Modelling the behaviour of the pervious foundation of a dyke and its treatment with relief wells

Mohamed Zahra
Centre d'expertise hydrique du Québec, Canada
Joseph Chahde
Hydro-Québec, Québec, Canada
Jacques J. d'Astous, & Hélène Tremblay
Centre d'expertise hydrique du Québec, Canada

ABSTRACT
The Moncouche Dyke of the Kénogami lake reservoir in northern Québec (Canada) was built on a V shaped valley filled with granular pervious fluvioglacial deposits. Although sheet-pile cut-off was driven into the foundation to a depth equal to 54 % of its hydraulic head, heavy seepage downstream upon its very first impoundment in 1924 forced the construction of a pervious blanket, which was extended gradually to the limit of a downstream pool. On the 1996 July Saguenay flood, new seepage sources had topped the blanket. The seepage in the foundation is analyzed and simulated through a 2D finite elements model in order to assess measures to reduce uplift seepage gradients. Deep relief wells are found to be an appropriate and cost effective measure.

RÉSUMÉ
La digue Moncouche est construite dans une vallée en forme de V remplie de dépôts granulaires fluvioglaciaires perméables. Un rideau de palplanches est foncé dans la fondation à une profondeur égale à 54 % de la charge hydraulique. Lors de sa mise en eau en 1924, d'importantes fuites ont conduit à la mise en place d'une berme jusqu'en bordure du bief aval. Lors du déluge en juillet 1996, de nombreuses résurgences ont été observées au pied de la berme. Les infiltrations dans la fondation sont analysées et simulées au moyen d'un modèle d'éléments finis dont l'objectif est de proposer des mesures pour réduire les gradients de sortie élevés. L'installation d'une série de puits de décharges est la solution appropriée et optimale qui fut retenue.

1 INTRODUCTION

The Moncouche dyke is one of the important water retaining structures of the Kénogami lake reservoir. Upon its very first impoundment in 1924 heavy seepage and springs forced the construction of a downstream pervious blanket and other remediate measures. After the 1996 July huge Saguenay flood, safety requirements for water retaining structures and forecast volumes of floods to be considered have been restated. The new criteria require the heightening of the structures in order for the reservoir to contain temporarily the PMF flood which in turn increases substantially the hydraulic head on the structures. In view of this, the repercussions of higher head on the seepage foundations of the Moncouche dyke have to be addressed. Seepage analyses run on numerical model indicate that abnormally high uplift gradients would prevail in the foundation. However, drainage oriented analyses show that the construction of a line of deep relief wells would be an appropriate and cost effective measure destined to reduce significantly the destabilizing hydraulic gradients. The use of relief wells in other projects in Québec has proved to be successful. Efficiency and periodicity of maintenance measures of relief wells depend on the choice of materials to be used.

This article presents the geotechnical conditions prevailing in the foundation of the Moncouche dyke. It describes the modelling of the existing pore water pressures in the foundation, the estimated pore pressures and seepage to be evacuated once the line of relief wells is put in place. A well designed pumping test conducted recently on the downstream terrace showed results which are in good agreement with those anticipated by the numerical model.

2 DYKE DESCRIPTION

The Moncouche dyke is a 190 m long, 8.7 m high sand and gravel earth fill structure lying between the Kenogami Lake and a downstream pool named the Petit Lac Moncouche (Figure 1). Its impervious core is a concrete wall connected at its lower end to a metal sheet piles driven to a variable depth (Figure 2). It is believed that the driving of these piles has stopped somewhere in the pervious formations recognized by borings some 20 m under the top of the foundation (Techmat 1992).

