Distributed Fibre Optic Temperature Measurements in RCC-Dams in Jordan and China

M. Aufleger
Laboratory of Hydraulic & Water Resources Engineering, Technische Universitaet Muenchen, Germany

M. Conrad & Th. Strobl
Institute of Hydraulic & Water Resources Engineering, Technische Universitaet Muenchen, Germany

A.I. Husein Malkawi
Civil Engineering Department, Jordan University of Science & Technology, Irbid, Jordan

Y. Duan
Department of Hydraulic and Hydropower Engineering, Tsinghua University, Beijing, China

ABSTRACT: The paper focuses on an approach of crack potential assessment in Roller Compacted Concrete dams mainly using a extensive temperature measuring system. The fundamentals of the method will be presented as well as three practical examples in Jordan and China including some first results.

1 INTRODUCTION

1.1 *Crack formation and zero stress temperature*

Crack formation in mass concrete significantly depends on the behavior of the young concrete responding to temperatures. To avoid thermal induced cracks, mass concrete has to be optimized with respect to the development of hydration heat, which in turn depends on the concrete mix, the dimensions of the structure, and the sequence of construction. However, development of the material properties of concrete during the first days after its placement is a complex topic, and thermal induced stresses are highly variable throughout a structure.

At first, compressive stress appears due to the thermal induced expansion of volume with restrained deformation, which in the beginning partly relaxes because of the initial low modulus of elasticity. After the maximum temperature is exceeded, a small de-crease of temperature is sufficient to compensate the compressive stress at a now very high modulus of elasticity. The temperature, which then causes a stage of no stress is called zero stress temperature (Mangold 1994; Plannerer 1998; Fig. 1).

A further decrease of the temperature generates tensile stress, which can exceed the tensile strength of the concrete leading to crack building. The higher the zero stress temperature of the concrete and the temperature decrease to an average ambient temperature is, the higher is the resulting potential of thermal induced cracking. The cracks have to be divided in surface cracks and transversal cracks. Transversal cracks will not appear for a long period, as the hydration heat, which increases relatively rapid, in general is flowing off very slowly.

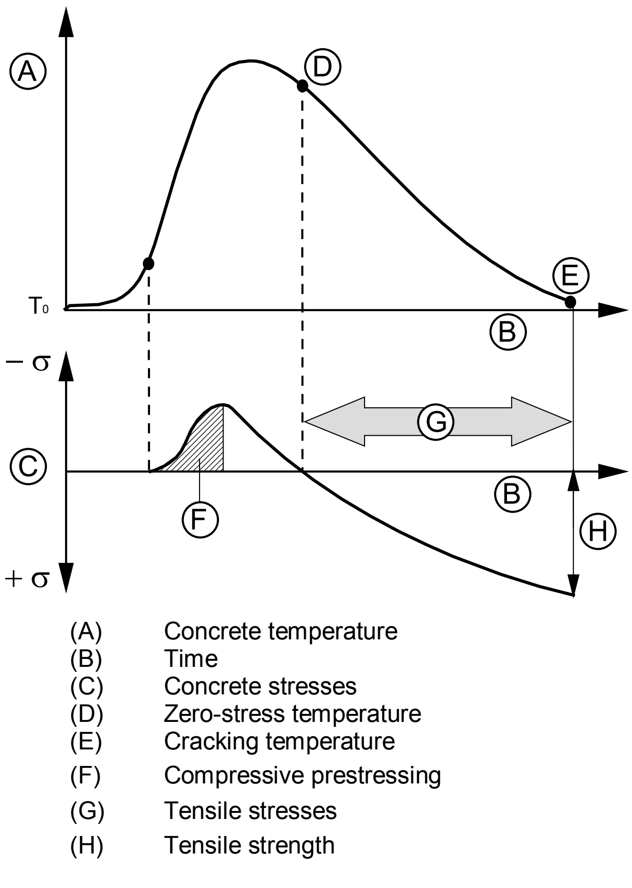

Figure 1. Stresses in young concrete under restrained deformation.

1.2 *Objective of own research work*

Depending on the spatial distribution and the temporal development of the zero stress temperature and the actual concrete temperature thermal induced stresses can be strongly variable over the dam body. The better the temperature development within the dam is known, the more reliable the risk of cracks can be assessed. The actual research work is making use of three tools:

- Extensive temperature measurements.
- Stress measurements at selected locations.
- Numerical analysis considering the early age properties of concrete.

