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CASE STUDY

Long-term dam safety monitoring of Punt dal Gall arch dam in Switzerland

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ABSTRACT The 130 m high Punt dal Gall dam is located at the Swiss-Italian border in the South-eastern part of Switzerland and was completed in 1969. The dam is founded on highly folded and partially crushed dolomite and limestone formations. A grout curtain with an area of 120,000 m^2 was provided for controlling seepage. For the monitoring of the dam deformations five inverted pendulums were installed in the dam and three in the rock foundation of the right abutment outside of the dam. For a seasonal water level fluctuation in the reservoir of about 60 m the maximum amplitude of the radial displacement is 25 mm, which includes both the effects of the water load and temperature effects. Furthermore a comprehensive geodetic network was established, 57 joint meters were installed and cracks in the crest gallery are monitored by crack meters. There are also thermometers, piezometers and rocmeters. Springs at the left and right banks of the dam are monitored and chemical analyses of the seepage water and springs are performed regularly. The dam is equipped with strong motion instruments and several near-field earthquakes have been recorded in the past. The paper describes the long-term safety monitoring of this 42 years old arch dam. A short description of the Swiss practice in dam safety monitoring and emergency planning is also given.

KEYWORDS dam safety concept, arch dam, dam instrumentation, dam safety monitoring

1 Introduction

Punt dal Gall dam is located at the Swiss-Italian border in the South-eastern part of Switzerland. Roughly half of the dam is located on Swiss and Italian territories and most of the reservoir is located in Italy. The double curvature arch dam has a height of 130 m, a crest length of 540 m, and the width of the dam at the crest and the base is 10 m and 29 m, respectively. The concrete volume of the dam body is 780, 000 m^3. The dam was completed in 1969 and the first impounding took place in 1970. The reservoir volume is 164 Mm^3 and the reservoir surface is 4.7 km^2.

Details about the design and construction of the dam have been published by Gilg [1]. The dam is founded on highly folded and partially crushed dolomite and limestone formations. Below the right abutment there are gypsum and marl layers with artesian waters. Due to these special foundation conditions an extensive program of rock investigations was carried out including permeability and grouting tests and deformation and shear tests in exploratory galleries. A grout curtain with an area of 120, 000 m^2 was provided for controlling seepage, which is more than twice the cross-sectional area of the valley at the dam site. For the monitoring of the dam deformations five inverted pendulums were installed in the dam and three in the rock foundation of the right abutment outside of the dam. For a seasonal water level variation in the reservoir of about 60 m the maximum measured radial displacement amplitude is about 25 mm, which includes both the effects of the water load and temperature. Furthermore, a comprehensive geodetic network was established, 57 joint meters were installed, and cracks in the crest gallery are monitored by crack meters. There are also several thermometers, piezometers and rocmeters installed in several blocks.

Springs at the left and right banks of the dam are

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monitored and chemical analyses of the seepage water and springs are performed regularly. The seepage water collected from the drain holes is less than 2.2 L/s. The dam is also equipped with strong motion instruments and several near-field earthquakes have been recorded in the past years.

Due to very low temperatures in winter acoustic phenomena from rock fracturing due to freezing have also been observed.

The layout and the upstream face of the dam with the grout curtain are shown in Figs. 1 and 2, respectively. The downstream face is shown in Fig. 3.

