the project designers and project management from P.W.G.S.C. and the Owner, to discuss the results and to come to a resolution on how to proceed with and improve upon the results of the grouting operation without drastically changing the scope of work.

The different points of view became very obvious during the discussions:

ECO expressed the view that the main issues were the borehole preparation and the inadequate grout formulations, as specified.

The full Lugeon water tests indicated a mud filling phenomena. The factual information from the water tests indicated that holes could be virtually brought to refusal using only water. The grouting (in which a suspension grout - "thicker than water" - is used) obviously resulted in poor penetrability and hence low filling ratio. The borehole preparation system (air/water flushing) described in the specifications was not adequate nor suitable to prepare the boreholes for grouting. The permeability in the limestone wall and monolith structures at Kingston Mills Locks was caused by voids, open joints, cracks, deteriorated mortar, sands, silts, fines, debris, roots and gouge. Loose fine particles in turn were picked up by the microfine cement grout turning it into a suspension grout with uncontrollable d_{10} and hence very limited penetrability. In order to truly and effectively improve the injectability of the structures another borehole preparation technique and/or use of a suitable solution grout rather than a suspension grout (totally departing from the scope of work given in the specifications) was necessary. The given budget allotted to perform the contract work did not allow for drastic departures from the scope of work. Changing the scope of work at this stage, would also have given the contractor the "opportunity of a life-time" to more than make-up for his underbidding of the project.

The researchers blamed the low grout takes, encountered during the early grouting days, on the slightly modified mix design used during the first seven days and the water testing.

During these early grouting days a "modified" microfine cement based grout with enhanced penetrability, good resistance against pressure filtration and bleed free, containing 2% bentonite, silicafume and lower percentages of deflocculator was tentatively approved for use. The mix design outlined in the "specification" had deflocculator as the only additive in the microfine cement formulations, with the percentage of deflocculator being higher than what is commonly used in the grouting industry.

[Note: in total, the first seven days (from November 25, 1994 to December 08, 1994) of grouting involved the addition of bentonite in the grout mixes. In the case of the microfine cement based formulations silicafume as well as bentonite were added to the formulations]. The amenability coefficient was typically low and the apparent Lugeon value of the formation, established with the grout, dropped very quickly.

In spite of the adjustments to the grout formulations to suit the circumstances, the grout takes were very low as well as the amenability coefficient.

7.5) Consensus Trial Measures, Methods and Procedures

The following measures were agreed to be taken (during the technical meetings) as immediate and most acceptable measures, within budgetary constraints, to try to correct the problem of the grout holes refusing (with water) during the Lugeon water testing and hence improve the amenability of the formation and thus provide the best possible end product under these difficult circumstances:

- a more extensive air/water flushing exercise in both duration and volume of water.
- variations in air/water delivery to the hole
- borehole preparation by open hole flushing (sleeve pipe installed after the flushing operation). This was attempted on two holes. The amount of caving experienced from flushing with the open hole system required redrilling of these two holes with casing (due to the amount of caving and hole collapse encountered during the open hole flushing, the sleeve pipe could no longer be installed). When the time came for grouting of these holes, a balanced stable microfine cement based suspension grout was used, but no appreciable increase in penetrability was attained.
- "relief holes" (900 mm deep) were drilled using hand-held rotary percussion drills. This concept came about when it was observed during the air/water flushing operation of the primary holes in the downstream end of the west wall of Lock No. 48, that an extensive (greater than 200 litres) amount of silty debris was washed out from an old mooring cable anchor hole. The "relief holes" were intended to act as an escape route for the removal of debris, gouge, silts and other fines during the flushing operation. The "relief holes" were drilled in the face of the structures in close proximity (within 100 to 1000 mm) of the sleeve pipes (in an effort to simulate the effects as were observed from the mooring cable anchor hole). This was attempted on Monolith No. 5 and Monolith No. 6. Relief holes were drilled on the navigation side of both of these Monoliths including the backside face of Monolith No. 6 (a free standing structure). The relief holes flushing concept did not work in these locations. The relief hole concept was abandoned.

7.6) Final decisions/directions on how to proceed with the remainder of the contract.

The results of the above measures, at best only marginally improved the injectability of the structures. P.W.G.S.C. (unilaterally) made the final decision on how to continue with the project. The directions on how to proceed with the remainder of the contract were:

1) Carry on with the mix designs as per the contract documents,
2) Eliminate the water testing. Perform only one Lugeon water test per structure per phase (i.e. primary and secondary phase), and
3) Reduce the air/water flushing time for the borehole preparation to a maximum of 20 minutes per hole.

By eliminating water testing no real meaningful engineering could be conducted during the operation. As a result, the role of the Engineer of record was more or less reduced to note keeper.

However, as a whole, given the decisions pertaining to the means, methods and materials all within the scope of the contract documents (i.e. without major change in scope, materials or borehole preparation techniques) the grouting operation was executed as designed. Alternatively, substantially better results could have been attained but this would have involved a substantial change in scope of work, extremely difficult in view of the given time and budget restraints.

8. DISCUSSION OF EVENTS

8.1 BOREHOLE PREPARATION

The amenability of the structures to microfine cement based suspension grout was low to very low (with the exception of a few holes). To deal with this problem (without drastically changing the scope of the work) modifications to the procedures used to prepare the boreholes for grouting were attempted, including:

- the drilling of horizontal relief holes (i.e. relief holes to create a exit for debris, sands, silts, fines and gouge during air/water flushing,
- air/flushing with open holes,
- no flushing of boreholes,
- up-set time for flushing,
- "unlimited" flushing (as much as required),
- variable air/water feed rates during flushing,
- no water/Lugeon testing

None of the above "quick-fix" measures noticeably improved the penetrability/injectability of the structures.

8.2 MEDIUM TO BE GROUTED

In ECO's opinion, insufficient attention was given to the fact that the grouting of a lock structure revolves around three issues:

- grouting of cracks and crevices with variable width, for which the engineering principles of rock-grouting are applicable.
- grouting of deteriorated mortar, in a heterogeneous and irregular matrix, for which the basic soil grouting principles are applicable subject to the following considerations:
- limited thickness of the "layers" (with reference to Cambefort's Layer Theory)
- in-situ permeability of the deteriorated mortar
- the presence of silt and sand-particles which are picked up by grout permeating the formation which substantially change the characteristics of the suspension-grout introduced into the formation.

A balanced stable mix/formulation with good resistance against pressure filtration is required to effectively grout a structure with such diverse characteristics.

The designers resorted to an unstable mix, with high K_{pf} (poor resistance against pressure filtration) causing immediate segregation of the particles, which even occurred in the grout lines.

8.3 UNIVERSITY OF SHERBROOKE TESTING PROGRAM

The University of Sherbrooke research program was carried out in the east wall of Lock No. 47, and involved the following six holes: P3, S4, P4, P5, S6 and P6 (see appendix 4 for exact locations).

