STRATEGY FOR THE REHABILITATION OF SALANFE DAM

Patrice Droz[1], Jean-François Seignol[2*], Raphaël Leroy[3], Liviu Boldea[1]

[1]Stucky Ltd, Renens, Switzerland

[2]Université Paris-Est, IFSTTAR, SOA, F-75732 Paris, France

[3]Alpiq, Lausannelpiq, Lausanne, Switzerland

Abstract

This paper presents the ongoing study of a gravity dam affected by alkali-silica reaction (ASR) and the strategy planned for its rehabilitation. The aim is to lower its stress-state by slot-cutting. The position and number of these slot cuttings will be determined by use of numerical modelling. The first steps of the study are described: analysis of in situ monitoring of the dam, laboratory tests on concrete samples, numerical model representing the consequences of ASR on the structure, introduction of special elements to take into account the slot-cutting and preliminary computations to elaborate a global strategy.

Keywords: AAR-treatment, monitoring, gravity dam, numerical modelling

1 INTRODUCTION

Dam managers have sometimes to face internal swelling reaction in their structure (Charlwood, 2011). The main problem induced by these pathologies lies in the change occurring in the material stress-state, with potential consequences on structural reliability. Hence, evaluation of the modified stress-state is the main goal of structure re-assessment based on numerical modelling. But the numerical tool may also make it possible to design and calculate treatment solutions such as reducing internal stresses by slot-cutting.

These questions are illustrated in this paper by the case-study of Salanfe dam, a gravity dam in which Alkali-Silica Reaction (ASR) was proven and the displacement of which have been monitored for several years.

Material investigations and structure monitoring are first described, focusing on the ASR-induced displacements. The strategy for the dam rehabilitation is then introduced. Last, the numerical tool aimed at dimensioning the slot-cutting procedure is introduced, as well as first results obtained on preliminary numerical models.

2 THE DAM AND ITS PATHOLOGY

2.1 Description of the dam

The Salanfe Dam was built in 1952. It is located near the city of Martigny (Valais, Switzerland) at an altitude of 1925 m above sea level on the Salanfe Plateau in Swiss Alps. It is used to produce hydroelectricity from the waters of the Salanfe and Saufla Rivers. The dam holds a reservoir of 40 mio. m^3 of capacity.

* Correspondence to: jean-francois.seignol@ifsttar.com

Salanfe is a concrete dam classified in the gravity-dam category, according to its profile. The upstream face is vertical and the downstream face has a slope of 1:0.742 to the 1915.60 m level, then 1:0.2 to the crest. The crest length can be divided into 4 straight sections: a central part which is 260.65 m long, the right wing composed of 2 sections of respectively 74 m and 76 m, and the left wing measuring 206 m. The total length at the crest is 616.65 m; the maximum height above the foundations is 52 m. The foundation of the dam is located in sound gneissic rocks and of excellent geomechanical resistance. See Figures 1 and 2.

The dam consists of 42 blocks which are for the most part 14 m long and separated by construction joints. Each joint contains a vertical shaft with a diameter of 100 cm. Some of these shafts are equipped with a pendulum. Inspection galleries measuring 2 m wide by 2.5 m high are located at various levels between levels 1882.00 and 1908.00 from block 6 to 33. They are accessed from the downstream face via seven transversal galleries as well as via vertical shafts positioned on the construction joints. The dam is equipped with an overflow spillway and the intake is located in the dam body (block 18).

2.2 Monitoring

The dam is equipped with several monitoring systems such as pendulums and extensometers and, since 1993, with a geodetic and levelling network to follow the evolution of its deformations. The results of this equipment allow disorders to be detected so that the engineers can intervene to correct the problem in due time. The dam has constantly been deformed by the hydrostatic load and the effects of seasonal thermal variations. Blocks 13 and 23 are equipped with direct pendulums whose measures are interpreted since the initial setting in November 1953. New pendulums were added in blocks 18, 28 and 29 since 2005.