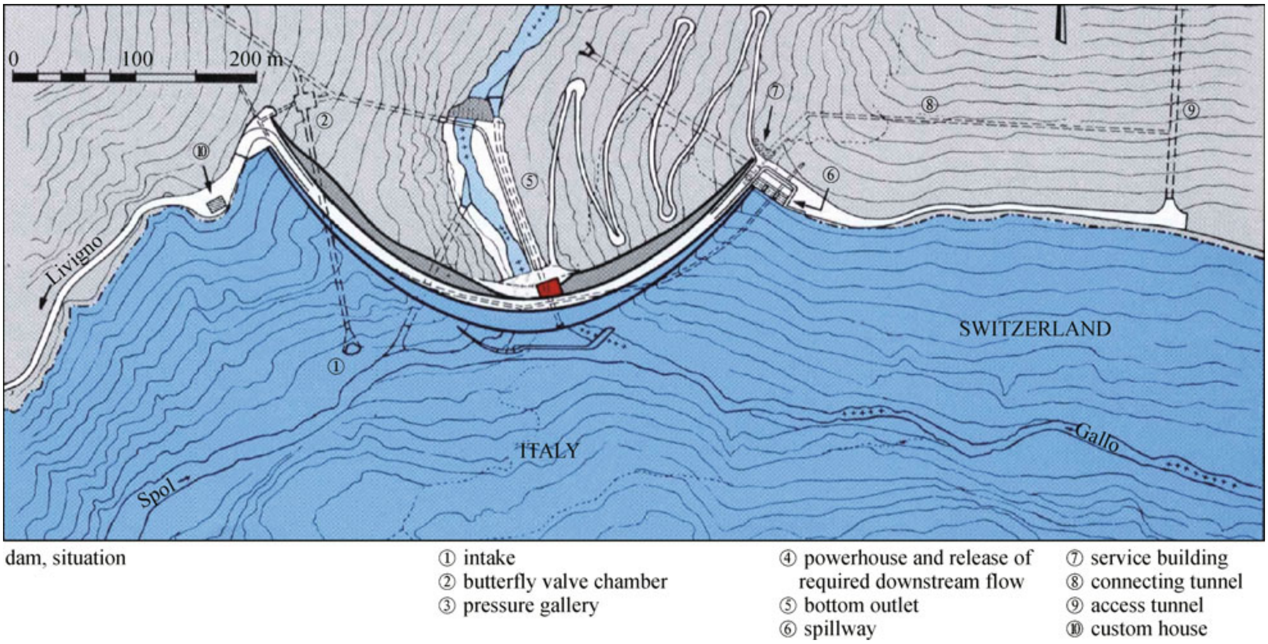

Fig. 1 Layout of Punt dal Gall arch dam

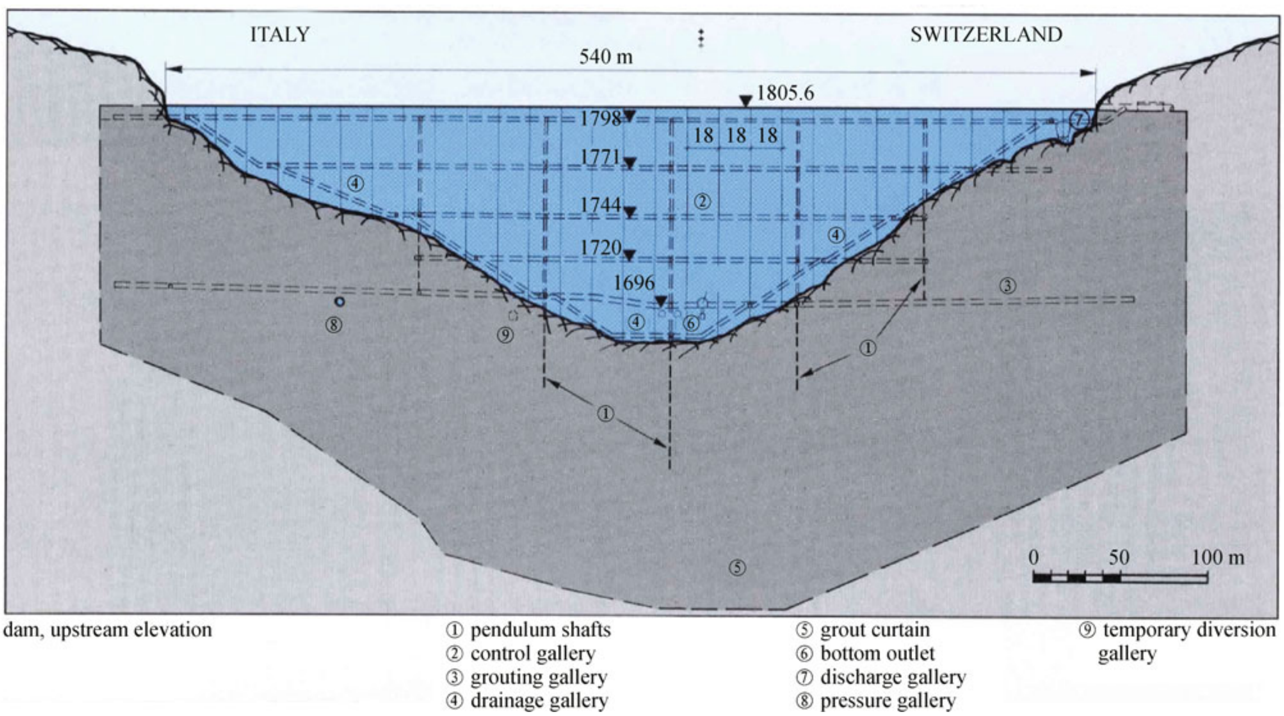

Fig. 2 Upstream face of dam with grout curtain

Fig. 3 Views of downstream (left) and upstream (right) faces of the dam

2 Dam safety

2.1 Overview

Today a comprehensive safety concept is used for projects with large damage potential such as large storage dams. It includes the following elements:

1) structural safety,
2) dam safety monitoring,
3) operational safety and maintenance, and
4) emergency planning.

Usually design engineers are primarily concerned with structural safety; however, for large storage dams, all safety elements listed above must be included. Structural safety means that dams have to be designed and constructed according to the current design guidelines (mainly flood and earthquake design criteria) and taking into account local site conditions.

In the operation phase, dam safety monitoring, regular maintenance, reliable operational guidelines and well-trained personnel are the key elements.

In the case of abnormal behavior and incidents from the natural and man-made environment emergency action plans (EAP) are needed. Such plans must also include operational guidelines of dam and reservoir for abnormal situations such as large floods, etc.

An important element of an emergency concept for large storage projects is the installation of a water alarm system. The basis of such alarm systems is a dam break flood wave analysis in order to identify the people at risk. In Switzerland some 65 dams have an operable water alarm system. The first systems were istalled over 50 years ago and have been upgraded periodically.

An important aspect is that for warning and the evacuation of the population only one dam break scenario is considered in which it is assumed that the dam fails instantaneously. The critical failure mode has to be determinded by the dam engineer following the available dam safety guidelines. Today, it is possible to perform flood wave analyses for many different scenarios. However, from the point of view of alarming people it is not practical to modify the areas that have to be evacuated according to the flood scenario. Such systems would need – if considered at all – extensive training of the affected population and the people in charge of the emergency management. Theoretically this is a good idea but in practice it cannot be used.

2.2 Dam safety management

Dam safety management includes the following:

1) Periodic visual inspections of the dam and reservoir area and regular review of the important monitoring data;

