

Full Automatic Leakage Detection at Ilisu Dam by the Use of Fibre Optics

Jürgen Dornstädter - Geophysicist, **Axel Fabritius** – Geophysicist

Philipp Heidinger - Geophysicist

GTC Kappelmeyer GmbH, Heinrich-Wittmann-Straße 7a, D-76131 Karlsruhe, Germany

Email: dornstaedter@gtc-info.de, fabritius@gtc-info.de, heidinger@gtc-info.de

Tel.: +49-721-60008; Fax.: +49-721-60009

Summary

The leakage detection system at Ilisu dam using fibre optics is based on distributed temperature sensing and the heat-pulse method. The sensing element of the method is a fibre optic cable, which is installed along sensitive points of the dam, i.e., along the perimeter joint and selected CFRD block joints.

The system comprises a fibre optic cable, which is placed beneath the perimeter joint on its entire length and additionally beneath selected expansion joints on the steep left dam abutment. The permanently installed DTS and additional auxiliary electronic equipment allow for a fully automatic monitoring of the dam. The system will monitor the status of the dam and trigger alarms at predefined status changes.

Further, the curing temperature has been monitored using distributed fibre optic temperature sensing in one concreting block. A mathematical model has been adapted to predict the temperature.

1. Introduction

The Ilisu Dam – still under construction - is located on the Tigris River in Turkey, about 15km east of Mardin, Dargeçit. After completion it will be the 4th biggest energy producing dam in Turkey. The installed capacity is 1200MW. The dam is a concrete faced rock-fill dam with a maximum height of 135 m, a crest length of 1820 m, crest width 15m and a total dam embankment volume of 43.000.000m³. Its effective storage capacity is 10.60 hm³.

The instrumentation of the dam comprises piezometers, total pressure cells, hydraulic settlement cells, accelerometers, soil and magnetic extensometers, inclinometers, joint meters, strain gauges and weirs for measuring the amount of seepage water as well as other devices. Complementary to the conventional instrumentation, a leakage detection system based on distributed fibre optic temperature measurements was installed.

There are three approaches to detect seepage. The first approach, a passive approach – using temperature probes or simple fibre optic sensing cables - is based on absolute temperature changes within the body of the dam caused by seepage water. This method is limited to cases with a temperature gradient between the seepage water and the dam material. Nevertheless, the method is often an invaluable seepage indicator.

To surpass this limitation the second approach is used – the heat-pulse method or temperature difference method. It is referred to as an active method. In praxis this method is mostly used in combination with fibre optic hybrid sensing cables. By heating the fibre optic sensing cable, cable sections within zones of higher water saturation or even flow zones appear as sections with increased heat transport, i.e. they heat up less. By calculating the temperature difference between the measurements before the start of the heat-pulse and at the peak of the heat pulse, zones of seepage become clearly visible.

The third approach is the calculation of effective thermal conductivities along the cable. The method is an advancement of the heat-pulse method. In case of seepage the approach yields zones of increased effective thermal conductivities.

Both, the temperature difference and the effective thermal conductivity are sensitive methods to measure seepage or changes in the saturation level of the ground. Especially if both methods are combined they constitute a highly effective and sensitive tool to detect and permanently monitor seepage in large dams.

The first technique, especially with the use of temperature probes, has been developed to measure in-situ temperatures at different depths (up to 30-40 m) within existing embankment dams [2]. The second and third approach - the temperature monitoring along optical fibres has been designed for fast and convenient recordings of the temperature distribution in dams of any composition and geometry in which optical fibres have been included during construction or rehabilitation.

Further, a test has been started to monitor the curing temperature of concrete by means of distributed fibre optic temperature measurement in one of the concreting blocks. The aim is to get more and detailed information about the temperature development and additionally to possibly predict the further temperature development using an initially measured data set.