Distributed fibre optic temperature measurements in conjunction with scientific concrete stress measurements enable new detailed investigations about the correlation between the temperature development and the stress states as ruling factor for the crack building in massive construction elements. The measuring results serve to calibrate numerical analysis, which include the stress development of the young concrete. At the end an efficient method for dealing with crack building in mass concrete dam structures should be established in the future.

A key role of this approach is assigned to the assessment of typical zero stress temperature distributions in concrete dams considering different parameters and boundary conditions as

- Concrete properties
- Geometry of the dam including joints
- Speed of construction
- Ambient conditions
- Construction and treatment methods.

Vertical zero stress temperature gradients, especially caused by breaks or extensive interruptions of the concrete pouring respectively, are as likely as horizontal temperature gradients usually caused by the interaction of concrete temperature and ambient temperature. In consequence the zero stress temperature is varying widely over the dam body. Determining typical zero stress distributions for typical parameters and boundary conditions (see above) will lead to an optimization of the structure and the way of construction.

For developing this research work in Roller Compacted Concrete (RCC) dams an international research project, financed by the DFG, which is the central public funding organization for academic research in Germany, is carried out under participation of engineers from Germany, Jordan and China.

2 TEMPERATURE AND STRESS MONITORING

2.1 *Distributed fibre optic temperature measurements*

The development of fibre optic temperature laser radar systems opens up new dimensions in dam monitoring. The technology allows very accurate and economic measurements of temperature distributions along fibre optic cables. Generally, in dam engineering, the demands for structure monitoring are high. Here, a field of various promising applications for distributed fibre optic temperature measurements arises (hydration heat, leakage detection).

Distributed fibre optic temperature measurements (DFOT) allow the reliable determination of temperature distributions in mass concrete. Usually, concrete temperatures are monitored by conventional thermocouples or thermistors, permitting only spot measurements. In contrary, fibre optic cables provide the possibility of continuous inline temperature measurements along the fibre cable integrated into the dam structure.

In terms of any in-situ instrumentation, RCC is not very favourable as high loads are applied to the instruments by heavy earthmoving equipment and other vehicles, involved in the rapid construction process (Fig. 2). Therefore a cable type, featuring high compressive and tensile resistance, was chosen (Fig. 3).

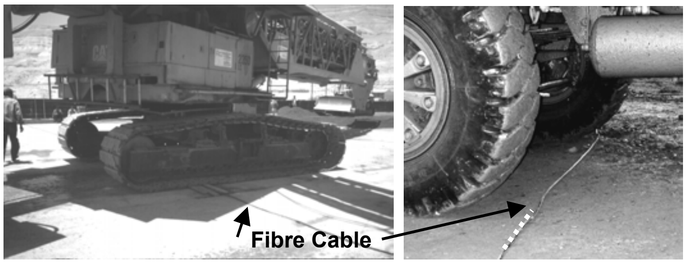

Figure 2. Fibre cable impacts due to on-site equipment.

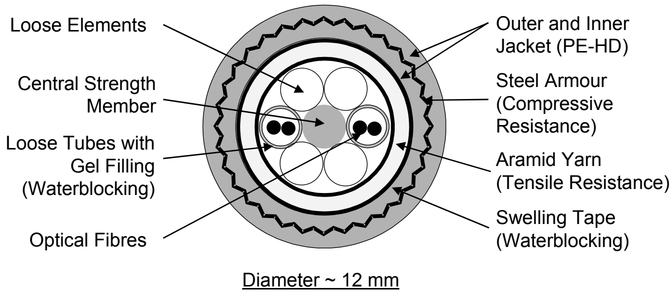

Figure 3. Cable type chosen for Wala Dam and Mujib Dam.

The installation of the fibre optic cables is performed during the continuous RCC placement operation. The cable is laid out and fixed on the desired level shortly before the new RCC layer is covering it. With the up to date experiences it could be proofed, that the installation of the fibre cables can be well integrated into the rapid RCC construction process without causing any delay.

