THE ST.LAWRENCE SEAWAY (QUÉBEC, Canada)

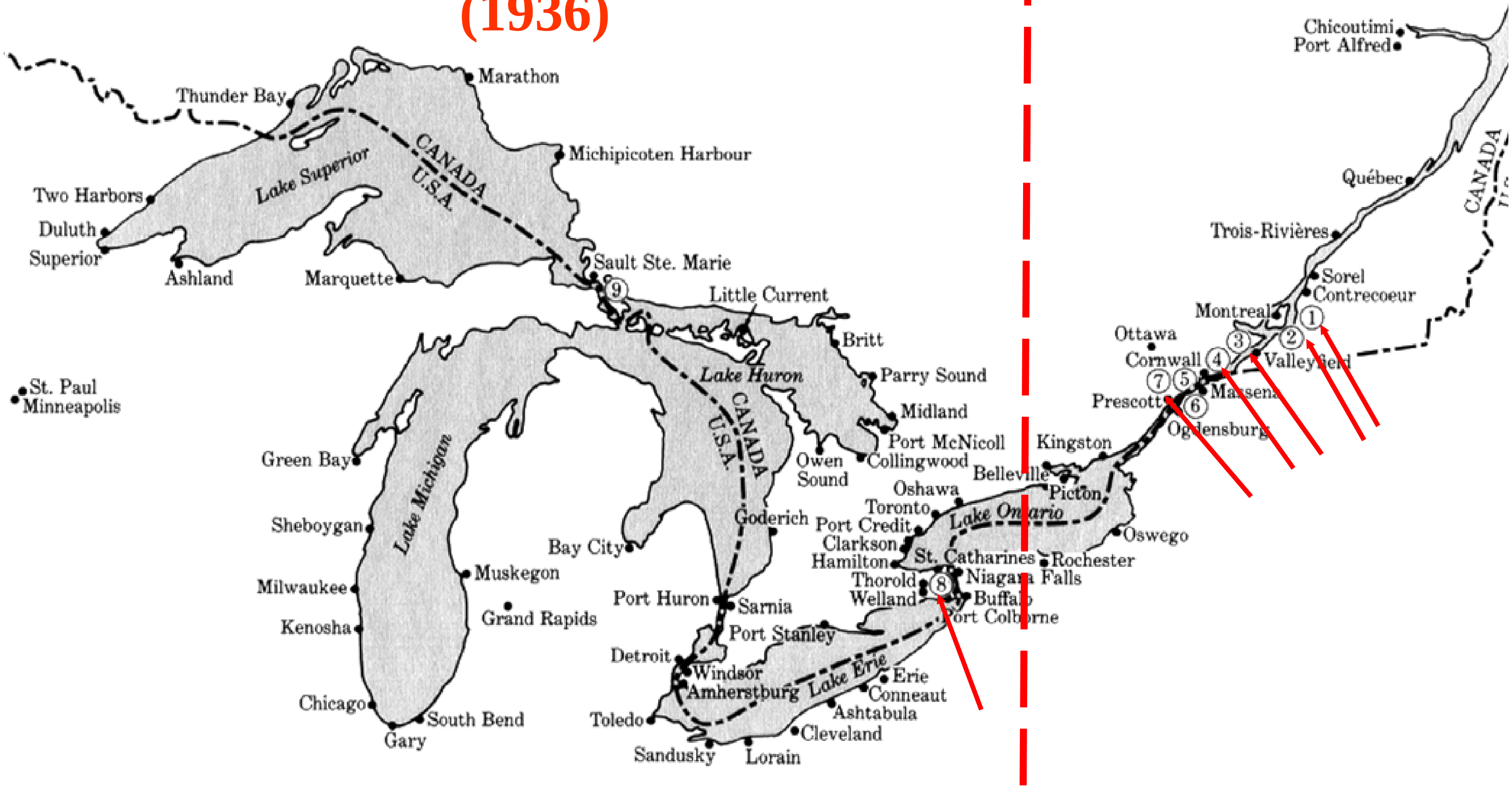
REHABILITATION PROGRAM OF NAVIGATION LOCKS AFFECTED BY ALKALI-AGGREGATE REACTION

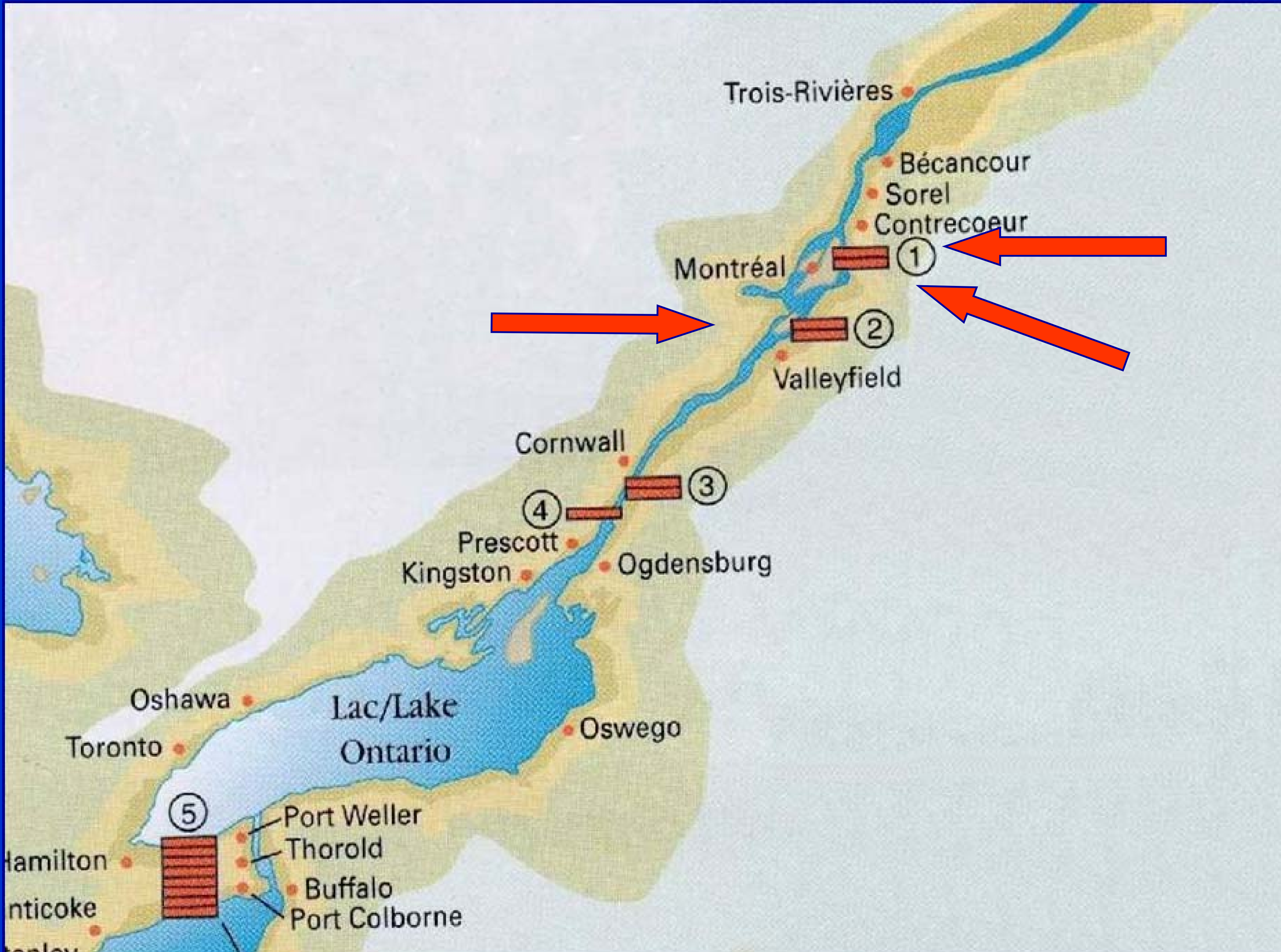
By : Marie Gaudreault ing, M. Eng

INTRODUCTION

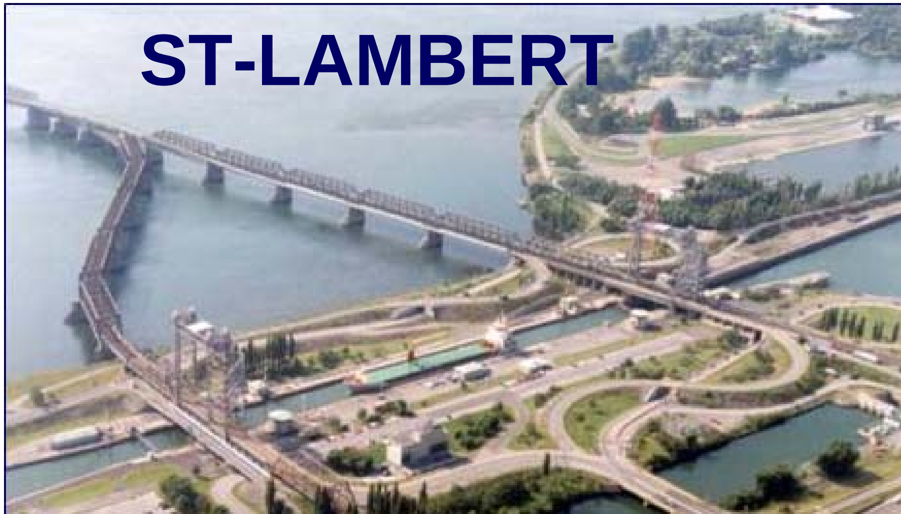
NIAGARA REGION (1936)

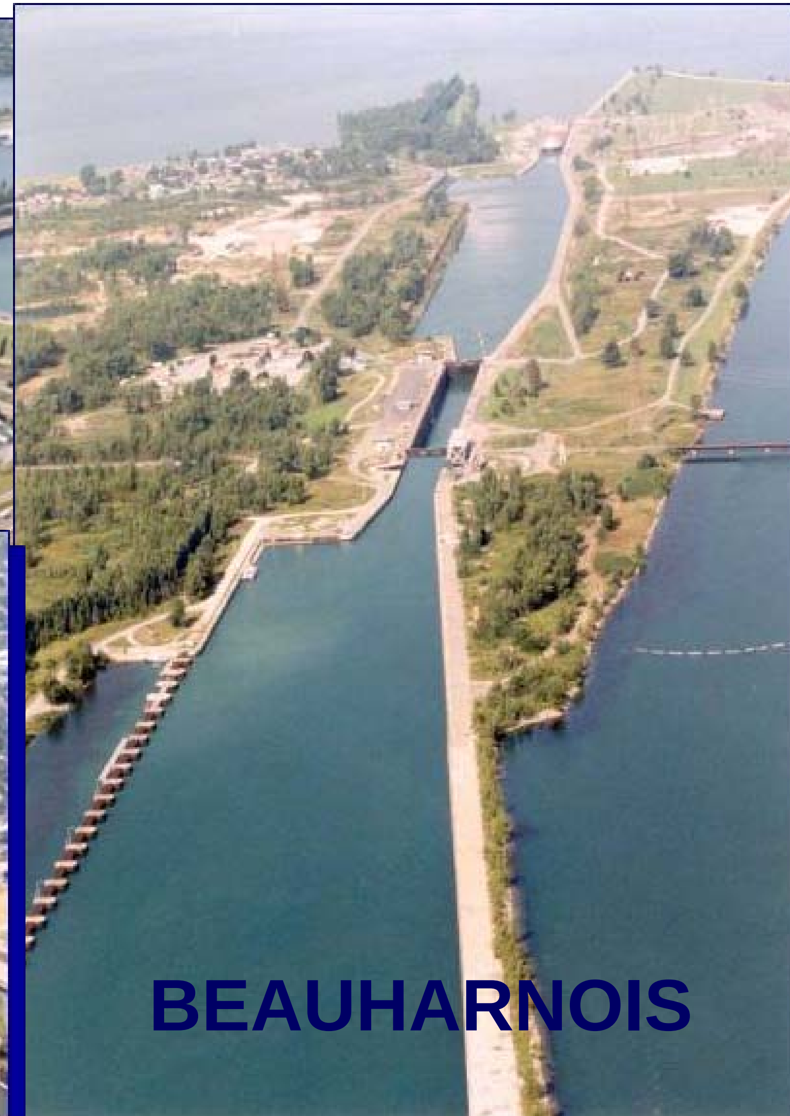
MAISONNEUVE REGION (1959)