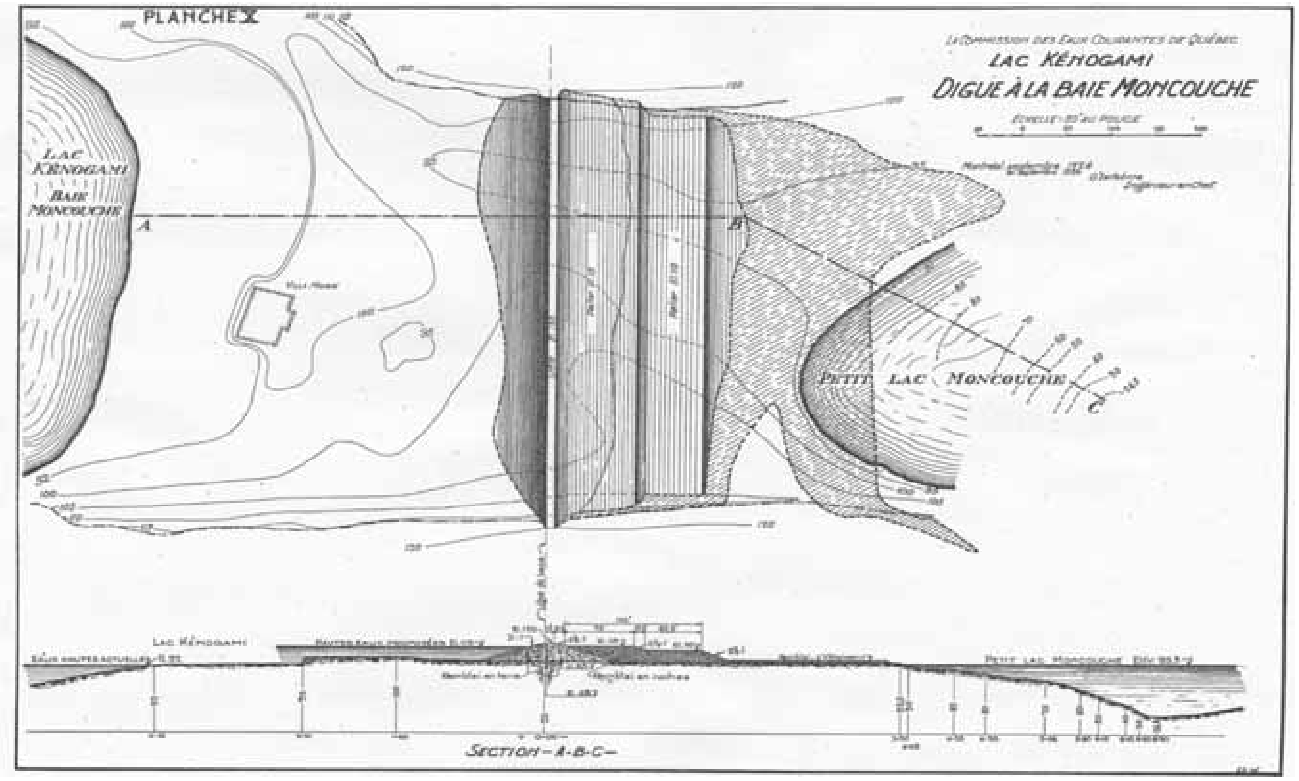

Figure 1. General layout and cross section of the Moncouche dyke

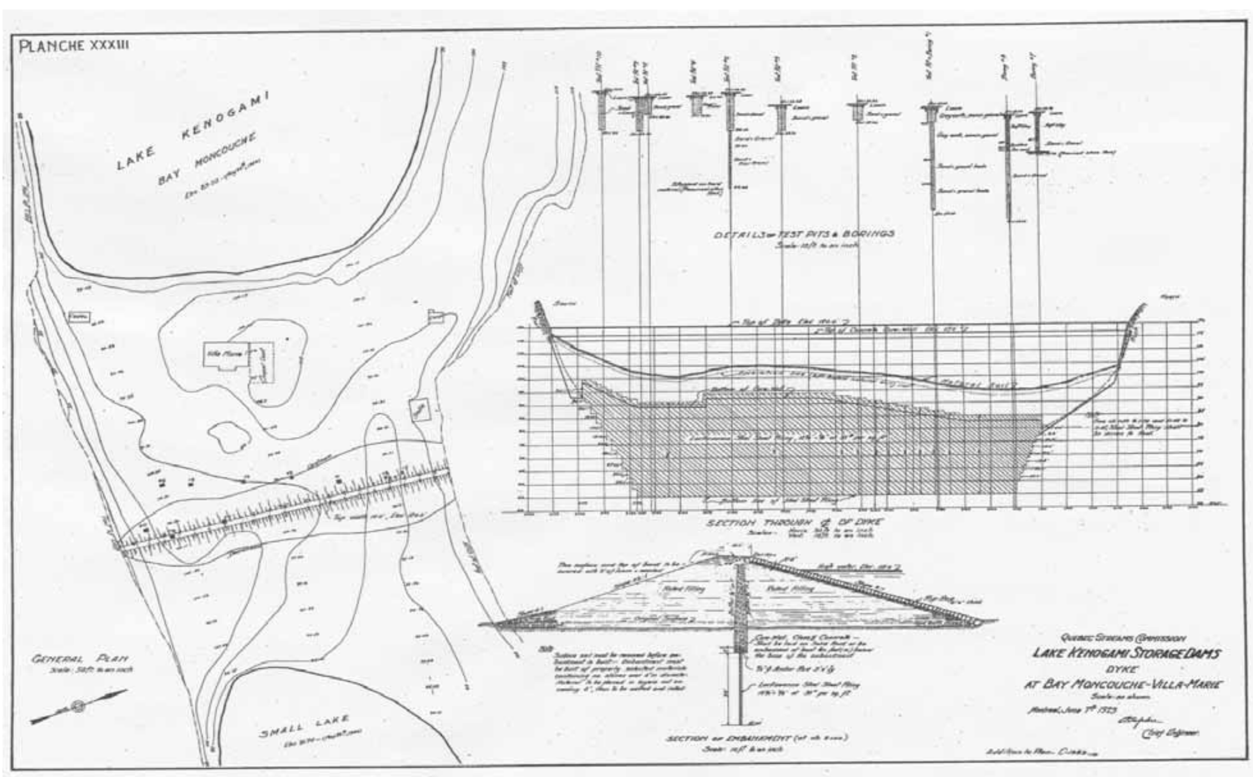

Figure 2. Cross section of the Moncouche dyke

2.1 Geotechnical Conditions

According to two geotechnical investigations (Techmat 1992, les Laboratoires SL 2001), the foundation is formed predominantly of pervious granular deposits covered by a thick clayey silt natural blanket. The stratigraphy of the downstream terrace is described as a succession of layers of compact to dense gravelly sand, dense sand and fine to medium sand with traces of silt. At the border of the downstream pool however, at least 3 borings and numerous dynamic cone penetration tests revealed that, down to 12 meters; the upstream blanket as well as the granular sandy deposits underneath are loose. N counts from SPT confirmed by dynamic CPT tests are on the average around 10 and seldom higher than 20. Pockets and lenses of cobbles and boulders have also been encountered in borings. Figure 3 shows the location of all borings.