2) Preparation of an annual dam safety inspection report, which includes the assessment of the dam monitoring data (inspection is done by independent dam expert together with the dam safety engineers of the dam owner);

3) Detailed inspection by independent experts every five years. For this inspection, depending on the nature of the project, a dam engineer, an engineering geologist and other experts may be needed.

Furthermore, inspections and increased frequency of readings will be required after unusual events such as an earthquake or major flood, etc.

During the deatiled inspection 3) the main design criteria will also be reviewed. This is an important aspect for most of the existing dams, which have an average age of around 60 years in Switzerland. For example, these dams were designed against floods and earthquakes using design criteria and also methods of analysis, which are considered as outdated today. Therefore, a reassessment of the safety of the dams is needed when design and safety concepts have changed. Accordingly, in recent years the flood safety of all Swiss dams has been reviewed and modifications made. At the moment the earthquake safety has to be reviewed using modern design criteria and methods of analysis. The dam owners were given ten years to complete this task and the deadline is in 2012. Moreover, effects due to climatic changes can be incorporated easily by following this concept. The corresponding changes in, e.g., the hydrology are expected to be much less dramatic than those experienced with the seismic safety of older dams, which were designed for a seismic coefficient of 0.1 and today, seismic forces and stresses can be several times larger than those obtained in the past. Thus, the dam engineers are familiar with such processes.

2.3 Failure modes

The safety of dams should be assessed on the basis of critical failure modes. These failure modes depend mainly on the dam type, the local conditions, the hazards from the natural and man-made environment and the vulnerability of the dam with respect to these hazards. Therefore, in a first step the main hazards have to be listed and the possible failure modes for each hazard shall be given. In a second step it shall be analyzed which of the hazards can be reduced or eliminated by protective structures for avalanches, rockfalls, water waves in the reservoir, illegal access, etc. and which cannot be controlled such as floods, earthquakes, war, etc. Finally, instruments have to be installed which allow the monitoring of these failure modes.

