LEAKAGE DETECTION IN DAMS – STATE OF THE ART

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ABSTRACT

Internal erosion is one of the most frequent reasons of failure and deterioration of embankment dams. Internal erosion is controlled by construction properties (e.g. filter and drain design, grain and pore sizes) and hydrodynamic conditions within the dam. While construction properties are usually known, poor information is available on the local hydrodynamic situation inside the embankment. Hydrodynamic parameters vary strongly inside the dam due to local inhomogeneities and the most critical hydrodynamic parameter inducing internal erosion (material transportation phenomena) is the pore velocity of the seeping water. The onset of internal erosion starts at low pore velocities. Thus a method for the detection of seepage zones of low pore velocities can prevent the development of damages.

The existence of reliable methods for the detection of internal erosion is indispensable to anticipate the failure of embankment dams.

Using the temperature of seepage water as a tracer, applied to dams since 1953, has demonstrated to be a reliable method to detect and monitor in-situ the seepage flow conditions, even at extremely low velocities, i.e. detecting internal erosion at an early stage of development. Nowadays it is even used to estimate the leakage rate. The paper demonstrates how to measure in-situ ground temperatures along an array of temperature probes and alternatively along optical fibres – passive and active method. Examples from a dam along the Danube will be given as well as a description of the automatic operated permanent fibre optic leakage monitoring system of the Knezevo Dam in Macedonia.

1. Introduction

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.

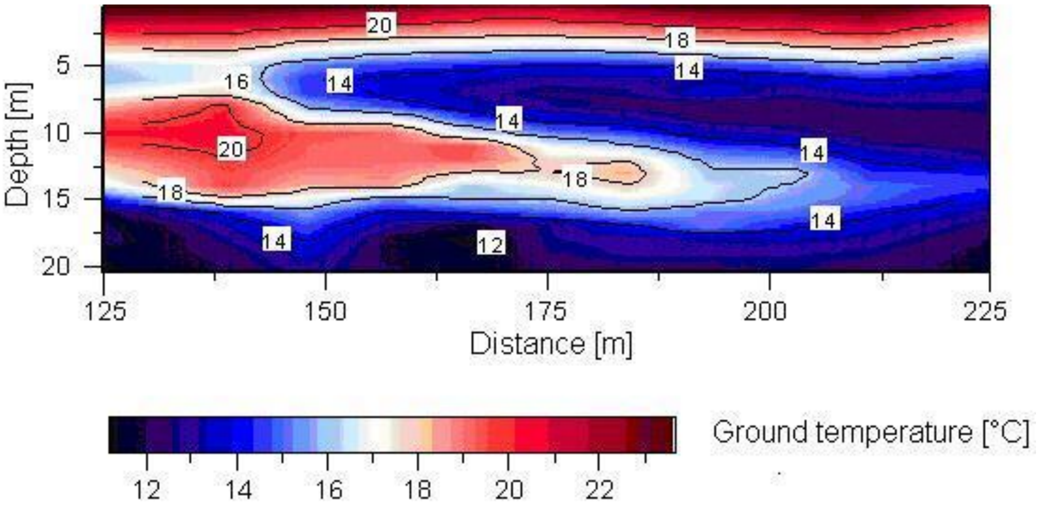
2. In-situ temperature measurement techniques

2.1 Temperature probes

This technique provides temperature measurements in sediments and embankments down to depths in excess of 30-40 m. Metallic tubes, consisting of several threaded sections, are rammed into the ground along a profile to result in an array of temperature probes as shown in Picture 2.1.1. Chains of temperature sensors generally placed at 1 m interval are inserted in the tubes. The in-situ ground temperatures at different depths are taken after the tube's temperature has adapted to ground temperature. As the measured temperatures are immediately mapped on the field-computer, the initial spacing of the temperature probes can be reduced where temperature anomalies are detected. Thus, vertical and horizontal boundaries of seepage zones, as presented in Picture 2.1.2, are localised on site.

To date, temperature probes have been applied to embankments of about 500 km length in all and to other hydraulic structures, e.g. ship locks, showing an increasing demand for reliable and successful detection of seepage zones and leaks and also anomalous flow in the foundations of dams. Temperature probes are appropriate for the quality control after construction or repair works.