Three test holes were drilled in the area of the University of Sherbrooke research program, to verify the results of the grouting program at this location. The test holes T1, T2, and T3 were each water tested prior to grouting. (For the test hole locations see Appendix 4). Of primary significance was test hole T1, that was located 1.2 metres from secondary hole S4, and test hole T3, that was located 0.75 metres (between secondary hole S4 and primary hole P4). (Test hole T2 was drilled 1.6 metres from S6). The reason for the drilling of test hole T3 was because the visual inspection of the core from test hole T1 did not reveal any grout from the adjacent primary hole P4, nor secondary hole S4. Contrary to the test holes drilled at Hartwells Locks, the drilling did not demonstrate evidence of grout penetration. The drilling of a test hole, a distance of 0.75 metres away from a grouted hole was required to reveal evidence of grout in the core. No visual effects from the grouting was noted from a test hole drilled 1.2 metres from a grouted hole. This hard evidence, indicates the requirement for reduced hole spacing (perhaps as much as 3 times the number of holes) to achieve the optimal desired results of grout penetration and overlapping grout cylinders.

The Lugeon values followed by the respective grout takes for each of the three test holes are given below:

T1: zone A -23 Lu, Leaked from bottom zone
zone B -29 Lu, Leaked from bottom zone
zone C - 8 Lu, 400 litres - leaked to surface

T2: zone A - 3 Lu, 24 litres
zone B - 3 Lu, 6 litres
zone C - 30 Lu, 11 litres

T3: zone A - 28 Lu, 26 litres
zone B - 3 Lu, 62 litres
zone C - 24 Lu, 5 litres

Conclusion: The penetrability of the grout used for the University of Sherbrooke test program was not compatible with the design spacing of grout holes. In spite of these results, no change to the drill hole pattern was made to reflect the actual penetrability of their grout formulations.

It was unfortunate that the information gathered by the University of Sherbrooke research program team was not made available, until well after the conclusion of the work, hence could not be utilized to enhance the quality of the rehabilitation program.

Consideration must be given to actual field conditions and obtainable grout-spread in accordance with the specified spacing between the grout-holes.

8.4 GROUT FORMULATIONS/MIX DESIGNS

The final mix designs used on the bulk of this project were as per the parameters and ranges outlined in the specifications (i.e. no bentonite in any of the formulations, no silicafume in the microfine cement formulations, and percentages of deflocculator higher than normally used by professional grouting contractors practising in the province of Ontario). There were seven grouting days during which bentonite, silicafume and deflocculator were used as per the instructions of the engineer of record.

The U of S/P.W.G.S.C. researchers expressed the opinion that the use of bentonite in the mix designs have damaging effects to the durability, penetrability and the final strength of the grout. They claimed that the introduction of bentonite increases the cohesion of the grout mix and limits penetrability into the structure. They ignored the well researched and documented effect of the super-plasticiser which off-sets the slight increase in cohesion caused by minor amounts of bentonite. Several other arguments/factors could have played a role in the low injectability of the structure such as the bag grouting operation and past grouting operations performed over the last 15 years.

The (unsupervised) bag grouting (although it would be an incredible coincidence if that was the case for every hole grouted up to that period in time) might have smeared a number of holes during the start-up phase. It must be recognized that this could have happened (i.e. the first bag grouting operation performed on site involved the barrier bag grouting of 21 primary holes, and coincidentally each of those holes had "below-anticipated" grout takes).

Another factor, which is somewhat overlooked, is past maintenance grouting and test grouting programs (i.e. the operations from 1989 and 1992-93) in the same areas which were first grouted, potentially blocking readily accessible grouting pathways for future grouting operations. It is well appreciated amongst the grouting practitioners that "contaminated" structures are more difficult to grout than "virgin" structures.

8.5 PROBLEMS ASSOCIATED WITH GROUT SETTLEMENT IN THE LINE

During the project, the grouting contractor had many problems pertaining to "grout settlement in the lines". Over the course of a day's grouting the deposit of grout accumulated at the bottom of the grout line would create many problems during the clean out at the end of the day. Some days, the grout lines fully plugged only half way through the day. The cement particles drop out of suspension, and accumulate at the bottom of the grout line. Usually, at the end of the day when the grout lines are dragged over to the wash-out pit, the grout deposits accumulated at the bottom of the grout lines, flake/spall off and cause a jam when water is used to flush the system. This problem pertained to the mix design used, and only partly to the length of return line.

The "grout settlement in the lines" problem persisted for most of the project, until approval for a lower percentage of deflocculator was given. In actuality, the table in the specifications was unclear as to what "lower bounds and upper bounds of percentages of deflocculator were permitted with respect to the "upper limits" and "lower limits" of water cement ratios allowed.

The forces of the Rideau Canal Maintenance during the grouting of Old Slys Locks obtained first hand experience on the effects caused by the U of S formulation in which premature segregation of the particles in their rather flat holding tank above the pump, occurred immediately. The crew, their engineers and supervisors noticed the absolutely dramatic change in segregation caused by the introduction of 2% bentonite to the portland cement mix.
In Old Slys, it was (again) demonstrated that the grout-takes with the bentonite enhanced grouts considerably exceeded the ones without bentonite.
We also refer to our report on Chaffey's Waste Weir repairs for the explanation of segregation in suspension grouts.
It should also be noted that in one instance, during the removal of coping stones on Lock # 48/Monolith No.4, the annular space around one sleeve pipe was not even filled, most likely because the flow channel in the grout hoses, had choked off.

8.6 LOCATIONS REQUIRING FUTURE MONITORING

The grouting in some locations was "compromised" because of either fear of not meeting the completion date (work schedule), specific field conditions, monetary considerations, grout mix formulation or a combination of several or all of these factors. The following areas in particular demand attention and/or further grouting:
1) Sill No. 3 (sill between Monolith No.'s 5 and 6),
2) Sill No. 2 (sill between Monolith No.'s 3 and 4),
3) Wingwall south of Monolith No. 1,
4) Monolith No. 1,

5) Lock No. 49 West chamber wall.
6) Relief holes on Lock No. 48 West chamber wall and Lock No. 49 west chamber wall.
7) General coping stone elevation.
8) Monolith No. 5.

Remedial work could be provided by Rideau Canals' maintenance crews now that they are equipped for "emergency" grouting operations.

Issue No. 1: See section 6.1 for factual background of the grouting. Based on the events and results of the grouting on this sill, monitoring of the sill floors or breast wall for water leakage is warranted.

Issue No. 2: The grouting of Sill No. 2 was very similar to Sill No. 3. The major difference was in the sequence of drilling. In order to accelerate the overall schedule (by at least one week), the drilling of all four holes on the breast wall (two primary and two secondary) was executed at the same time. During the grouting operation grout leakage was evident throughout most mortar joints on the lower recess floor and upper sill and breast wall (which was similar to what was found during Sill No. 3 grouting operations -the only difference being that this time some mileage was obtained from the primary holes). The pointing of this breast wall prior to grouting was very difficult because of flowing water conditions via the face of the breast wall during pointing. The grouting operation also revealed many "uncontrollable" grout leaks via the face of the breast wall and as a result of these leaks, the operation was terminated prematurely. Observations and monitoring of the breast wall, especially the upper sill just downstream of the gates should take place. It would not be surprising to see "water-boiling" in these locations some time in the future. We consider this area very critical.