Of main concern in the dam safety monitoring are (i) deformation measurements in concrete dams which include joint movements and the formation and growth of cracks, (ii) changes in the foundation of the dam such as uplift, seepage and erosion etc., and (iii) aging of safety-relevant equipment and dam and foundation materials.

If new failure modes have been identified then additional instruments are required.

In the subsequent sections the dam safety monitoring of the Punt dal Gall arch dam is presented.

3 Dam safety monitoring of Punt dal Gall arch dam

The main types of monitoring equipment installed in the Punt dal Gall arch dam are as follows: inverted pendulums, joint meters, crack meters, rocmeters, manometers (uplift pressure), and temperature gauges in concrete. The deformations of the dam are measured by inverted pendulums as shown in Fig. 4. Due to the strong seasonally varying temperature effects the maximum radial displacement of the dam is in winter when the water level in the reservoir is already decreasing. The maximum annual amplitude of the radial displacement is about 25 mm; the tangential displacements are small.

Besides the deformation monitoring by pendulums and joint meters, a geodetic survey of the deformations of the dam and the reference points in the abutments and reservoir area is also performed every five years. Some movement of reference points has been found which was also due to local conditions, i.e., creep, temperature etc. For the dam safety monitoring a comparison is also made between the observed radial displacments and those obtained from a statistical model. The differences between measured and predicted displacements are less than 3 mm. If larger deviations should occur then the reasons for this behavior have to be explained and if necessary, the statistical model has to be updated as well. Moreover, besides time history plots it is useful also to prepare other diagrams, showing correlations with the water level etc.

In Figs. 5 and 6 the variation of the uplift pressure is depicted. It can be seen that the pressure in boreholes AS1 to AS3 varies with the water level in the reservoir. Also from the long-term records 1990–2010 no qualitative changes in the pressure regime can be found. As the grout curtain has not a uniform thickness, the pressure in the borehole AS1, which is located upstream of the theoretical location of the grout curtain, is smaller than the hydrostatic pressure from the reservoir. This indicates that the grout curtain also extends into the zone of borehole AS1.

Figure 7 shows the seepage water collected in three different zones of the dam. The total seepage is less than 2.2 l/s. Most of the seepage water comes from the left abutment zone. As expected, the total seepage is directly correlated with the water level in the reservoir.

From Fig. 8 it can be noted that the maximum seepage water has reduced from ca. 2.8 l/s in 1990 to 1.5 l/s in 2010, which may be due to clogging of parts of the boreholes.

Furthermore there are 14 springs which are continuously monitored. In winter several wells are frozen and no measurements can be taken. Also the wells monitored do not represent the total seepage through the dam foundation. Periodic water analyses are carried out of the water collected from the wells and the drainage holes. pH values and the electrical resistivity are measured, which fluctuate considerably during the year. In general, the pH of the springs is about 8 $+/-$ 1. However, in some of the drainage holes the pH is as high as 10–12, which indicates that parts of the grout curtain may be dissolved locally. However, the seepage water is very small and therefore this is a phenomenon which has to be observed.

Finally some cracks have developed mainly in the uppermost control gallery of the dam. Some of the larger cracks are equipped with crack meters. As can be seen from Fig. 9 the crack width is also varying with time. The cracks are opening in winter and are closing in summer when the concrete temperature near the dam crest is