Trois-Rivières
Bécancour
Sorel
Contrecoeur
Montréal
1
2
Valleyfield
Cornwall
3
4
Prescott
Kingston
Ogdensburg
Oshawa
Lac/Lake
Ontario
Toronto
Oswego
5
Port Weller
Thorold
Buffalo
Port Colborne

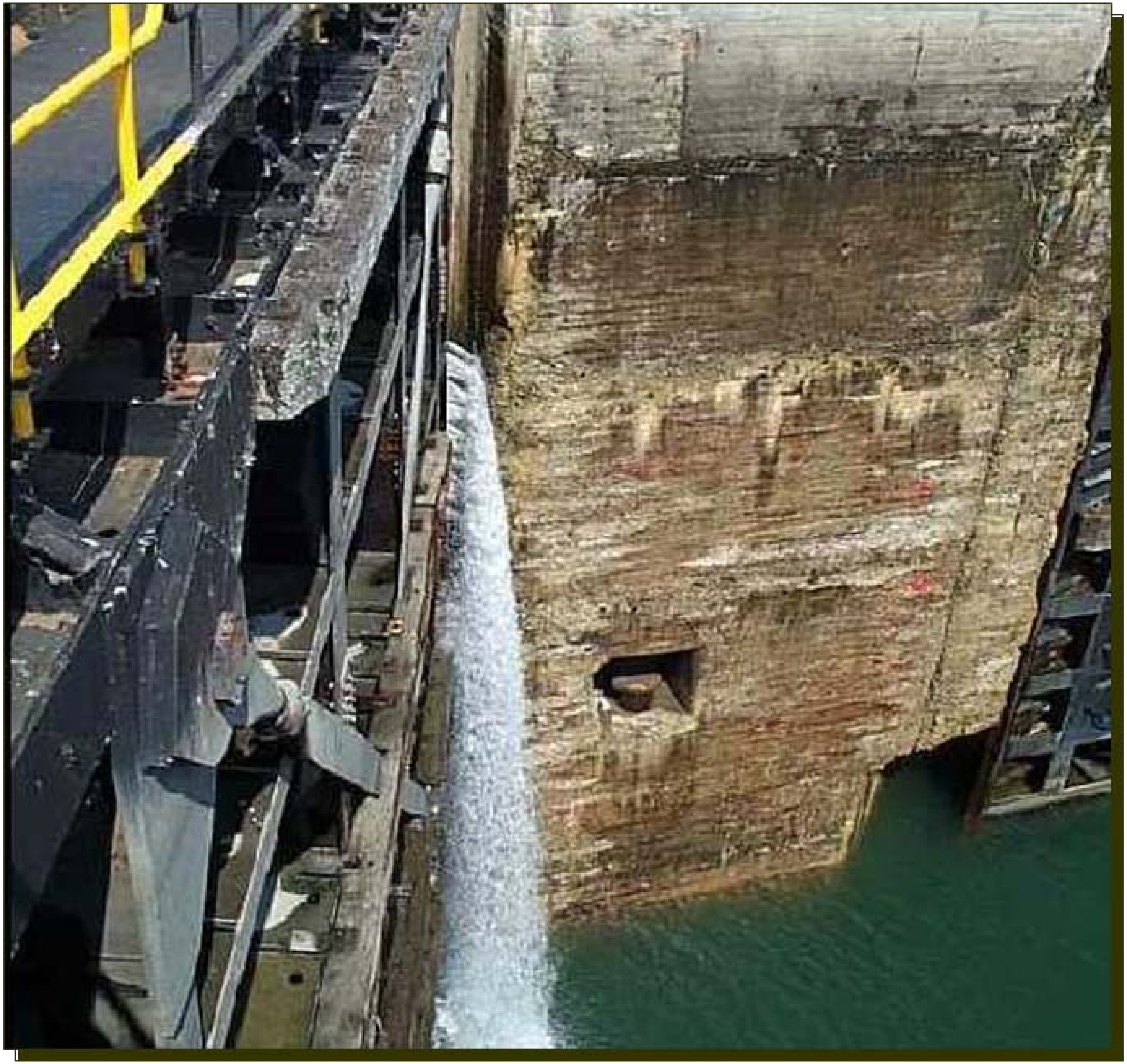
Projects affected by AAR in the MLO sector





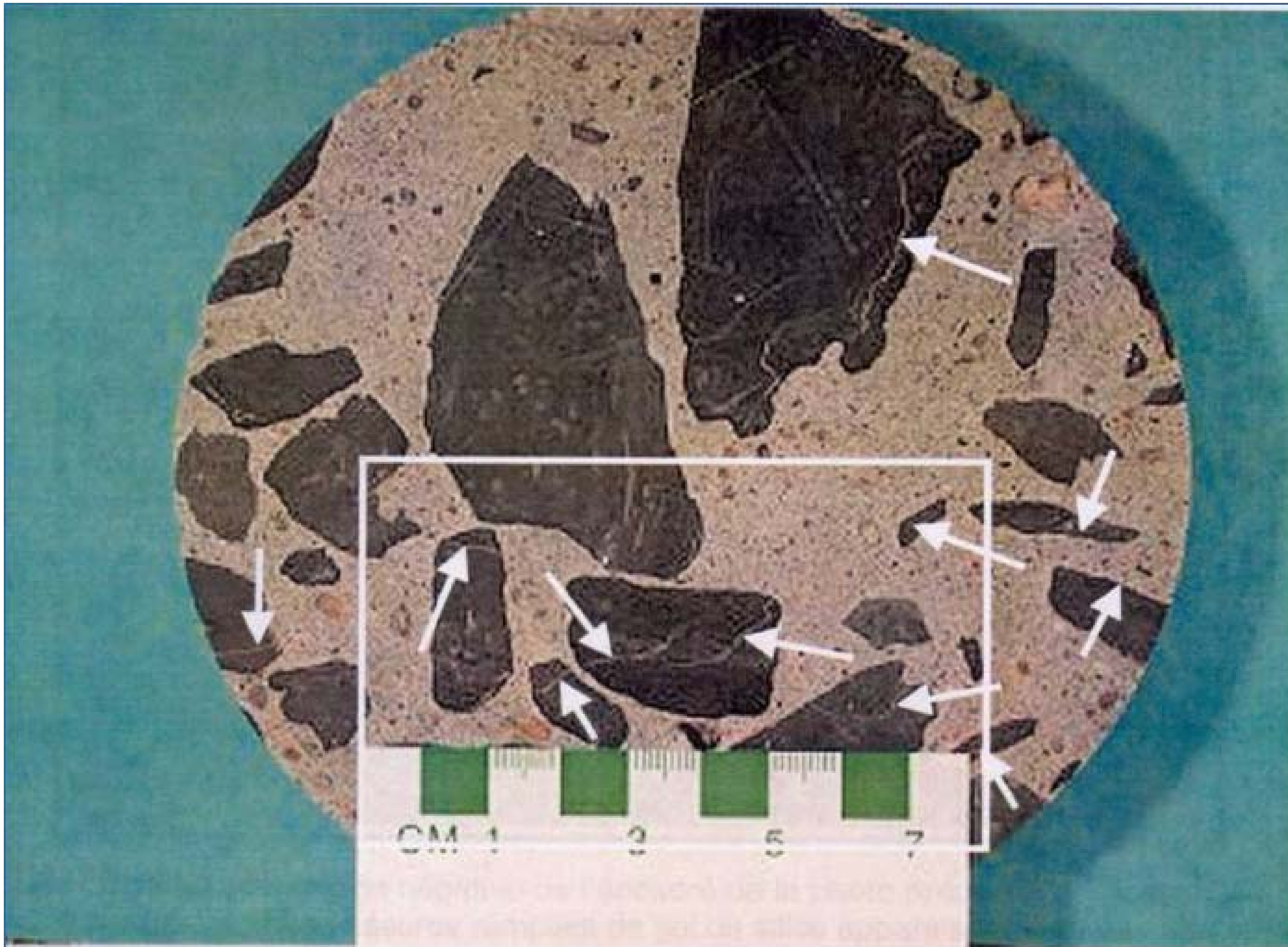
DIAGNOSIS

- Identified in the early 80's
- Persisting occurrence of operational problems due to mechanical equipment "jamming" tight
- Surveying records
- Visual symptoms associated with concrete swelling due to AAR
- Laboratory testing for reactivity potential of concrete aggregates



Visual Symptoms

Laboratory Testing



Testing - Aggregates

- Lower and Upper Beauharnois Locks
  - From excavated material
  - Postdam sandstone Formation
  - Tested highly reactive
- St-Lambert & Côte Ste-CatherineLocks
  - Argillaceous limestone
  - Tested very highly reactive in St-Lambert and highly reactive in Côte Ste-Catherine

Testing - Concrete Characteristics

Lock	Na_2O_{eq}*	Expansion (%)	
		Residual	Absolute
St-Lambert	3.03 kg/m^3	0.022	0.180
Côte Ste-Catherine	4.49 kg/m^3	0.013	0.077
Beauharnois 3	3.75 kg/m^3		-
Beauharnois 4	4.84 kg/m^3	0.015	0.144

*Water soluble alkali content

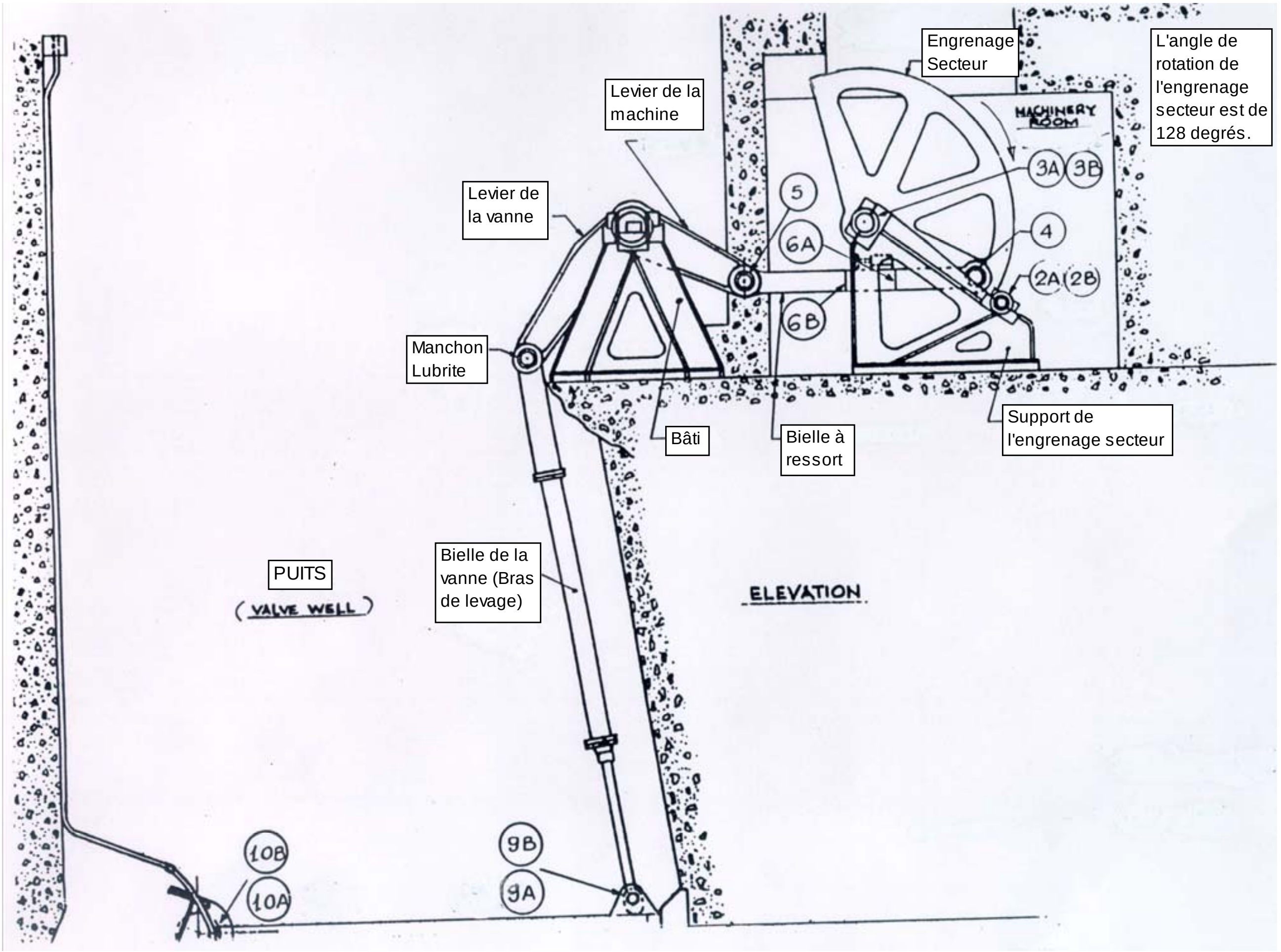
MAJOR ON-GOING EFFORTS

- In the field
  - On-Going Maintenance Program
  - On-Going Instrumentation Program
- Theoretical
  - Pre engineering study
  - Pilot project