Issue No. 3: The wingwall south of Monolith No. 1 was also targeted on an accelerated work schedule program. This structure too, had all three holes (one primary and two secondaries) drilled during the first pass (one phase). The site conditions at the time of hole preparation were most unfavourable. The surface immediately next to the hole location was thawing and was very muddy from the drilling operation. It was difficult (almost impossible) to prevent fines, debris, gouge from falling back into the hole during the borehole preparation (air/water flushing operation). The grout take on these three holes was negligible. Additional holes were not pursued because of the likelihood of obtaining similar results from the additional holes due to the unfavourable site conditions that potentially (highly likely) contributed to the low takes encountered during the grouting of the three holes in the first phase.

Issue No. 4: The grouting of Monolith No. 1 was also on the critical path affecting an earlier completion date. The grouting of the primary and secondary holes on both Monolith No. 1 and No. 2 was done with the gates in place. Special precautions and attention was given to ensure no grout would hinder the operation of the doors after grouting was complete. During the primary grouting some communication was made towards the hollow-quoin. The grouting operation was hence suspended prematurely on these holes. The secondary hole grouting indicated a higher take than the primary holes. No additional holes were requested at this location.

Issue No. 5: The general grouting of the west chamber wall of Lock No. 49 is of concern. Given that no recorded grouting operations had taken place in the last fifteen years at this location, it was believed that grout takes would have been appreciably greater. The difference between the west wall and east wall of Lock No. 49 were the specific site conditions encountered at the time of drilling and grouting. The west wall had flag stones removed, thus exposing the limestone screening to the elements and drilling operations. The drilling and air/water activities that followed created contamination of the grout holes. Similar to the wingwall downstream of

Monolith No. 1, the borehole preparation activities could have contributed to the low overall grout takes. This wall should be monitored closely, in the future, for signs of seepage. Four relief holes were drilled below the navigation level (lake level) to bring down any build-up of water head behind the lock. Unfortunately, it is very possible that these holes will get plugged fairly quickly (from moss, floating debris etc..) and not serve their function as intended.

Issue No. 6: As part of the grouting program, drainage/relief holes were requested on the west chamber wall of Lock No. 48 and on the West Chamber wall of Lock No. 49. Four relief holes were installed in the west wall of Lock No. 49 below the lake water level. Twelve relief holes were installed in the west chamber wall of Lock No. 48. These holes were placed below the navigation level in the lock. It would be advisable to have these holes checked at the fall of each year and preferably washed out and reamed out if necessary. The preliminary indications were that they were definitely working. They brought the "line/level" of moisture staining on the lock wall down substantially over a period of several days.

Issue No. 7: It was observed during the removal of several coping stones in need of replacement (east chamber wall of Lock No. 48 -downstream portion, Monolith No. 4 and Monolith No. 6) that there was an abundance of ungroutable debris including clayey silts, organics (black top soil) and roots. If these conditions prevail throughout the lock structure it would not be surprising if one should observe continued deterioration of the coping stones over future freeze thaw cycles.
Furthermore, throughout the grouting operations, it was observed time after time, that a preferential travel path for the grout was to the surface. Even when grouting the lower zones of a borehole, grout travel was more often than not observed to make its way to the surface, before showing up elsewhere. The future grouting of any locks should take consideration of these observations, and devise a means of treating these situations. In the meantime, monitoring of the state or condition of the upper elevation of stones should be executed, and if deterioration persists, the discussion mentioned above could explain part of the reason for the deterioration.

Issue No. 8: The overall low grout takes on this Monolith is of concern. The full (water) Lugeon testing on Monolith No. 5 indicated that a mud filling phenomena was present with all zones tested. Especially in the downstream section of the Monolith, the grout takes were alarmingly low, these low grout takes coincide with water tests indicating mud filling. The fact that during the horizontal anchor grouting in this section consumed large amounts of "anchor-grout" is indicative that the structure was not adequately permeated with the vertical grout holes.

9. LITERATURE REVIEW

The Canadian grouting industry has an excellent reputation in the international grouting business. This in spite of deplorable and disastrous projects by black magicians. Fortunately, dinosaurs like Cementation and Intrusion Prepact were brushed away by performers, only in protected strongholds do the pirates of the industry manage to survive.

Alex Naudts organised and significantly contributed to the first and second international grouting conferences in Canada and recently published a handbook on soil grouting (without royalties). A summary of our evaluation on rock and structural grouting is enclosed in appendix 1-C (Evolution in rock grouting: from black art to engineering science).

In the international, grouting industry, the two international grouting conferences in New Orleans have produced a number of credible, well researched papers.

A lot of research work has been performed on the penetration characteristics of cement based suspension grouts: regular and microfine. ECO has fully taken advantage of the findings of credible research work or evaluation both short and long term and studied the factual information on its own projects to develop and advance the engineering aspects in grouting. ECO has always built on the theories and findings of others to create progress.
It is true that the success-rate of the projects in which ECO was responsible for the design, is virtually 100 %, compared with a 50% industry average.
The apparent Lugeon theory is a simple way of evaluating a rock-grouting project.
We do not apply the GIN-method, developed by the reputable Lombardi and Deere, to evaluate a rock-grouting or structural grouting project. We are however of the opinion that this IS a credible engineering system to make intelligent decisions during a grouting operation. Too many people in the industry do not pay enough attention to the "signals sent back by the formation" during a grouting operation.

The following is a brief review of some credible publications which have had an impact on professional grouting practice in Ontario and which relate to the project on Kingston Mills.

Improvements in quality, predictability, long term performance, penetrability of cement based suspension grouting have made steady progress by findings from both the scientific and the contracting community. Information provided by honest practitioners as well as world renown authorities in grouting continuously enhances the grouting industry both in Ontario and internationally.

From the first international grouting conference in 1982 on "Grouting In Geotechnical Engineering" in New Orleans, we believe that the papers from Houlsby provided substance and direction to the cement grouting practice.
Dr. Don Deere produced credible information on the behaviour of bentonite/cement grouts.

"An ideal mix should be a uniform, stable mix that has a viscosity sufficiently low to be easily pumped into rock cracks but not so low as to travel long distances without appreciable pressure drop." "An unstable mix is commonly taken as one with more than 5% sedimentation. Most cement-water slurries are therefore unstable mixes... The low sedimentation value may also be achieved by adding to the thin mixes a small percentage of activated bentonite. A 3:1 volume mix requires 4% of bentonite and a 2:1 mix only 2% of bentonite to limit the sedimentation to 5% or less. ... Stable mixes, then, may be obtained by the addition of small percentages of bentonite." "It is thus apparent that bentonite does increase appreciably the funnel viscosity of a cement slurry. Small amounts of bentonite appear to be preferable, sufficient to reduce sedimentation and bleeding but not so great as to impair significantly the pumpability and penetrability."