2. In-situ fibre optic temperature measurement techniques

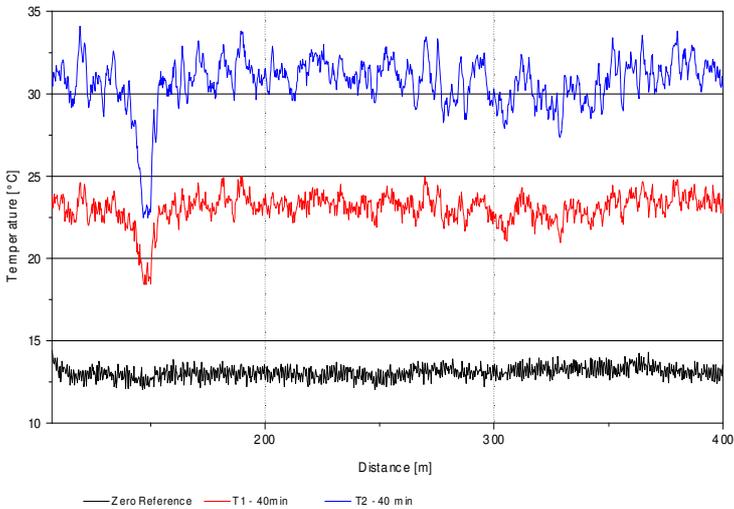
2.1 Distributed temperature sensing with fibre optics

Fibre optic temperature sensing operates by sending a short laser pulse (< 10 ns) into an optical fibre. The backscattered light is analysed with Raman spectroscopy, providing Stokes and anti-Stokes intensities. The ratio of Stokes to anti-Stokes intensities is proportional to the temperature at the reflexion point (equals the measuring point). The localisation of the measuring point is the distance along the fibre calculated from the duration the backscattered light needed and the velocity of light. The method provides a temperature profile distributed along the entire optical fibre.

The distributed fibre optic temperature sensing method enables high resolution temperature measurements along a conventional optical fibre of up to 30 km of length. This method is suitable for the surveillance of dams, dikes and other hydraulic structures. The integration of optical fibres in the structure of new constructions or within the scope of renovation and repair works provides the exact localisation of emerging leaks by temperature monitoring along the inexpensive fibre optic cable.

In the scope of repair works, optical fibres are often installed right behind sealing devices where the temperature shows no difference to the temperature of the retained water. For such situations the optical fibre has been enhanced by an electrical wire in order to generate a heat

pulse in the vicinity of the cable. If both, the optical fibres and the electrical wires, are combined within the same cable, the cable is referred to as a hybrid cable. The installation of hybrid cables provides fibre optic temperature measurements while the cable is heated (see heat pulse method, HPM, next paragraph). The electrically induced heat is dissipated at locations of seepage or increased flow and the temperature along the fibre does not increase as much as at places where no flow exists (see Picture 2.2.1). Leakage detection using HPM is thus independent of the temperature gradient between retaining water temperature and the dam temperature.



Picture 2.2.1 Temperature measurements along optical fibres at different times of heating, showing distinct seepage zones

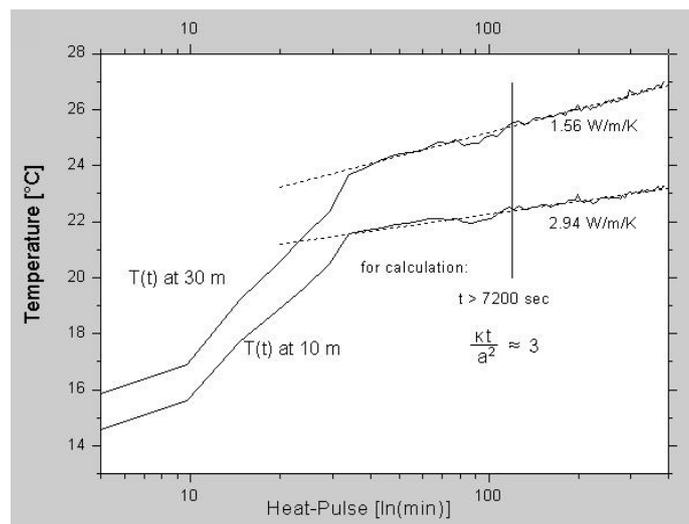
The fibre optic sensing method was first applied in 1996 [3]. Since then, worldwide more than 180 km of hybrid cables were considered in the scope of many new constructions and rehabilitation works as a continuous surveillance device or for occasional inspection [4]. Furthermore, a more elaborate analysis of HPM reveals an estimation of pore velocities.