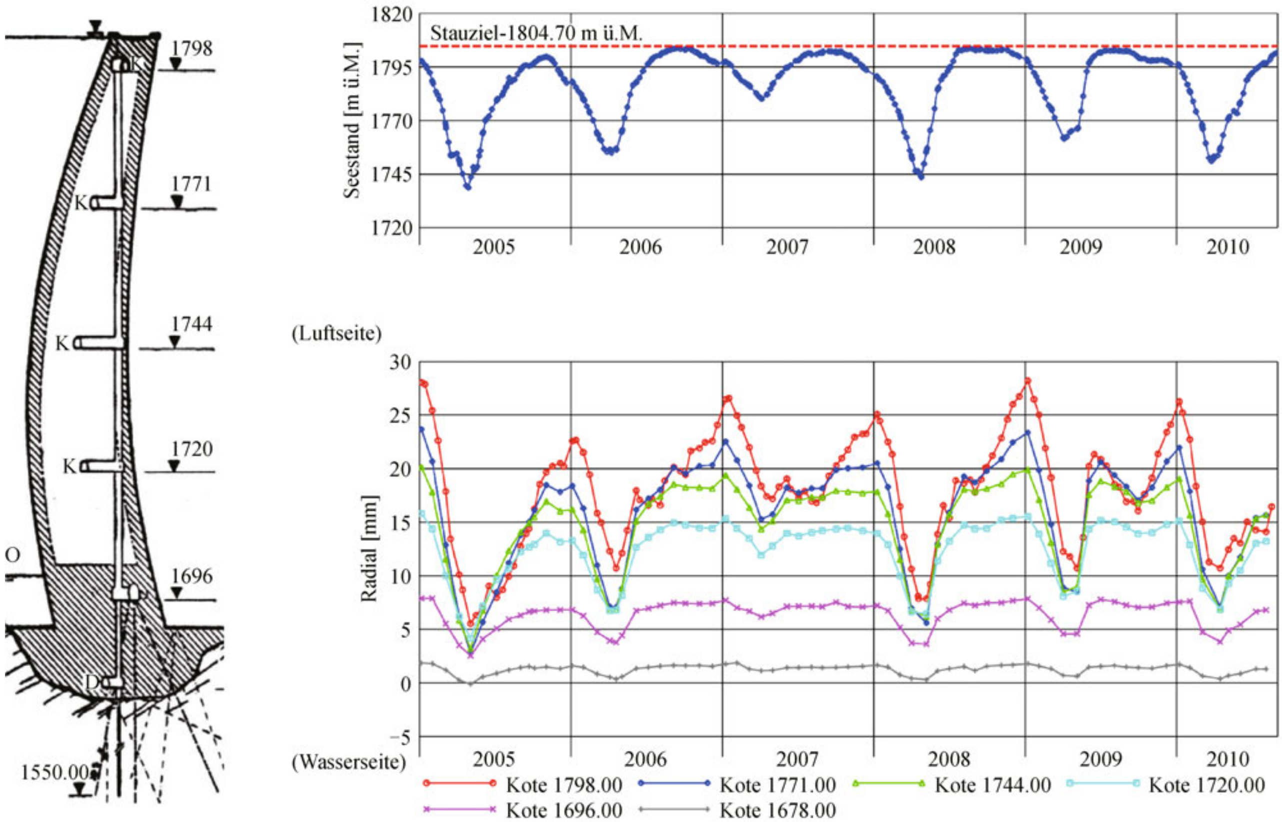

Fig. 4 Time histories of radial displacements at six elevations of inverted pendulum in block 17. The seasonal water level variation is shown in top figure

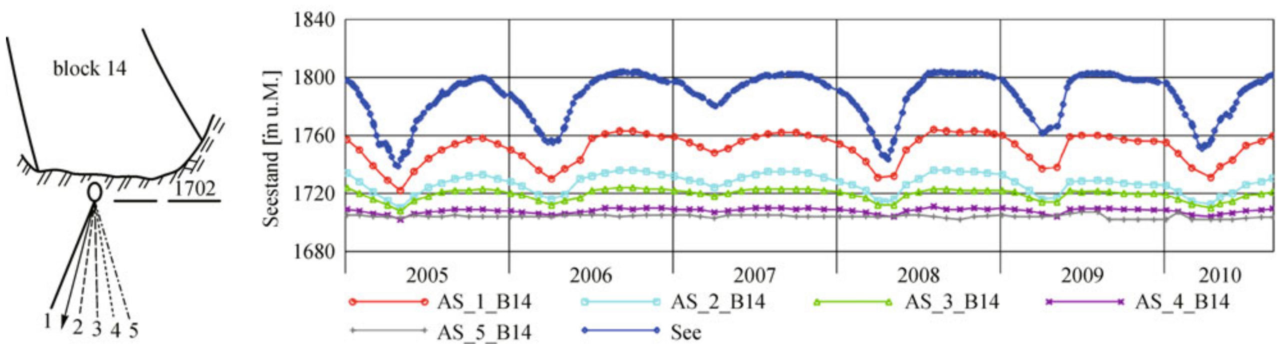

Fig. 5 Uplift pressure measurements at five locations in block 14 (grout curtain is located between drillholes 1 and 2 (left))

maximum. In Fig. 9 the reference axis is that at the time when the crackmeter was installed and the crack was open. The crack opens by about 1.5 mm within one year.