"...the Marsh funnel viscosity is an important measure of the true viscous nature of grout slurries; as the Marsh funnel reading increases, so do the yield point stress and plastic viscosity of the grout. Also, for a given W:C ratio the Marsh funnel viscosity increases rapidly with and increase in bentonite content. Thus, the Marsh funnel viscosity is an important index property for quality control of field mixes, particularly of the bentonite content."

It should be noted that in later publications, Dr. Deere acknowledges that the use of super-plasticiser off-sets the increase in cohesion caused by the bentonite.

Burgin, C.R. (1979) conducted credible research work in the University of Florida and wrote a book called: Investigation of the Physical Properties of Cement-Bentonite Grouts for Improvement of Dam Foundations. Burgin investigated the laboratory strength of hardened grout samples. We quote Burgin, who also elaborated on the long term performance and chemical attack on bentonite cement grouts:
"For thinner grout mixes the bentonite lowered the strength by 50-75%. For the thicker mixes the strength was reduced by only 25% or so, and it made little difference if the bentonite content were 2% or 8%. The samples with 1.5:1, W:C by volume, regardless of bentonite content gave 28 day strengths around 9 MPa. This is equivalent to a weak concrete and in the author's opinion is the minimum strength to be achieved".

Unfortunately, the team that evaluated and directed the grouting in the granitic formation in Pinawa for the Atomic Energy Waste Storage, did not consider bentonite as an additive in the cement based suspension grouts. Keil et al state that the researchers "felt" that bentonite could jeopardize the long term performance of the grout.

The Romans used clay-phyllosilicates of the 1-1 structures in their "bastardmortars" for the aqueducts in aggressive marine environments. More than two thousand years later, these mortars are still intact. Although bentonite is a clay-phillosilicate of the 2-1 structures, the ion-exchange between the sodium of the clay-type products and the calcium of the cements is very similar.

In 1992 the second international grouting conference on "Grouting, Soil Improvement and Geosynthetics" took place, sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers in cooperation with the ASCE/AIME Underground Technology Research Council Louisiana Section (1982) and the International Society of Soil Mechanics (1992). These events were held in New Orleans, Louisiana. World renown authorities elaborated on the behaviour of cement based suspension grouts. Authors such as Gallavresi, Dr. D. Bruce, Dr. R. Granata, DePaoli, Bosco, Hakanssen, Hassler and Dr. H. Stille brought credible work to the table pertaining to this matter.

The following quotes are taken from papers by these grouting specialists:
From the publication by B. De Paoli, B. Bosco, R. Granata, and D.A. Bruce we quote:
"Stable mixes: these tended to show an improved water retaining capacity: K_{pf} remained in the 0.7 to 0.18 range and K_{pc} remained limited in the 2 to 20 range. Bleed was always less than 2 % within 4 hours. Stable mixes with additives: the resistance to pressure filtration was enhanced: K_{pf} was always below the limit value 0.04 while K_{pc} did not exceed 3. There was no bleed."
"Strength and permeability characteristics were measured only on stable mixes (both ordinary and additivated), leaving out the unstable mixes that are generally characterized by final C/W ratios much greater than the initial ones. In general, higher strengths were obtained, with equal C/W ratio, by the additivated mixes. Permeability values were, however, more interesting: mixes with additives showed, on average, a 10 times lower permeability than ordinary stable mixes and these results were further regulated by the additive content."

"The addition of appropriate dispersing agents to the grout permits the use of bentonite for effective stabilization of the mixes, while preventing the associated worsening of the rheological characteristics."
(for the description of pressure filtration coefficient we refer to the paper by Naudts and Narduzzo for the CIM, in appendix 1-C.)

One of the main conclusions by U. Hakansson, L. Hassler, H, Stille, on the behaviour of microfine cement based grouts was: "By combining bentonite and plasticizer in the grout, significantly improved flow properties (i.e. low yield stress, low plastic viscosity) can be achieved."

Even as far back as 1982, when deflocculators were not common, bentonite was considered the appropriate additive to stabilize grout mix formulations. By studying the above papers from these authors, it is prudent for the grouting practitioner to consider the evidence given by these engineering scientists in the field of grouting.

In conclusion, bentonite combined with deflocculators will give cementitious based grouts better flow properties enhancing their penetration into a structure rock-or soil matrix, or a combination of these factors.

10. GENERAL EQUIPMENT OVERVIEW

A professional grouting operation utilizing state-of-the-art grouting techniques was implemented on this project as was executed in Hartwells Locks, Upper Beveridges Locks and Ottawa Locks. The industry standard in sleeve pipes, barrier bags, colloidal mixers, agitation tanks, moyno pumps, X-Y recorders, grout hoses, packers, pressure gages and grouting materials were used to execute this project.

All drilling was by rotary diamond drill. A variety of drills were used on this project; a Diamec 232, a track mounted, a skid mounted and a small Hilti core drill.

P.W.G.S.C. has obtained sufficient experience and is now familiar with all of the above equipment, for they have been used in past projects such as Hartwells Locks, Upper Beveridges Locks and Ottawa Locks. Therefore, there is no need to elaborate on it any further in this report.

11. ALTERNATE ANCHOR SYSTEM - MEMBRANE ANCHORS

The conventional anchoring system designed for this project was executed wherever feasible considering the limitations of the contractors installation techniques. (i.e. where the lock structures were founded on bedrock). The design for the conventional anchoring system ("Williams" anchor) required the bond zone of the anchor to be founded in three metres of competent bedrock.

These procedures were followed for the anchors installed in Lock No. 47, Lock No. 48 and the upstream portion of the west wall of Lock No. 49. In the remainder of Lock No. 49 however, the bedrock was typically deeper than 17.08 metres (56 feet), measured from the top of the structures. This was the deepest depth drilled during this project. In view of the site logistics and the installation methods used by the contractor, an anchor of 17 metres was the maximum length of anchor he could handle. Pre-tender borehole investigations indicated the conventional anchors would have to have been drilled and installed at depths exceeding 37 metres (for the bond zone to be in competent bedrock). In order to avoid drilling these great depths, an alternate anchoring system (membrane-anchors) with similar performance characteristics as the Williams conventional anchors was proposed.

The membrane type anchors were formally approved after a load test was successfully performed. The membrane anchors were utilized on most of Lock No. 49 (including the wingwalls) south of Monoliths No. 1 and 2.

The membrane anchor has a free length and a bond zone. The bond zone consists of a geotextile bag (sausage like in appearance) strapped over the same diameter anchor bar (the geotextile membrane is inflated with cement based grout, compacting the surrounding soil during the slow inflation process, creating an irregular bulb of grout in the soil) as used for the conventional Williams anchors. The free length section is identical to the conventional Williams anchors.
Three tubes run out from the top of each membrane anchor system. One tube is used for the grouting (inflation) of the membrane geotextile bag. One tube is used to grout the free length inside the protected corrugated plastic sheathing and the other is used to grout the free length zone outside the corrugated plastic sheathing.