2.2 Heat Pulse Method (HPM)

The heat pulse method has been developed to measure local in-situ thermal conductivities and to estimate pore velocities of seeping water in existing earth fill dams and in the foundation. This method is based on generating a well defined heat disturbance of the ground represented by a line heat source. The line heat source is most easily realised with electrical wires.

In 1991 the line heat source was combined with temperature probes, i.e. electrical wires were inserted into the hollow tubes in addition to the chain of temperature sensors. In combination with optical fibres, HPM was first applied in 1998 [4].

As soon as the heat source has been switched on, the temperatures within the measuring device rise quickly and in the case of pure thermal conduction they will increase constantly on a logarithmic time scale (see Picture 2.3.1). In the case of convection, provided by a seepage flow, the temperatures tend towards some asymptotic value – the final temperature. According to its thermal conductivity, the material surrounding the temperature measuring device dissipates the induced heat. The larger the pore velocity is, the larger the heat dissipation, i.e. the lower the final temperature. A similar phenomenon is observed when switching off the heat source (relaxation). No fluid flow generates a slow cooling process and the undisturbed ground temperature is reached after a long time. An existing fluid flow results in a fast adaptation to undisturbed ground temperatures.



Picture 2.3.1 Temperatures versus time at different depths within a vertical probe as a result of HPM Both temperature adaptation processes (heating and relaxation) are used

for the determination of thermal conductivities of the material at the temperature measuring point. Thermal conductivities of soil and construction material range between 0.8 and 4.5 $\text{Wm}^{-1} \text{K}^{-1}$. Thermal conductivities exceed by far these values when fluid flow occurs and they are then proportional to flow velocities. The heat pulse method offers thus the facility to estimate qualitatively pore velocities from ground temperature surveys.

The theoretical interpretation of temperature surveys undertaken with the heat pulse method is described in [5].

The penetration into the soil or construction material of the temperatures induced with HPM depends on the duration of heating, the strength of the heat source and on the flow velocity. The ongoing development of HPM envisages a more accurate estimation of pore velocities. The approach of pore velocities as described above has been applied in temperature probes in embankment dams and along hybrid cables.

The opposite method of HPM is the frost pulse method. On sites without electrical supply, velocity estimations are technically feasible by cooling the tubings of temperature probes instead of heating them. Temperature surveys are monitored while cooling the tubes with liquid CO₂. Similar to HPM, the evaluation of data obtained with the frost pulse method reveals a qualitative estimation of the pore velocities.

3. Application example

3.1 Knezovo Dam

Situation

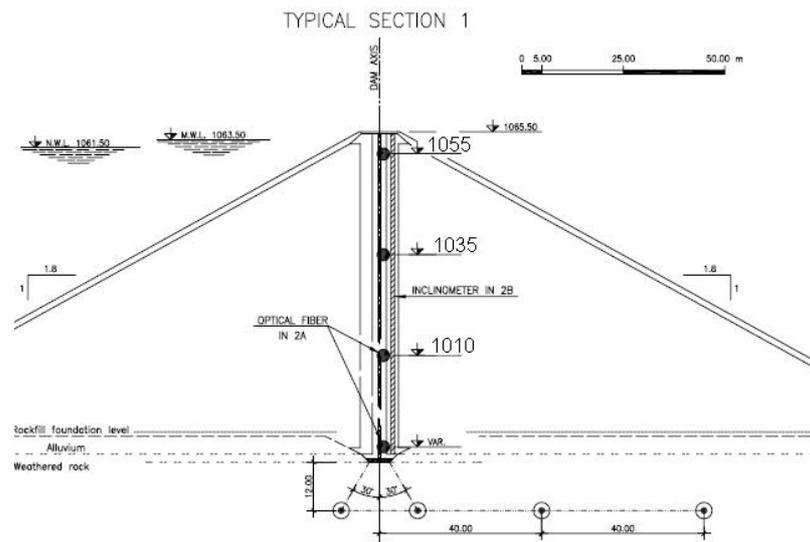
The Knezovo Dam is located in the upper stream of the Zletovica River, about 80 km east of the Macedonian capital Skopje [6]. It is the main element of the Zletovica Basin Water Utilization Improvement Project with the purpose of water supply, irrigation and power generation. The Knezovo Dam (pict. 3.2.1) is an asphalt core rock-fill dam with a maximum height of 83 m, a crest length of 270 m and a total dam embankment volume of 1,700,000 m³. The effective storage capacity is 22,500,000 m³. The instrumentation of the dam consists of piezometers, total pressure cells, extensometers and weirs for measuring the amount of seepage water as well as other devices. Additionally to the conventional instrumentation, a leakage detection system based on distributed fibre optic temperature measurements was installed.



