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ASSESSMENT OF THE EFFECTS OF SLOT-CUTTING IN CONCRETE DAMS AFFECTED BY ALKALI-AGGREGATE REACTION

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ABSTRACT

The concrete of Beauharnois, La Tuque, La Gabelle and Rapides Farmers power plants located in Québec Canada experiences alkali-aggregate reaction. The rate of swelling varies from moderate to high, causing distortion of the structures. Typical manifestations of concrete swelling include closing of the expansion joints, structural cracking, distortion of the turbine throat rings (resulting in reduced clearances of the turbine runners), obstruction of intake and spillway gates, as well as occasional infiltration. Common measures employed to remedy these problems involve post-tensioning and/or concrete slot-cutting. In this paper, the long-term effects of slot-cutting are assessed by analyzing the results of in-situ measurements and by means of a finite element analysis based on non-linear continuum theory incorporating chemo-mechanical coupling. The numerical analysis pertains to the junction of the concrete dam and the water intake structure of the Beauharnois power plant, while the respective displacement histories were recorded at the Beauharnois, La Tuque and Rapides Farmers plants over a long period before and after the performed concrete slot cuttings.

Keywords: alkali-aggregate reaction, concrete dam, monitoring, numerical analysis, power plant, slot-cutting, swelling

INTRODUCTION

A large number of hydraulic structures in Canada and around the world are affected by the deterioration of concrete resulting from the alkali-aggregate reaction (AAR). One of the primary concerns for these structures is to provide assurances for their safety and the integrity and to justify the often high cost of the proposed corrective measures. The remedial measures undertaken in the refurbishing of concrete structures affected by AAR depend on the level of deterioration of the concrete. They can be classified as follows: (i) major; in which case the structural behaviour is altered (e.g., slot-cutting of concrete, extensive post-tensioning to stabilise cracked concrete masses, etc.), (ii) minor; in order to insure uninterrupted functioning of the equipment without modifying the structural behaviour, and (iii) a combination of both.

The slot-cutting of an affected concrete structure (dam, a water intake structure, power house infrastructure, spillways etc.), was and still is recognised as an effective remedial measure. The subject was recently discussed at the Workshop on Swelling of Concrete Dams (Montreal 1997). While the literature related to rehabilitation of affected structures is quite extensive (see, for example, Leger 1997, for a critical review), there is a noticeable lack of publications related to the long-term assessment of the slot-cutting by means of either in-situ monitoring or an appropriate numerical analysis.

The present paper focusses on the numerical simulation of the slot-cutting in Beauharnois power plant, as well as on the analysis of displacement histories monitored at Beauharnois, La Tuque and Rapides Farmers power plants situated in Quebec, Canada . The main objective here is to examine the long-term effects of slot-cutting and to judge whether this procedure is an appropriate remedial measure. The numerical simulations are based on a non-linear continuum theory for modelling the mechanical effects of the reaction (after Pietruszczak, 1996) and employ a contact algorithm for monitoring the progressive closure of the slot.

REMARKS ON SLOT-CUTTING AS A REMEDIAL WORK MEASURE

Most of the Hydro-Quebec's concrete hydraulic structures are the gravity type of structures. In the past thirty (30) years a number of remedial actions undertaken involved the slot-cutting. With the exception of the partial slot-cut at the junction of the right gravity dam and the water intake structure at Beauharnois power plant in the early 1970's (the first slot-cutting experiment), the other decisions involving slot-cutting are difficult to justify. In most of these cases, the main factor was the lack of an appropriate alternative solution.

In general, the decision concerning the slot-cutting is often based on the intuition of the designer and does not involve an adequate analysis of the long-term effects. This is largely due to the fact that relatively little work has been done in the development of numerical models that are able to follow the time history of the reaction and predict the extent of structural damage resulting from it. Also, the decision does not usually involve a critical interpretation of the monitored pre and post slot-cutting behaviour of the existing structures. The basic factors influencing the decision include: (i) exaggerated statements concerning the safety conditions (claims pertaining to the lack of adequate stability or potential loss of integrity of the structure, etc.), (ii) simplistic analyses, involving rather unrealistic material modelling and stipulating rectification of the operational inconveniences (such as reduction in the radial clearances of the discharge ring), (iii) lack of alternative solutions at the time when the decision for the remedial action is expected.