The membrane geotextile bag section is first installed down the hole and a coupler is used to attach the free length section.
The grout tube to be used for the grouting of the membrane bag passes through a cylindrical tube. A vinyl-ester gel is used to seal the grout tube and the anchor rod in place in the cylindrical tube. Punch-lock clamps are used to fasten the geotextile bag over the cylindrical tube assembly.

Additional slots were cut along the grout tube that ran to the bottom of the membrane bag just in case the end of the tube would get plugged.

Two injection tubes reach to the bottom of the free length section: one of the tubes was coupled to the injection tube used for grouting of the membrane bag, and the other was taped tight against the anchor bar, for grouting of the free length zone. A third injection tube was encapsulated within the corrugated plastic sheathing for the grouting of free length zone after the anchor was stressed. The typical effective length of the "bond zone" (membrane bag length) to achieve the desired lock-off load (90 kips) as the other conventional anchors was 9.15 metres for the type of soils on this project.

Once the hardware for the anchor was installed down the hole to the required depth, the membrane bag was injected with a stable high early strength cement based grout of 0.4 water/cement ratio. Effective injection pressures at lock-off went as high as 120 psi. The grouting was done gradually, usually over a period of one hour to lock in the horizontal stresses in the soil. The stressing of the anchors usually occurred 3 to 7 days after grouting in order to give the membrane anchor grout time to gain strength. Originally, the contractor was seeking 30 MPa strength in his grout. Cylinders that were cast and tested revealed only 24 MPa was attainable in 3 days, however the grout installed in the membrane bag had been pressure filtrated and hence was of much greater strength than 24 MPa. Nevertheless, a waiting period of minimum 3 days was utilized prior to any stressing.

The inflation of the membrane bag (with the cement grout) against the native soils formed a grout bulb compacting surrounding soils and locking in the stresses in the soil (in essence the membrane anchor is an enhanced high friction pile).
Several problems were encountered during the execution of the membrane anchors. The most obvious problem was not getting the required volume of grout into the bag. The potential reasons for this was the plugging of the injection tube, or the injection tube being kinked during insertion into the anchor hole or during the raising of the anchor prior to installation (i.e. rubbing against the forks of the fork-lift), or contamination (backfilling of surface cuttings and/or caving) of the hole prior to the installation of the anchor. Another often encountered problem was the "blow-out" of the membrane bag (grout came to surface before any pressure was gained). The membrane bags could have torn or ripped during insertion. Alternatively, the membrane bags could have had defective stitching causing the blow-out to the surface.
Generally, when the proper grout volumes were injected and proper lock-off pressures were attained, the anchors passed when stressed.

12. RECOMMENDATIONS FOR FUTURE GROUTING PROGRAMS

Careful analysis of the results of the various grouting operations have demonstrated that each lock system has uniquely distinct characteristics. These characteristics vary from lock to lock and are the result of a combination of different factors:

- aging effects on the locks constructed with slightly different materials, different types of stones, different wall-thicknesses

- exposure to many freeze thaw cycles: walls (and other elements of the structure) above the ground are affected in a different way than walls (or portions thereof) in contact with the soil. Shade or direct exposure to the sun, also makes a difference.

- nature and approach to the maintenance programs involving remedial grouting on specific (targeted) locations, pilot test programs, past "full-scale" grouting programs.

- environment in which the lock is located. The chemistry and nature of the surrounding soils or rock formation has an impact on the long term behaviour of the structure. Precipitation of calcite will take if there is a hydraulic gradient from a limestone formation towards a lock under particular conditions. The presence of very fine soils in the vicinity of the wall will gradually lead to void-filling of the structure with these fine particles. The presence of a land-fill adjacent to a lock structure could leach or precipitate different ions in the structure, under the right conditions.

- specific construction details, pertaining to drainage of walls and monoliths. Preventive measures pertaining to water-seepage below the floors, dissipation of flow energy, permeability and nature of the formation through which the seepage has to go.
  Total hydraulic gradient.

- influence of site location, its geology and immediate surroundings.

From the above it is obvious that a focused site investigation is required to determine the scope, magnitude and approach to the maintenance work prior to preparing specifications for any future lock grouting works.

The Rideau Canal Engineering and Maintenance department has acquired most of the necessary equipment to execute site specific investigations and small scale grouting projects when and if required.

Future pressure grouting could utilise the in-house equipment and resources from Rideau Canal's Engineering and Maintenance Department to implement a focused investigation. With some guidance and input from P.W.C and from some true grouting and rehabilitation specialists, a proper, site specific design could be developed covering all eventualities. Specifications are either performance specifications or are descriptive. Descriptive specifications should be clear, and should be covering all the aspects of the operation, in sufficient detail.

ECO has a reputation for writing sound, very detailed specifications without ambiguities. In none of our projects, in which ECO was responsible for writing the specifications, claims for extras have been made.

Mr. Ben Groves (with Rideau Canal) has pointed out that specifications for the construction of highways, in the "early" days, contained numerous flaws. Contractors successfully claimed for differing site conditions. The designers learned from these cases and adjusted and gradually tightened the specifications. Nowadays, the transportation specifications are more fair and more clearly defined: the contractors know that there is virtually no room to make up for a low bid.

The grouting specifications for the pressure grouting of the structures on the Rideau Canal and other waterway systems need considerable improvement to produce a level playing field for the bidders.
It should be considered to do a complete overhaul involving a totally different approach to the tendering process to provide the best product for a given price.

After the rather poor grouting program at Ottawa Locks, ECO made a number of recommendations. One was to provide a two-phase rehabilitation program, with two different contracts, executed consecutively. The first program is used to fine-tune the operation and provide on site investigation and engineering while performing the rehabilitation work and to establish new bid items and unit rates where (and if) required. Enclosed to this report, the recommendations after the grouting of Ottawa Locks are enclosed in Appendix 1-B.

The second contract is the execution of the bulk of the work. The Owner does not have to choose the contractor who performed the first phase to do the second phase. The stage for the second contract is set during the first phase. The Contractor and the Owner are provided with considerably more room to manoeuvre in a two-tier contract.
The so-called test program as conducted in Kingston Mills was not at all consistent with the suggested two phase contract. Actually the opposite of the intent of the suggested two phase contract was accomplished.
The following discussion outlines issues and topics that should be expanded upon from existing specifications, or detailed and developed into future specifications and contract documents:

<u>Pre-bid Phase:</u>

Future specifications should definitely contain clear information for the following (much of the existing information can be found in current specifications but should be expanded upon and incorporated in future specifications along with the newly discussed other issues):

- measured drill hole depths: explicit description of the criteria pertaining to the length of hole for which the contractor will be paid. (i.e. consideration for hole collapse must be given and this must be mentioned in the documents). Also: will the contractor be paid for the length of sleeve pipe installed ? How much caving is considered acceptable ? Or, will the measurement for payment be based on the drilled depth prior to sleeve pipe installation? Will the contractor be forced to select a drilling technique/grouting technology that eliminates the collapse of the hole? The logistics and cost-impact should be evaluated in the feasibility stage. Regardless what is decided upon, a clear description should be given pertaining to the payment-item.

