SEISMIC ASSESSMENT AND STRENGTHENING OF A SLENDER ARCH DAM

N. Nilipour[1] and L. Mouvet[2]

[1] *M.Sc. Civil Engineer, Project Manager, STUCKY Ltd, Switzerland*
[2] *M.Sc. Civil Engineer, Head of Dams Department, STUCKY Ltd, Switzerland*
Email: nnilipour@stucky.ch, lmouvet@stucky.ch

ABSTRACT :

With the ageing of existing dams, introducing of new safety regulations and evolution of Earthquake and dam Engineering and computation; the safety reassessment of existing dams is inevitable. In the legal framework of dam surveillance in Switzerland, dam owners have to conduct seismic assessment studies of their dams based on the recently implemented federal Guidelines.
Les Toules 86-m high double-curvature arch dam has been built in the early sixties and enjoys a particular design. The Dam has been constructed in a wide and U-shape valley with very high ratio of the crest length to the height. The dam was built in two separate phases, leaving a special joint grouted later on. Recent static and dynamic verifications based on the reassessed seismic hazard studies showed that the dam does not meet the seismic safety requirements. Therefore, the reservoir maximum operation level was lowered by 10 m as an immediate safety measure before conducting more sophisticated studies and developing of a strengthening concept. More detailed analyses allowed understanding the behavior and weak points of the dam. Dynamic analysis revealed the necessity of cantilevers and arch strengthening as well as shear keys in the middle part of the dam. On this basis, some strengthening alternatives were studied and compared. The final solution comprises several reinforcing measures. Firstly, a downstream strengthening in form of abutment thickening transfers the load from over-loaded cantilevers to the thickened arches. Secondly, adding shear keys in the vertical joints guaranties the stability of the blocks in case of seismic events. Moreover, local foundation treatment and some other rehabilitation works have been planned. The construction has started in 2008 and will be completed by 2011.

KEYWORDS: Arch dam, seismic assessment, strengthening, Swiss dam safety Guidelines.

1. INTRODUCTION

First dams have been constructed some thousands of years ago. Although some of them still exist, most of them have been failed to last for very long time. The level of development of the science and technology of the Man and limited water and energy demand didn't encourage him to build many large, modern and long-lasting schemes until the 19th century. In the industrial countries, most of the large dams have been erected in the 20th century, therefore, are modern and well-design and constructed structures. However, it should be borne in mind that since then earthquake and dam engineering, the design tools and material science have been significantly progressing. On the other words, today's design and safety criteria are noticeably evolved compared with those of the golden era of dam construction in the developed countries. Hence in order to have the same level of safety and technology of the infrastructures, existing old dams are continuously subject of verification and checking. Additionally, the ageing, in some cases unusual behavior and abnormalities demand safety checking of the existing dams. Therefore, safety reassessment of old dams based on new safety regulations, considering the state-of-the-art of earthquake and dam engineering and computation, is nowadays an important task of dam engineers. The lessons learnt from these verification studies are very valuable experiences to improve the concept and design of many new large dam projects under study and construction all around the World.

1.1. Swiss Guidelines for seismic verification of Dams

Based on the Ordinance of 1998 on the safety of the water storage structures, the Federal Office for Water and Geology (FOWG) has prepared Guidelines for implementation of this Ordinance in collaboration with representatives of Cantonal authorities of surveillance, of scientific circles, of professional organizations and of the Economy. Accordingly, the Guidelines for seismic verification of water storage structures have been elaborated during 1999-2000 within the framework of a Working group constituted of Swiss experts in the domains of Dam, Earthquake engineering and Geology. The results were published in 2003 as Basic Documentation for Seismic Verification of Water Storage Structures (Darbre et al. 2003), with the main objective of the protection of human life, properties and environment located downstream of the water storage schemes against the safety check earthquake. According to these Guidelines, all the existing dams should be analyzed for seismic verification within ten years after coming into force of these Guidelines. That means more than 200 Swiss dams should go through this safety control procedure until 2012. It should be noted that in 2006 the dam division of FOWG has been transferred to the Swiss Federal Office of Energy (SFOE), which is today the highest supervisory authority for all dams in Switzerland. In practice, however, the SFOE delegates responsibility for the supervision of several hundred small dams to the relevant cantonal authorities.