Numerical Analysis

A rational prediction of long-term effects of a remedial work requires a specialized software with an adequate constitutive law and the time integration scheme. Most of the existing attempts to model the time history of the reaction are based on commercially available codes and involve the introduction of 'equivalent thermal load' in either linear or nonlinear finite element analysis (cf. Leger et al.1995). In general, this type of analysis does not account for the sensitivity of AAR-induced expansion to the actual temperature history, confining stress, evolution of humidity, etc. Also, there is no provision to model progressive degradation of material properties, as well as the development and propagation of micro/macrocracks. Thus, the solutions based on simplistic approaches, involving 'equivalent thermal loads' or constrained deformation conditions, are not fully reliable and should be viewed with caution. The results of the slot-cutting simulations at Beauharnois power plant presented here, are the product of an elaborate time stepping procedure involving a constitutive theory able to incorporate all important parameters which affect the swelling of the concrete.

Interpretation of Monitored Behaviour

The majority of the existing power plants have monitoring systems adequate for routine auscultation of the overall structural behaviour. The appropriate assessment of the direction and the magnitude of permanent displacements caused by the concrete expansion requires systematic observations over a relatively long period of time. The prolonged period of observation provides the possibility of distinguishing between the permanent expansion of concrete and the reversible deformations due to temperature fluctuations.

The measured records at Hydro-Quebec's structures, in particular at Beauharnois power plant, provide sufficient information for an adequate interpretation and foresight of the damaging effect of the alkali-aggregate reaction. The rate of expansion at Beauharnois power plant is the highest (50-70 micro strains/year) among the hydro plants affected by the reaction in Quebec. The power plant is 1000 m long; the accumulated vertical and upstream-downstream displacements are in the vicinity of 100 mm. The monitoring system was improved in the late 60's and at this stage there is a substantial amount of data available covering the period of over thirty years. Careful analysis of the results of these observations (Gocevski 1995) allows to foretell the long-term implications of the slot-cutting. Based on this information, it is very difficult to justify the recent remedial measures at La Tuque (slot-cut in the left gravity dam, 1993) and especially at Rapids Farmers power plant (slot-cut of the left gravity dam and the added backfill in the downstream side of the dam, 1994). The summary of the observed results for Beauharnois, La Tuque and Rapide Farmers power plants are provided in the next chapter. From the presented data it is clear that a careful interpretation of the monitored pre and post slot-cutting behaviour of the structures leads to a conclusion that this remedial measure is not efficient and should not be consider.

Safety Conditions

The observed formation of surface macrocracks, together with deformations interfering with the normal turbine operation and the «assumed» or inadequately calculated high stress concentrations in concrete mass, are often used as a justification for choosing the slot-cutting as a remedial measure.

The concrete swelling modifies the geometry of the structure. The cracking pattern developed during the expansion process often leaves an impression that it may affect the stability and the integrity of the structure. However, the extensive structural static and dynamic analyses performed for most of Hydro-Quebec's power plants, demonstrate that for these gravity type structures, both the change of geometry and the cracking have little effect on either stability or integrity.

The instruments installed over the last thirty years permit precise measurements of displacements in the monitored structures (in fraction of millimetres). The graphical representation in a distorted scale displacement/height, differing 1000 to 5000 times, often gives the impression that the displacements are excessively high. In reality, for a gravity type of structure of height 20, 28 and 37 metres (Rapide Farmers, Beauharnois and La Tuque) the observed displacements are insignificant.

The in-situs stresses obtained by overcoring technique in both Beauharnois (Gocevski 1995) and Mactaquac (Swelling of Concrete Dams 1997, D.D. Curtis) have an average value of 3.5 MPa. This is far bellow the registered concrete average compressive strength of 30 MPa. The slot-cutting at both power plants reduced the stresses by 0.9 to 1.3 MPa. Therefore, the often cited reason of slot-cutting in order to reduce the accumulated stresses in the concrete (safety concern) is not justified.