Maintenance Program

- Mechanical adjustments
  - Valve and gate re-alignments
  - Roller tracks re-positioning
- Structural modifications
  - Reconstruction of concrete recesses
  - Reconstruction of access covers
- Crack injections
- Confinement and strenghtening techniques

Valve lever arm realignment



Taintor Valve lever arm realignment

F/E Taintor Valve side seal realignment

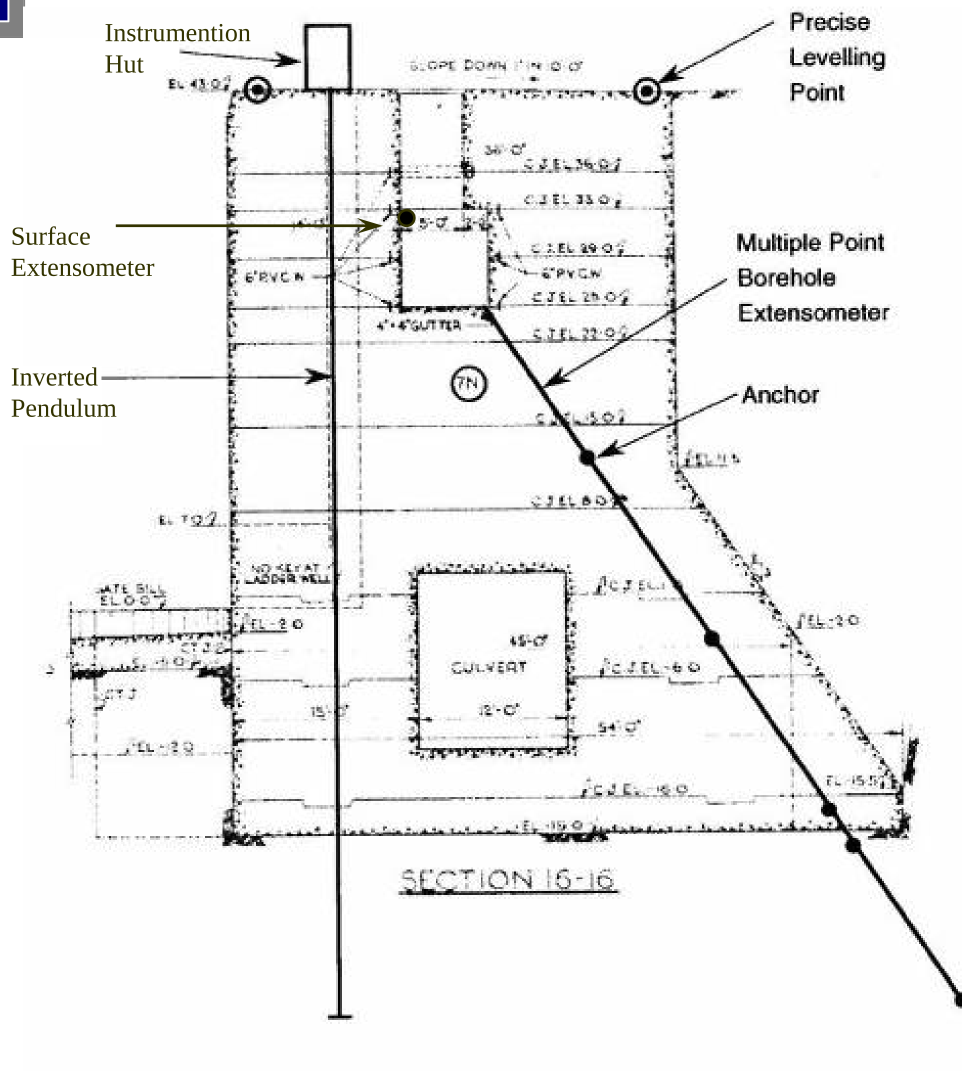
Gate Realignment

Structural Modifications

Crack Injections

Confinement and strenghtening

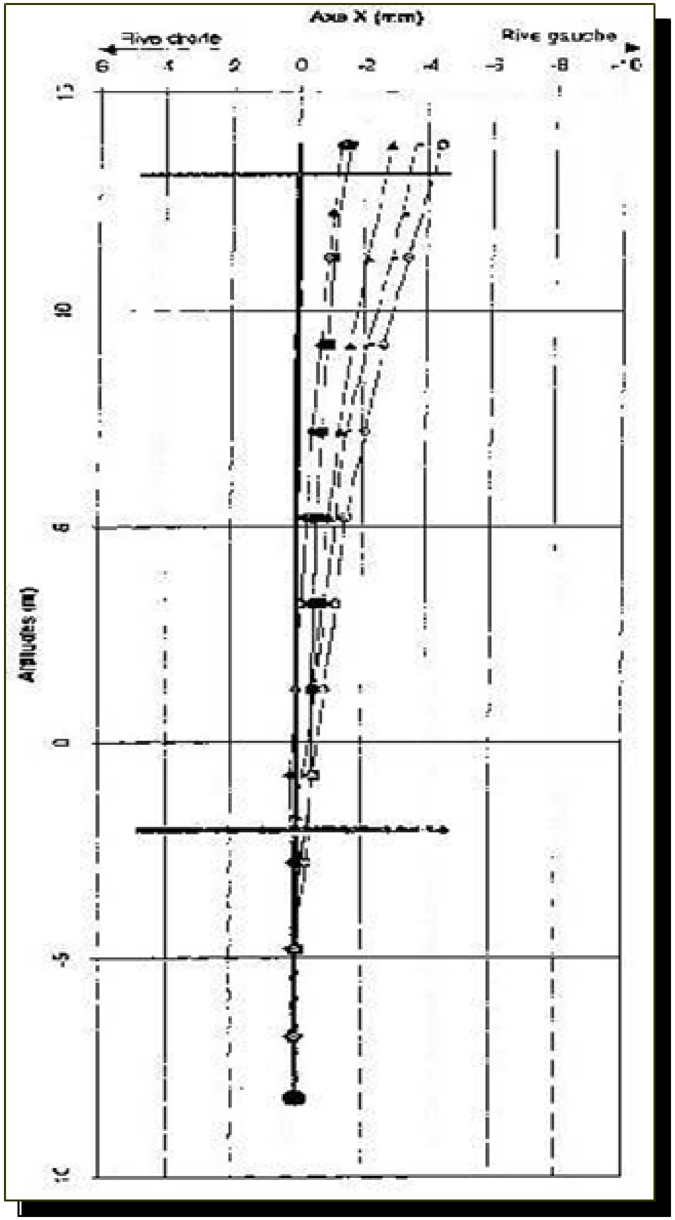
Monitoring



- Inverted pendulums
- Extensometers
- Crack width measurement
- Survey Network for specific monoliths displacements