- method(s) of drilling should be specified, including the range of bore hole sizes. Load limits on the walls and monoliths should be provided. Consideration should be given to specify the protection of the coping stones with plywood or other suitable means. The criteria pertaining to the anchoring of the drill should be realistic and explicitly stated. If anchors are allowed, the maximum size, depth, locations in which they can be installed (i.e mortar joints etc) or not installed (spiders or bollards etc), how the anchor is to be retrieved after its use, how the surface is restored (material - acceptance criteria) and when (i.e.

immediately after drilling or at the conclusion of the project).

- sleeve-pipe lengths (with or without stick-outs): the payment item should be clearly defined. (i.e. a length above the existing level of coping stone should be specified). A size range of lengths of sleeve pipes delivered to site could be specified. Criteria pertaining to sleeve-pipes not installed to full depth should be provided.

- Performance criteria pertaining to the quality of the sleeve pipes should be specified. The sleeve pipes must behave in a predictable manner with respect to the pressure required for the opening of the sleeves. This has been a real and serious issue, because there are sleeve pipes on the market which behave unpredictably due to smaller outlet holes below the sleeves and different stiffness of the sleeves.

- barrier bags: The minimum length should be specified, as well as the system to be used to attach the barrier bags (i.e.punch lock clamp). This length is dependent of the borehole diameter and condition of the structure being grouted. The characteristics of the desired type of geotextile should also be specified.

- all equipment should be specified, i.e. colloidal mixer, giving ranges of r.p.m., agitation tanks, pumps, valves, packers, pressure gauges (with suitable range of operation), flow meters, X-Y recorders, flow meters to measure volume of water for every batch etc... The action requested by the Owner from the contractor should be clearly outlined, in case the equipment does not function according to clearly specified standards or criteria.

- all grouting materials, cements, grouting ingredients and additives should be specified, clearly defining the properties of each individual additive or ingredient. The ranges (percentages) and limits in which the ingredients will be used in the formulations should be stipulated. The maximum and minimum water cement ratios should also be stipulated. Sodium methacrylate (drastically increasing the resistance against pressure filtration) should form part of the list of the additives of the formulation of cement based suspension grouts.

- the limits in rheology (including the tolerance for approved mix designs) should be stated. If ultimate strength is stated, it should be realistic: based on facts. Water-cement and Cement/additive ratios should be defined with the knowledge in mind that a range of Marsh Values can be obtained depending on the equipment, the mixing time and the time of the sample taking. Therefore the testing procedures should be clearly defined.

- The acceptable amount of sedimentation (or bleed) should also be stipulated. The standard for the test should be stipulated. The frequency of testing should be defined. Upper and lower limit of the pressure filtration coefficient for the various formulations should be stated. The frequency of testing should be outlined.

- the range and tolerance in specific gravities (wet density) for different formulations should be given.

- Detailed logging of a pre-determined number of (cored) borehole should be strongly considered.

- the refusal criteria for the grouting must be clearly and explicitly stipulated for single hole grouting and for multiple hole grouting.

- Clear specifications pertaining to multiple hole grouting: when it is permitted, when the contractor is obliged to resort to this technique should be spelled out. It therefore appropriate to introduce a clause stating that claims for "slow-take" grouting operations will not be entertained.

- Establish a number of provisional bid-items to cover eventualities and unforeseen site-conditions, without having to enter into negotiations with the contractor:

  • relief holes: as a provisional item in future specifications it would be beneficial to incorporate the use of relief holes as part of the specifications. Whether they will be used or not will be dependent on site conditions. Consideration should be given to make relief holes intersect the vertical drill-holes.

  • flushing procedures - horizontal jet lance - cage flushing - air/water flushing. The method(s) should be explicitly described in full detail, including duration, ranges of water and air-pressures, detailed drawings of pipe-systems and hook-ups, one-way-valves, volume of water and air etc. All these items must be covered to avoid discussions.

  • Horizontal grout-holes in particular locations: length, drilling technique and bore-hole preparation should be specified as well as the grouting procedures for these types of holes.

- Acidization should become a standard technique for the preparation of boreholes. ECO has recommended P.W.G.S.C. several times to utilize this technique to dissolve calcium salts in cracks and crevices. Unfortunately this recommendation has not been followed. The reaction between H_3PO_4 and $Ca(OH)_2$ and $CaCO_3$ and Aluminum salts present in cement-based products and complex calcium-salt ions produces water, CO_2 (gas) and Aluminum and calcium phosphates. The aluminum and calcium phosphates are innocent products, used as fertilizer, and in some pills. The benefit of acidization has been studied by all major oil-well drilling companies as well as ECO, who introduced acid-flushing in the rock- and structural grouting.

A paper by Alex Naudts, pertaining to the influence of acidization in limestone based formations, was presented during the international conference on "soil and rock improvements in underground works" held in Milano (Italy) in 1991.
Presently, this is an internationally accepted technology, not only for crack-injection, but also for rock-grouting in geotechnical engineering. Dr. Felix Verstraeten recently informed us about this trend and the evaluation away from hydrochloric acids (producing the hygroscopic calcium chloride) towards diluted phosphoric acids, not producing hygroscopic, nor aggressive/corrosive products. The specifications should detail the procedures, storage, dilution, environmental precautions etc.

- sealing measures during grouting, materials, time allowance - and fair compensation to contractor. The present specification has addressed this issue pertaining to the materials for different categories of leakage. These must now be expanded upon providing fair compensation for clearly explained activities and procedures to stem leaks. The contractor should not unnecessarily be burdened with an activity he cannot realistically estimate.

- heating temperature, minimum temp. prevention of frost into structure. This is a very important, critical, serious, vital aspect of winter grouting operations. A clear description of the term "winter conditions" should be provided and for how long a minimum temperature must be maintained before, during and after grouting. The minimum temperature to be maintained within the housing must be explicitly stipulated. A realistic and achievable value must be determined. This may be dependent on the housing method selected. Perhaps the type of housing should be stipulated in future specifications, and the number of access doors and width, height and lengths of clearances. This is important for the day to day drilling and grouting operations. An acceptable hoarding system is one whereby drilling at desired locations can be readily accessed, access to grout holes is maintained and access for cleaning of grout spills and sealing of grout leaks during grouting can be done easily. In order to reduce the risk burden for the contractor, it might be appropriate to work out a scheme (unit-rate) whereby the contractor is bidding per "degree-day", reflecting temperature and time. Nevertheless, the heating and housing provision is imperative to a quality end product, and the specifications should reflect this.

- insulation requirements on lines and/or inline heaters on all grout lines and piping systems during winter grouting operations must be explicitly stated.