Pendulums in blocks 13 and 23 allow the long-term monitoring of horizontal displacements. As shown on figure 3, the drift started soon after the dam was built and then accelerated in the 1970s. Since the dam was commissioned, the total irreversible downstream-upstream displacement is approximately 35 mm.

A geodetic network was set up in 1993 in order to monitor deformations of the dam and its supporting soil. As for the downstream-upstream movements, the vertical displacement of the crest has continued over time. In 17 years, the elevation has reached 35 mm at points 125 and 127. It has also doubled in the last ten years compared to the reference state. Figure 4 shows the downstream-upstream movements of the crest.

The upstream drift of the crest is amplified by the bends giving an "arched" form to the plan. This situation is typical of arch dams where swelling of the concrete leads to an increase in the length of the arch, which is only possible outwards, namely upstream.

The swelling in the main part of the dam between blocks 11 and 27 pushes the extremities of this part in opposite directions. Detailed inspections exhibited cracks in the galleries and on the downstream face. Crack meters have been set in transversal gallery in block 29 and in the lower inspection gallery in block 28. Their monitoring exhibits irreversible displacements both as crack opening and in the direction perpendicular to the wall facing.

2.3 ASR detection

General

The different symptoms observed on the dam are signs of an expansive reaction occurring in the concrete. To ascertain its nature, material samples are analyzed. The aim of these tests is the identification of the concrete components, the characterisation of the microstructure and the presence of swelling reaction traces.

The aggregate is siliceous limestone. Main mineral phases identified by XRD are quartz (silica) and calcite. Petrographic examination reveals the presence of a large quantity of aggregates showing signs of potential ASR (Alkali-silica reaction), particularly gneiss and mica schists exhibiting rough and wavy-edged quartz. Observation on a Philips XL 30 SEM (Scanning Electron Microscope) was also performed.

Results

Cement grains are relatively well hydrated and the remains of non-hydrated clinker grains are rare. Next to the clinker, neither slag nor flying ashes are visible in the binder. Chemical analyses have shown the presence of alkali in the cement paste that should not be neglected.

The concrete shows a high and heterogeneously distributed apparent porosity (macropores) in its microstructure. A relatively high porosity in the transition areas between the cement paste and the aggregates is also observed, which tends to weaken the concrete cohesion.

In every sample the presence of siliceous-calcareous-alkali gel was observed (see Figure 5), demonstrating the presence of alkali reaction. This gel is cracked or showing hillocks and is principally situated at the interface between the cement paste and the aggregates.

Small quantities of ettringite are also observed in every sample. Its habitus is frequently in aggregates of thin needles, but can also be massive in some rare cases. It corresponds to secondary ettringite, which is commonly visible in concretes showing alkali reaction; in such cases, the available alkali are used by the silica-gel formation. Hence, in the case of the Salanfe concrete, the presence of ettringite is not linked to an internal sulfatic reaction.

These observations and measurements conducted on the seven concrete samples have led to the conclusion that an alkali reaction has developed in the Salanfe dam concrete.

2.4 Material tests

Once the ASR ascertained, different laboratory tests have been performed on a large set of sample cores. Some specimens are submitted to residual expansion tests [1] in order to evaluate the residual swelling potential in the concrete. These tests are still ongoing. Other are used to assess physical and mechanical properties. Testing was performed in compliance with SIA standards. They have been performed by Holcim Technical Center in Eclépens. Sample cores have been drilled out from blocks 13, 15 and 29, in areas considered as representative with regards to observed concrete degradation.

Compressive strength :

The obtained compressive strength varies between 9.8 and 50.2 MPa with a mean value around 27 MPa. Whereas this mean value is normal for this kind and this age of concrete, the large scattering (even amongst samples from the same block) means a strongly heterogeneous material. 60% of the samples gave strength lower than the mean value. It can be due to drilling in areas with initial weakness (such as honeycombing or bad compaction) or in areas where material was damaged by ASR.

Young's modulus :

Once again a large scattering is observed, from 7,000 to 36,500 MPa. One third of tested samples were under the mean value of 22,100 MPa, for the same reasons as compressive strength tests.