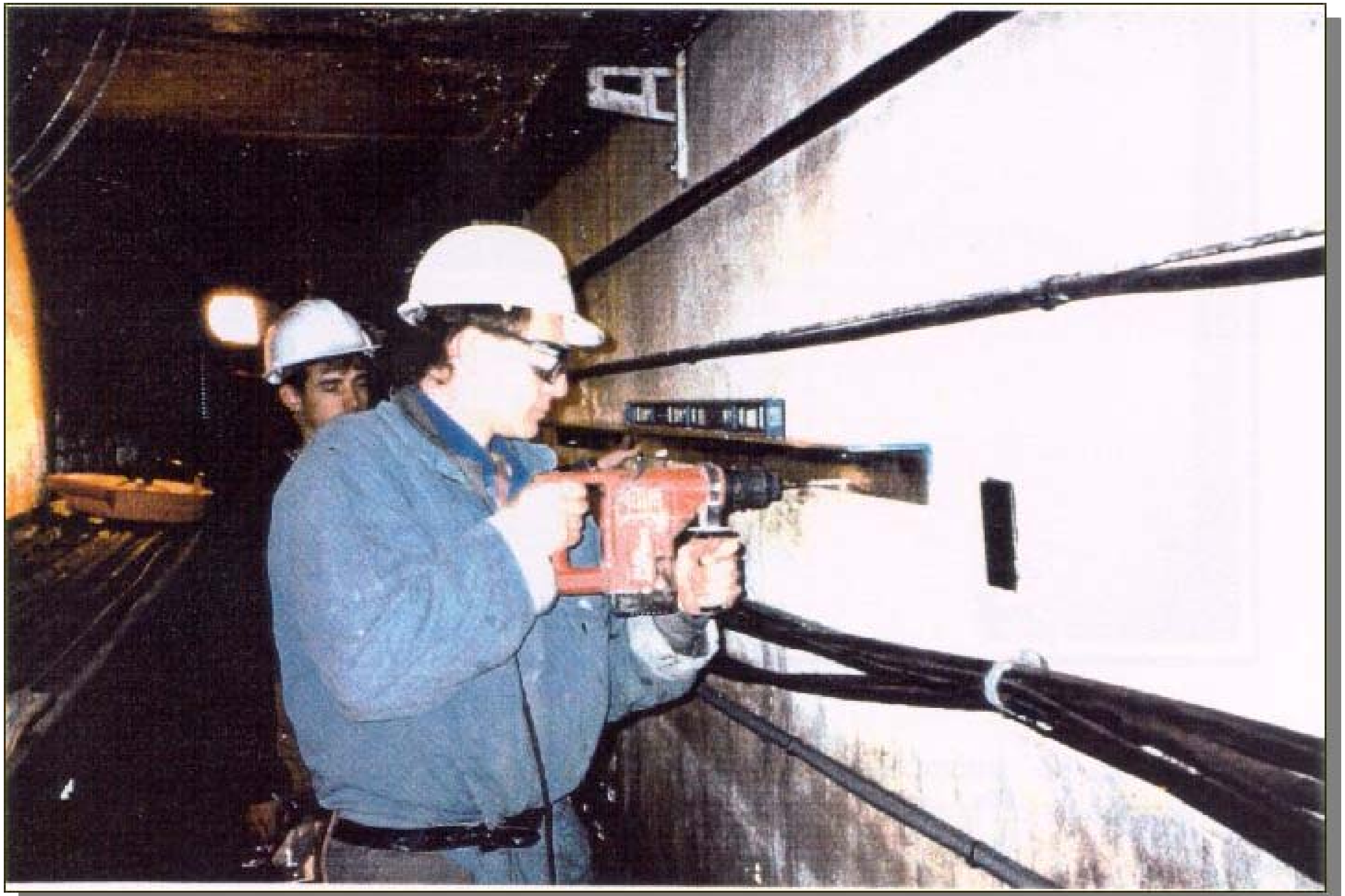
Inverted Pendulum

Inverted Pendulum

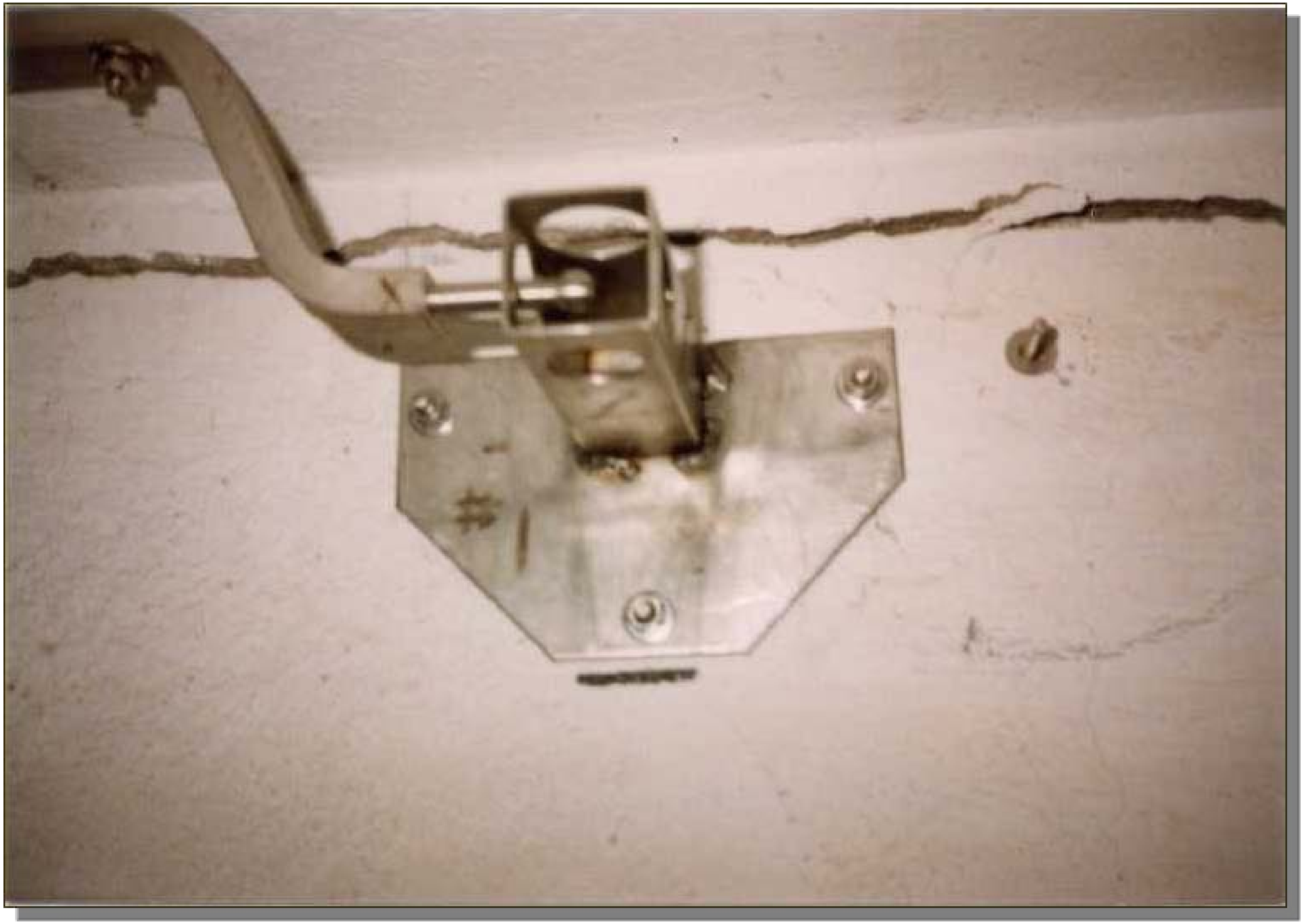


Inverted pendulum results

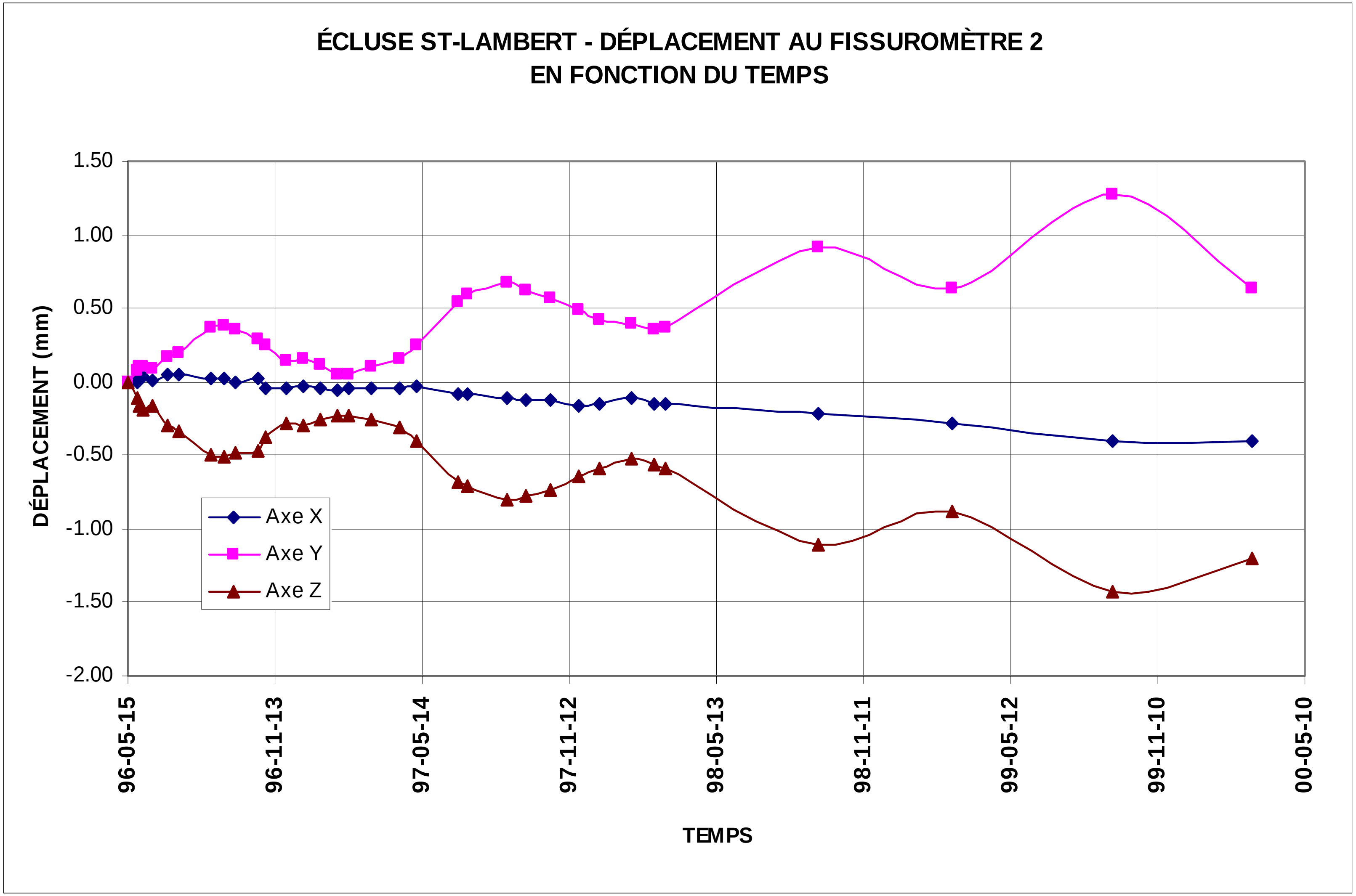
Surface Extensometer



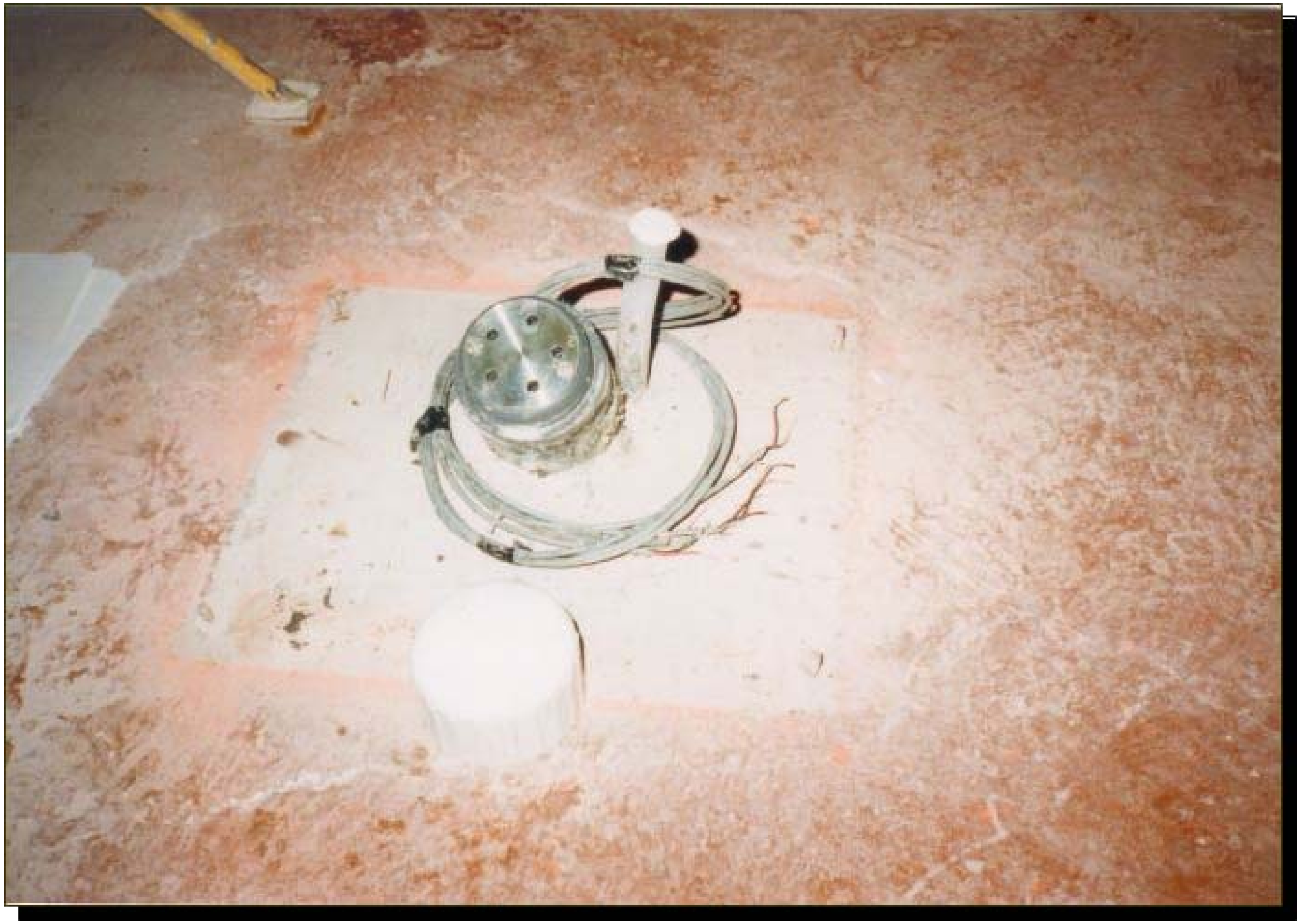
Crack width measurement



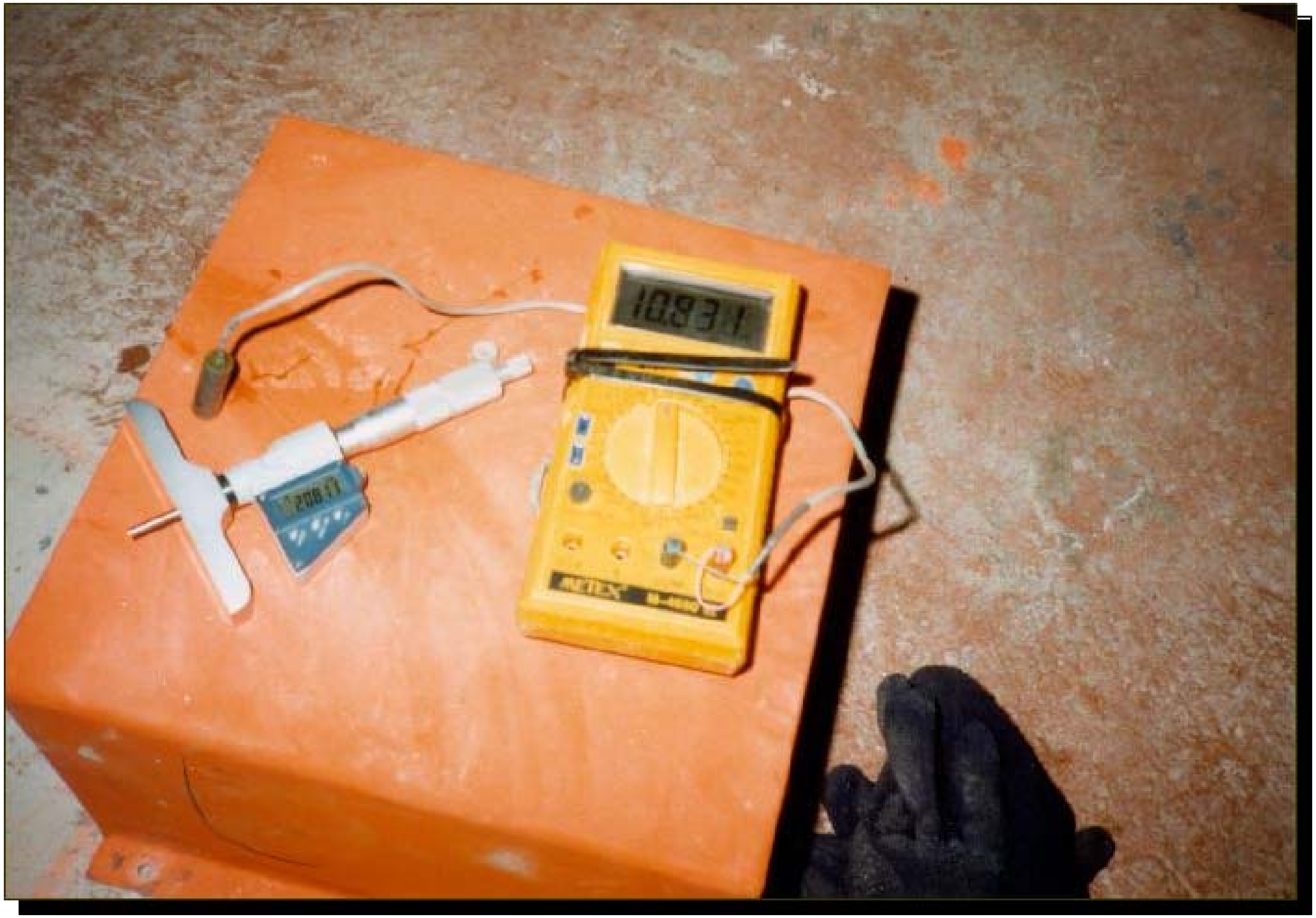
Crack width measurement



Multiple Point Extensometer



Multiple Point Extensometer



Surveying

Upstream stop logs

Upstream stop logs

Total gap surveyed = 15,2mm reduction over last 5 years

Therefore, under current conditions, upstream lock width reduces across monoliths 1S - 1N by an average of 3 mm per year (approximately 1 inch every 8 years). Inverted pendulum results are 2mm/yr at monolith 1S and 0,8mm/yr at monolith 7N, therefore showing the same trend.

Monolith 36S

Downstream stop logs

Monolith 36N

Downstream stop logs

Total gap surveyed = 21,9 mm reduction over last 5 years

Therefore, under current conditions, downstream lock width reduces across monoliths 36S - 36N by an average of 4,4 mm per year (approximately 1 inch every 5 years). Inverted pendulum results are 2,25 mm/yr at monolith 34S and 1,25mm/yr at monolith 29N.

MAJOR ON-GOING EFFORTS

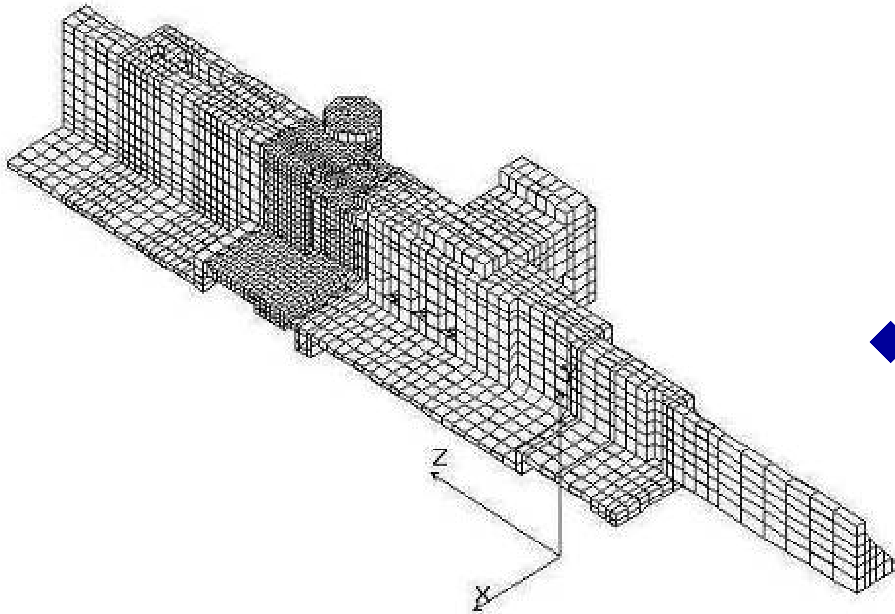
- **In the field**
  - On-Going Maintenance Program