As per the Guidelines, three classes of dams are distinguished:

- **Class I**: dams higher than 40 m or higher than 10 m with a reservoir volume of larger than 1'000'000 m3. It should be mentioned that every 5 years all Class I dams are subjected to a complete detailed inspection by an approved dam expert and obviously, the safety criteria are more restrict for Class I dams.
- **Class II**: dams higher than 25 m or higher than 15 m with a reservoir volume of larger than 50'000 m3 or higher than 10 m with a reservoir volume of larger than 100'000 m3 or higher than 5 m with a reservoir volume of larger than 500'000 m3,
- **Class III**: all other dams.

The Guidelines define the safety check earthquake as well as the analysis procedure, main assumptions and safety criteria for the different dam Classes. The details for the Class I dams are described below for the Les Toules arch dam.

2. LES TOULES ARCH DAM

Les Toules double-curvature arch dam is located in Southwest of Switzerland in the Canton of Valais in the region of Grand-Saint-Bernard Pass close to the Swiss/Italian border. The dam has been built in early the sixties and enjoys a particular design. The Dam has been constructed in a wide and U-shape valley. It has a slight abutment thickening, a high vertical curvature and no shear keys in the contraction joints. Due to the shape of the valley, the ratio of the crest length to the dam height, 5.35, is quite high for an arch dam. Having a boldness factor of 35, Les Toules arch dam is one of the slenderest existing arch dams. It should be mentioned that for an arch dam of 86-m high, a boldness factor of maximum 25 is recommended. Experience shows that for the dam with a boldness factor of higher than this limit, the probability of having long term behavior abnormalities is higher. Additionally, the dam was erected in two separate phases, leaving a special joint grouted later on to make a monolithic structure. It is interesting to know that according to the documents of that time the volume of the dam was considerably decreased to make the arch dam alternative competitive with an embankment design.

Table 2.1 Some characteristics of Les Toules arch dam

Crest level	masl	1811.0
Maximum water level	masl	1810.0
Foundation level	masl	1725.0
Maximum height (H)	m	86
Crest length (L)	m	460
L/H ratio	-	5.35
Crest thickness	m	4.20
Base thickness	m	20.50
Concrete volume	m3	240’000
Boldness factor	-	35