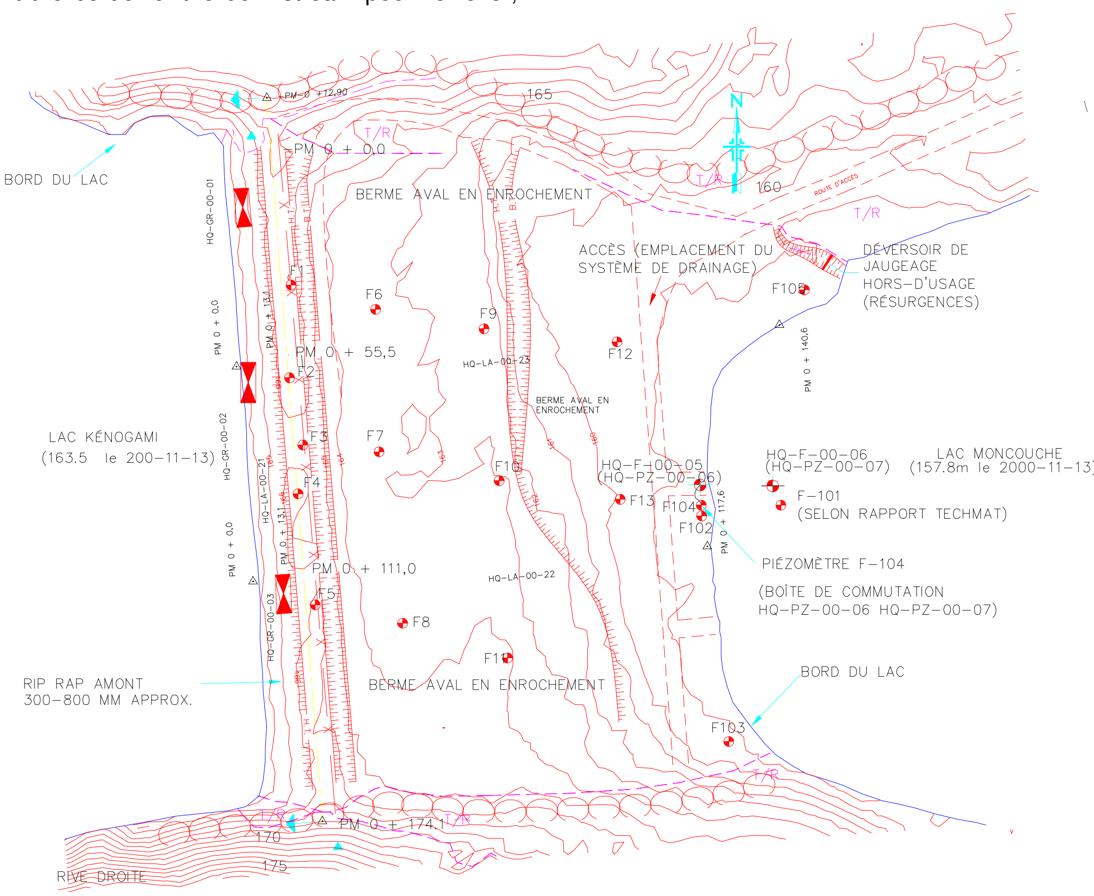

Figure 3. Location of borings in the downstream terrace

It is believed that the natural blanket extends far enough downstream some 20 m under the surface of the pool to create restriction on the seepage section, leading to high uplift exit gradients (Figure 4).

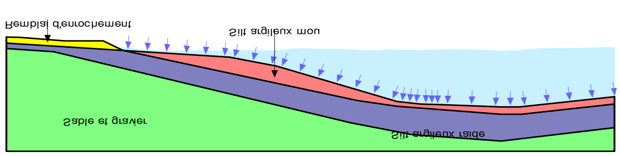

Figure 4. Natural blanket cover

3 PIEZOMETRIC OBSERVATIONS

During the two geotechnical investigations, 34 hydraulic open pipe type piezometers were installed in borings (Figure 3) at different depths and offsets to monitor the water pore pressure in the downstream foundation.

Figures 5 and 6 show 17 years of records of the seasonal variations of piezometric levels at the axis of the dyke and close to the downstream pool respectively, as well as the reservoir and the downstream pool levels. From Figure 5, one can detect a small increase in the piezometric level at the sheet piles wall location, but still an average of 47% of the 5.7 m total head is dissipated at this point which is considered to be normal. On the other hand, Figure 6 indicates clearly the important deficiency of dissipation of hydraulic potentials along the terrace; high elevation heads still prevail in the vicinity of the downstream pool, the Petit Lac Moncouche.

Piezometers installed under and in the vicinity of the Petit Lac Moncouche show an artesian level in the order of 1 m to 2 m relative to ground surface (Figure 7). It is believed that this artesian condition is not a locally measured one. It is actually confirmed regularly by reported wet spots on the ground surface and the absence of ice cover on the Petit Lac Moncouche during the winter.