  - On-Going Instrumentation Program

- **Theoretical**
  - Pre engineering Study

Pre engineering Study - The Team

- SLSMC Engineering
- Numerical Modelling Expert
  - Hydro-Québec
- Geology/Petrography Expert
  - NRCAN
- Materials Expert
  - Laboratoire de Béton
- Non-Destructive Testing Expert
  - Sherbrooke University
- Instrumentation Experts

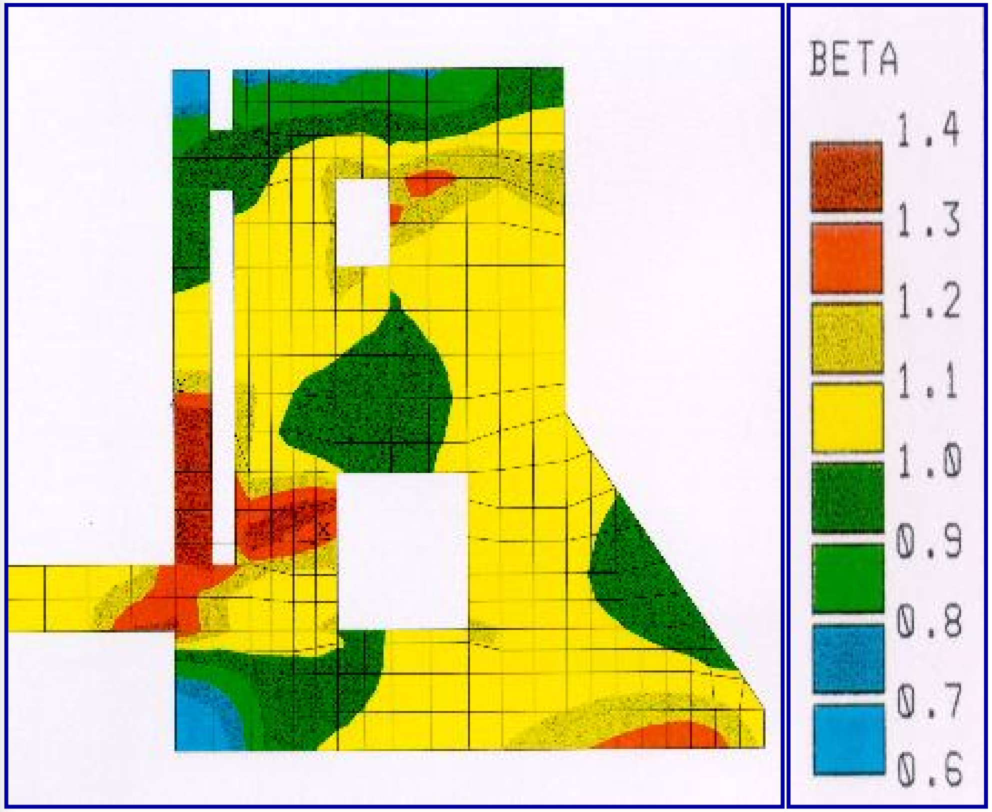
The Model

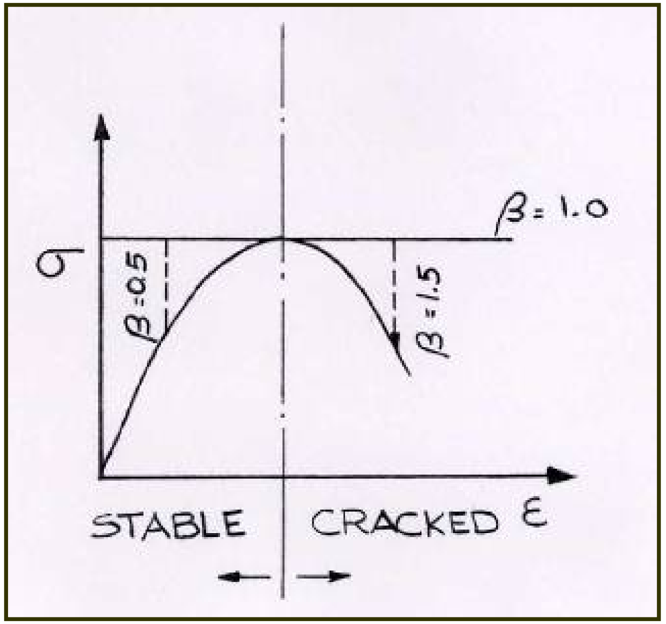


- models include 1/2 length of the lock to model lateral confinement effect
- Refinement of the mesh for specific monoliths

Initial Results (2000)

- Extent of damages
  - Distribution of stress intensity factor ß
  - ß > 1.0 = Strain softening response (macro-cracking)





Results of the parametric study (2001/2002)

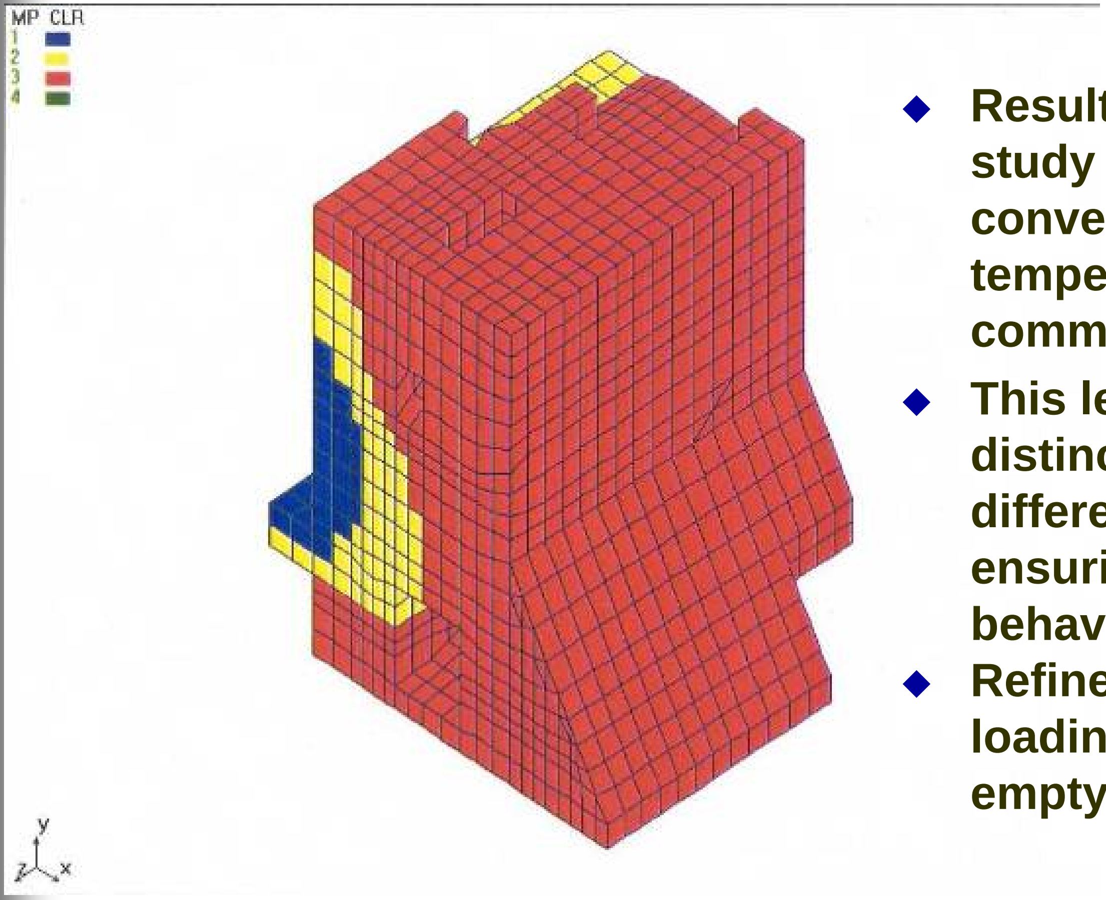
Parameter	Original parameter	Parameter Variance	Variance %	Ratios ΔD_X (%)
Modulus of Elasticity (E)	21Gpa	14GPa	-33	3
		28Gpa	+33	2
Poisson Coefficient (ν)	0,2	0,15	-25	2
		0,25	+25	2
Compressive strength (f_c')	27Mpa	15Mpa	-44	5
		40MPa	+48	4
Reinforcing Steel ratio (ρ)	7,88%	5,76%	-27	1
		10,00%	+27	1
Volumetric Expansion Rate (γ)	0,005775 @ 0,01155	0,00289 @ 0,00578	-50	**45**
		0,00866 @ 0,01732	+50	**60**
Time steps for effective AAR	20 equiv. yrs	24 equiv. yrs	+12	13
		26 equiv. yrs	+24	27