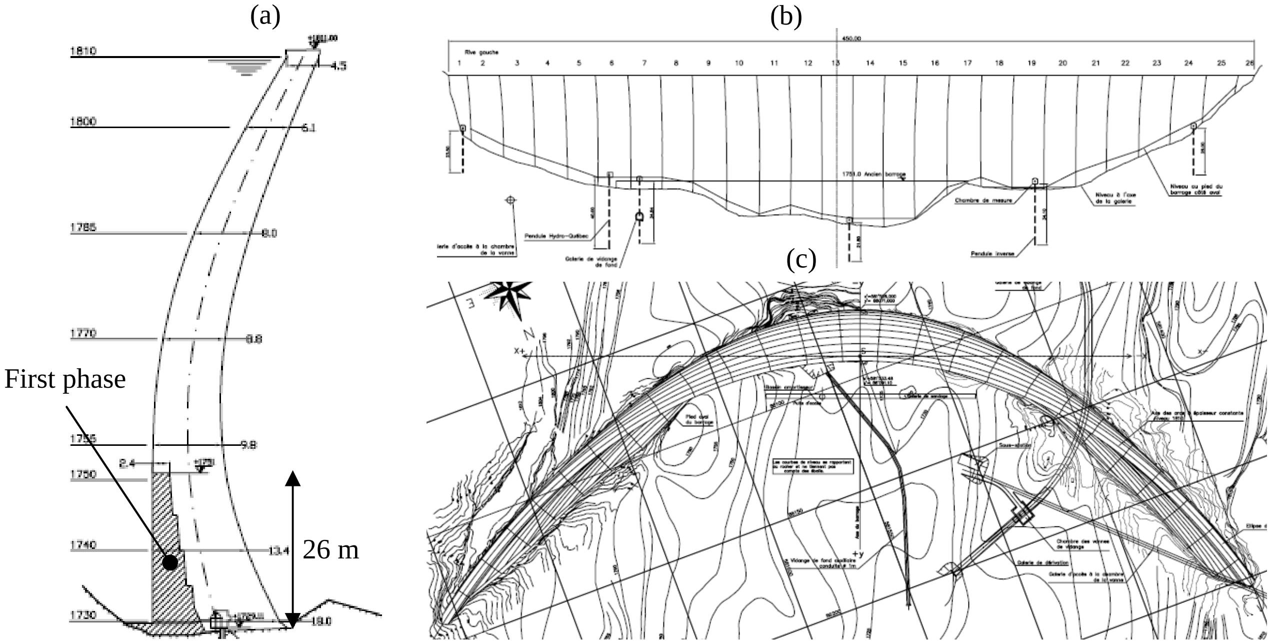

Figure 1 Les Toules double-curvature arch dam, (a) Crown Cantilever, (b) Developed upstream Elevation, (c) Situation

2.1. Dam Monitoring and Behavior

In general, the dam has been well monitored and maintained from the first impounding of the reservoir and there is no important abnormality in its behavior. However, there are some particularities in this respect, which are worth to be mentioned:

1. Due to important curvature of the cantilevers, the low mean thickness of the dam and the length of the arches, some leakage appeared through concrete joints during the first impounding. Only an important

grouting campaign could reduce the leakage discharge to acceptable values.
2. The grouting of the joint between the two phases of the construction could never be properly fulfilled. This point is very strongly monitored and shows some limited movements and increasing water pressure in it. In the long term, the opening of the joint can increase due to its degradation. Therefore, the monolithic behavior of the dam cannot be guaranteed. However, according to the conducted studies, the participation of the upstream part of the dam is not significant and has small effect on the global behavior of the dam.
3. Some local irreversible displacements have been observed in the foundation of the left blocks, probably due to the lower quality of the rock foundation in this zone.
4. Some small cracks have been observed on the upstream face of the dam, which were repaired and seem to be stable with no opening increase tendency.
5. Due to high vertical curvature of the cantilevers, it is difficult to install direct plumb lines in the dam. Hence the displacements of the dam are monitored using optic measurement of targets installed on the downstream face as well as polygonal geodesic measurements,

2.2. Seismic Hazard Assessment of the Site

The Dam was design and constructed at the early sixties with the knowledge and tools of Dam and Earthquake Engineering of that time. It should be added that in the past due to limited knowledge on seismic hazard of the country, most of the old dams in Switzerland were designed with pseudo-static method and for horizontal peak ground acceleration (PGA) of 0.1 g using arch-cantilever grid model.
As per the Guidelines of SFOE, PGA of the dam site should be determined based on the seismic hazard map of the country published in 1977. This map provides the seismic intensity isolines for seismic events with return periods of 1’000 and 10’000 years. The seismic intensity is then transformed in PGA using a logarithmic formula.
For Class I dams such as Les Toules dam, both earthquake characteristics and the safety criteria are stricter. A 10’000-year return period seismic event is required as the safety check earthquake. This gives a PGA of 0.33g for the dam site, which is 3.3 times higher than the original design PGA of the dam. Given a requested 5% damping ratio and a spectral acceleration amplification of 2.5, it was almost obvious that the dam would not satisfy the new safety criteria. Therefore, a specific seismic hazard study has been carried out in order to determine more precisely the PGA value based on local faults and the geology of the site as well as to select three proper recorded earthquakes corresponding with local geological and cinematic conditions.
Seismic hazard study of the site was performed both on the deterministic and probabilistic basis and resulted in a horizontal PGA of 0.28g and 0.19g for the vertical component. On the other hand, based on the seismic investigations and available database, three earthquake records have been adopted:

- South of Iceland, 17/06/2000, magnitude : 6.6 Mw, duration : 30 s, PGA : 0.19g
- Athens (Ano Liosia), 07/09/1999, magnitude : 6.1 Mw, duration : 30 s, PGA : 0.12g
- Frioul earthquake, 15/09/1976, magnitude : 6.1 Mw, duration : 16.5 s, PGA : 0.21g

Three components of the selected earthquake records have been scaled to match the target acceleration spectrum required by SOFE. Finally, the maximum acceleration of the three generated time-history set has been adjusted to the design PGA.