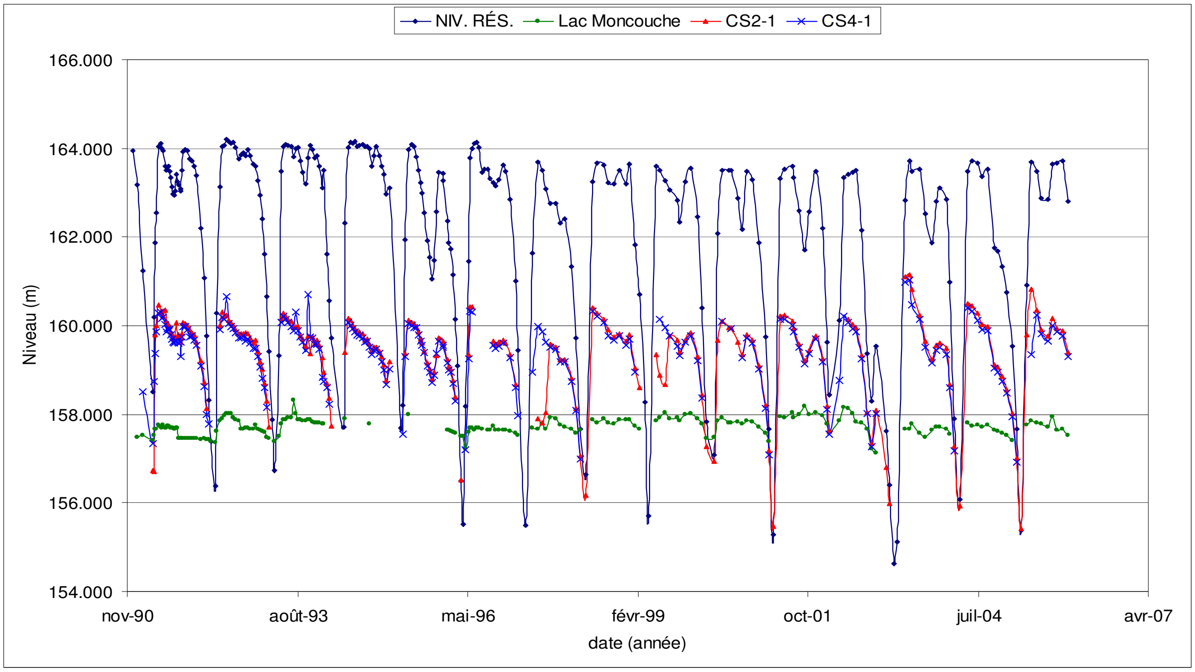

Figure 5. Piezometric level at the axis of the dyke compared to upstream and downstream water levels.

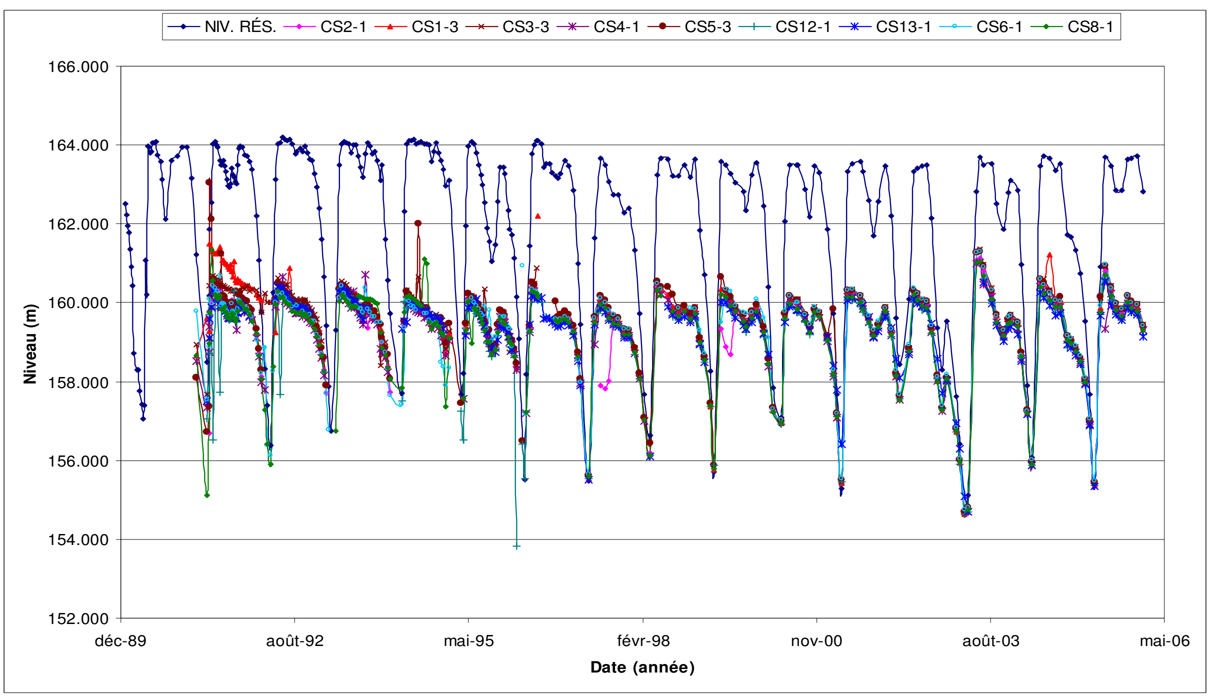

Figure 6. Piezometric level close to the downstream pool compared to upstream and downstream water levels.