Picture 2.1.1 Installation of an array of temperature probes



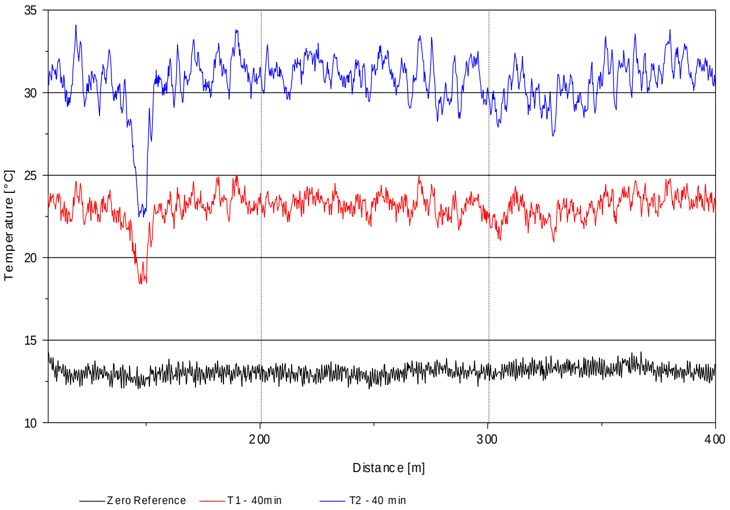
Picture 2.1.2 Temperature distribution resulting from a survey of an array of temperature probes

2.2 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].

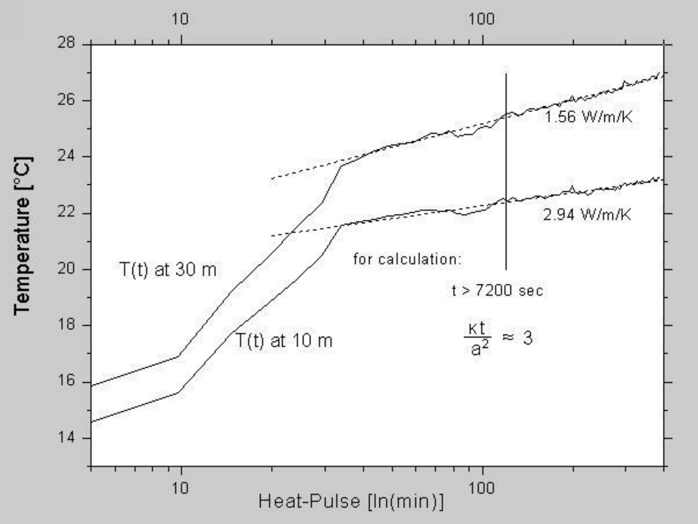
Furthermore, a more elaborate analysis of HPM reveals an estimation of pore velocities.

2.3 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 [3].

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 $Wm^{-1} K^{-1}$. 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 CO_2. Similar to HPM, the evaluation of data obtained with the frost pulse method reveals a qualitative estimation of the pore velocities.

3. Application examples

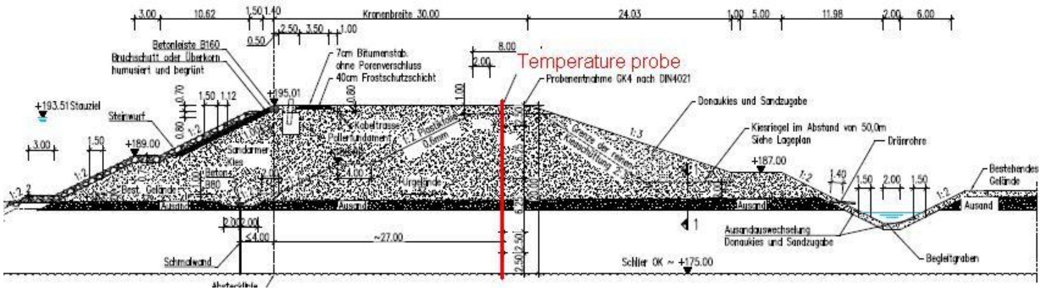
3.1 Embankment dam on the Danube

Situation

The embankment dam is situated about 2 km upstream of the biggest power plant on the Danube River in Altenwörth. The power plant was built between 1972 and 1976 and is able to produce 1.968 GWh annually. In July 2009 a significant seepage zone was detected using in situ temperature measurements within the embankment dam. As a consequence rehabilitation measures were planned. As rehabilitation method BioSealing came into operation [6]. Directly before the rehabilitation with BioSealing in 2010 the extent and the amount of seepage was verified with the use of temperature measurements over an extended period. The measurements confirmed the findings from 2009 and additionally the analyses of the temperature development over time revealed seepage rates in the order of 4-5L/s. These values were confirmed by the application of electronic flow meter gauges at the downstream toe of the dam. The cause of the seepage was attributed to a perforated internal membrane lining (embrittlement).