3. BACK ANALYSIS AND CALIBRATION OF THE MODEL

Before starting detailed dynamic analysis, calibration of the finite elements (FE) model had to be fulfilled based on the concrete test results and the measurements for both static and dynamic behavior of the dam. As for the static calibration, firstly the concrete measured temperature values have been simulated with analytical transient thermal solution proposed by Stucky & Derron 1957. This allowed determining the thermal concrete parameters and boundary conditions, which have been accordingly used as input of the FE thermo mechanical analysis. Subsequently, displacements of the FE model have been calibrated with displacement measurements at three different blocks by adjusting the mechanical characteristics of the concrete and rock foundation.
Considering difficulties due to some plastic displacements, the opening of the joint between upstream and

downstream parts and slight cracking after 50 years of operation. It should be also mentioned that in order to cover the full possible range of the dam behavior, the joint between the two construction phases of dam has been studied in two extreme modes: a) full opening, i.e. no contact, b) perfect contact, i.e. monolithic behavior.
Dynamic calibration of the dam has been carried out on the basis of the natural frequencies and also mode shapes, both obtained by the ambient and forced vibration test of the dam. The measured mode shapes and frequencies have been compared with those obtained by finite elements model for the first ten vibration modes of the dam. On this basis, dynamic modulus of the concrete as well as the behavior of the construction joints between upstream and downstream part of the dam could be determined and used for the dynamic analysis of the dam.

4. STATIC AND DYNAMIC VERIFICATION OF THE DAM

4.1. Static Analysis

Static and dynamic analyses of the existing dam allowed verifying the safety of the structure based on the SFOE Guidelines. Static analysis showed high vertical tensile stresses on the upstream face of the dam for full reservoir load case, regardless of the temperature load conditions. These stresses are mostly on the heel of the cantilevers on the banks and reach 5 MPa for full reservoir combined winter temperature load case as it is shown on Figure 2. Such high vertical tensions for static load case could produce cracks on the upstream face of the dam, an opening of the dam/foundation contact, or decompressing of the foundation on the heel of the dam. All these phenomena have been observed in the dam faces in some extent. The compressive stresses are also high but acceptable with a maximum value of 12 MPa on the downstream face for static load cases.

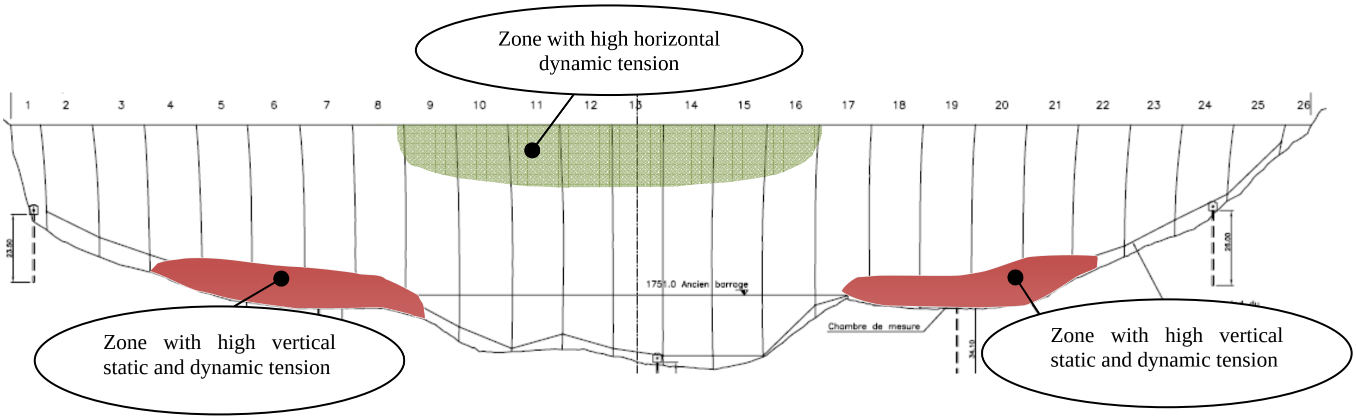

Figure 2 Summary of static and dynamic analysis of Les Toules dam, Developed Upstream Elevation