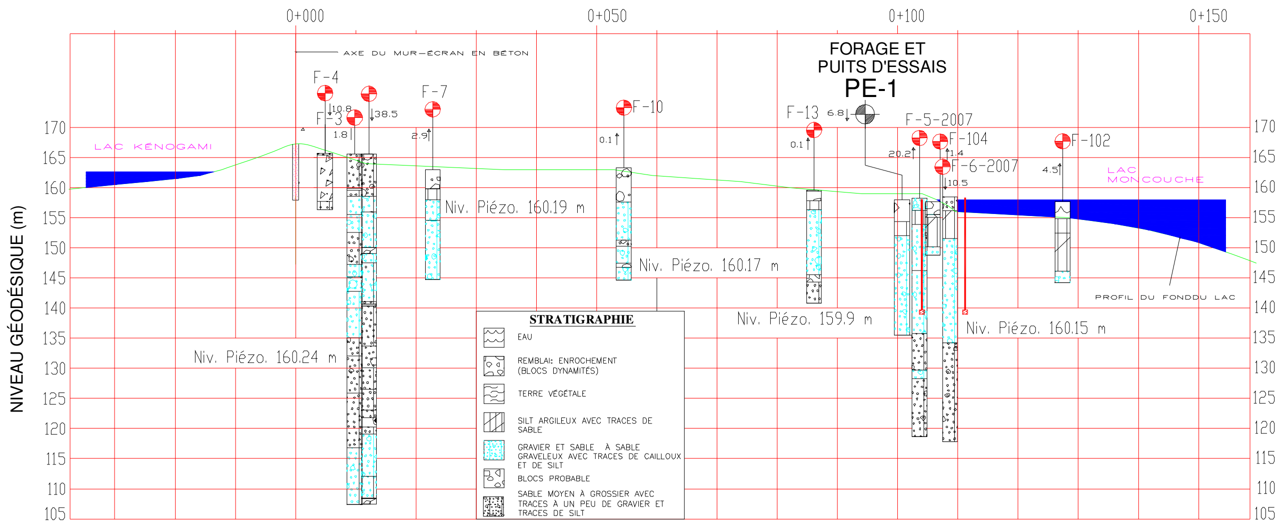

Figure 7. Piezometric level along the terrace

4 SEEPAGE ANALYSES

The cross section modelled in these analyses is located at the central part of the valley. This section cuts through heterogeneous pervious deposits extending to the deep part of the Petit Lac Moncouche. This section is chosen to obtain a realistic conservative reproduction of the existing piezometric levels. The conditions at other cross sections are considered similar or at least less critical. Therefore these cross sections can easily be interpolated from the analyzed section and available respective data. The different layers and their hydraulic conductivities considered in the model are obtained from the logs of borings and permeability tests conducted during the previous investigation. The numerical model and other data are shown on Figure 8.

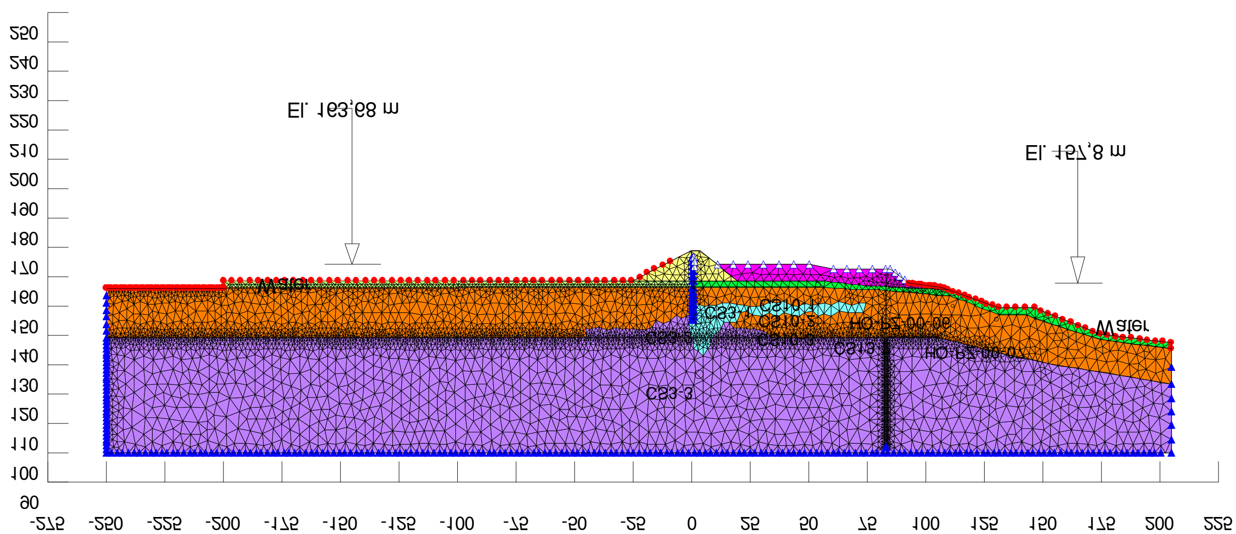

Figure 8. Geometry and limits of the numerical model

4.1 Modelling existing conditions

In the upper clayey silt deposit, permeability tests conducted in borings F-91-06 and F-91-13 yielded values ranging between 1.4×10^{-4} and 1.9×10^{-3} cm/s. In the pervious deposits, permeability tests have been conducted at different elevations in almost all borings. In the gravelly sand formations, hydraulic conductivity varied from 9×10^{-5} to 1.1×10^{-1} cm/s, while in the sand and gravel, values ranged between 9.2×10^{-2} and 9.0×10^{-5} cm/s (Techmat 1991). The wide range in the measured hydraulic conductivities suggests that an average value should be used. But, it rather strongly indicates the necessity to conduct a pumping test to locate the most pervious zones in the deposit.

A mean reservoir operating level fixed at 163.68 m is applied to the upstream of the model; while downstream, the most often recorded water level, 157.8 m at Petit Lac Moncouche was applied.

Calibration of the model using the mean recorded piezometric observations was achieved by slight alterations of the soils hydraulic conductivities and introducing minimable realistic physical anisotropy in the upper deposit. Figure 9 shows the position of the water level along the section and contours of total head which best fit those measured by the piezometers. Figure 10 depicts contours of cross hydraulic gradient, from which, one can see the amplitude and the crowding in the vicinity of the toe of the downstream blanket. Table 1 lists recorded and calculated total heads at significant locations through the model. Overall differences range from 0.2 m to 1 m. The lowest are those relative to the center of the valley while the highest are found at the two far sides of the valley. This reflects the limits of the capability of a 2D model to simulate 3D geometry. However, it is considered that results obtained from the model satisfactorily represent the mean seepage conditions that prevail throughout the foundation.