The cracking pattern due to alkali-aggregate expansion and/or temperature variations is already well established at the time of the decision to slot-cut the concrete mass. This pattern is the least forceful way for the structure to accommodate to the required movements. It is unlikely that the addition of a new crack (the slot-cut) will force changes in this pattern which will improve the structural safety.

Operational Inconveniences

The power plants affected by the concrete swelling frequently experience the reduction in radial clearances of the discharge ring. To correct the ovalization of the ring, the slot-cuts between units are commonly suggested. It is believed that the slot-cuts should provide uniform (symmetric) reduction in radial clearances, hence prolong the uninterrupted operation. The experience at Beauharnois power plant clearly demonstrates that the expansion in the unsymmetrically distributed concrete masses of the spiral case can not be influenced by imposed slot-cuts.The above comments are the result of more than eight years of active research in numerical modelling, laboratory and in-situ testing and analysis of many remedial work interventions involving slot-cutting in Hydro-Quebec's and other structures affected by the concrete expansion due to alkali-aggregate reaction.

RESULTS OF MONITORING PRIOR AND AFTER SLOT-CUTTINGS

In order to substantiate the above remarks, some results concerning the actual displacement histories recorded at the Beauharnois, La Tuque and Rapides Farmers powerplants are presented here and briefly discussed.

Fig.1 shows the geometry of the gravity dam and portion of the water intake structure at Beauharnois power plant. At the same time, Fig.2 presents the evolution of horizontal displacements measured at the crest of both structures prior and after the slot-cutting (from 1971 to 1994). Two diagrams are shown. The bottom one presents the longitudinal expansion of the water intake structure, whereas the diagram at the top shows the upstream-downstream displacements of the gravity dam.

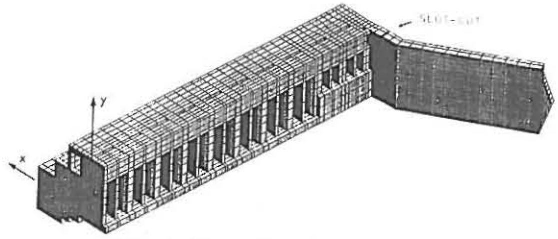

Fig. 1: Geometry of the problem

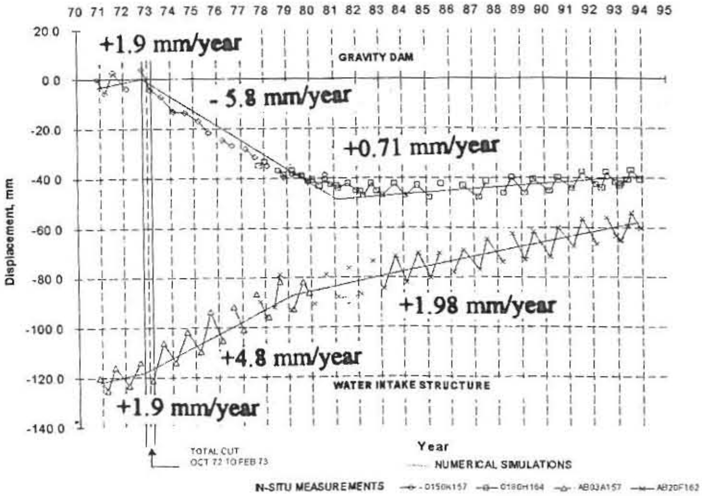

Fig.2: Evolution of horizontal displacements at the crest of the gravity dam and the water intake structure following partial slot-cutting in 1972

Prior to slot-cutting in October 1972, both the gravity dam and the water intake structure had an annual rate of irreversible deformations of 1.9 mm/year. The reversible movements following the temperature cycles had a maximum amplitude of 8 mm. After the partial slot-cut was completed in February 1973, the gravity dam experienced a rebound of 42 mm at the top. The direction of the movement reversed after the closure of the gap, and the annual displacement rate became close to that before the slot-cutting. The expansion of the water intake structure accelerated from 1.9 mm/year to 4.8 mm/year, stabilising at 1.98 mm/year after the closure of the gap in 1979.