4.1. Dynamic Analysis

Based on SFOE's Guidelines, dynamic analysis of Class I dam is conducted using a linear elastic model and a time-history modal analysis approach with viscous damping. In the absence of any data, dynamic elasticity modulus can be estimated by an increase of 25% of the static elasticity modulus. As for the tensile strength, it can be calculated as 10% of the dynamic compressive strength, which is obtained as 1.5 times static compressive strength. However, the maximum allowable dynamic tensile strength is limited to 4 MPa and in case of exceeding the tensile strength, the damage, redistribution of the stresses and local stability of the damaged zone have to be checked.
First ten natural frequencies of dam are situated between 1.4 and 5.0 Hz. Such low frequencies for a 86-m dam shows clearly the flexibility and slenderness of dam.
Leaving no strength reserve by static load cases, it was almost obvious that dynamic analysis of the dam would not meet the safety criteria using the new PGA value with an elastic model. The results of the time-history dynamic analysis for the three selected earthquake records showed that the dam would experience very high vertical and horizontal tensile stresses in case of a seismic event. Obtained maximum vertical tensile stress is about 12 MPa in the same zone as the tensions occur due to static load cases. High horizontal tensions have been also obtained in the central part of the upper arches; see Figure 2, which can create significant opening of the radial joints. The radial joints of the dam enjoy a helical geometry but without any shear keys, which is not

favorable to withstand large joint opening. Therefore, the dynamic stability of the upper parts of the cantilevers was of concern and had to be considered in strengthening concept. Although horizontal tensions could be released by the opening of vertical joints, high vertical tensile stresses are of important concern. Such high vertical tensions confirm the necessity of strengthening of the dam. The compressive stresses reach also high values as 19.5 MPa, however, remain acceptable for the dynamic load case.
The results of the static and dynamic verifications based on the reassessed seismic hazard studies showed that the dam does not meet the seismic safety criteria requested by the Guidelines of SFOE. Following these analyses the maximum reservoir level is lowered by 10 m as an immediate safety measure and studies started in order to develop a strengthening concept taking into account the weak points of the dam revealed by the static and dynamic analyses.

5. STRENGTHENING ALTERNATIVES

Different strengthening alternatives were studied to solve the problems jeopardizing the safety of the dam. Apart from the high tensile stresses for both static and dynamic load cases, deterioration of the joint between the two construction phases, local foundation stability problem on the left bank, slight cracking of the upstream face in the central part of the dam and insufficient capacity of the spillway had to be also considered as secondary issues to be dealt with in the reinforcement concept.
Many different possible solutions were studied to improve the safety of the structure. Among them can be mentioned:

- Applying water pressure on the downstream face of the dam to compensate the hydrostatic pressure of the reservoir by constructing another dam further in the downstream,
- Lowering permanently the reservoir maximum water level and transferring the extra water to other reservoirs nearby,
- Strengthening the central part of the dam by individual buttresses on the toe of cantilevers,
- Reducing artificially the crest length by massive artificial abutments both on upstream and downstream,
- Thickening of the dam on the banks,
- Adding shear keys in the vertical joints,
- Adding a seismic belt at the dam crest,
- Pre-stressing and strengthening by steel or carbon sheet reinforcements.