Tensile strength

The tensile strength varies from 0.2 to 2.7 MPa with a mean value of 1.2 MPa, which is 1 MPa lower than expected value when considering material compressive strength.

Water permeability

These measurements are consistent with the strong heterogeneity observed with regards to mechanical properties, being scattered from 5.7 to 38.6 $g/m^2/h$.

3 REPAIR TECHNIQUE

Managing and repairing ASR-affected structures is a difficult matter. Up to now, there is no efficient technique to prevent the reaction from developing. There only exists methods affecting ASR-effects and trying to limit the induced degradation [2].

3.1 Purpose of repairing

The rehabilitation project for Salanfe dam aims at returning it to acceptable stress and strain states in order to guarantee dam safety for every situation.

3.2 Different techniques

Different techniques have been tested on various ASR-affected concrete structures. They can be divided into four types.

Protection against water ingress

Various waterproof membranes or coatings can be applied to reduce water ingress and, hence, slow down ASR-kinetics [3], but their efficiency on structures as large as dams is not assured [4]

Reinforcement with anchoring, prestressing or rebars

This set of techniques can be applied to reduce concrete strain by confining it and to improve structural safety [3,5]. However, its efficiency often decreases when applied to large and massive structures.

Injection of chemical or gas (lithium)

This technique consists in having lithium ions infiltrating the concrete, since this chemical species can inhibit ASR. The main problem lies in the ion-diffusion process, which limits this technique to very thin structures (such as concrete roads, for instance).

Stress-release by slot-cutting

The fourth possibility consists in lowering the compressive stresses induced by prescribed concrete swelling by sawing a part of the structure, as detaile *infra*.

3.3 Slot-cutting

The rehabilitation project developed for Salanfe dam is based on sawing the upper part of the dam in order to release compressive stress and *ergo* lower the arching effect due to the elbows in the dam. Since Salanfe is a gravity-dam, it does not need any arching effect to correctly resist the water pressure and this is why the rehabilitation aim could be to totally restore the initial stress state. Nevertheless, aiming to have a small remaining compressive stress level after slot-cutting was considered as a better option in order to use the arching-effect to keep the joints closed.

Slot-cutting with diamond-wire has already been applied to other dams, for instance Mactaquac in Canada [6], Chambon in France, Pian Tessio in Italy, and Center Hill, TN in the USA [7].

The sawing device is composed of a diamond-wire the diameter of which is about 10 to 15 mm, a main wheel anchored in the downstream face and pulleys. Wire diameter may vary according to the slot height to compensate for strain induced by sawing.

The rehabilitation project does not take into account other techniques in order to restrain or stop future ASR-development, but some crack injections, mainly in the galleries, may also be scheduled. Complementary measures as well as repeating slot-cutting can of course be studied in further phases of rehabilitation, depending on the monitoring of the dam evolution.

In this initial step, the aim is to define a first slot-cutting scenario. A scenario consists in giving the following directives:

- position of the (various) slot-cutting;
- their height (from crest down to altitude z);
- width of the slot-cutting.

In the case of future supplementary slot-cutting, optimization of schedule should also been studied, in particular in the case of Salanfe dam, the accessibility of which is complex.

4 USE OF A NUMERICAL TOOL

Numerical modelling is used for preliminary testing of different slot-cutting scenarios. The following section presents the preliminary computations used to determine the strategy of the global study.