In terms of reduction of accumulated stresses at the junction of both structures, the intervention can not be justified. The relieve of 1.2 MPa is lower than the precision of the measuring instruments and lower than 5% of the evaluated strength of the concrete. Also, in relation to structural deformations the intervention was counterproductive. In general, during the period of the closure of the gap, a 20% increase in the accumulated displacements was observed. It was reported by the maintenance staff that this has hampered the operation of the head gates neighbouring the slot-cut. Thus, the benefit of the intervention, if any, was only temporary. After the closure of the gap in 1998 the structural behaviour continued to follow the same pattern as before the slot-cutting.

The displacements at the crest of the left gravity dam at La Tuque power plant (pendulums #0915F153 and #0916F153) are presented in Fig. 3. For the period from 1979 to 1993, the permanent longitudinal, upstream-downstream and vertical movements were 8, 16 and 24 mm, respectively. The corresponding movements accumulated during the entire life of the powerplant, estimated by extrapolation, are 20, 40 and 60 mm. For a gravity type of structure, of height of 30m at the point of pendulums, the reported movements are insignificant in terms of both stability and structural integrity.

The behaviour observed during the period from 1995 to 1999, following the slot-cutting of 1993, reveals that no important changes took place. The water intake structure expanded faster (5-7 mm) closing the slot and, together with the gravity dam, experienced a rebound of about 7 mm. No noticeable changes in the vertical movement were recorded. The effect of the slot-cutting was not detected by the device measuring the joint movements, as presented in Fig. 4. It may be concluded that the power plant did not benefit from this remedial intervention.

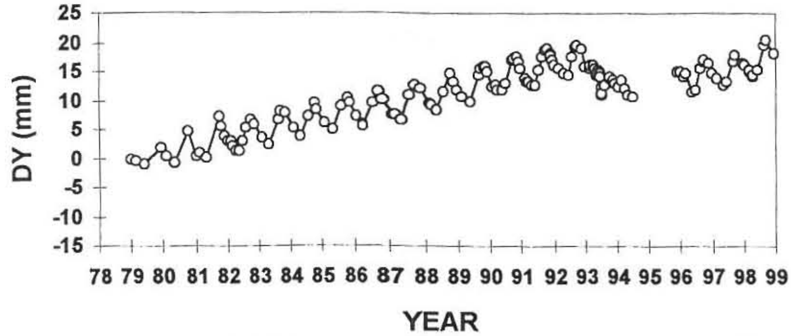

Fig.3: LaTuque-pendulums 0915F153 and 0916F153 before and after the slot-cutting of 1992. DY - upstream-downstream displacements

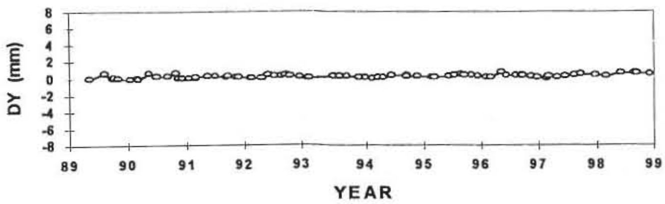

Fig.4: La Tuque- displacements of the joint measuring device #0920M147 before and after the slot-cutting of 1992. DY-upstream-downstream

The accumulated movements of the Rapides Farmers powerplant from 1927 (the time of construction) until 1994 (i.e., the time of slot-cutting at the junction of the left gravity dam and the water intake structure) are estimated to be approximately 35 mm in all directions. The measurements recorded since 1984 (pendulums #0590F073 and #0590F072) are presented in Fig. 5. The conclusions are similar to those for La Tuque powerplant. For a gravity type of structure, of height of 20m at the point of the location of pendulums, the reported movement of 35 mm for the last 60 years is insignificant in the context of stability and integrity of the structure. The slot-cut in the direction DY (Fig.5) did not substantially modify the structural behaviour either. The changes may be considered as temporary until the closure of the gap between the separated concrete masses.