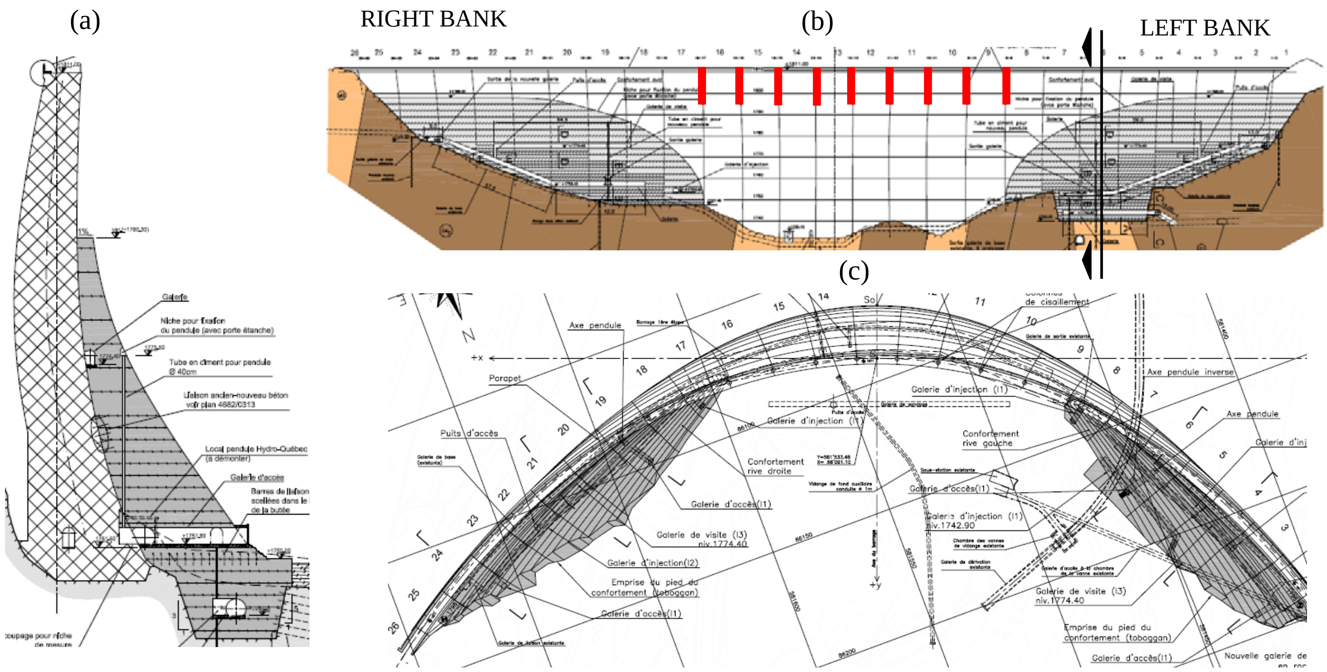

Figure 3 Final strengthening alternative of Les Toules arch dam, (a) Vertical Section, (b) Developed Downstream Elevation, (c) Situation

Obviously, the cost of each alternative plays also an important role to find the most suitable solution. Additionally, the effect of the strengthening alternative on the operation of the power plant cascade was located downstream was considered. However, the main objective remains to deal with the high tensile stresses and seismic stability of the dam. Without going into details of all the alternatives and their comparison, the final solution can be described by two main parts, see Figure 3:

a) Downstream strengthening in a form of abutment thickening transferring the load from over-loaded cantilevers to the thickened arches and accordingly to the abutments. This would reduce significantly the vertical tensile stresses for both static and dynamic load cases.
b) Adding cylindrical shear keys in the vertical joints guaranties the stability of the blocks in case of seismic events. There are shown in red in Figure 3.
c) On the left bank, a particular foundation treatment is foreseen in order to increase the safety against sliding of the particular blocks founded on the weak rock layer.

The downstream thickening concept of the dam was determined by several 2-dimensional analyses of cantilevers and arches. Then to define a proper and optimum 3-dimensional shape, in the first step the reinforcement geometry was drawn for vertical sections to give a smooth increase of the cantilever thickness and to avoid stress concentration. Secondly, horizontal sections were verified and with an iterative optimization procedure a smooth 3-dimensional geometry had been obtained, which is in the same time well integrated in the existing dam geometry and represents a total volume of 65’000 m3.

6. STATIC AND DYNAMIC ANALYSIS OF THE STRENGTHENED DAM

Static and dynamic analyses were performed to check the final geometry of the strengthening concept. The vertical tensile stresses are almost brought down to zero on the upstream heel of the cantilevers. It should be noted that the remained tensile stresses are due to thermal loads, which are in some cases unavoidable. Compressive stresses are in the same order of magnitude as those of existing dam, i.e. 12 MPa.