Concrete expansion study under variable temperatures and humidity - NRCAN and Laboratoire de Béton's mandate

Type de pierre	TEMPÉRATURE AMBIANTE (°C) / HUMIDITÉ (%)															
	5				15				23				38			
	100	95	90	85	100	95	90	85	100	95	90	85	100	95	90	85
Spratt Contrôle (VM1)	10	11	*	*	38	27	*	3	92	59	*	29	**0,129%**	87	68	0.044
Calcaire St-Jean 5-56 (VM2)	31	*	*	*	71	*	*	*	77	84	*	*	**0,096%**	*	*	*
Calcaire St-Jean 5-20 (VM3)	41	34	*	*	50	44	*	3	117	59	*	15	**0,103%**	123	83	8
Grès Postdam 5-56 (VM4)	6	*	*	*	19	*	*	*	27	10	*	*	**0,180%**	42	*	0
Grès Postdam 5-20 (VM5)	34	39	*	*	45	38	13	*	95	34	1	*	**0,076%**	212	51	0

- **Expansion results to date (104 weeks), mandate to be extended until all samples have reached their max expansion**
- **.04% to .12% considered reactive, > .12% very active**

Optimization of model



- Results of the laboratory expansion study were used to obtain conversion ratios in order to correlate temperatures and humidity on a common scale.
- This led to the identification of three distinct zones in the model having different expansion rates, thus ensuring a better fit of the global behaviour under AAR expansion
- Refined model included earthquake loading for worst case scenario: lock empty and damaged under AAR.

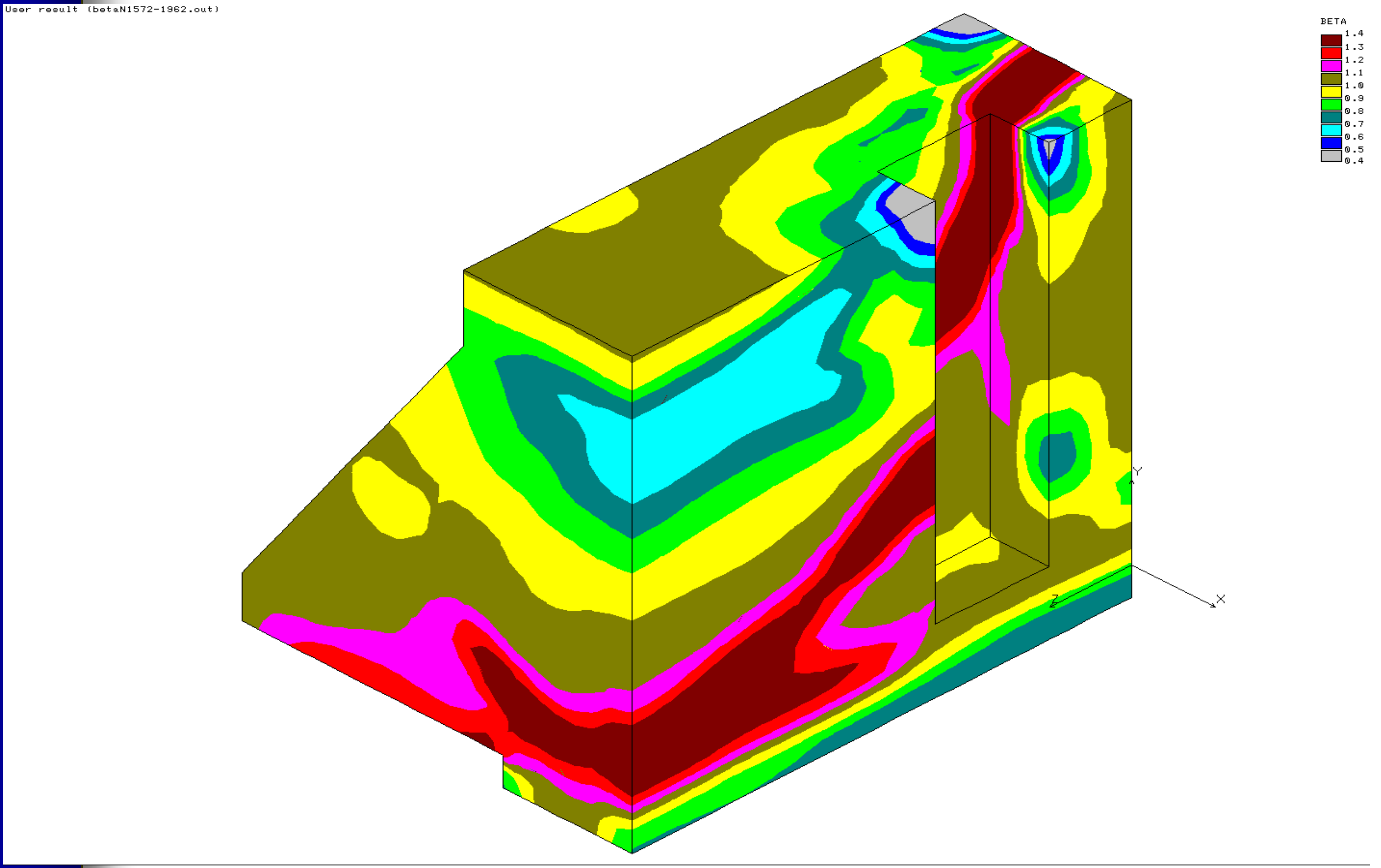
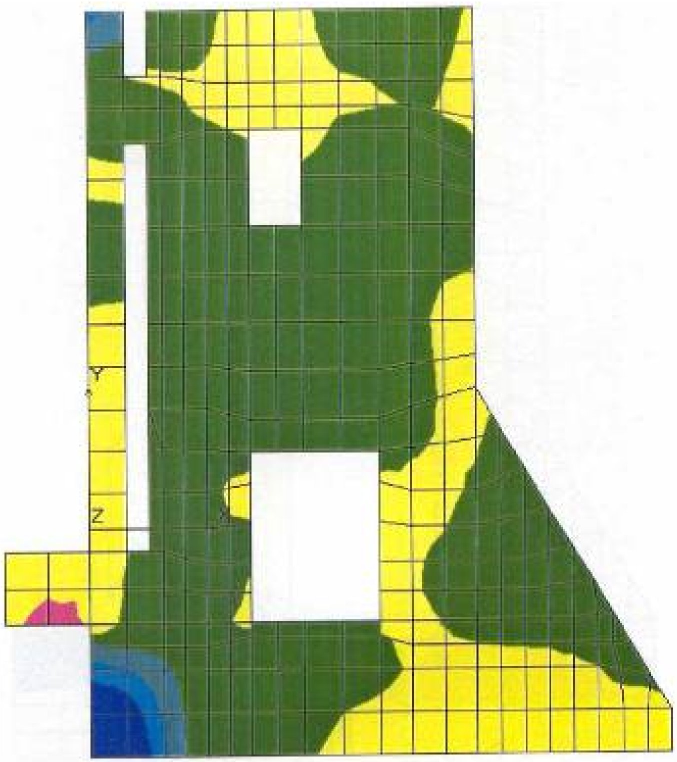


Fig. 2.4-4 Stress Intensity Factor (β) of Block-1S at step 1572 (2014, view-1) (Self Weight + Soil Pressure + 52 Years AAR + Seismic) (analysis-1)

Validation Process

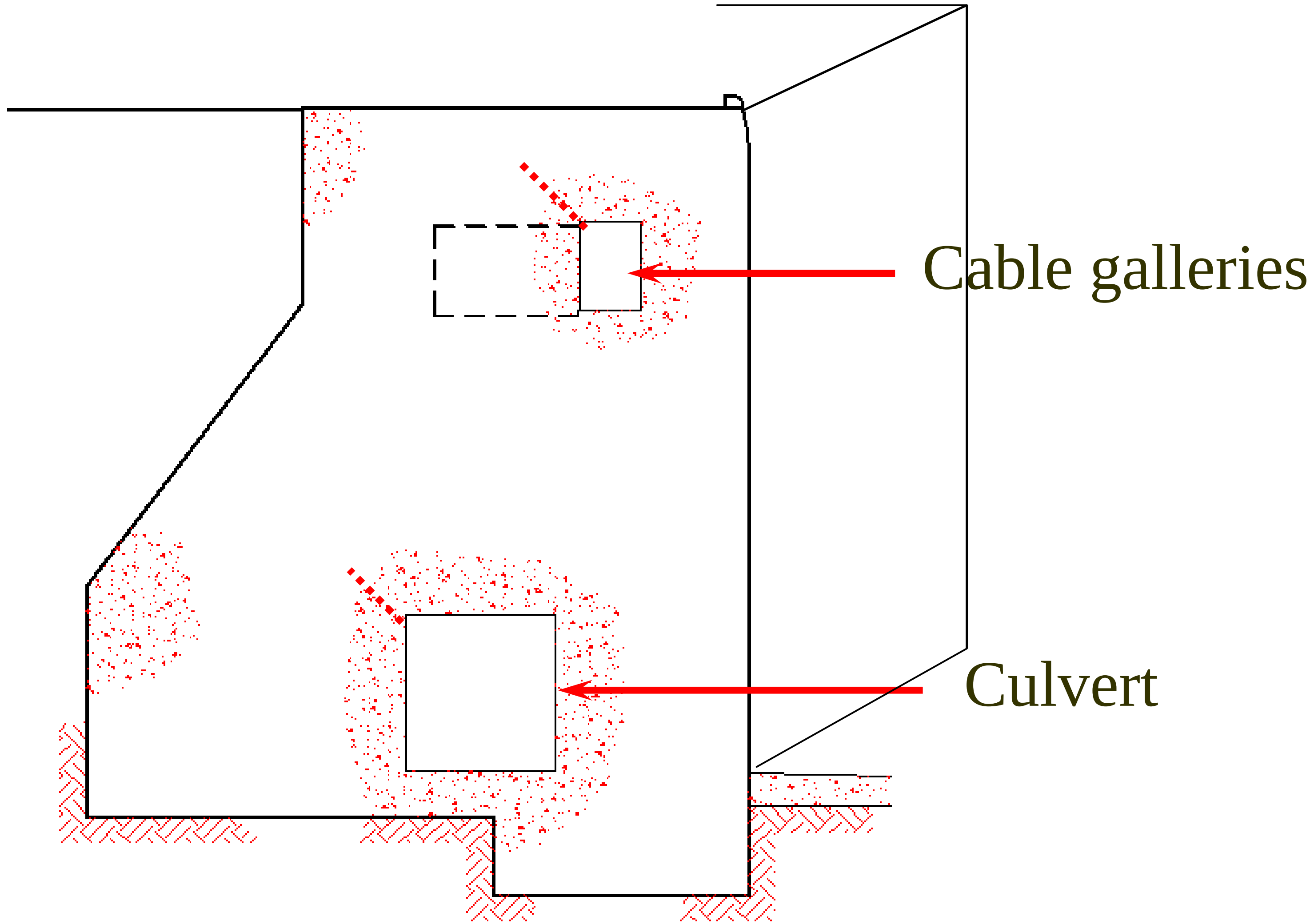


- How good are the results
  - Layout of damaged zones (WHERE TO ACT)
  - Reliability of extrapolations (WHEN TO ACT)
- Validation strategies
  - In-situ measurements
  - Sonic tomography