With the so installed measurement system temperatures may be monitored with a spatial resolution of 0.25 m and an accuracy up to ± 0.2 K allowing the detailed visualisation of temperature gradients within the RCC structure. Resulting from the monitored distributed temperature gradients a conclusion in terms of internal restraint or eigenstresses respectively can directly be made.

As part of the spatially distributed temperature development in the dam during construction and operation also the hydration heat itself can be determined, delivering a clear picture of the in-situ concrete maturity in the dam.

As consequence of the above it may be stated, that accurate monitoring of distributed temperatures inside young concrete may also contribute to a better understanding of the evolution of the mechanical properties within a concrete dam. In turn, the improved knowledge about the mechanical concrete properties (elastic modulus, tensile strength, tensile strain capacity) helps as a prerequisite for the determination of distributed cracking potentials.

2.2 *Monitoring of stress histories in mass concrete structures by stressmeters*

Cracks in mass concrete structures in most cases are not caused by external loads but by restraint stresses or eigenstresses (Wiegrink 2002). Restraint stresses occur, when deformations (e.g. thermal or shrinkage) are constrained by internal (temperature distribution) or external (friction, bond) restraints. In contrary to load induced stresses no external deformations are measurable with restraint stresses. When measuring restraint stresses in young concrete the evolution of the elastic modulus of early age concrete as well as aged concrete has to be considered as the modulus changes during hydration and varies over some magnitudes.

Generally restraint stresses can only be estimated and temperature criteria are used to avoid cracking. These often unreliable temperature criteria may possibly be substituted by real stress criteria including also temperature gradient criteria in respect of eigenstresses.

As realistically measuring stresses in young concrete by ordinary stress-gauges with a constant elastic modulus and also strain gages are not suitable Plannerer (1998) enhanced an existing stressmeter (Fig. 4) to monitor restraint stresses even of the early age concrete in real concrete structures. Until recently only structures consisting of conventional vibratable concrete (CVC) were equipped with these stressmeters for one-dimensional stress measurements.

For measuring restraint stresses in concrete it is essential that the stressmeter has the same extensional stiffness as the surrounding concrete. As the elastic modulus of concrete is developing with proceeding degree of hydration, also the stiffness of the stressmeter has to increase in the same scale as that of the surrounding concrete.

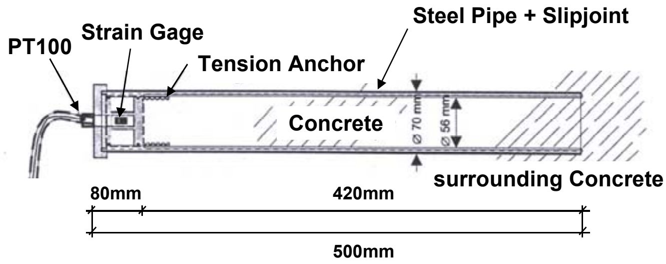

Figure 4. Longitudinal section of stressmeter.

To achieve a satisfying convergence of the extensional stiffness of the concrete and the stressmeter the stressmeter consists of a strain gage of small diameter and a steel pipe filled with concrete. The filled steel pipe decreases the influence of the strain gage on the stress measurements resulting in a systematic error of the stressmeter of less than 5 %. Wiegrink (2002) gives more details about the measurement principle of stressmeters.

As well as for the DFTM also the installation of the stressmeter has to be adopted to the special RCC conditions. In comparison to CVC where compaction of the concrete is easily possible within the stressmeter pipe, the RCC has to be compacted layerwise with a hammer. For the filling of the stressmeter pipe the maximum aggregate was screened off, so, the modified maximum aggregate size was at a 1/3 of the stressmeter diameter maximum. To ensure a good bond between the stressmeter and the surrounding RCC the two stressmeter pipe ends were molded into the RCC by CVC dovetails. After installation the whole area was recompacted by heavy rollers.

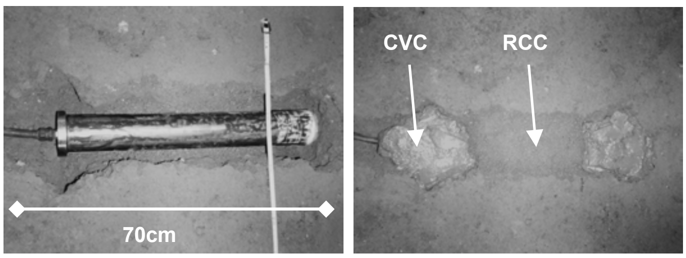

Figure 5. Installation sequence of stressmeters in RCC.