Layout

Over a distance of 200m from Danube-km 1982.650 to 1982.850 temperature probes were rammed from the crest up to 21 m deep into embankment. The distance in between the probes varied from 5 to 20 m. Within the probes the temperatures were recorded at 1 m intervals. See picture 3.1.1 for a cross section of the embankment and the position of the probes with respect to the dam's geometry.



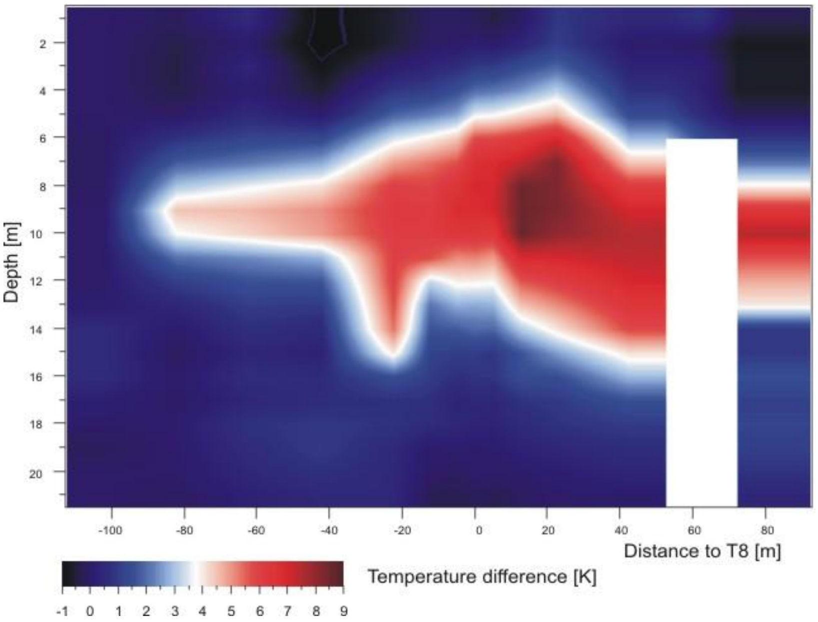
Picture 3.1.1Cross Section of the Embankment

Measurement Results

Temperature measurements were undertaken in July 2010 and July 2011 i.e., before and after the bio grout injections. From the evaluation of the absolute ground temperatures in the embankment a 185 m long section was narrowed down suggesting significant seepage mainly in a floodplain sand layer 9-10 m below crest. On two locations (km 1982.7635 and 1982.7285-1982.7185) seepage occurs as well above and below the sand layer. Picture 3.1.2 shows the temperature difference to the undisturbed ground. Evaluating the development over time of the phase shift of the ground temperatures and the Danube water temperatures one can estimate the amount of the seepage flow. The evaluations suggest a decrease in seepage from approximately 5 to 1,7 L/s after the bio grout.

The measurements showed in summary, that significant seepage still occurs but the amount of seepage has lessened considerably.

In 2012 additional bio grout injection took place, which reduced the overall seepage flow down to 1.0 L/s. Temporarily the seepage flow had been reduced to as low as 0.3 L/s.



Picture 3.1.2 Temperature difference to the undisturbed ground in July 2011 after the rehabilitation measures