4 Visual Inspection

The visual inspections include the upstream and downstream faces of the dam body (Fig. 3) and the different control galleries.

At the upstream face some local signs of frost damage can be seen. At the downstream face some efflorescences are visible, mainly along concrete lifts in the upper part of the dam, which are subjected to seasonal wetting and drying. These features are monitored photographically. Of importance is if new wet spots have developed or leakage has increased. The situation has been stable. A problem with wetting and drying in combination with freezing temperatures is that aging of the concrete at the dam surface is faster than in other parts not exposed to such processes and weather.

On the crest of the dam there is an important road from

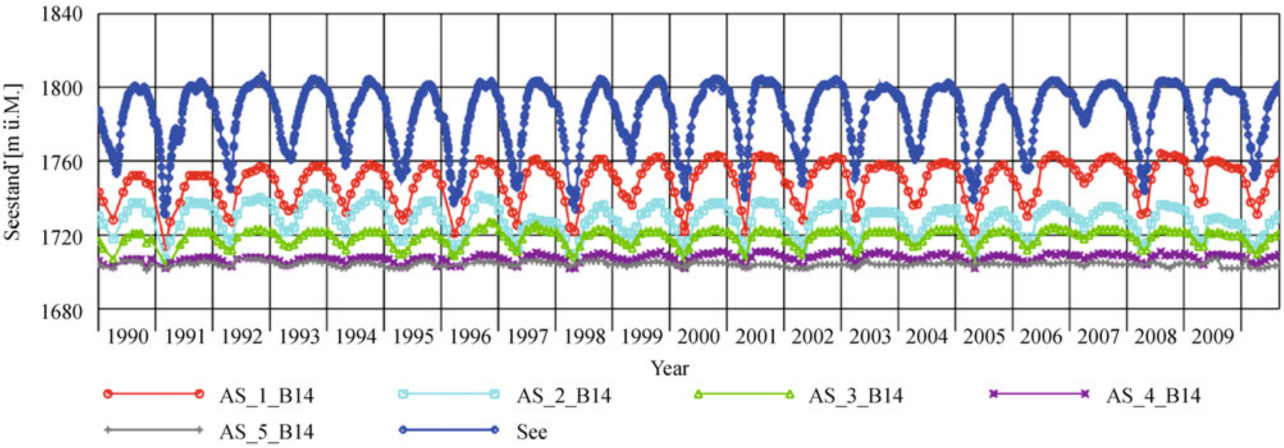

Fig. 6 Long-term uplift measurements in block 14 (Note: The top curve represents the seasonal variation of the reservoir water level)

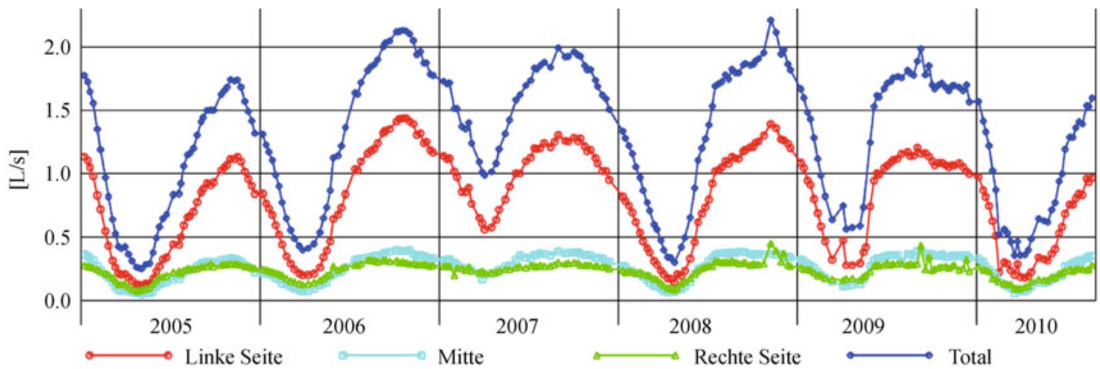

Fig. 7 Time history of the seepage water collected from three zones of the dam, i.e., Linke Seite (left), Mitte (middle) and Rechte Seite (right)

Switzerland to Italy. The drainage water from the road surface is collected in the crest gallery, which has led to the accumulation of dirt in this gallery causing increased maintenance.