- a slight modification to the location of some of the grout-holes and angle of drilling should be seriously considered. The grouting at Old Slys Lock during April 1995 had considerable success by moving the location of the boreholes closer to the face of the coping stones and drilling the holes at such an angle to avoid the backwall of the lock. This resulted in better grout travel, since the grout does not become too contaminated by the gouge and debris typically encountered in the backwall-portion. In Hartwells Locks the grout spontaneously moved to the rather permeable zone in the 400 to 800 mm thick facing zone of the stones and travelled along the entire wall in this area, during the grouting of the primary grout-holes. During the grouting of the secondary holes, more microfine cement grout was used, which typically travelled within the rubble portion of the lock-walls The conditions encountered in Old Slys and Hartwells did not exist in Ottawa Lock, but partially existed in Kingston Mills.
  Again, a two phase program or test-program would reveal the nature of the structure.

- The sod or flagstone butting-up against the coping stone should be stripped back at a depth suitable for the installation of a concrete pad or a flowable grout to act as a permanent seal. This also has beneficial effects to the end-product. It eliminates infiltration via the upper portion of the backwall, while during grouting it acts as a competent containment for the grout, reducing the number of premature terminations of the grouting operations due to leaks to surface.

- use of horizontal grout holes. In future grouting operations, consideration must be given to horizontal grout holes. On the Kingston Mills Locks project, great success was achieved from the grouting via several horizontal anchor holes (A2 anchors). Although it should be noted that elsewhere in the structure the grout takes were negligible. This however is no reason not to explore the potential of horizontal grout-holes on future projects. In the Old Slys Lock grouting operation, great success was attained with horizontal grout holes, which confirmed the potential of the approach. It also shows that every lock structure has its own unique features and characteristics. Perhaps the most logical approach is to incorporate horizontal grout-holes in future specifications as a Provisional Item. If the two contracts approach would be selected, during the phase I contract, the suitability of these holes could be evaluated.

- the use of provisional items should not be overlooked nor under utilized. Provisional items allow the client the opportunity to cover potential situations and yet cover exaggerated "claims-for-extras".

Other considerations - Solution grouting:

Solution grouting (old name: chemical grouting) plays an important role in the grouting industry. Often, where suspension grouts cannot achieve technically desired results the opposite is true for solution grouts. Naturally, solution grouts have dramatically better amenability when compared to suspension grouts. The amenability of the structures at Kingston Mills Locks for suspension grouts in monoliths and walls was very low even for microfine cement based suspension grouts.

In fact, based on the evidence obtained from the test holes (T1, T2 and T3) on the east chamber wall of Lock No. 47 (location of University of Sherbrooke research program) it was discovered that inadequate grout penetration was observed in the test hole drilled 0.75 metres away from a grout-hole. An additional 400 litres of grout was placed in this hole, only a few feet away from the grout-hole, in spite of the numerous grout seams encountered in the core. This quantity could have been higher if the grout would not have leaked causing the premature termination of the operation. We are puzzled why the U of S did not act and decrease the grout-hole spacing from 6 metres (as per their recommendation) to a fraction of this number.

This hard, irrefutable evidence confirmed the requirement for decreased hole spacing (perhaps as much as 3 times the number of holes) to achieve the desired results of the pressure grouting operation, with overlapping grout cylinders.
Extra grout holes implies extra costs for increased drilling, increased number of sleeve pipes, increased labour-component, increased time. Unfortunately suspension grouting may not be adequate to reduce the permeability to sufficiently low levels and enhance the structural integrity.
Hence the money spent on such an operation might not be money well spent. The amenability method provides a clear answer to the suitability of suspension grouts. If the apparent Lugeon value, established with microfine cement based grouts is less than 60 %, The Owner would be better off to cancel the entire suspension grouting operation and resort to solution grouting.

The reason for mentioning solution grouts here, is to make the designers of these rehabilitation projects aware that there are sound options or alternatives if and when suspension grouting is not suitable for a particular rehabilitation project.

Solution grouts could be used in conjunction with cement based suspension grouts. The following solution grouts should be considered:

- acrylamide solution grouts (low gel-strength, very low viscosity, ideal for permeating matrix of mortars silts and sands, neurotoxic in its liquid form). Material cost: $ 1 400/cubic metre (formulated - 10 % solids content). This is a durable grout. Freeze thaw resistance can be substantially improved by adding glycol to the formulation, which prevents desiccation of the gel in the long run.
- Silacsol: the only durable sodium silicate grout, which provides adequate strength to the soils. This is not an evolutive solution grout, contrary to the classic sodium silicates.
  The price of the product depends on the mood of the people holding the monopoly on this product (Soletanche). The product is durable. The material cost is approximately $1600/ cubic metre.
- Water-reactive polyurethanes:
  A tailor formulated crude MDI-based, solvent free, water reactive polyurethane prepolymer would be probably the best bet both from a durability and an environmental stand-point. These products react with the water and the moisture in the formation and are very durable. A low amount of catalyst should be used to obtain a very slow and long reaction during the chemical reaction between the water and the prepolymer. The cost per cubic metre end-product (allowing for the expansion) if bought directly from the manufacturer, is

approximately $3500 per cubic metre.

- Two-component polyurethane foams, as used in the German coal-mines. The water-compatible polyurethane foams (Wasserfest) are suitable, provided they can adequately be retarded. Nowadays Wittlich also has combinations between sodium silicate and polyurethanes which provide a very hard very durable end-product. The penetrability of these products is a problem, because they are evolutive solution grouts, contrary to the aforementioned products. If bought directly from the manufacturer, the price per cubic metre is approximately $ 3 500 per cubic metre.
- Two-component polyurethane elastomers, as were used for crack-injection during the rehabilitation of the blast damage at Hartwells' locks. These products have excellent durability, sufficient strength and remain flexible, also at minus 25 degrees Celsius. Unfortunately, they are very expensive, material cost is approximately $16 000 per cubic metre. The appropriate sub-family of elastomers needs to be specified, depending on site specific circumstances.

- Epoxy injection resins (water compatible type with amine-adduct or cyclo-aliphatic amine hardener). Only to be used after the structure has been adequately grouted with cement based grouts, the low viscosity epoxy resins will permeate the matrix during prolonged, multiple hole grouting schemes. The epoxy should be purchased directly from the manufacturer and not from formulators. In line-heating would be necessary to ensure adequate grout-penetration. If purchased directly from the manufacturer, the price would be approximately $ 12 000 per cubic metre.

In summary, if the two-contract system would be used, or alternately if a pre-design test program (preferably undertaken by Rideau Canal forces) would be used prior to undertaking a substantial rehabilitation program on a historical structure, a good program could be designed, or alternately, specifications could be adjusted to reflect the actual site-conditions.

It is a new trend to put a technical questionnaire together, prior to the tender, in which the contractor discloses in detail his method of bidding, pricing, staffing. The questionnaire covers all the activities and helps the contractor to analyze the project.
The duly filled out questionnaire is placed in a sealed envelope in escrow until disputes arise. At this point the envelope is opened and the assumptions and production rates including the associated costs are revealed. This is done for the general contractor and the important subcontractors.

Award Phase:

If all the above recommendations are implemented, this phase of the contractual procedures should become less onerous than in the past.

Especially if the two-contract system is in place, the stage is already set for the second contract, in which the Owner and the Contractor still have the chance not to award or to withdraw their bid.