4.1 Purpose of the modelling (vérifier tout l'orthographe avec un dictionnaire anglais US

The main purpose of the study is to provide the dam manager with different slot-cutting scenarios, and for each one its advantages with regards to the dam behaviour. These scenarios will then be compared, taking into account their cost (varying from one scenario to another) and practical feasibility. Advantages brought by a given scenario will be assessed according to:

- First, the short-term re-closure of each slot-cutting in order to avoid water ingress (even if it is possible to inject the slot-cutting afterwards); from a numerical point of view, it means the existence of compressive stresses in the two opposite faces of the slot-cutting.
- Lowering of stress in the dam, which is compared to initial stress state without rehabilitation; the new stress state will be compared to dam safety requirement (concerning both stresses in the dam concrete and in its supporting soil). The resulting stress state must be assessed near the slot-cuttings, but also at a significant distance in order to estimate a sort of "influence zone" around each slot-cutting.
- Lowering of dam drift (both in the upstream-downstream and vertical directions), or even a displacement back to the initial deformation of the sound dam. Note that decreasing these abnormal displacements is not the real aim of the rehabilitation project, but they represent the easiest means to monitor symptoms of ASR.

4.2 Numerical model for the dam

The finite element model used to assess the dam state is composed of a 760 m by 325 m by 98 m block representing the soil and the dam itself (see figure 6). Two models have been developed for this study. The first one, used for the following preliminary tests, is composed of 30,000 quadratic elements (14,000 for the sole dam) representing about 130,000 nodes. A second one, more refined, will be used to better represent large stress gradients occurring around the slot cutting as well as the galleries.

ASR-affected concrete is represented by LCPC model [8] completed by the relation binding stress-state and ASR-expansion anisotropy proposed by Multon and Toutlemonde [9]. Since residual expansion tests are still ongoing at the beginning of the numerical modelling step, mode parameters are adjusted with the help of monitored displacements [10].

4.3 Special elements for slot-cutting

Special elements have been developed [11] in order to represent the mechanical effect of slot-cutting. They are based on classical contact elements, the resolution of which is obtained through stiffness-penalty technique. Their main characteristic is to represent the slot-cutting width *w* by authorizing a limited interpenetration (of value *w*) of initially superposed nodes to represent the sudden disappearance of concrete. This makes it possible to represent each slot-cutting by elements of zero thickness, otherwise a very strong refinement of the FE mesh would be compulsory, which could dramatically increase the size of the problem to model.

In addition to the interpenetration test, which provides information on whether compressive stress can occur again through slot-cutting, these elements take into account friction (based on Coulomb's law) which checks whether the two parts will stay together in the future or if some kind of "shear-locking" device would be necessary.

4.4 Preliminary study: position of slot cutting

In these preliminary computations, two slot cuttings have been defined, as shown on figure 7. Their influence on displacements and stresses in the left elbow is discussed. Slot-cutting SC1 is located on the right of the elbow, at 170 m; slot-cutting SC2 is on the left at 40 m. Both are 20 mm wide and represent one-third of the total height of the dam at the same position. Four modelling with an ASR free-expansion of 0.25% are compared: no slot-cutting (SC0), only SC1, only SC2, and SC1 and SC2 together (SCall). Figure 8 shows the left-right displacements when only SC1 is active, which exhibits the strong discontinuity along the slot-cutting.

When considering stresses and displacements in the left elbow, very similar results are obtained with models SC0 and SC1 on one hand, with SC2 and SCall on the other. This exhibits the fact that slot cutting has a limited range of effect since sawing the dam at 170 m away from the elbow does not modify its behaviour, whereas slot-cutting at 40 m does. For instance, compressive stress in the elbow 5 m below the crest remains unchanged with model SC1, whereas it decreases by 37% with models SC2 and SCall.

This preliminary study advocates making a large number of slot-cuttings, regularly spaced, in order to obtain the best influence on the global dam behaviour.

5 CONCLUSIONS

This paper presents an ongoing study of a gravity dam affected by ASR. The purpose of this study is to define and validate a rehabilitation strategy aimed at restoring structure safety by lowering its stress-state. Up to now, the following points have been achieved:

- exploiting the various monitoring devices to exhibit the abnormal behaviour of the dam due to ongoing expansive reaction;
- ascertaining the occurrence of ASR by laboratory tests on concrete samples;
- proposing a remedial treatment based on slot-cuttings;
- developing a numerical model of the dam taking into account the effect of diamond-wire sawing of the concrete;
- preliminary tests to elaborate a global strategy.