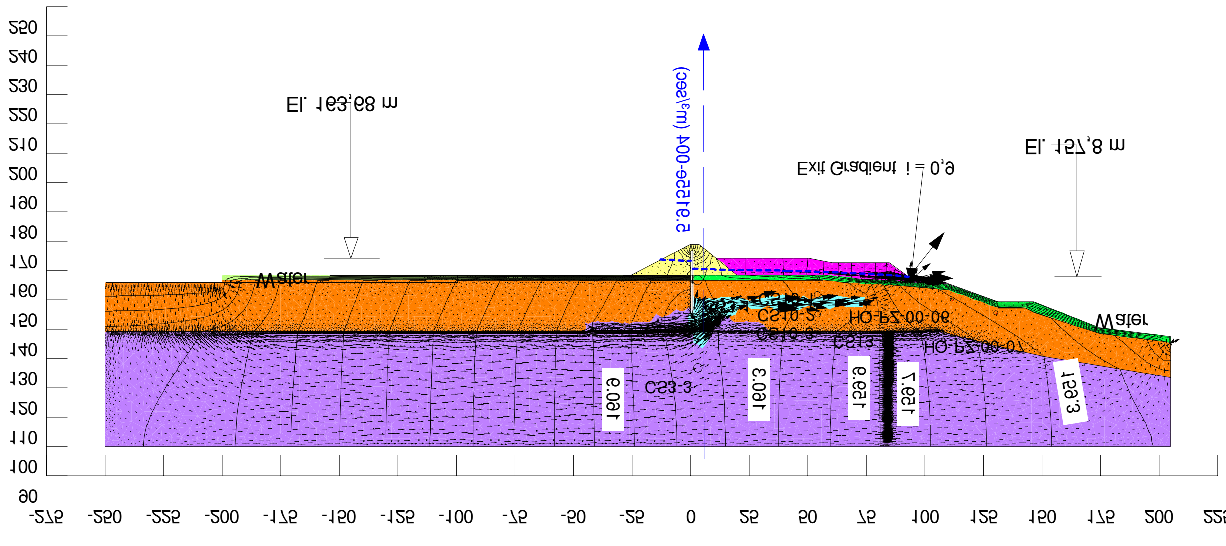

Figure 9. Contours of total head corresponding to existing conditions

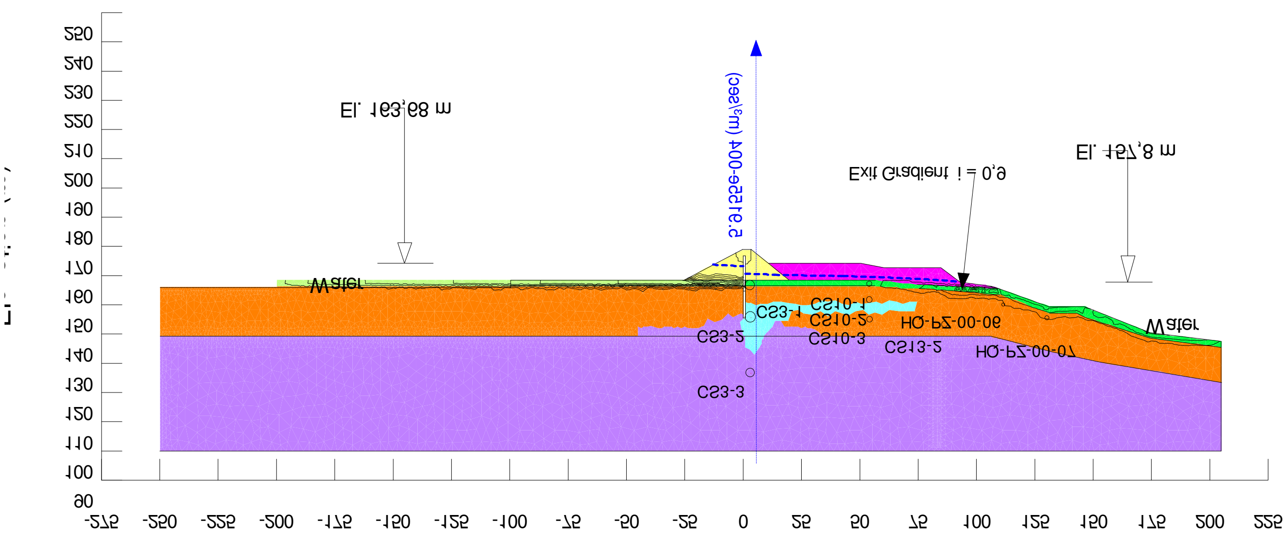

Figure 10. Exits gradients at the toe of the berm

Table 1. Recorded and calculated total head at significant locations through model

Date	NIV. RÉS.	Lac Moncouche	Piezometers											
			CS3-2		CS3-3		CS10-1		CS10-2		CS13-1		CS13-2	
			Rec.	Cal.	Rec.	Cal.	Rec.	Cal.	Rec.	Cal.	Rec.	Cal.	Rec.	Cal.
2001-07-27	163.59	157.53	160.13	160	160.19	160	159.57	159.40	160.08	159.40	160.00	159.50	159.9.18	159.50

4.2 Modelling of Relief Wells

In a 2D analysis, a line of closely spaced relief wells with appropriate weighting can be represented by a continuous slot running down to the pressurized aquifer. The excess of pressure at the mid distance between two neighbouring wells can be dealt with by a calibrated small rise of the slot discharge level.

Both piezometric observations and model calculated total heads indicate that the most severe seepage conditions are located at the interface of the granular deposits and the upper clayey silt blanket in the vicinity of the downstream pool. Consequently, a drainage slot whose depth can be varied was incorporated in the model located at a small distance upstream from the toe of the downstream blanket. The upstream water level that corresponds to the expected PMF condition was assigned for this modelling case.