Picture 3.2.1 Knezevo Dam during construction (July 2010)

Layout

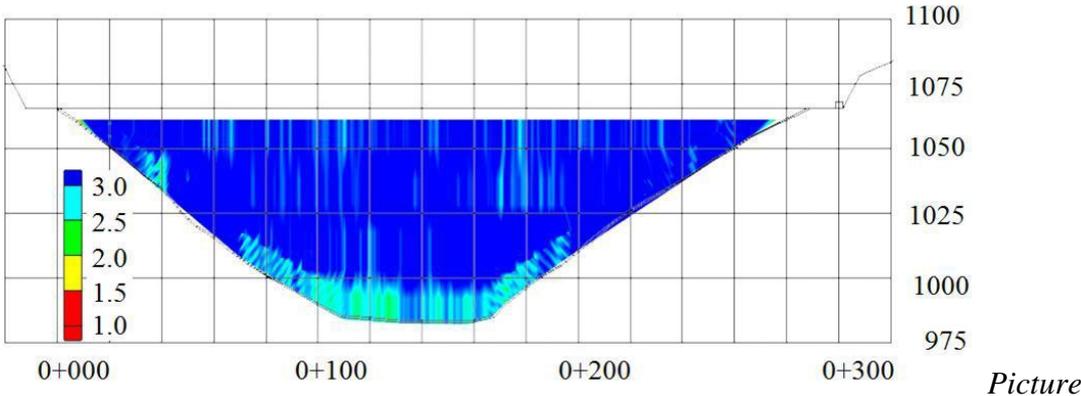
According to the design, the fibre optic cable for leakage detection runs in the direction of the dam axis along the interface between the asphalt core and the foundation and at el. 1010 m.a.s.l., el. 1035 m.a.s.l. as well as el. 1055 m.a.s.l. (pict. 3.2.2). Overall, about 1.5 km of fibre optic cable was installed. The cable was placed in the drainage and transition zone downstream of the asphalt core. The instrumentation house is located on the right bank above the dam crest, and provides all necessary facilities, such as a power supply and internet connection, to operate the system automatically. The specified heat input is 8 W/m cable.



Picture 3.2.2 Fibre optic cable position with respect to the asphalt core

Measurement Results

To evaluate the change of seepage conditions in the dam due to impounding of the reservoir and during operation of the dam, reference measurements before filling the reservoir are necessary. The reference measurements were carried out when the impounding of the reservoir was started (14-7-2010). The obtained temperature differences are shown in Picture 3.2.3.



3.2.3 Reference measurement – temperature differences before impounding In most parts of the dam the results of the reference measurement show no anomalies. Only at the lowest part of the dam the temperature differences do indicate that the material around the cable is saturated or minor percolation is present. In general, the variations of the temperature differences are mainly caused by different thermal conductivities of the surrounding soil material. The thermal conductivity of a soil depends, among others, on mineralogical composition, the bulk density and the water content.

A leakage simulation test was carried out to check for proper operation of the installed system. For this purpose a water tank was placed at the dam crest and the amount of seepage was adjusted to approximately 0.15 l/s to prove the sensitivity of the system. Water was infiltrated at two different points. The infiltration at the first location was started at 9:45h and lasted for about 3 hours. Since it was assumed that the infiltrating water flows along the slope, infiltration was started at a second point at 13:30h. This infiltration lasted for about 5 hours.