Although numerical modelling of the dam is still in progress, first conclusions can be drawn from preliminary models:

- performing slot-cutting do have an influence on dam stress-state and displacements;

- this influence has a limited range, which advocates for slot-cutting in several places along the dam.

Aknowledgements: The authors would like to express their greatest thanks to Patricia Roure (Itech) for her help.

6 REFERENCES

[1] LCPC (1997): Alcali-réaction du béton – Essai d'expansion résiduelle sur béton durci. Projet de méthode d'essai LPC44, LCPC (in French)

[2] Godart, B., Sims, I., Nixon, P., Capra, B., de Rooij, M. and Wood, J. (2012) The Rilem guidance on appraisal and management of structures damaged by AAR. To be published in this conference.

[3] Fasseu, P. (2001) L'expérience française sur le traitement des ouvrages, In Seminario degradação de estruturas por reacções de origem interna, Dec. 2001, Lisbon, pp 11.

[4] Charlwood, R. G. (2011) Managing AAR affected dams. In Pina, C., Portela, E and Jorge, G. (eds) Proc. 6th Int. Conf. on Dam Engineering, Lisbon, pp. 15-24, LNEC.

[5] Charlwood, R. G. (2011) Rehabilitation Techniques for AAR Affected Dams and Hydro-Electric Projects. In Pina, C., Portela, E and Jorge, G. (eds) One-day course Concrete Dams Subjected to AAR: Diagnosis, Modelling and Rehabilitation, Lisbon, LNEC.

[6] Curtis, D. (2000) Analysis and structure response to recent slot cutting at Mactaquac Generating Station. In: Bérubé, M.A, Fournier, B. and Durand, B. (eds) Proc. 11th Int. Conf. on Alkali-Aggregate Reaction in Concrete, Québec City, pp. 1283-1291.

[7] Hull, K. (2007) Center-Hill Dam. Mitigating Effects of Alkali-Aggregate Reaction with Vertical Slots. In Special Workshop on Chemical Expansion of Concrete Dams a Hydro-electric Projects. http://www.dam-research.org/Granada-2007/index.html

[8] Li, K. and Coussy, O. (2002) Concrete ASR degradation: from material modelling to structure assessment. Concrete Science and Engineering (4): 35-46.

[9] Multon, S. and Toutlemonde, F. (2006) Effect of applied stress on alkali-silica reaction-induced expansion. Ciment and Concrete Research (36): 912-920

[10] Leroy, R.,Boldea, L.I., Seignol, J.F. and Godart, B. (2011) Re-assessment and treatment-design of an ASR-affected gravity dam. In Dams and Reservoirs under Changing Challenges, Lucerne, Switzerland.

[11] Omikrine-Metalsi, O., Aïtsi, M., Rigobert, S., Toutlemonde, F., Seignol, J.F. and Boldea, L.I. (2010) Integration of contact elements and creep in RGIB-modulus of the FE-program Cesar-LCPC. Application to structures affected by internal swelling reactions. In Hydro 2010 Int. Conf. Lisbon.