Validation strategies in-situ displacements

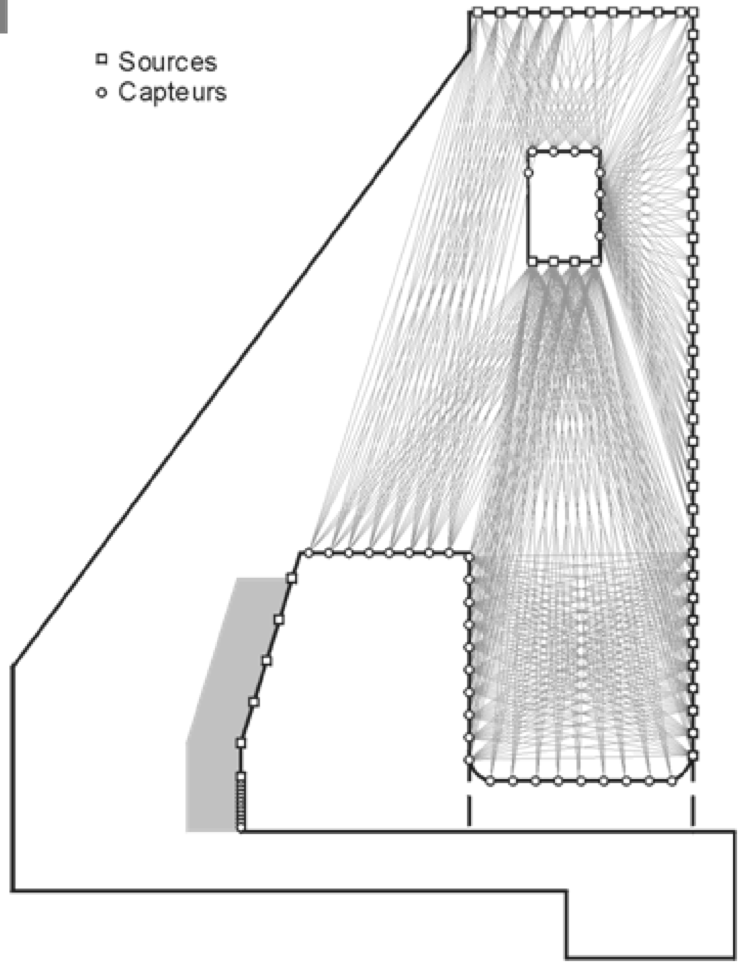
Monolith 7N			
Direction of growth	Model @ 42 yrs	Corrected annual growth	Pendulum avg. annual growth
Transverse	18mm	0.56mm	0.7mm
Vertical	47mm	1.47mm	1.6mm
Longitudinal	10mm	0.31mm	0.23mm

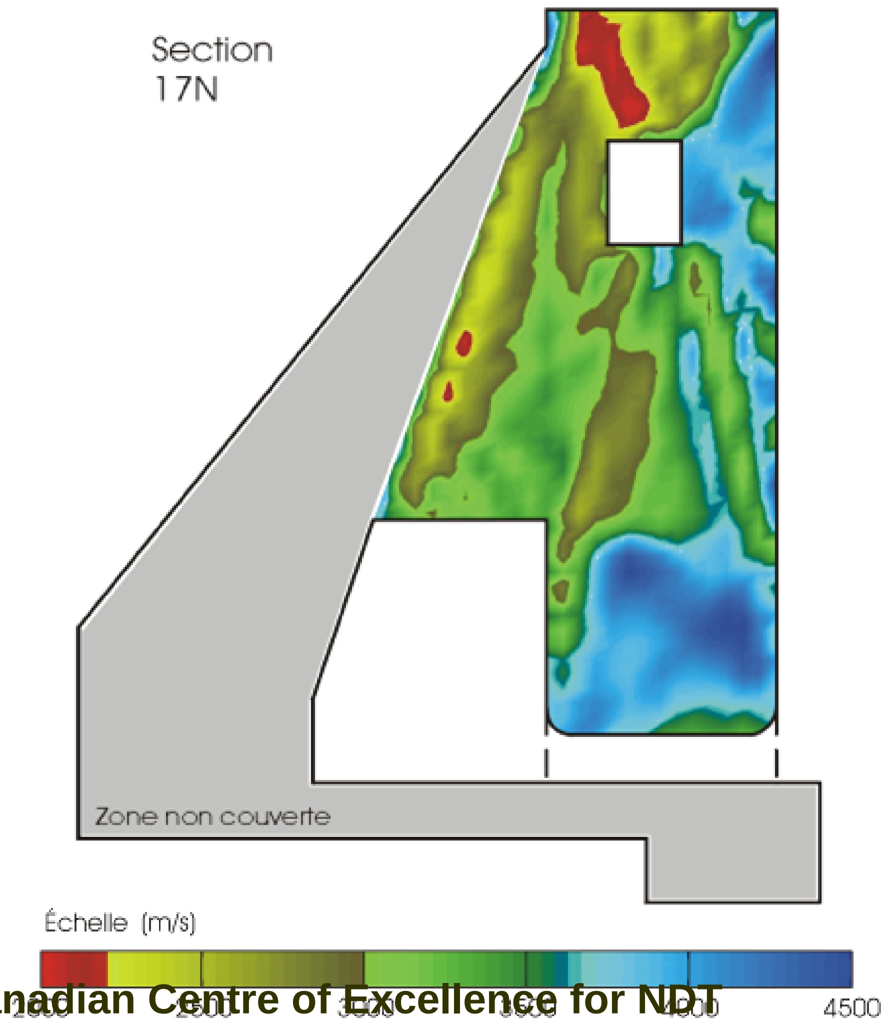
Predicted crack locations



Observed cracking

Validation of Results
In-situ non-destructive testing





By University of Sherbrooke and the Canadian Centre of Excellence for NDT

Sonic Tomography - St-lambert Lock

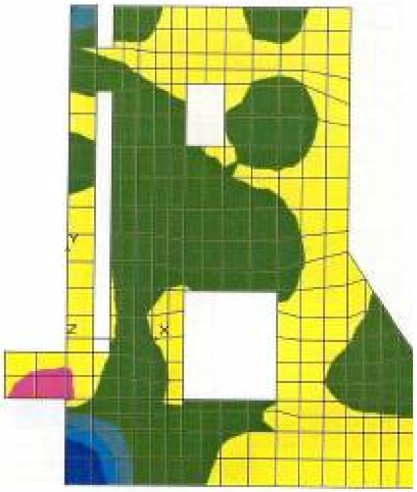
Installation of sources

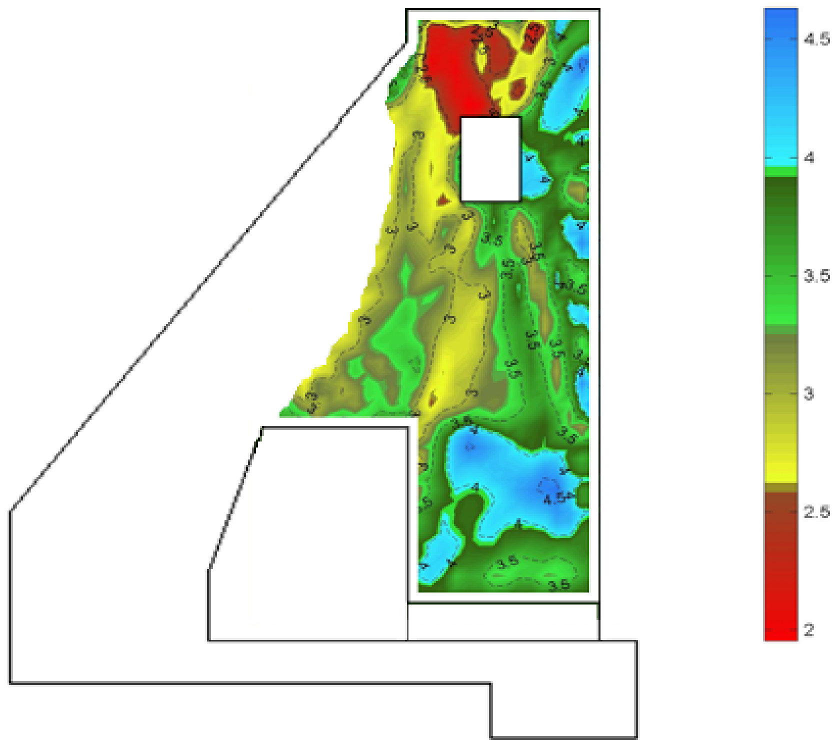
Sonic Tomography - St-lambert Lock

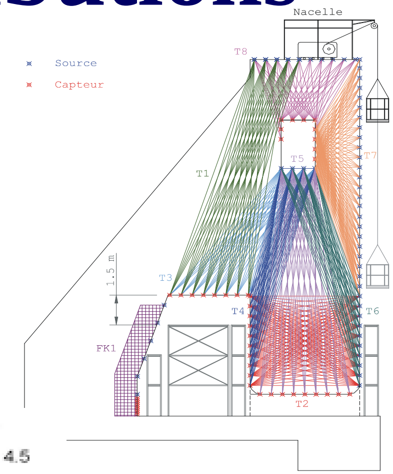
Installation of captors

Data acquisition system

Comparison of damage distributions







Limit State criteria

- Modelling indicates that there is sufficient strength reserve in the monoliths to withstand the current rate of concrete growth for at least the next 20 years.
- The fastest growing lock is St-Lambert. Rate of growth results in the closing in of the lock walls of 5mm per year. As the lock chamber keeps shrinking and the optimization of the navigation season puts more demand on manoeuvrability room, operational requirements now become the trigger for rehabilitation works.
- Limit state was thus been established at critical width of 79’- 6’’ (78’ ship beam + ice buffer on either side)

Projections of lock widths

Maisonneuve Region AAR concrete growth projections - Without project

Assumption: Critical zone for passage of 78 footers in ice condition is 79' - 6" to 79' - 9" (78' + 6" of ice buffer on either side + another 6 to 9 " clearance on tie up side for operation ??)

St-Lambert Lock (*Lock 1*)

	Lock width at coping	Comments	Costs to maintain (all in 2005 $ value)	Other Considerations
2005 (**Measured**)	79' - 9"	Lock width in critical zone for 78 footers, frequent difficulties for passage and extraneous efforts to de-ice lock walls		Our records show greater transit difficulties than in past years for the last 2 weeks of operation
2008 (Projected)	79' - 8"	Lock width in critical zone for 78 footers, frequent difficulties for passage and extraneous efforts to de-ice lock walls	Allocation for gate, valve, ice flushing gates, ship arresters and bridge lock adjustments and realignments, based on past history, is approximately $1,500,000. for years 2006-2008	
2013 (Projected)	79' - 7"	Lock width in critical zone for 78 footers, frequent difficulties for passage and extraneous efforts to de-ice lock walls	Allocation for gate, valve, ice flushing gates, ship arresters and bridge lock adjustments and realignments, based on past history, is approximately $2,500,000. for years 2008-2013	
2018 (Projected)	79' - 6"	Lock width in critical zone for 78 footers, frequent difficulties for passage and extraneous efforts to de-ice lock walls	Allocation for gate, valve, ice flushing gates, ship arresters and bridge lock adjustments and realignments, based on past history, is approximately $3,000,000. for years 2013-2018	
2023 (Projected)	79' - 5"	Starting with 2019 season, 78 footers can no longer navigate in ice conditions	Broad estimate for rock anchors is approximately $7,000,000 per lock, over minimum of 3 years installation, between 2018 and 2023	According to Earhtquake resistance analysis, factor of safety against sliding becomes borderline - **Rock anchors needed**
2028 (Projected)	79' - 4"	Starting with 2019 season, 78 footers can no longer navigate in ice conditions		

Reliability model - baseline

St. Lambert Lock AAR Event Tree

Baseline Scenario (FAF)

	Level of Failure	Likelihood of Occurrence Given a Failure	78' Vessels Not Allowed	76' Vessels Not Allowed	Upgrade to Reliability
		1%			
	Closure Type 1	5%	Entire Season	Entire Season	None
		90%			
St. Lambert Lock		9%			
Beginning of Study - 2020	Closure Type 2	90%	Entire Season	30 days	None
Years 2021 - 2040		9%			
Years 2041 - 2060					
		90%			
	Closure Type 3	5%	30 days	0 days	None
		1%			

There is no physical repair assumed for this component under this scenario. It is assumed that the costs will be associated will moving these goods by other means or transferring to smaller ships and the costs associated with that effort.