Picture 3.2.4 shows significant anomalies at the right slope between el. 1025 and el. 1050 which are caused by the infiltration at the first point. As already anticipated during the test, the infiltrating water runs off the slope causing an anomaly between St. 235 and St. 250, which, in turn, increases with continuing infiltration. Further temperature anomalies are observed at the lower part of the dam, especially around St. 120. The anomalies intensify

during the measurements. Both time characteristics and position suggest that the anomalies are caused by the increase of water level due to impounding of the reservoir.

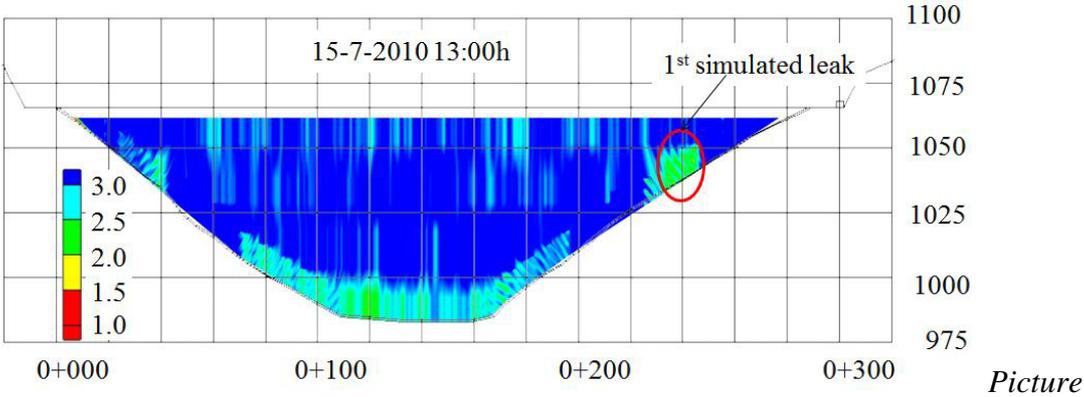


Fig 3.2.4: Leakage Simulation – temperature differences show anomaly caused by infiltration

The operation of the fully automatic online leakage monitoring and detection system was commissioned in August 2011. For easy surveillance the application is browser based. The online application shows the status of the fibre optic leakage detection system.

4. Description of the Full Automatic Leakage Detection at Ilisu Dam

Once completed the dam monitoring will cover the perimeter joint and selected CFRD block joints.

The fibre optic cable will run from GS2 through a calibration tank to dam station 0+600m down to the toe (within the joint) of the CFRD dam and from there underneath the copper stop between the plinth and the CFRD (see figure 4.2) up to dam station 1+980. From there the cable runs within the joint of the adjacent concreting blocks to the crest.