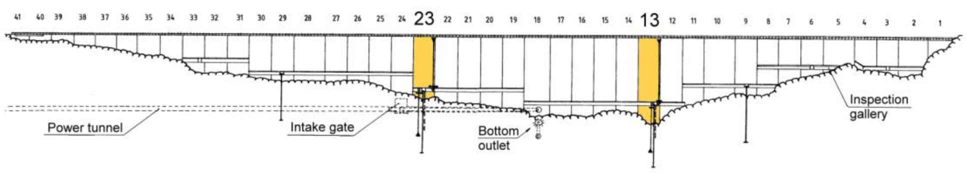

FIGURE 1: upstream developped elevation of the dam

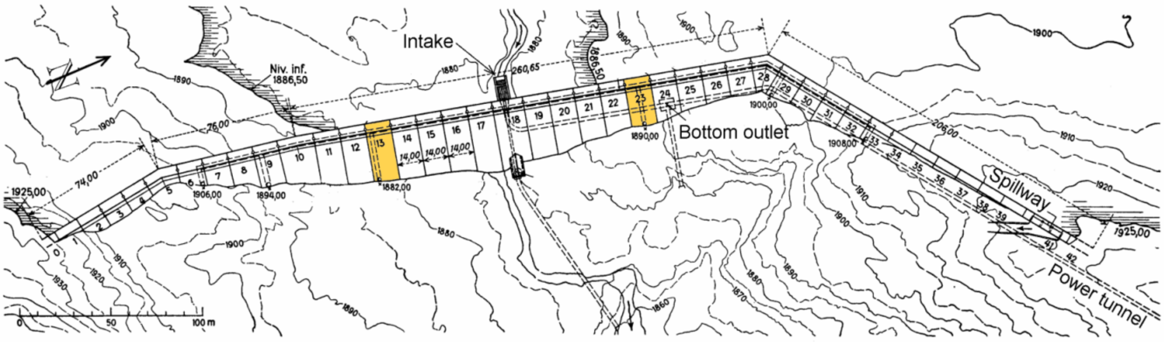

FIGURE 2: plan view of the dam

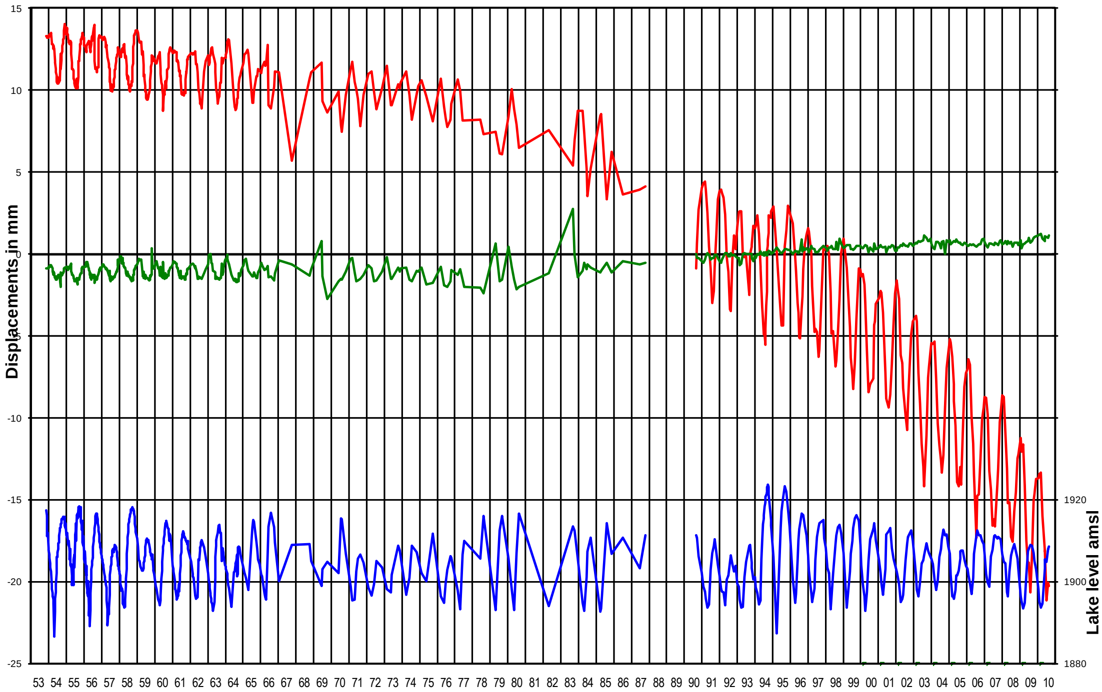

FIGURE 3: displacment of block 13 versus time (red is upstream-downstream, green left-right) and lake-level (blue)