During the pre-award meeting, because of the economically difficult times the Owner should find out if the contractor understands the task ahead and has covered these activities. With the unopened bid-method in escrow, there is little room to manoeuvre for the contractor. It is at this time that the low bidder will have to disclose his philosophy justifying his numbers.

Usually, because of the framework of past specifications it was extremely difficult, if not impossible to disqualify a contractor once he was the low-bidder. The general conditions or supplementary general conditions must be expanded in this respect.
We also suggest that the low bidder should be given the chance to bow out without losing his bid-bond.

Unless a specialist grouting contractor bids the work as a general contractor, general contractors (not experienced in grouting) will generally retain the services of a specialist grouting contractor in order to meet the existing requirements of the specifications.
For the pressure grouting of the locks at Kingston Mills, the contractors counted on their ability to negotiate rather than on their ability to perform, when they put their numbers down...
"Soft claiming" involves a great deal of diplomacy and is less confrontational and usually involves reasonable amounts of money; "hard claiming" is a much tougher game involving the legal skills of both parties and precedents pertaining to the matter. Since court-cases are costly, the amounts claimed are usually a multiple of the "soft claims". The contractor usually receives the benefit of the doubt and ambiguities in the specifications are typically blown out of proportion (benefiting the contractor).

To avoid a repeat of the circumstances (ambiguous and inadequate specifications countered by a "soft claiming-for-everything") on future projects a number of measures should be taken.
Existing clauses protecting the client when unbalanced bids are apparent, should be enforced when they can be legitimately used to disqualify the contractor.

Briefly elaborating, (particular to this project), the costs for heating and housing were unrealistically low. At the pre-award meeting the contractor was able to justify the reasons for his low prices on these items (i.e. he stated he owned all the scaffolding and the housing was costing him only the labour it took to put it up, other items in the contract were "loaded-up" to cover overhead and profit).

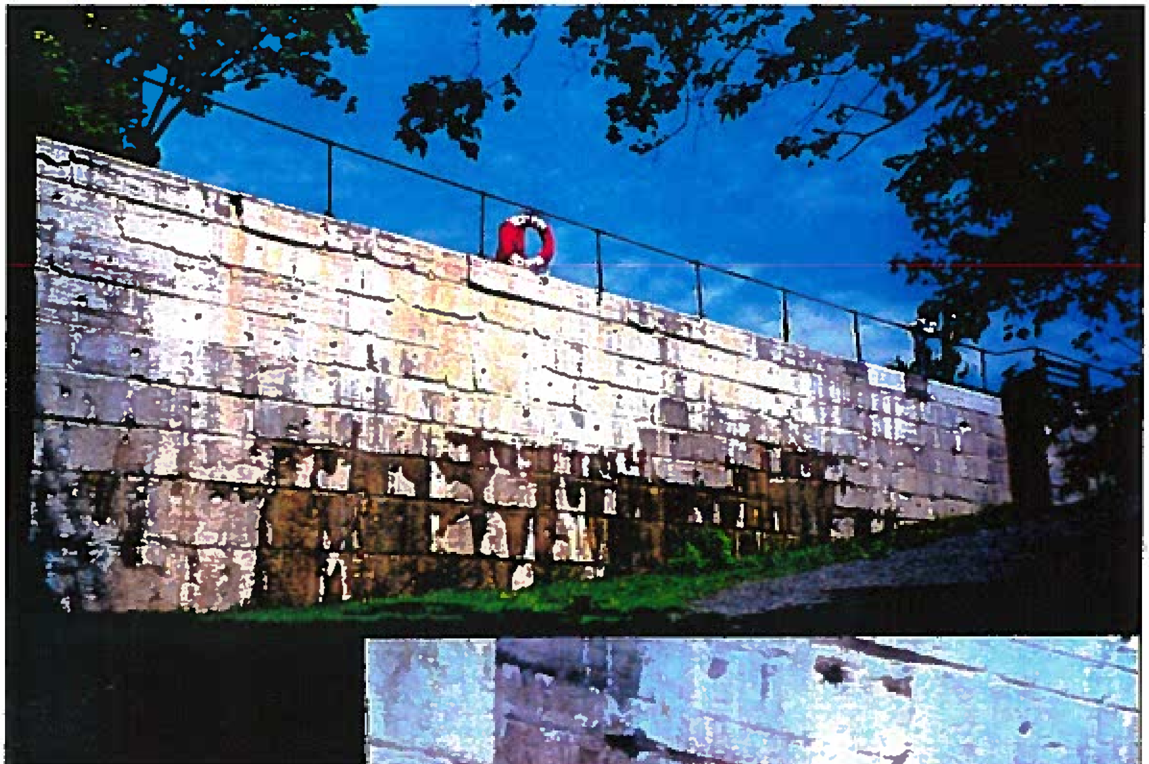
If more quantifying details (bidding method placed with the questionnaire in escrow) are requested, the most suitable contractors should be the low bidder for prices at which they are able to perform the work.

One thing is clear it is not in the interest of the general public that the contractors with the best "fast-talking" skills should be the ones doing the work.

Post Award Phase:

The best way to "out-wit" a contractor is to be more knowledgeable than he is at his own game. If a contractor finds "holes" in the contract documents, the Owner is often faced with playing a defensive role rather than an aggressive offensive role in a project.
Under these circumstances, it helps to have a competent site supervision team, one that has lived through several Lock rehabilitation operations, a team such as the one provided for Kingston Mills.

13. PRESENT CONDITIONS



P1 : (Above) Exterior face of the free standing wall (East wall of Lock No. 47.

P2 : (Below) View of exterior face of East wall of Lock No. 47. Close-up of down-stream section of wall, adjacent to Monolith No. 6.

P3 : (Above) View of exterior side of Monolith No. 6 (free standing monolith structure)

P4 : (Below) View of exterior side of Lock No. 48 east chamber wall (free standing structure)

P5: (Above) View of Monolith No.5

P6: (Below) View of Monolith No.3 and upstream portion of East Chamber wall of Lock No. 49.

P7: (Above) View of west chamber wall of Lock No. 49 and upstream portion of Monolith No.1

P8: (Below) View of east chamber wall of Lock No. 49 and downstream portion of Monolith No. 1

P9: View of Monolith No. 2 and downstream portion of the east chamber wall of Lock No. 49.

14. CLOSURE

The interpretation of this report requires and assumes a certain level of understanding of grouting and grouting related issues.

Each rehabilitation project is distinctly different and the selected grouting rehabilitation methods need to be tailored to the circumstances.

We hope this report leads to an honest review of the approach taken to the rehabilitation of historical structures. We owe it to the public and the future generations. ECO is prepared to assist P.W.G.S.C. in every way possible in preparing better contract documents to obtain the best possible end-product for the lowest price, without giving contractors the opportunity to claim their way through the project.

This report has been made for discussion purposes only and can not be used for the development of grouting specifications for any "other" project without explicit and written consent of the authors.

We like to thank P.W.G.S.C. for the opportunity to participate in a series of lock rehabilitation operations.

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