As can be expected, results indicated that a slot running down to the total thickness of the granular deposits could yield substantial pore pressure relief on its upstream side and almost removes the excess of pore pressure relative to the downstream pool level. If a partial slot penetrating 18 m in the aquifer was installed, the model results (Figure 11) indicate that 80% pressure relief could be achieved upstream and also remove almost all the excess pressure downstream. While these improvements in gradients and pore pressure conditions are purely theoretical, the model results indicate that relief wells would be effective and be an appropriate measure.

Based on the model results, Table 2 lists the expected volume of water, by time units required to be evacuated from a line of relief wells corresponding to three reservoir levels if 6 to 10 wells were installed.

Table 2. Expected amounts of water by time units to be evacuated from a line of a relief wells

Res. level (m).	**Total flow to evacuate (l/s)**	**Flow per well (l/s)**				
		6	7	8	9	10
163.68	131.62	22	18.8	16.45	14.62	13.16
166.65	209.22	34.87	29.88	26.15	23.24	20.92
167.2 (PMF)	223.57	37.26	31.93	27.94	24.84	22.36

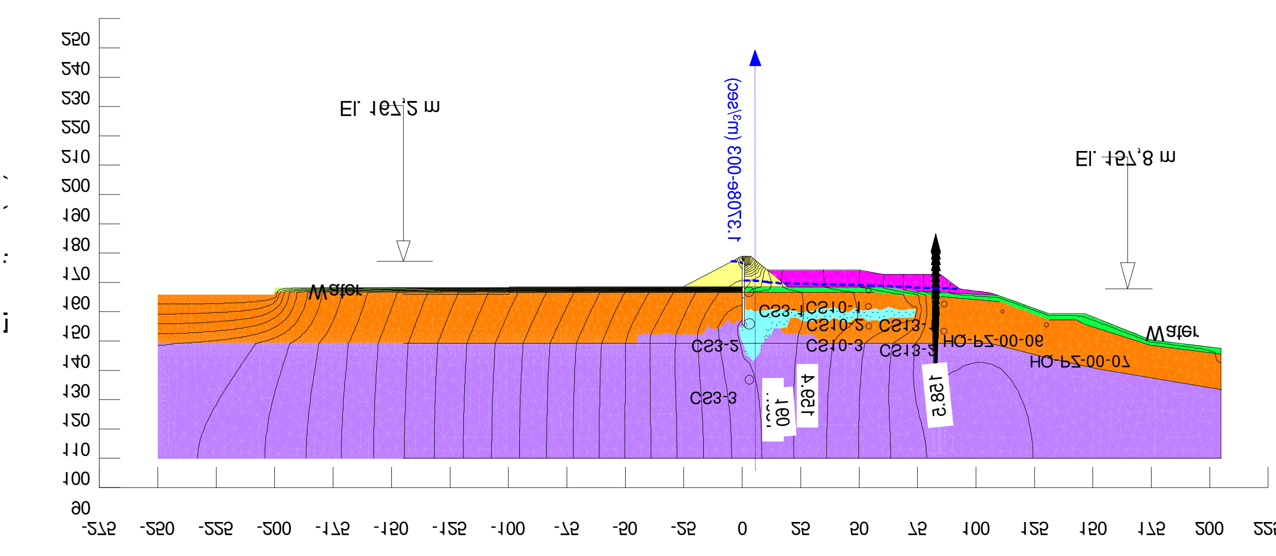

Figure 11. Contours of total head corresponding to modelling case of relief wells

5 PUMPING TEST

The volume of water to be captured by the wells can alternatively be calculated on the basis of pumping test data, recorded pore water pressures and site specific downstream discharge data where available. A pumping test was conducted in a well designated by letters PE-1 on Figure 12.

Near the bottom of PE-1 the pumping test revealed a highly pervious formation. The transmissivity, calculated from Darcy's law, for this formation ranged between 11000 and 15500 m^2 per day. It was considered from analysis of boring data adding a flow provision of approximately 10% relative to the underlying pervious layers would be realistic. Hence the total transmissivity of the aquifer would be 17000 m^2 per day and the relief wells would be required to evacuate a total of 18360 m^3 per day. The horizontal hydraulic gradient considered in Darcy's law was chosen from the linear regression shown on Figure 13. This regression is based on piezometric data gathered from around the well PE-1 and the different corresponding reservoir levels. During the pumping test, the flow at the Petit Lac Moncouche outlet was successfully measured and the hydrological model was recalibrated to yield a transmissivity value of 17335 m^2 per day. It should be pointed out that the measured the discharge of 13000 l/min at Petit Lac Moncouche was, very similar to that obtained from the finite elements numerical model.

For the PMF conditions, a hydraulic gradient of 0.9% was extrapolated from the linear regression of the horizontal gradient relative to the water level of Kenogami Lake reservoir (Figure 13). Estimated flows of 23400 m^3 per day would have to be evacuated by the proposed relief wells for this condition.