Moreover, in some of the wet or temporarily wet vertical block joints, lift joints and old cracks of the control galleries efflorescences are visible as shown in Fig. 10. They may affect the monitoring instruments. However, this is a maintenance issue rather than a dam safety issue. Nevertheless, this is a feature, which can be observed in many concrete dams. Optically these efflorescences are disturbing.

The surface spillway connected to a tunnel has a capacity of 270 m^3/s. It is located on the right abutment (Fig. 11) and the downstream face of the gate is protected by a steel net. In addition, there is a bottom outlet with a capacity of 200 m^3/s. Operation of the spillway and the bottom outlet are also checked annually. In recent years, due to ecological reasons, an artificial flood was created in summer with a peak discharge of 41 m^3/s and 8 h duration. The environmental flow is 1.44 m^3/s. A special hydropower unit is provided to produce electricity from the environmental discharge.

As the catchment area is only 295 km^2, the safety flood is relatively small. Also, since completion of the dam the spillway has been in operation very few times.

5 Conclusions

The main conclusions from the safety inspections of the Punt dal Gall arch dam are as follows:

1) The arch dam built on a rather difficult foundation has behaved well during the past 42 years of operation. No abnormal behavior has been detected by visual inspections and by the analysis of the monitoring data.

2) The dam deformations due to seasonal temperature and water level variations are fully reversible. No long-term changes in the deformations have been observed.

3) Cracks have appeared in the crest gallery and the spillway structure; however, they are stable and are not related to a critical failure mode.