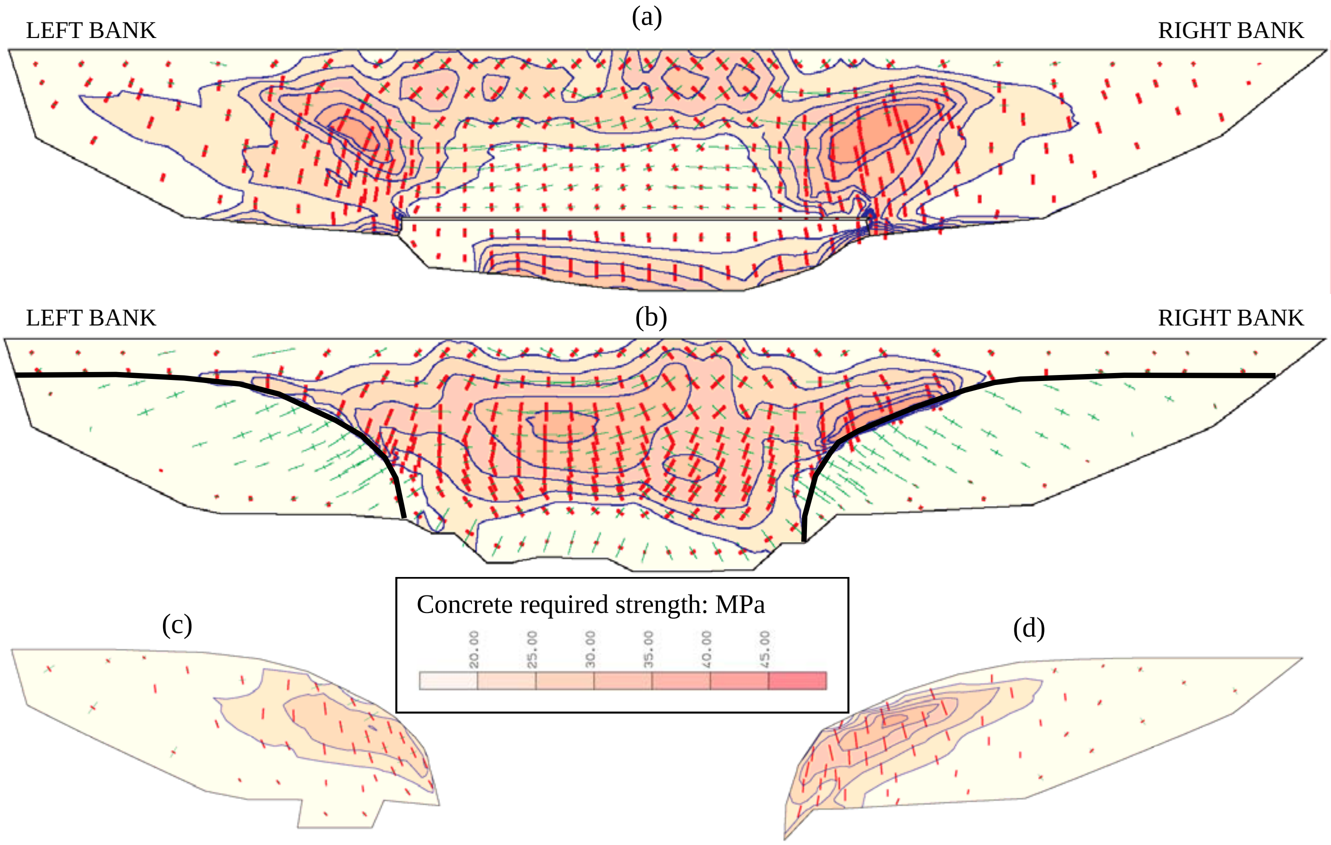

Figure 4 Envelope of maximum dynamic principal stresses and concrete required strength for the safety check earthquake combined with full reservoir and summer temperature load case, (a) Upstream developed view, (b) Downstream developed view, (c) and (d) Right and left Strengthening downstream developed view

Dynamic frequency analysis shows that the strengthening of the dam increases its natural frequencies by around 30% meaning the dam is more rigid and depending on the design response spectrum the dynamic response of the dam can be differed from that of the existing dam.
The dynamic analysis shows a very significant improvement of the stress pattern under seismic loads. Some exceeding of the concrete dynamic tensile strength (adopted as 7.5 MPa) on the downstream face with summer load combination. A slight exceeding was also observed on the upstream face for winter load combination. It should be added that these stresses are very local and situated on the limit of new concrete, therefore, are partly due to the singularity of the model because of the sudden geometry change, see Figure 4. It should be noted that the zone of critical vertical tensions have been shifted to the downstream face as shown in Figure 4. Hence the post-earthquake condition is more favorable than for the case of the existing dam where potential cracks would be on the upstream heel of the dam. On the downstream face, the risk of water pressure increase in a possible crack is zero and stresses due to static load combination are compressive and tend to close the crack. Additionally, the time-history of the stress for the critical earthquake record shows that the tensile strength exceeding occurs only twice during the earthquake with a total duration of 0.07 s with a maximum exceeding of 24%. The stress picture for both critical time steps of the tensile strength exceeding have been studied to evaluate the possibility of local stress redistribution and stability of potential detached blocks. For all cases, having sufficient compressive strength reserve, an increase of compression on the opposite face of the dam could compensate a possible cracking due to the high dynamic tensions.
Due to the strengthening of the arches, the dynamic behavior of the strengthened dam is different from that of the existing dam. Stresses in the arches are increased and higher horizontal tensile stresses can be observed in the central part of the upper arches. This made the necessity of the shear keys in the vertical joints more evident.