3 DFTM PROJECTS

In summer 1997 a 155 m long fibre cable could be installed in one concrete block of the conventional gravity dam at Birecik in Southeast-Anatolia. This was the first application of DFTM carried out by Technische Universität München (TUM) (Aufleger et al. 2000). In the frame of this paper attention should be turned to three RCC dams in the Hashemite Kingdom of Jordan and the Peoples Republic of China which are objects within the named research cooperation.

3.1 *Wala Dam, Wadi Wala, Jordan*

Wala Dam is owned by the Jordan Valley Authority and situated in the Wadi Wala, about 40 km south of the Jordanian capital Amman. It is designed as a hybrid dam, consisting of a central RCC gravity dam and embankment dams at the abutments. The dam has a maximum height of 52 m with a RCC volume of 221,000 m³. The about 120 m long concrete structure (crest length) is subdivided by transversal joints with a spacing of 15 m. For the RCC mix a medium cementitious content of 120 kg/m³ ordinary portland cement (OPC) and no pozzolan was selected, above 485.0 mASL it was reduced to a cement content of 100 kg/m³. The facings are formed by CVC with a cement content of 200 kg/m³, having a thickness of 0.6 m in average. Bedding mortar between each RCC layer extends in average 5 m from the upstream and 0.7 m from the downstream face.

Figure 6 shows the RCC cross section, the longitudinal and horizontal section of Wala Dam with the levels, measurement sections and the fibre cable layout for the DFTM. Having started in November 2000 approx. 2,500 m of fibre cable were installed until end of April 2002.

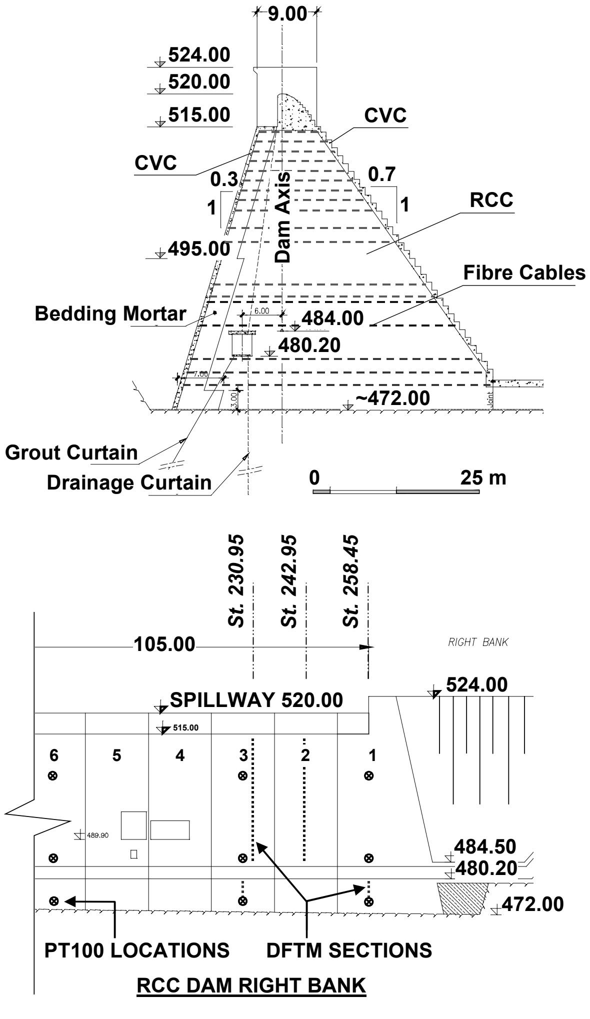

Figure 6. Wala Dam: Cross section and longitudinal section of the right bank

DFTM were performed quasi-continuously from installation of the first cables until to date. First results of the measurements from the project's start until the end of construction of the RCC dam are published in Conrad et al. (2002). Figure 7 represents some exemplary recent temperature distributions at one measurement level of Wala Dam.