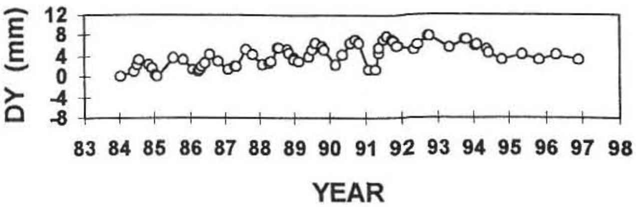

Fig.5: Rapide Farmers- pendulums 0590F073 and 0590F072 before and after the slot-cutting of 1994 DY-upstream-downstream displacements

NUMERICAL ANALYSIS

The main purpose of the numerical analysis was to evaluate the rationale behind the decision regarding slot-cutting at the junction of the right wing dam and the water intake structure of the Beauharnois complex (Fig.1). It has been suggested for some time that a complete slot-cut (i.e. through the entire height of the structure) is required at this stage of operation in order to achieve long-term objectives in terms of safety and integrity of the structures. The numerical simulations carried out here were aimed at assessing the mechanical implications of the proposed intervention.

Selection of Material Parameters

The concrete used for the construction was prepared with Portland cement which contained alkali from 0.8% to a maximum of 1.12%. The aggregate was taken from the excavated rock. In a large part of the structure, the concrete contains a sufficient amount of humidity for alkali-silica reactivity (i.e., relative humidity > 80%). The simulations were carried out by incorporating the constitutive framework proposed by Pietruszczak (1996). The constants specifying the rate of free expansion and the parameters appearing in the evolution laws have been identified from a series of tests performed at the University of Sherbrooke on samples extracted from the existing concrete masses. The values of maximum 30% reduction in elasticity modulus and 10% reduction in compressive/tensile strength were assigned.

The numerical analysis employed a constitutive model for concrete described in the article by Pietruszczak et al. (1988). The formulation invokes a non-associated flow rule and the yield surface is expressed in a functional form

$$f = \bar{\sigma} - \beta(\xi)\, k(\theta)\, \bar{\sigma}_c = 0 \; ; \; \dot{\xi} \sim (2\, J_{2\dot{\varepsilon}})^{1/2} \tag{1a}$$

where

$$\bar{\sigma}_c = \frac{-a_1 + \sqrt{a_1^2 + 4a_2(a_3 + I/f_c)}}{2a_2}\, f_c \tag{1b}$$

In the above equations a's are material constants, $I = -I_1$, $\bar{\sigma} = (J_2)^{1/2}$, $\theta = ⅓\sin^{-1}(3\sqrt{3}\, J_3 / 2\bar{\sigma}^3)$, where I_1 and (J_2, J_3) are the basic invariants of the stress tensor and the stress deviator, respectively. The function $\beta(\xi)$ is designated as the hardening function and its evolution depends on $J_{2\varepsilon}$, i.e. the second invariant of the plastic strain deviator. This function is defined in such a way that, in a stable regime, $\xi \to \infty \Rightarrow \beta \to 1$, which describes a homogeneous deformation mode associated with the formation of microcracks. The unstable response, corresponding to the formation of macrocracks, is characterized by a progressive decrease in the value of β, such that $\beta \sim 1-\varphi_r$ for $\xi \to \infty$, where φ_r defines the residual strength of the material. In general, the formulation pertaining to brittle response, although not rigorous, can still render a solution which is only weakly dependent on discretization

(Pietruszczak et al.,1988). At the same time, the distribution of β in the context of a boundary-valued problem will provide an indication of the extent of structural damage in the system.

The numerical simulations discussed here have been carried out assuming E_o=15,000MPa, v=0.2 and f_{co}=27MPa. The material parameters associated with elastoplastic response were the same as those cited in the original reference.