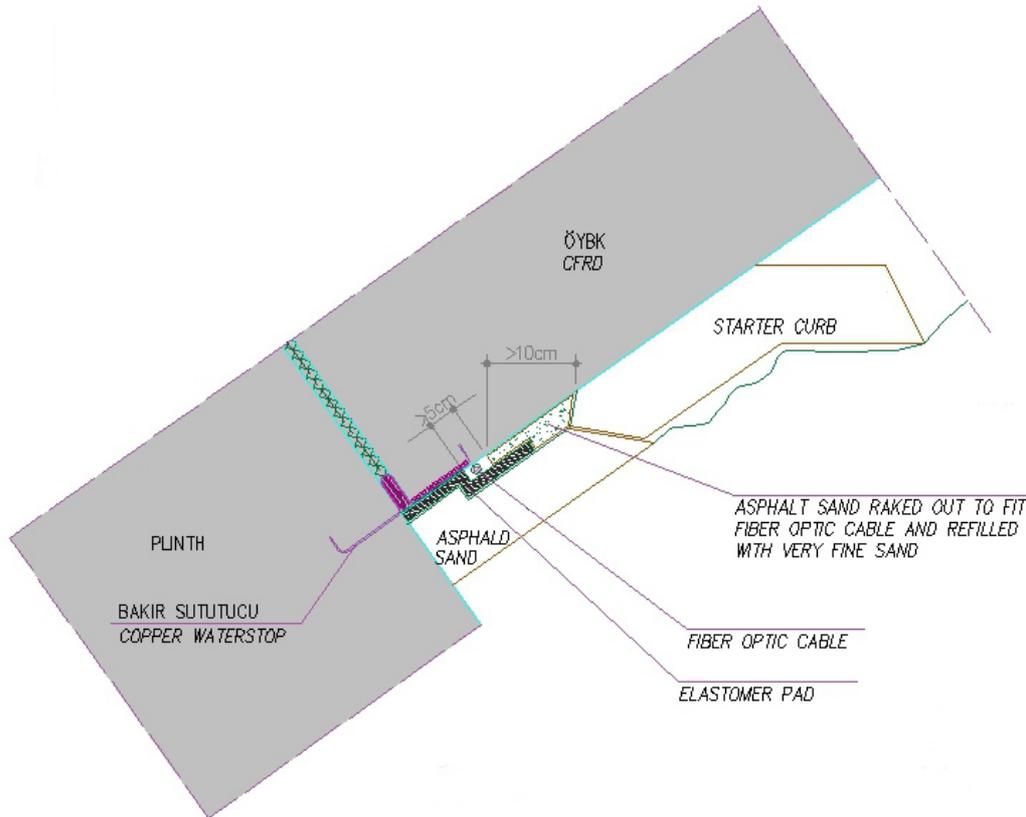


Fig. 4.2: Position of the fibre optic cable along the perimeter joint: The cable is deployed within fine sand underneath the copper stop.

From dam station 2+360 the cable is lead to GS1.

To avoid damaging the cable, it is laid in uniform sand ($CU \leq 2$) with a maximum grain size of 2 mm to 5 mm as cushion material.

Prior to the impounding a T_0 reference measurement and an in situ leak simulation will be performed. In order to maintain measuring accuracy and to obtain a reference value, a reference section is located at the beginning of the measurement section. The reference section consists of approximately 10 m cable placed in a water tank and is monitored permanently with a PT-100 Sensor.

After the dam completion the fibre optic leakage detection system will be finalized. It will run in a fully automated mode. Customized software will control the system and will provide – if desired – online access to the live status of the dam and trigger alarms at predefined status changes. The status changes are based on all three leakage detection approaches: the gradient method, the Heat-Pulse method and the determination of effective thermal conductivities.

5. Monitoring of the concrete curing temperature

We have developed a function of the curing heat development. The measured data can be used to determine parameters of this analytical function, which represents with best accuracy the measured data (method of least squares). Then this function with the defined properties can be used to predict the temperature evaluation.