3.2 Knezevo dam

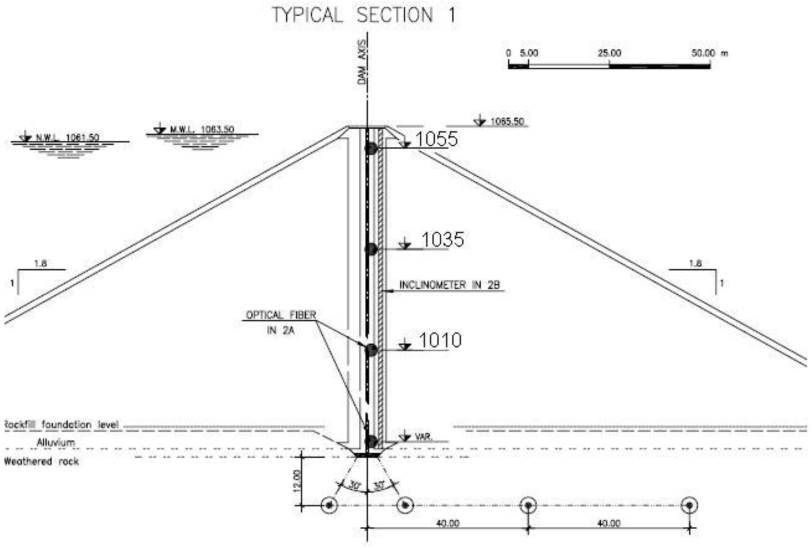
Situation

The Knezevo Dam is located in the upper stream of the Zletovica River, about 80 km east of the Macedonian capital Skopje [7]. It is the main element of the Zletovica Basin Water Utilization Improvement Project with the purpose of water supply, irrigation and power generation. The Knezevo 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 m^3. The effective storage capacity is 22,500,000 m^3. The instrumentation of the dam comprises piezometers, total pressure cells, extensometers 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.

Picture 3.2.1 Knezevo Dam during construction (July 2010)

Layout

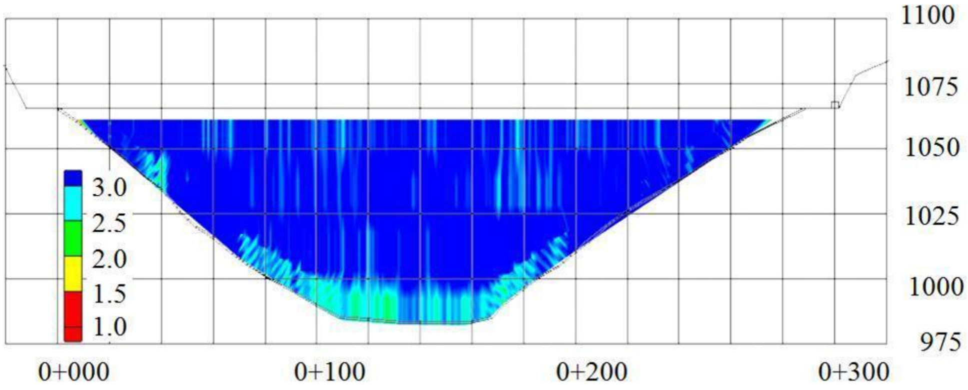
According to the design, the fibre optic cable for leakage detection runs in the direction of the dam axis along the interface between the asphalt core and the foundation and at el. 1010 m.a.s.l., el. 1035 m.a.s.l. as well as el. 1055 m.a.s.l. (pict. 3.2.2). Overall, about 1.5 km of fibre optic cable 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.

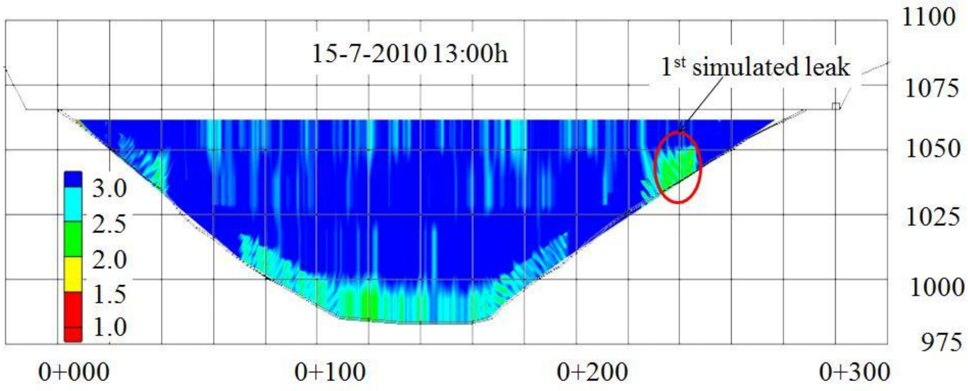


Picture 3.2.3 Reference measurement – temperature differences before impounding

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.



Picture 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. Summary

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.

5. References

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