Numerical Procedure

The numerical analysis was carried out in three stages. First, the solution due to self-weight of the structure and the pressure exerted by water and backfill soil was obtained. For this stage, the expansion joints between the units were considered operational. The second phase of analysis involved the simulation of the effect of continuing alkali-silica reaction. The reaction started immediately following the end of construction (1928), however, the overall swelling is believed to have started during the early 1940s. The expansion joints, initially about 5mm, were eventually closed, prompting a direct interaction between the units. The numerical analysis for this stage covers a period of fifty years, i.e from 1945 to 1995. The third stage of the analysis involved the simulation of both: (i) continuing deformation for an additional 50 years without slot-cutting, and (ii) 50 years of deformation following a slot-cut.

The numerical integration of the constitutive relation employed an implicit algorithm as described by Huang and Pietruszczak (1996). The simulations involving the slot-cutting were carried out by incorporating a contact algorithm for monitoring a progressive closure of the gap. A comprehensive review of numerical strategies for analysis of static contact problems is provided in the paper by Zhong & Mackerle (1992). The contact boundaries were modelled as an elastic-perfectly plastic material with Coulomb's friction law.

Numerical Results

The main objective of this set of analyses was to assess the long-term implications of the proposed deep slot-cut. Two different cases were considered and the results compared. First, the structural behaviour corresponding to 50 calendar years was simulated. Subsequently, the simulations for a period of additional 50 years were carried out with and without the slot-cut. The results of the simulations corresponding to the end of the first 50 year interval are shown in Figs. 6 and 7. Fig.6 presents the distribution of displacements in the direction of the water intake structure (along z-axis). The results indicate that the top 1/3 portion of the structure expands significantly more than the rest. This is primarily due to the fact that the rock foundation constrains the expansion of the concrete mass at the base. The crest of the structure is moving with an average rate of 1.9 mm/year, which is consistent with the field observations.

Fig.7 shows the distribution of the damage factor $\overline{\beta}$. The latter has been evaluated as $\overline{\beta} = \int |\dot{\beta}| dt$, where β is defined according to eq.(1). As explained earlier, $\overline{\beta} \rightarrow 1$ signifies local failure through formation of micro cracks (strain hardening regime). The values of the damage factor $\overline{\beta}$ exceeding one correspond to an unstable response associated with the formation of macrocracks. In general, the extent of structural damage after the first 50 years is rather limited. The macrocracks form only in the vertical piers of the first two units, which is primarily due to the geometry of the intake structure.

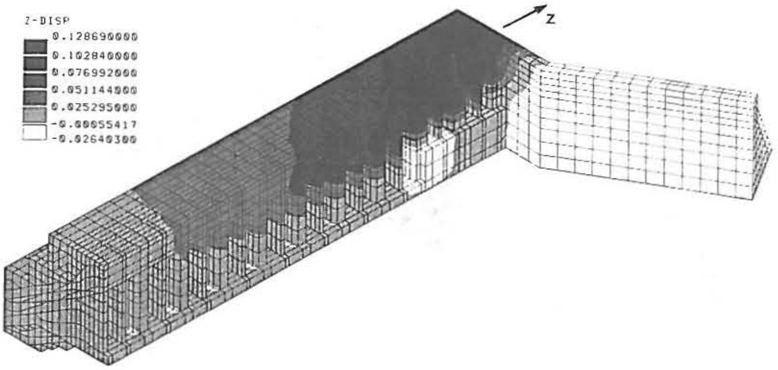

Fig.6: Distribution of displacements (along the z-axis) after the first 50 year interval