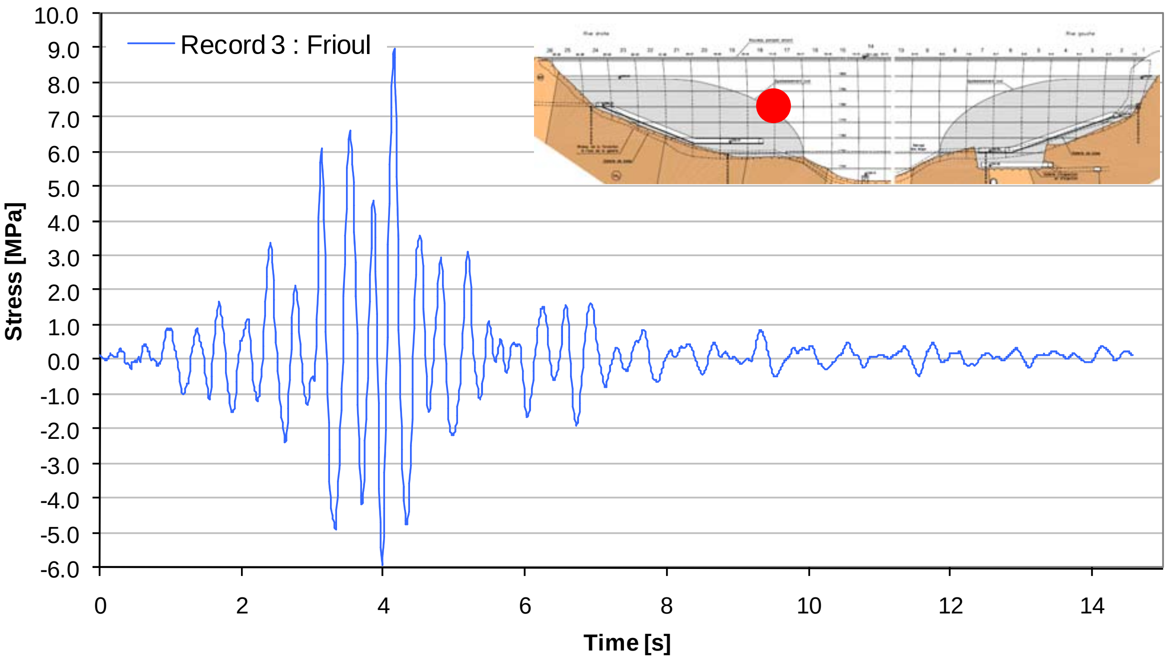

Figure 5 Maximum principal stress time-history for the safety check earthquake combined with full reservoir and winter temperature load case

Finally, the concrete required compressive strength has been determined for the new concrete, reaching 40 MPa for some zones. It should be added that the cement content of the concrete mix should be as low as possible to reduce the temperature heat produced by hydration of the cement. The thermal stress are more delicate for such rehabilitation works, as the existing dam will act as restrain to any thermal expansion or contraction of the new concrete. The contact and monolithism of the structure is guaranteed by steel anchors.

7. CONCLUSIONS

The verification and rehabilitation of the existing dams are of main concern in order to guarantee the safety of such important infrastructures and to meet today safety criteria using the state-of-the-art tools and knowledge of earthquake engineering. National Guidelines for such verification is an important ground for the dam community in order to define precisely the acceptable risk level and the methodology of the safety assessment.
The static and dynamic behavior of Les Toules dam in Switzerland has been studied. Seismic verification based on the newly in force Guidelines of Swiss Federal Office of Energy approved the necessity of strengthening of the dam. A unique strengthening concept was developed compromising a downstream thickening of the arches on the banks as well as adding the shear keys in the vertical joints to improve the dynamic stability of the dam during seismic events. The implementation of the strengthening measures started in 2008 and construction will be completed in 2011.
Due to complex behavior of arch dams, experience of dam engineer is an important factor to understand properly the behavior of the dam and to be able to detect any abnormality and to intervene in case of necessity of rehabilitation or strengthening works.

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