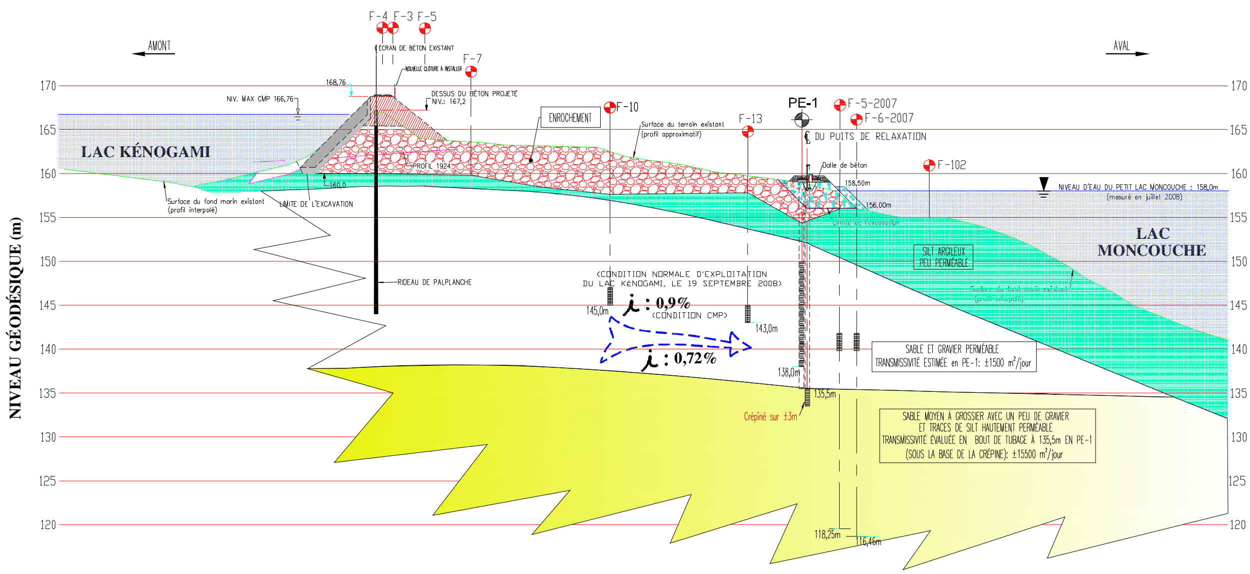

Figure 12. Location of pumping test (PE-1)

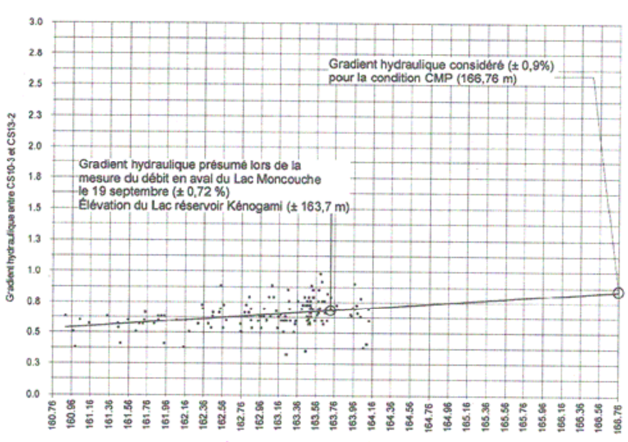

Figure 13. Linear regression of the horizontal gradient relative to water level of Kénogami lake reservoir

6 PROPOSED DESIGN OF RELIEF WELLS

The outlet level of relief wells at the collector pipe should normally be fixed slightly higher than the average annual level of the downstream pool (Petit Lac Moncouche). If the vertical water velocity inside the well is limited to 1 m/s, a 150 mm nominal diameter riser would be required to transit 1500 l per minute. At this velocity, the head loss would be 14 mm per meter between elevations 120 m and 158 m which correspond to the proposed cased section of the well. A 1.5 safety factor to account for the randomness of geotechnical parameters would put the capacity of such well at 1000 l/min. By applying the same factor of safety the screen length would need to need to be 3 m. As a result of this, ten relief wells will be required.

7 LIQUEFACTION HAZARD

The existence of artesian conditions in the 30 m thick granular deposit combined with low to medium SPT and dynamic CPT N counts called for liquefaction hazard assessment relative to seismic loading. To do this, the well known simplified procedure was used. CRR (Critical Resistance Ratio) was determined on the basis of N counts data from borings following the Seed and Idriss (1971) method revised by Idriss and Boulanger (2004) (Techmat 2008). The CSR (Critical Stress Ratio) was calculated by making use of the ProShake program. Minimum factors of safety of 0.8 and 0.7 corresponding to acceleration levels of 0.10g and 0.15g respectively were found. When conservatively considering the expected reduction in hydraulic heads following the installation of the recommended relief wells, the minimum factors of safety increased to 2.8 and 1.8.

8 CONCLUSIONS

Modelling of deep relief wells by a continuous slot has proved to produce similar results to those obtained from a pumping test. The planned specifications for the construction of the relief wells will include a procedure whose goal is to validate the values of hydraulic transmissivities extracted from the pumping test. This procedure consists of measuring the specific capacity of each well as the construction of the wells proceeds. Monitoring the reduction of the hydraulic heads by the existing piezometers while measuring the total flow in already constructed wells will help optimize the number and the location of the wells. The procedure would include installation of a minimum number of wells with subsequent addition of wells between the initial wells until the planned reduction of hydraulic heads is achieved.

REFERENCES

Commission des eaux courantes. 1930. Rapport de la Commission des eaux courantes, 1930.

Idriss I. M. & Boulanger R. W. 2004. Semi-empirical Procedures for Evaluating Liquefaction Potential during Earthquakes. *Proceedings of the 11th ICSDEE & 3rd ICEGE* 32 – 56.

Techmat inc. 1991. Analyse de la stabilité et la pérennité de la digue *Baie Moncouche. Lac Kénogami, ville de Laterrière. Rapport d'étude*, décembre 1991 (version finale).

Les laboratoires S. L. 2001. Investigations géologiques et géotechniques, Lac Kénogami. SL-00G134. *Rapport final, préparé pour Hydro – Québec*. Mars 2001, tome 1 à 6.

Seed, H. B. & Idriss I. M 1971. Simplified Procedure for Evaluating Soil Liquefaction Potential. *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 97, No SM9, Proc. Paper 8371, September 1971, 1249-1273.

Cegertec Qualitas. 2009. Rehaussement digue Moncouche. *Rapport de conception*, N/D : 14418-303, 19 janvier 2009.