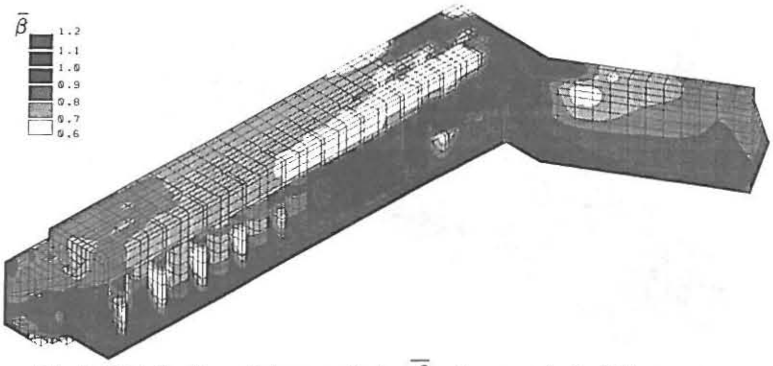

Fig.7: Distribution of damage factor $\overline{\beta}$ after a period of 50 years

Figures 8a and 8b show the distribution of the damage factor at the end of the second 50 year interval. The structural damage is much more pronounced now. What is interesting to note, however, is that the solutions with and without slot-cutting are, in fact, very similar. This applies to both the spread of the damage (Figs.8) and the displacement field (not shown here due to page restrictions) at the end of this period. The overall conclusion is that the proposed remedial action does not, in fact, improve the long-term performance of the structure.

CONCLUSIONS

The structural effects of AAR are frequently misinterpreted, and the proposed upgrading interventions (slot-cutting and post-tensioning) cannot always be justified. The past decisions regarding slot-cutting were based on inadequate numerical analysis and/or inappropriate interpretation of the monitoring results combined with exaggerated concerns about the structural safety and integrity. The magnitude of distortions and accumulation of stresses in the concrete masses are insignificant for a gravity type of structure, and should not be the reason for a major remedial intervention. In general, large-scale remedial work is very expensive and may often be counter-productive. Although the immediate results of slot-cutting intervention are somewhat encouraging, the long-term performance does not show any significant improvement. It appears that since the swelling process is relatively slow, some minor interventions may be sufficient to maintain the continuity of operation.

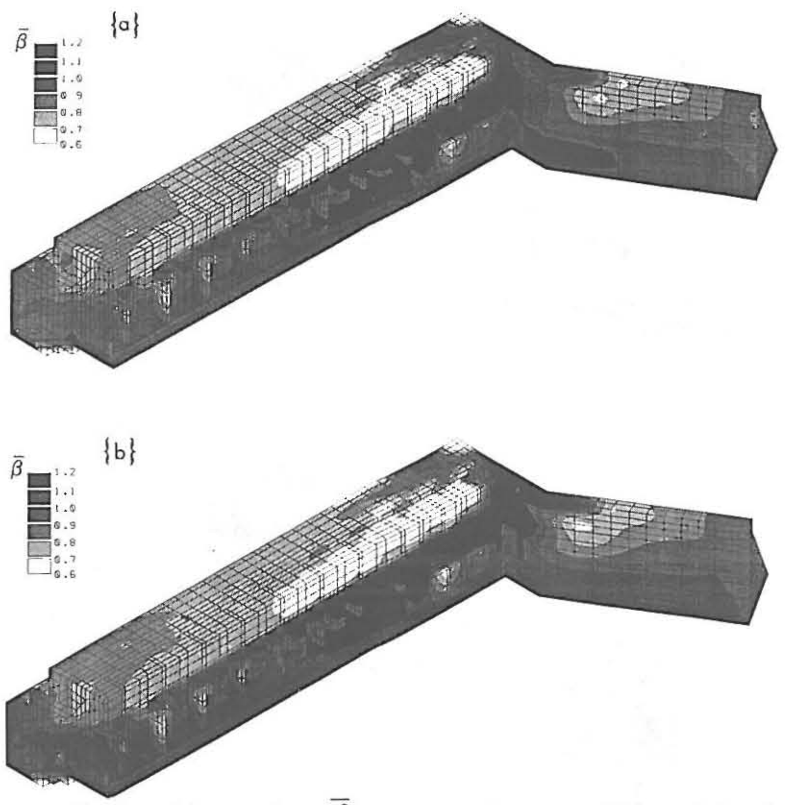

Fig.8: Distribution of damage factor $\overline{\beta}$ at the end of the second 50 year interval
(a) with slot-cutting, (b) without slot-cutting

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