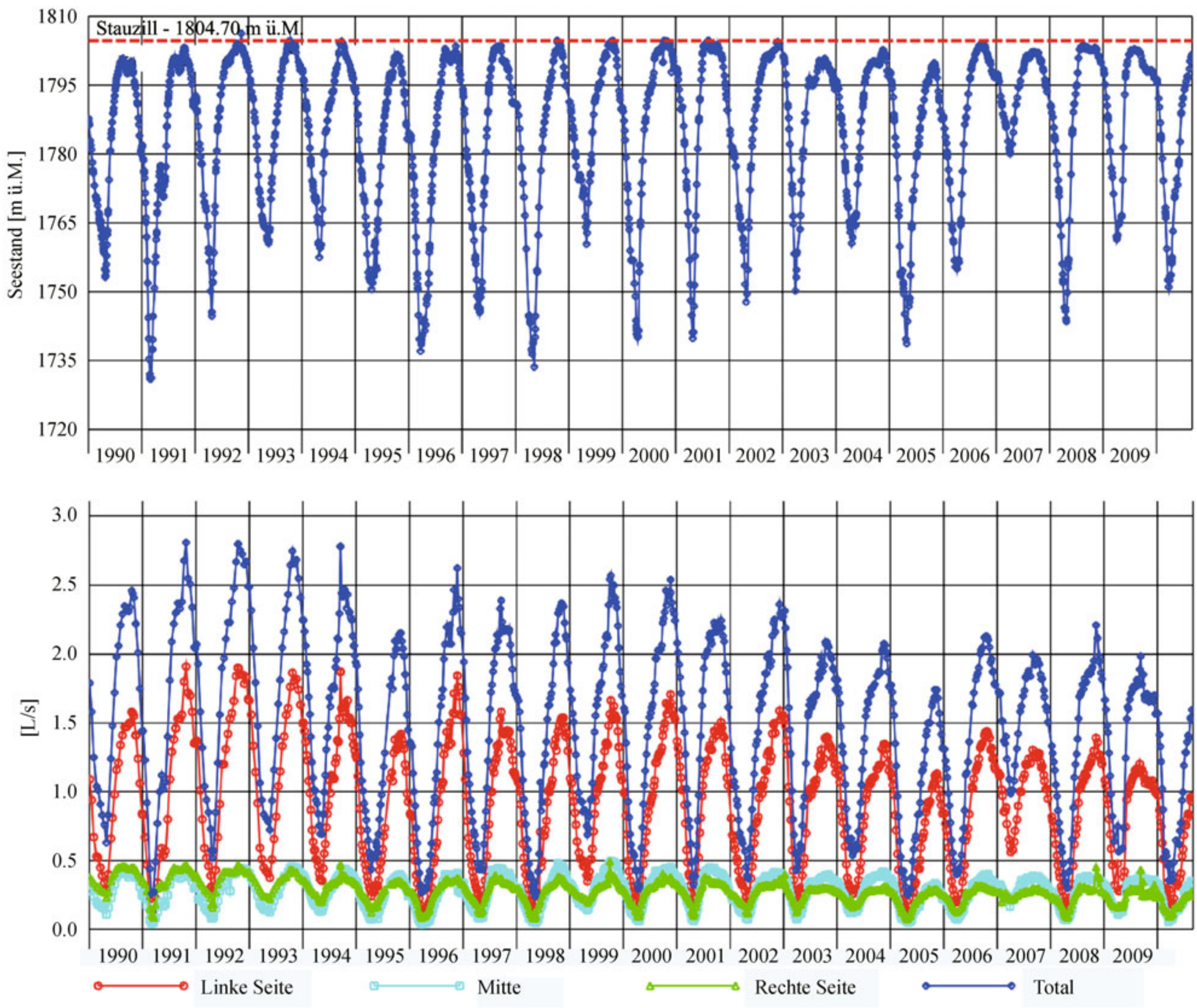

Fig. 8 Long-term record of seepage water collected from three zones of the dam, i.e., Linke Seite (left), Mitte (middle) and Rechte Seite (right)

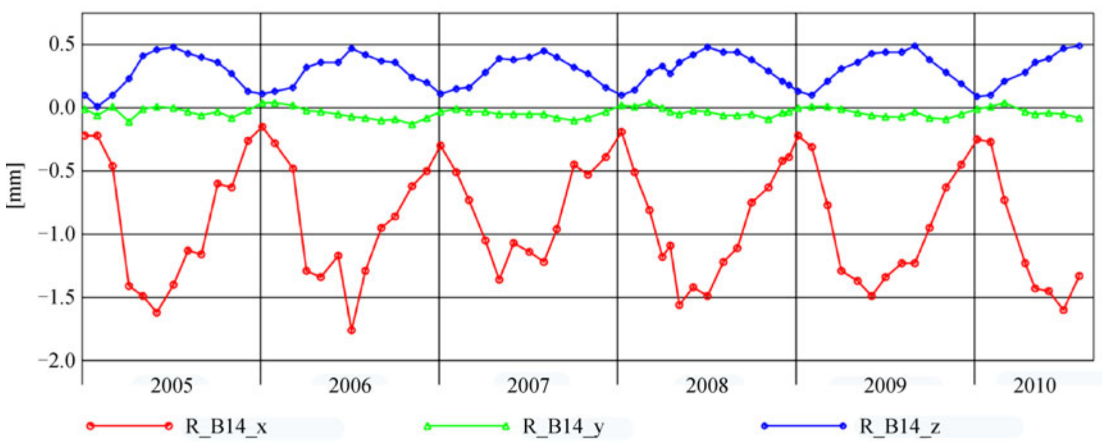

Fig. 9 Crack opening displacement of crack in crest gallery in block 14 as function of time (x: opening displacement; y and z: tangential movements of crack surfaces)

Fig. 10 Efflorescences in control galleries at crack (left) and at joint meter location (right)

Fig. 11 Upstream (left) and downstream (right) view of spillway of Punt dal Gall dam

4) Dam safety inspections are carried out annually by an independent dam engineer and detailed inspections with a dam expert and geologist are carried out every 5 years.

5) Safety evaluations have been carried out or are under way for new flood and earthquake safety criteria, respectively.

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Reference

1. Gilg B. Punt dal Gall Arch Dam, Swiss Dam Technique, Swiss Association for Water Economy, Publication No. 42, Baden, Switzerland, 1970