Reliability model – with project

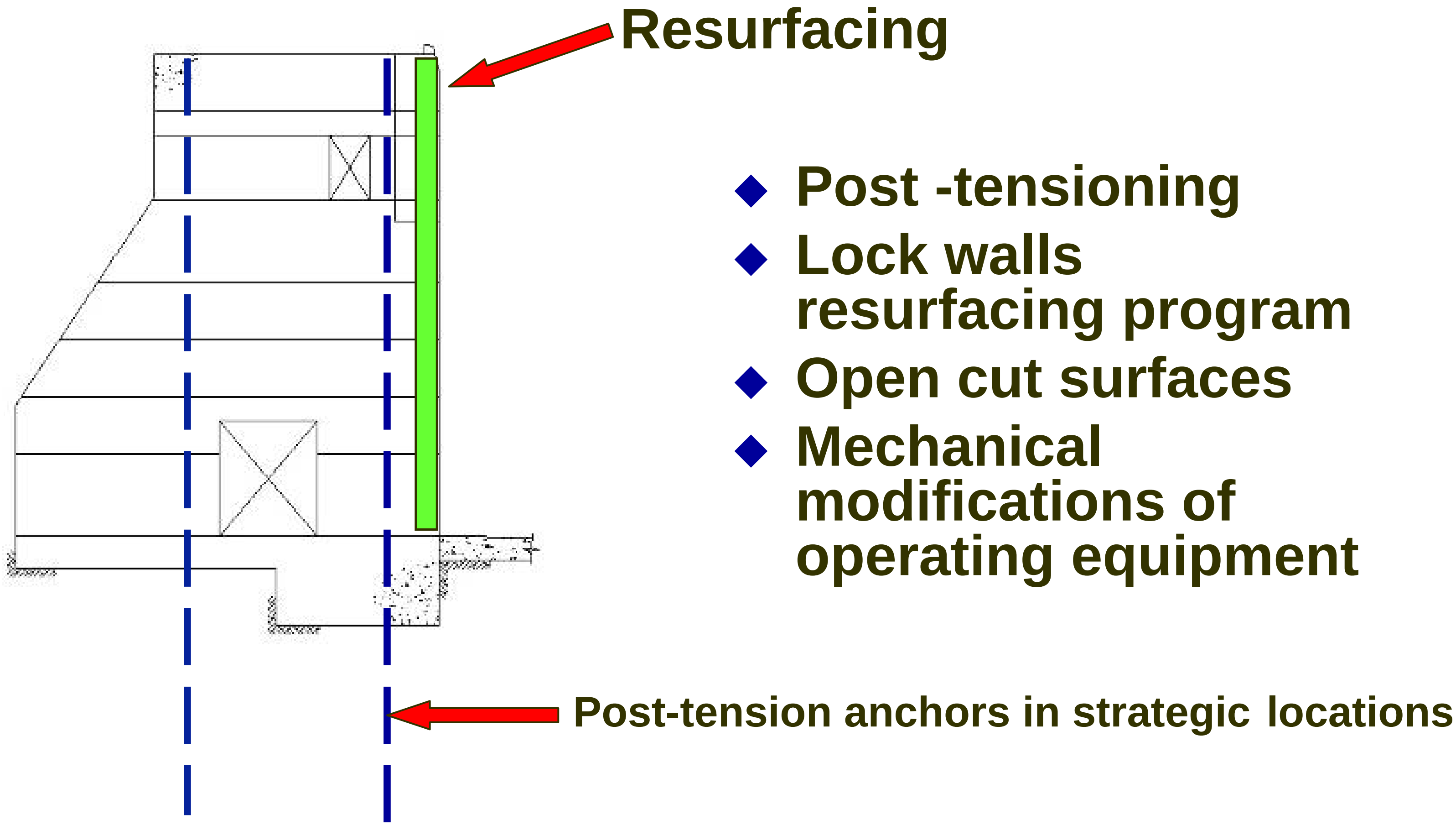
St. Lambert Lock AAR Event Tree

Advance Maintenance Scenario

	Level of Failure	Likelihood of Occurrence Given a Failure	78' Vessels Not Allowed	76' Vessels Not Allowed	Upgrade to Reliability
	Closure Type 1	0% 1%	Entire Season	Entire Season	None
St. Lambert Lock Years 1-25 Following Refacing Years 26-50 Following Refacing	Closure Type 2	10% 49%	Entire Season	30 days	None
	Closure Type 3	90% 50%	30 days	0 days	None

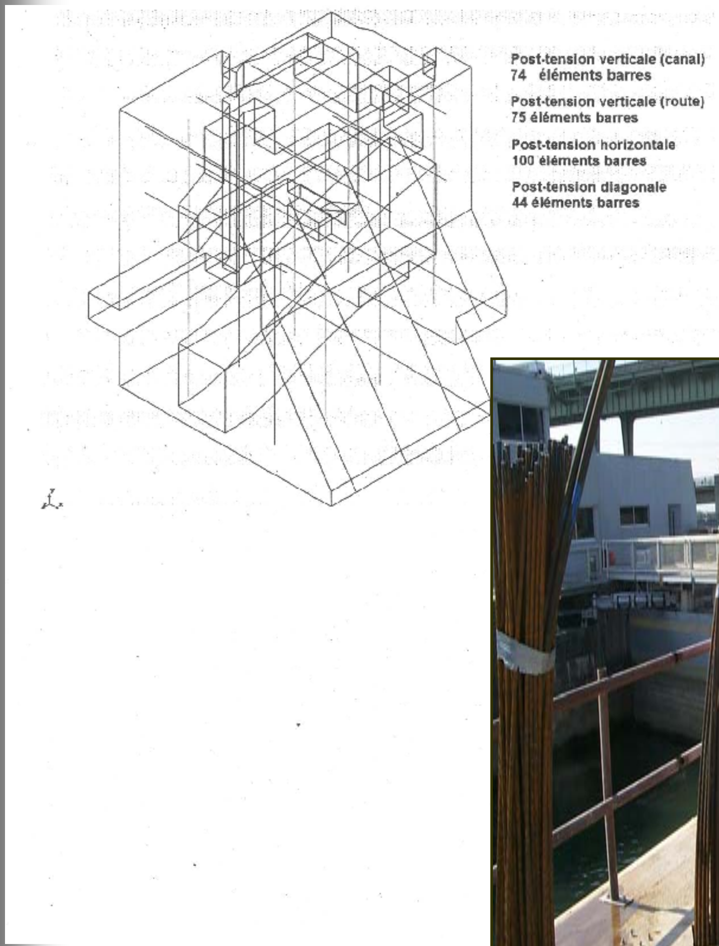
The cost of implementing the refacing is approximately $40 million. The work would be completed over 4 years at a cost of $10 million per year. There would be no shutdown of navigation required as it would be done during the winter maintenance season by contract. It can be assumed that the worst areas would be fixed first, thus, reliability will switch over to the Advance Maintenance Condition the second year of the 4-year effort.

Rehabilitation strategies



- Post -tensioning
- Lock walls resurfacing program
- Open cut surfaces
- Mechanical modifications of operating equipment

Post tensioning



- Modelling of post-tension anchors resulted in low efficiency in the long term. Rate of growth reduced by only small margin.
- Solution abandoned

Wall Resurfacing

- Precast panels or sliding formwork
- Challenges include:
  - Long term performance
    - Compatibility
    - Corrosion protection of anchors
  - Winter construction only

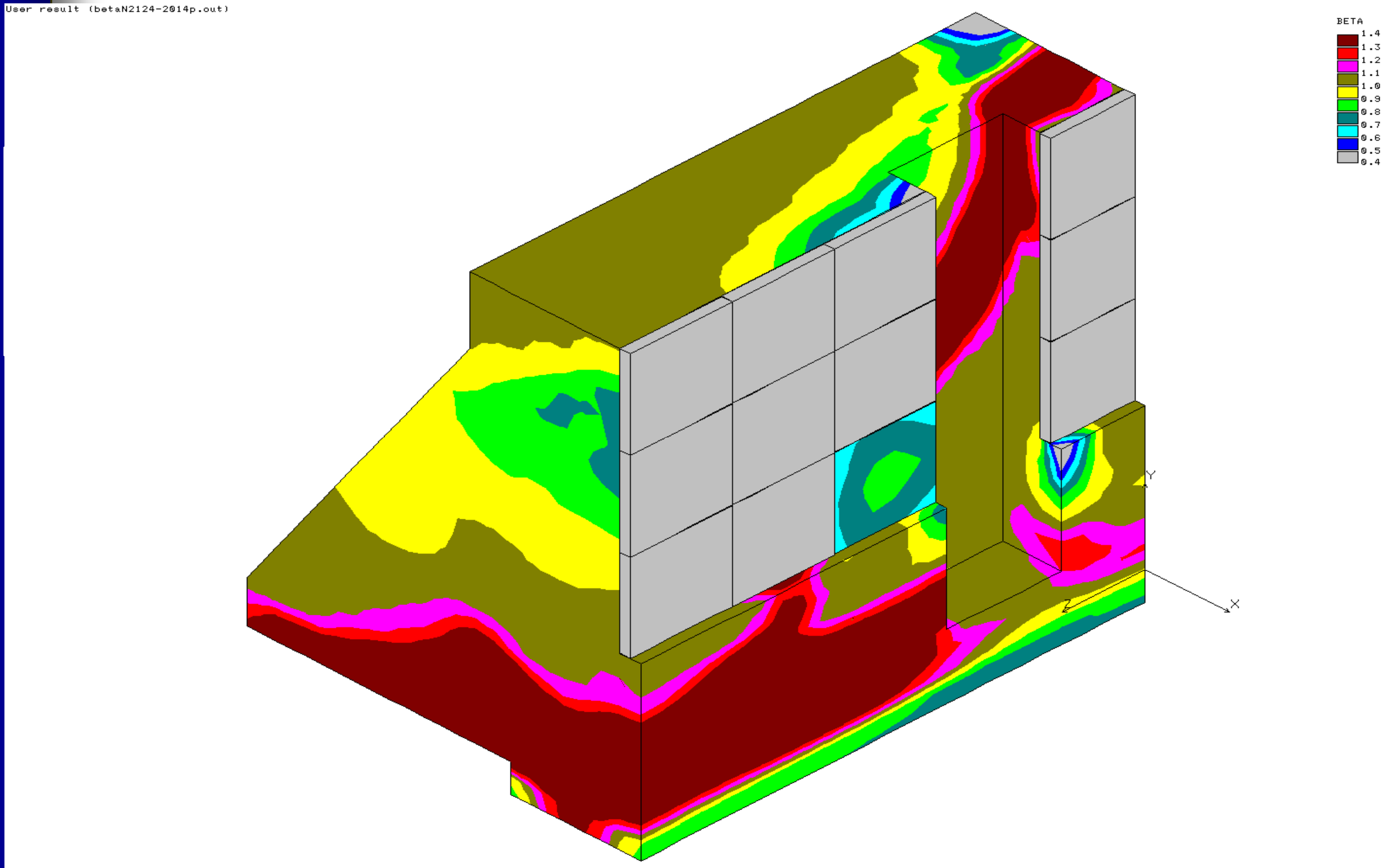


Fig. 3.3-5b Stress Intensity Factor (β) of Block-1S at step 2124 (2060, view-1) (Self Weight+Soil Pressure+98 Years AAR+Seismic) (analysis-2, with panel)

Activities planned for 2011-12 and 2012-13

- Risk analysis of rehabilitation strategies (ongoing)
- Design of retained solutions for pilot project (Fall 2011)
- Construction of pilot in winter 2012
- Debrief of pilot
- Quality Review (2012/2013)
  - Peer review: validation of retained technical solution
  - Constructability study
  - Cost estimates

RISK ANALYSIS - ongoing

- Critical review of modelling and monitoring results to date
- Expert panels – identification of possible solutions
- Risk analysis for each solution
- Recommendation of two best solutions for winter 2012 pilot project

Expert Elicitation

- Panel of experts to brainstorm and identify possible solutions
  - AAR experts
  - Construction techniques
  - Materials
  - Heavy machinery
  - Rehabilitation techniques
  - Operations - SLSMC
  - Engineering – SLSMC
- Timeline: From March 1st to June 15, 2011

ACTION PLAN 2010-2029

Year	Proposed Action
Annually	Monitoring and data analysis
2010-2012	Risk analysis and expert panel to identify possible solutions and constructability risks. Design of two options for pilot.
2011-2012 (winter)	Execution of pilot project
2012-2013	Quality review
2012-2014	Detailed design – Rehabilitation of St-Lambert Lock
2013-2018	Execution of works – St-Lambert Lock
2015-2022	Detailed design – Beauharnois Locks
2019-2026	Execution of works – Beauharnois Locks
2023-2025	Detailed design - Côte Ste-Catherine Lock
2026-2029	Execution of works – Côte Ste Catherine Lock

AAR Rehabilitation program, so we can …

- Pass ships through a safe and reliable waterway system…
- In a cost-effective, efficient and environmentally friendly manner…
- To meet our customers transportation needs…
- Until FY 2059

Thank You