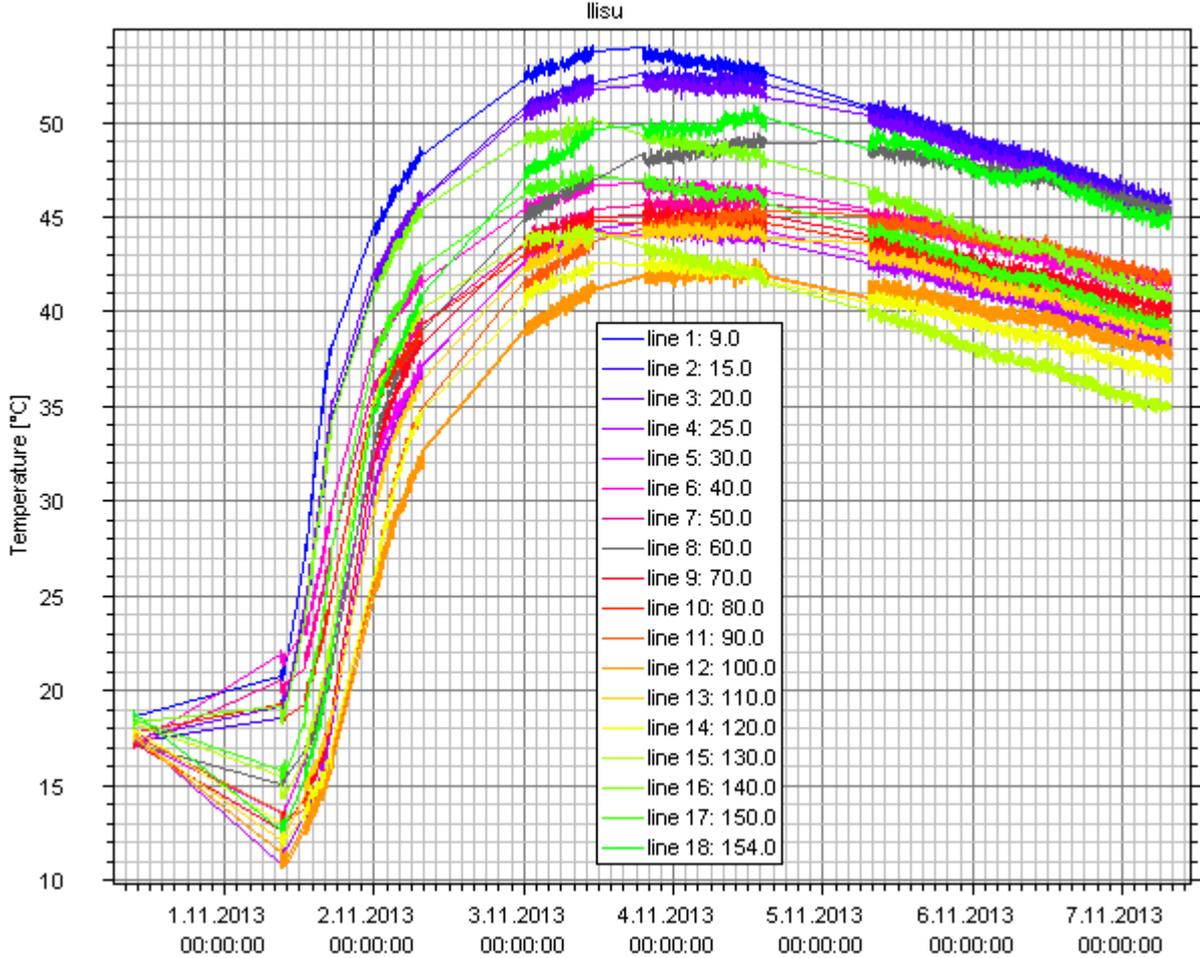


Fig. 5.1: Selected temperatures of the Ilisu dam

Figure 5.1 shows a selection of the measured data. At fibremeter 9 (blue line, must be somewhere at the beginning of the concrete area) there is a very high heat development, but because it's near the border of the concrete the cooling will be relatively faster. At fibremeter 60 (grey line), there is the longest duration of temperature increase within the measured data. These both representing coordinates were used for a calculation of temperature development using the analytical function.