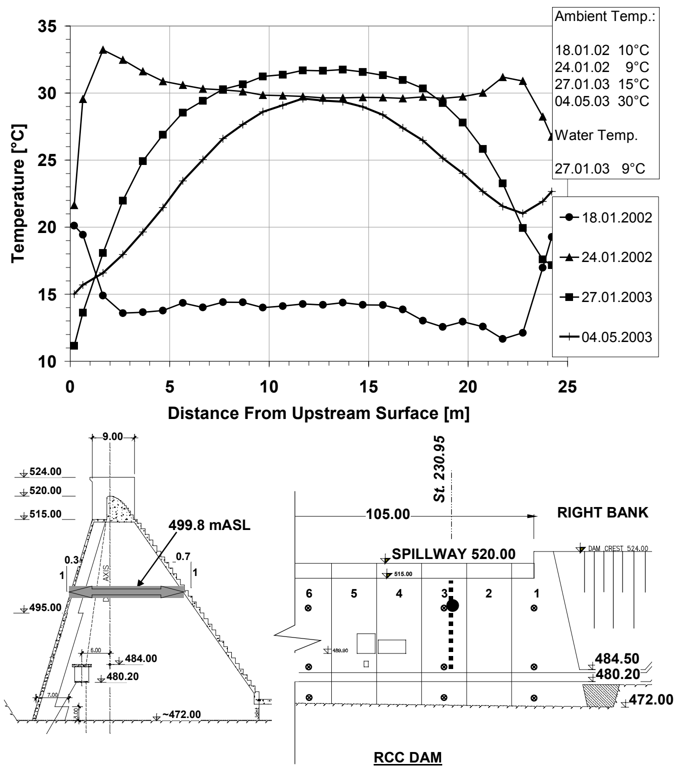

Figure 7. Wala Dam: Selected temperature profiles at block 3, elevation 499.8 mASL.

The displayed temperature distributions reflect the typical thermal behavior of a RCC gravity dam during concrete hydration and cooling of the structure. It is clearly visible that the DFTM enables detailed visualization of such temperature distributions and even of very steep temperature gradients. So, an immediate assessment of crack building potentials is allowed.

3.2 *Mujib Dam, Mujib Valley, Jordan*

In the Mujib Canyon, some 60 km south of Amman, another hybrid dam was currently completed. Mujib Dam, also owned by the Jordan Valley Authority, as well was designed as a central RCC gravity dam with adjacent earth fill dams at the valley flanks. Its maximum height reaches approx. 60 m, the total volume of the RCC structure will be 720,000 m³. RCC mix designation follows a low to medium cementitious content mix with 85 kg/m³ OPC and no pozzolan. At the facings CVC is placed against the shutters with a thickness of 0.3 m. A PVC membrane below elevation 150.0 mASL represents the watertight barrier for the RCC body. Bedding mortar between each RCC layer is spread at the upstream at one third of the dam width and to 2.0 m from the downstream face. A nominal contraction joint spacing of 60 m is applied at Mujib Dam. Only below the gallery these joints extend completely from upstream to downstream, above, they reach from the faces into the mass by one fourth of the dam width.

Figure 8 shows a brief overview of Mujib Dam, containing also the DFTM monitoring system and the stressmeters for in-situ restraint stress measurements. Since February 2001 roughly 4,000 m of fibre cables were installed at Mujib Dam. In total seven stressmeters at two elevations (144.00 mASL, 154.50 mASL) have been located in the dam centre and at the upstream facing.