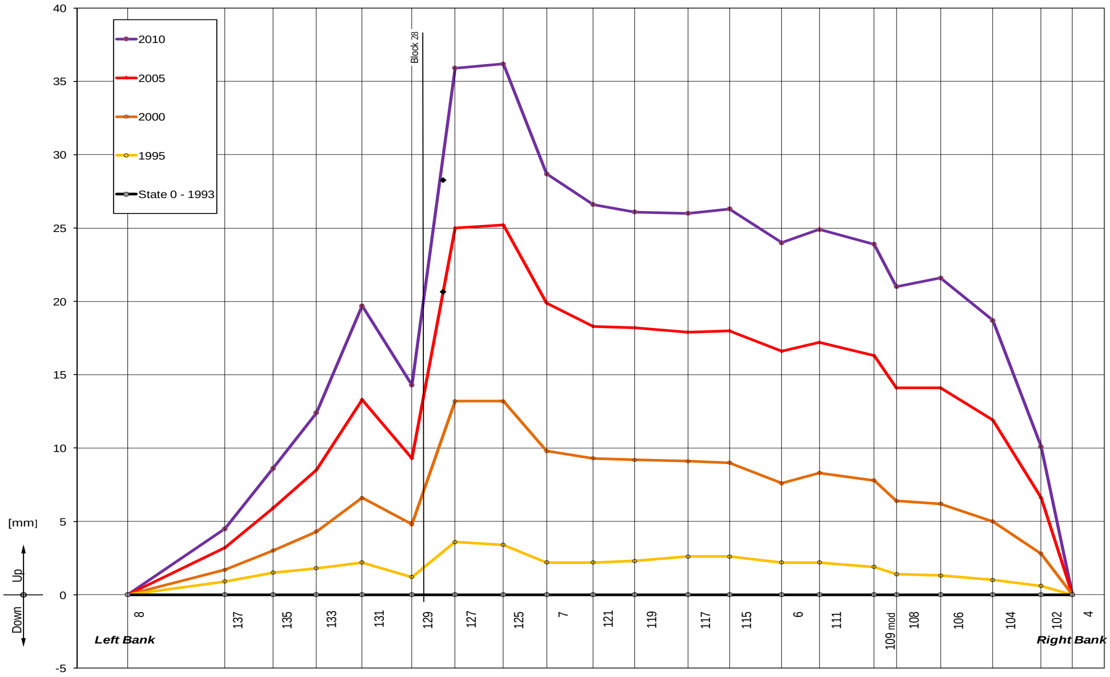

FIGURE 4: downstream-upstream displacements from 1993 to 2009 in mm, measured by geodesy

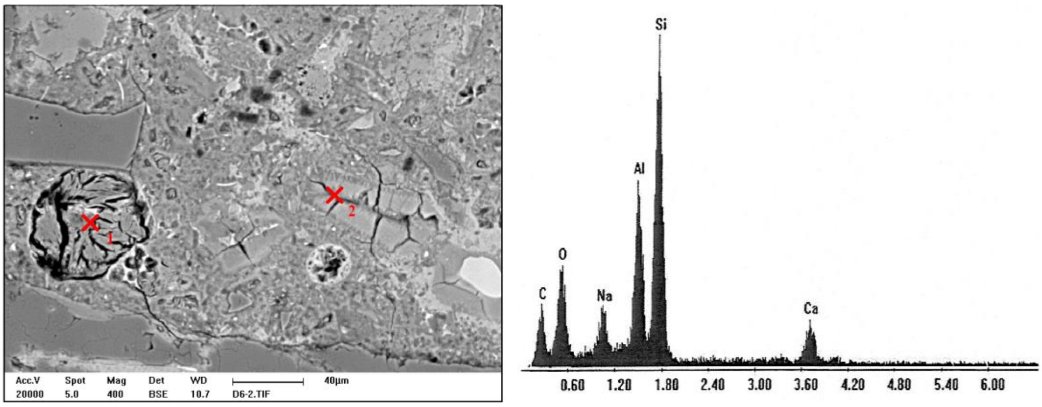

FIGURE 5: Voids full of ettringite (X1) and of ASR-gel (X2); XRD-spectrum for gel in region X2.