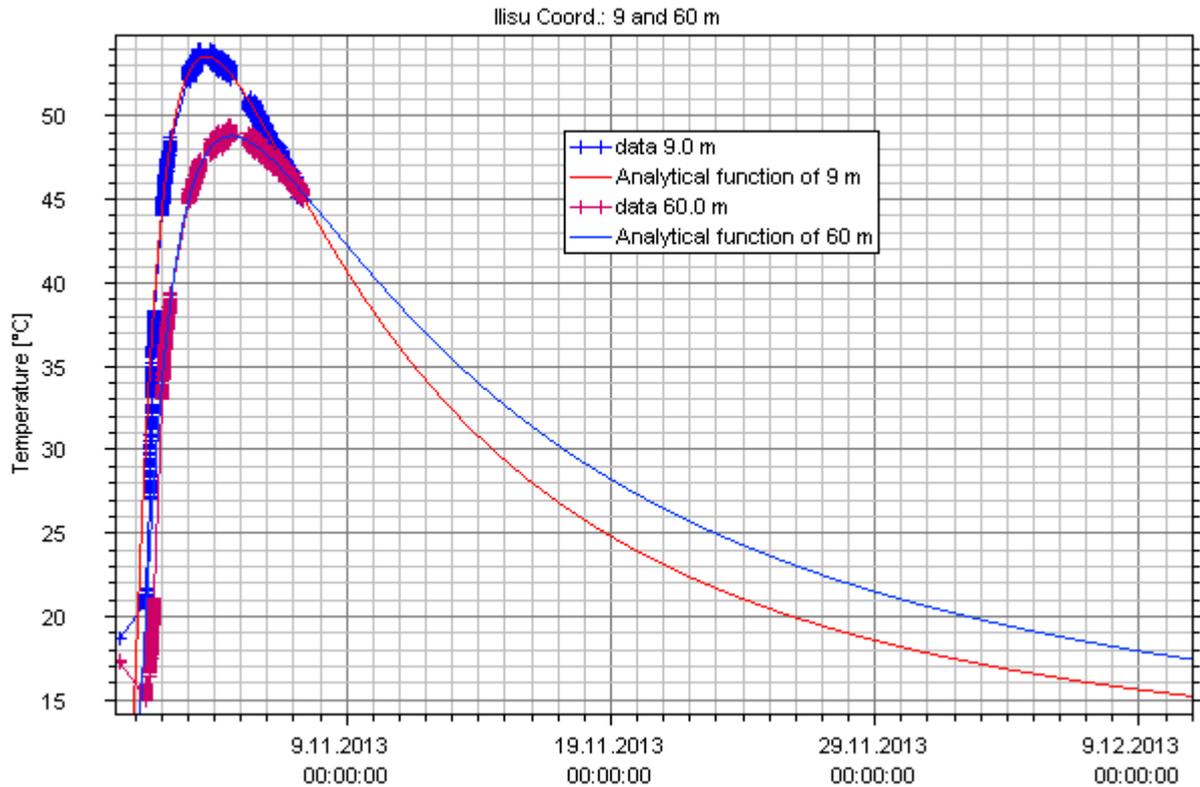


Fig. 5.2: Fit of the function to the data and prediction of concrete curing temperature evaluation

The results are displayed in figure 5.2. Temperature prediction was done for a little more than 1 month. At the prediction fibremeter 9 has a faster cooling and 30°C will be reached already at 14.11.2013 on midday. Whereas fibremeter 60 will need 3 days more to cool down to 30°C (17.11.2013 in the morning hours). As a result prediction of the temperature evaluation can be done. This is possible for all fibre elements within the concrete. This helps optimizing the planning of the construction.

6. Conclusion

In situ temperatures measurements, in the form of temperature probing or distributed fibre optic temperature sensing constitute a powerful tool for seepage detection and seepage monitoring. The method and its enhancements, such as the Heat Pulse Method, have served successfully as a leakage investigation and seepage monitoring tool for more than 100 dams and 500 km of embankments throughout the world. The curing temperature of a concreting block can be predicted, this helps planning the construction. Upon completion the Iisu dam

will be the biggest CFRD dam with a permanent fully automatic fibre-optic leakage detection system.

7. References

[1] Kappelmeyer, O. (1957). The use of near surface temperature measurements for discovering anomalies due to causes at depth. *Geophysical Prospecting*, The Hague, Vol. 3, pp. 239-258.

[2] [Dornstädter, J. (1997). Detection of internal erosion in embankment dams. *ICOLD*, Florence.Q.73R.7. 2: 87-101, International Commission on Large Dams, Paris.

[3] Aufleger, M., Dornstädter, J., Fabritius, A., Strobl, Th.(1998). Fibre optic temperature measurements for leakage detection - applications in the reconstruction of dams. 66th *ICOLD* annual meeting, New Delhi, pp. 181-189, International Commission on Large Dams, Paris.

[4] Aufleger, M., Dornstädter, J., Strobl, Th., Conrad, M., Perzmaier, S., Goltz, M. (2007). 10 Jahre verteilte faseroptische Temperatur-messungen im Wasserbau. 14. Deutsches Talsperrensosymposium/ 7th *ICOLD* European Club Dam Symposium, pp. 8 14, Freising.

[5] Carslaw H.S., Jaeger I.C. (1959): *Conduction of heat in solids*. Oxford University Press, London, 2nd ed.

[6] Aufleger, M., Goltz, M.; Dornstädter, J., Mangarovski, O., (2011): Distributed fiber optic temperature measurements in embankment dams with central core – new benchmark for seepage monitoring. 79th *ICOLD* Annual Meeting, Lucerne.