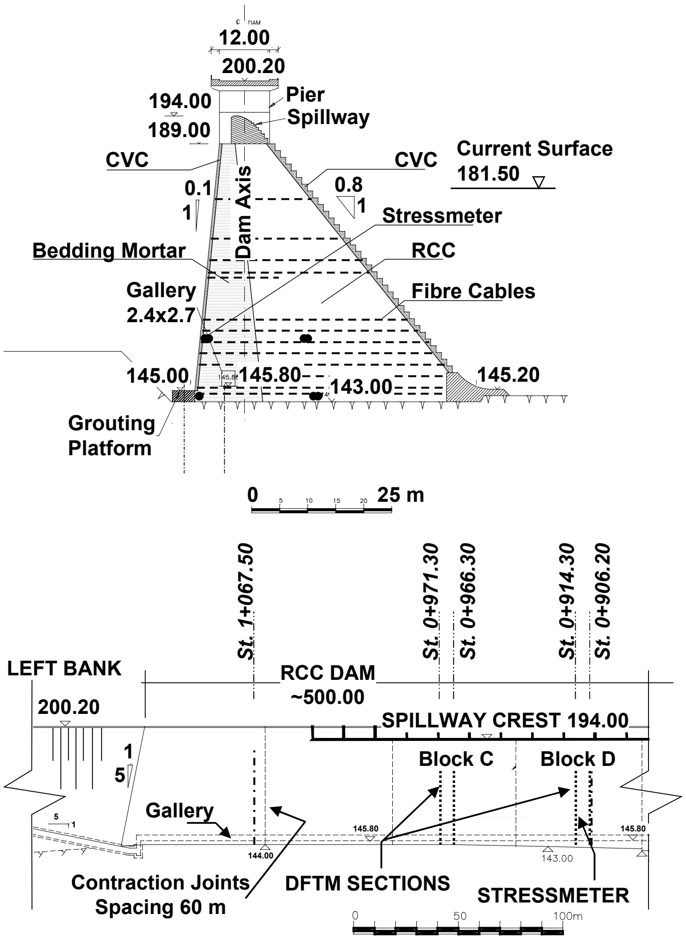

Figure 8. Mujib Dam: Cross section and longitudinal section of the left bank.

Also at Mujib Dam DFTM were taken quasi-continuously from the beginning of RCC placement until to date. Additionally, stressmeter readings were recorded continuously. As first DFTM results were already presented in Conrad et al. (2002) only results from the stressmeters shall be given here.

From the stressmeter recordings some zero-stress-temperatures could already be derived. As cooling of the dam takes place more rapidly at the dam facings, these monitored zero-stress-temperatures accordingly refer to the stressmeters installed in the upstream facing CVC and the close RCC (Fig. 9). The very slow cooling process in the dam centre leads to a much later zero-crossing of the stress path from compression to tension. Again the detailed temperature distribution monitored by DFTM is displayed. With knowledge of the distributed zero-stress-temperatures these DFTM results may directly lead to an idea about a spatial stress distribution in a certain section of the dam.

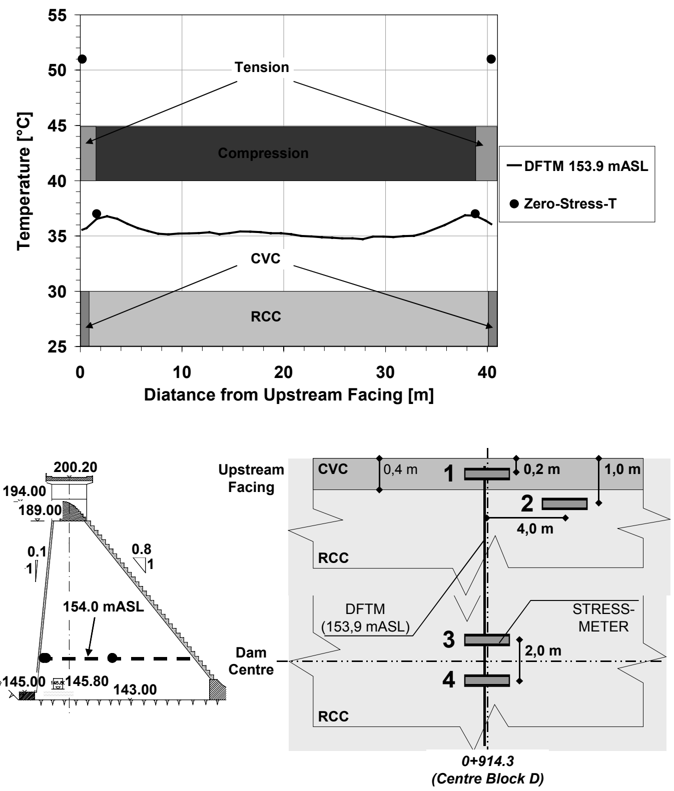

Figure 9. Mujib Dam: Zero-stress-temperature distribution and DFTM at the centre of block D, elevation 154.0 mASL.