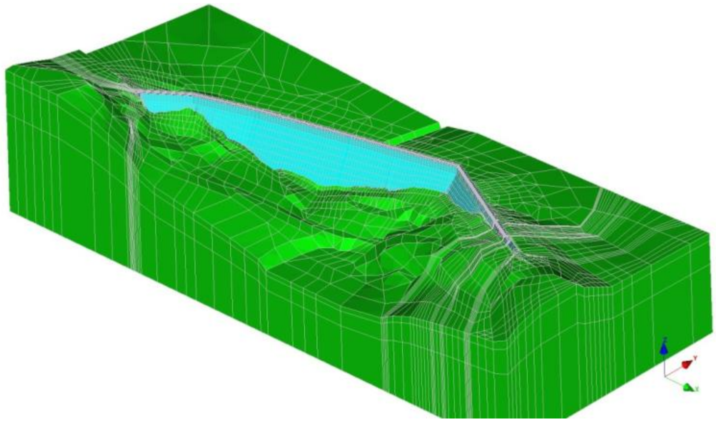

FIGURE 6: general view of the mesh of the dam and its soil

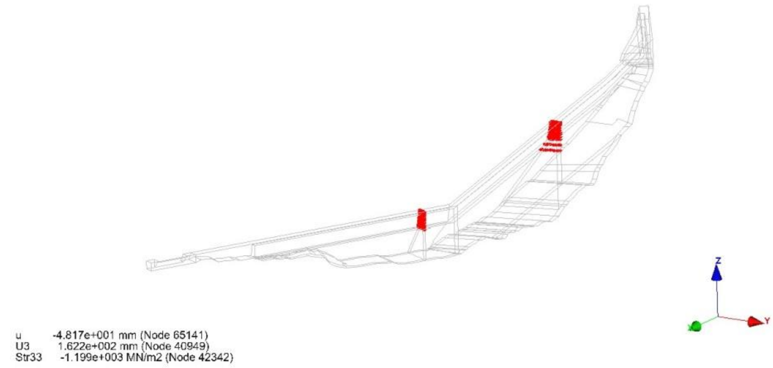

FIGURE 7: positions of the contact elements (red dots) representing the SC1 (on the right) and SC2 (on the left).

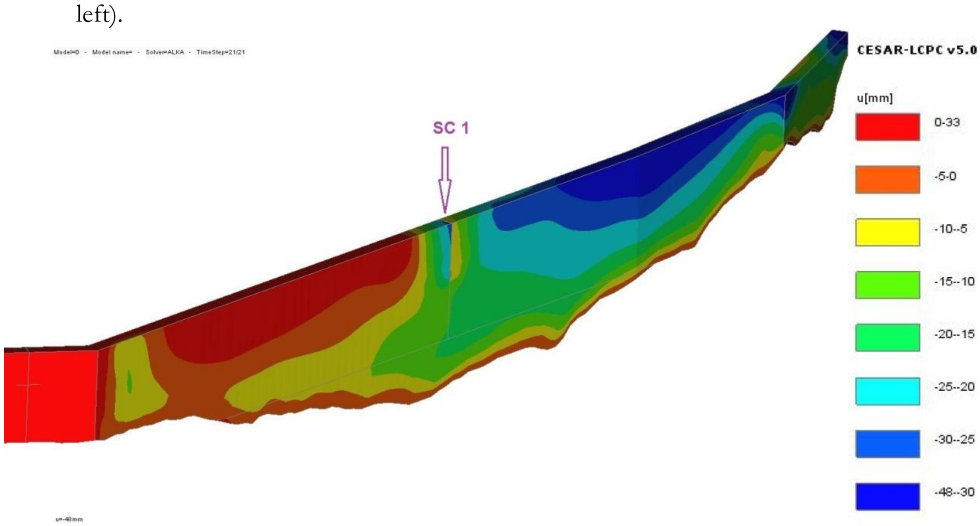

FIGURE 8: discontinuity of longitudinal displacement around slot-cutting SC1.