3.3 *Shimenzhi Arch Dam, Xinjiang, China*

The Shimenzhi Arch Dam is located near Urumqi in Xinjiang Uygur Autonomous Region in the north-west of China. The multi-centered arch dam was completed 2001 with a final height of 109 m and is so the second highest RCC arch dam in the world behind the Shapai Arch Dam near Chengdu (China). The Shimenzhi Arch Dam is designed as a very slender structure with about 30 m thickness at the base and 15 m at mid-height, exposed to extreme temperature differentials due to the extreme continental climate (Summer: +30 °C; Winter: -20 °C). Because of these considerable temperature changes, strain-stresses will occur with the consequence of high crack building potential. So, the temperature control of the RCC whilst the construction phase plays a big role in order to avoid cracks.

The main part of the Shimenzhi Arch Dam is built of RCC, consisting of 62 kg/m³ cement and 110 kg/m³ of flyash. As a watertight barrier and also for frost resistance the dam facings were cast with CVC consisting of 93 kg/m³ cement, 110 kg/m³ of flyash and magnesiaoxide as additive for compensation of volume contraction. The dam has only one transversal joint at the centre of the arch and additional short joints at special locations. For the prevention of too steep temperature gradients and the resulting risk of cracking, the reservoir of Shimenzhi Dam was partially impounded during construction time in winter, additionally an insulating coating was put on the exposed facings. Figure 10 presents the dam and the accomodated fibre cables, of which approx. 300 m were installed in May and August 2000.

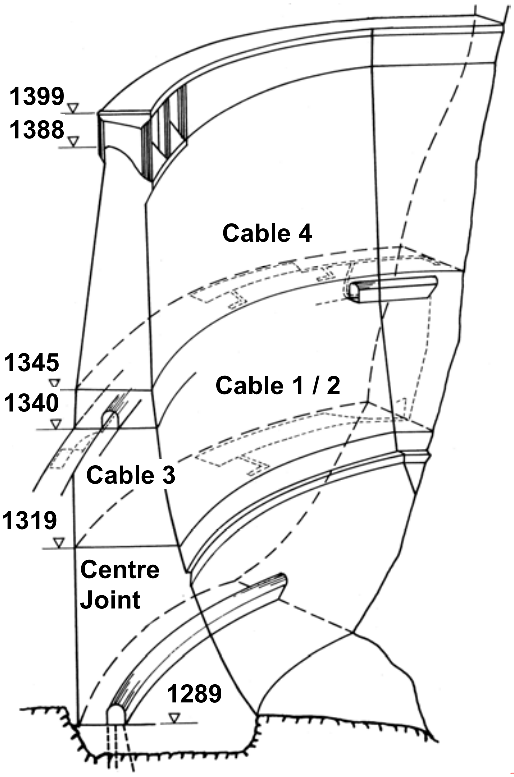

Figure 10. Isometric illustration of Shimenzhi A[redacted]m.

The evaluation of the measurements at Shimenzhi-Arch-Dam show various comprehensible effects, which prove the suitability of DFTM applied in RCC.

Due to the higher cement content of the CVC facings compared to the RCC core the temperatures

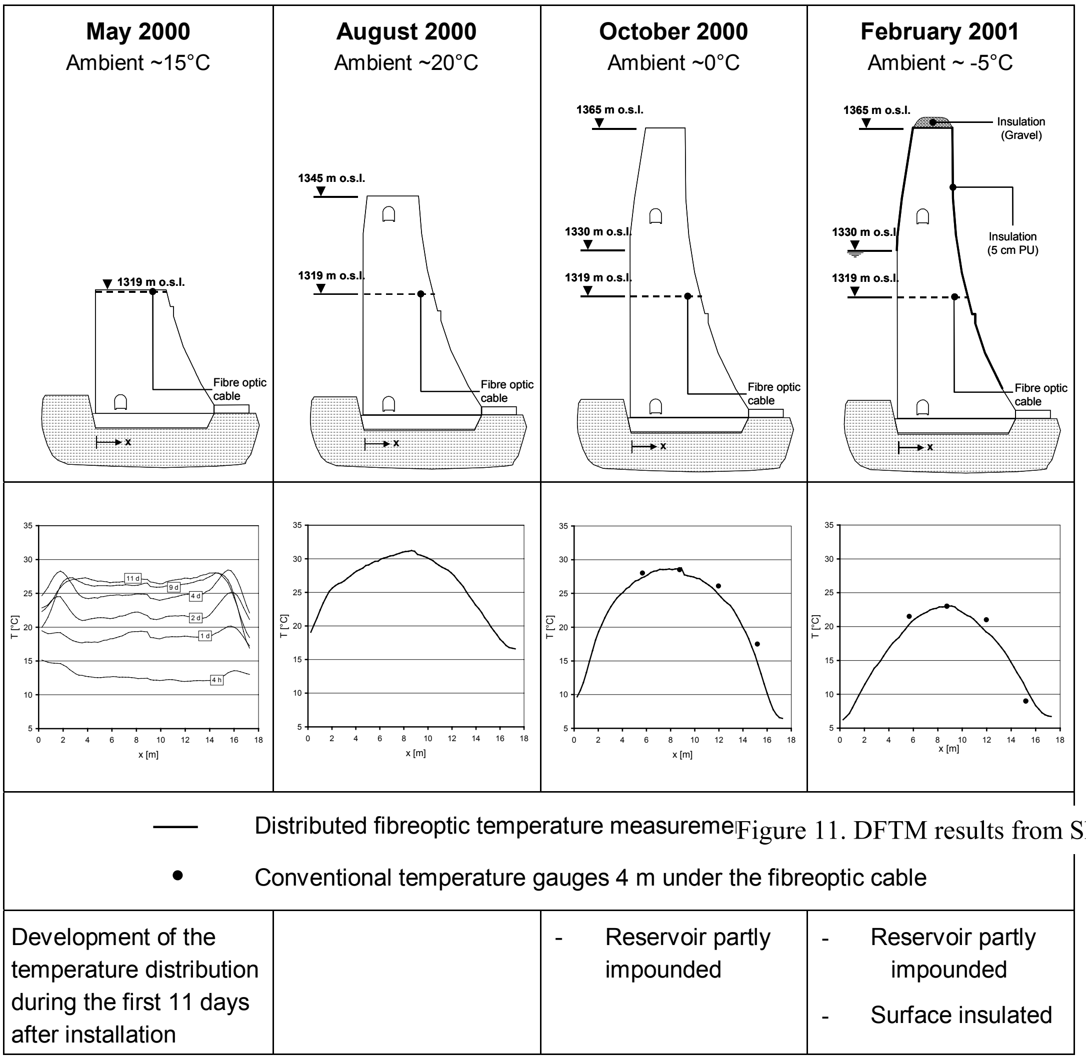

Figure 11. DFTM results from Shimenzhi Arch Dam.

rise much quicker in the CVC. This development is decelerated after around 4 days due to natural and artificial cooling effects (see May 2000, Fig. 11). The maximum temperature in the RCC is not reached until several weeks, showing the considerable retarded hydration by the present flyash. After 6 months the temperature in the RCC is already decreasing, however, during approaching of winter time steep temperature gradients occur at the dam facings, which could be perfectly monitored by DFTM.

4 CONCLUSIONS AND SUMMARY

Distributed fibre optic temperature measurements are a new and powerful monitoring system for concrete dams allowing a detailed temperature control based on very accurate linear measurements of distributed temperatures along a fibre cable. This measurement system proofed its suitability even under the harsh site conditions of RCC dam sites, where it has to be installed during the rapid construction process being

exposed to high vehicle and compaction loads.

Three applications of the distributed fibre optic temperature measurements in RCC dams are presented in the paper. Wala and Mujib gravity dams in the Hashemite Kingdom of Jordan and Shimenzhi arch dam in the Peoples Republic of China are objects within an international research project bringing together engineers from Germany, Jordan and China. This research projects aims at the in depth analysis of the thermal behavior of RCC dams in respect of thermal crack building potentials by detailed and quasi-continuous temperature monitoring, in-situ restraint stress measurements (stressmeters) and numerical analysis. In the frame of this research project Wala and Mujib dams became the most comprehensive DFTM equipped dams in the world up to date, also stressmeters were applied in RCC for the first time.

DFTM enable the visualization of detailed temperature distributions, allowing to assess various influences on the thermal behavior of RCC dams. In conjunction with the knowledge of distributed zero-stress-temperatures monitored by restraint stress gages (stressmeters) it is so possible to determine thermal stress distributions along certain sections in the dam. This in turn allows the better evaluation of present cracking potentials in the dam.

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