The failure of the Mostiště embankment dam

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SYNOPSIS. The Mostiste Dam on the Oslava River is a rockfill dam with a relatively thin inclined impervious core. The maximum dam height is 29 m and its crest length is 292 m. The Mostiste Dam was completed in 1960 and at that time it was the first compacted rockfill dam in the Czech Republic (CZ). Leakage first occurred in 1996 in the grouting gallery which indicated that its impervious core sealing might have been impaired. The results of follow up surveys carried out up to the end of 2004 demonstrated the progressive worsening of the problem. As a result, the reservoir level has been significantly lowered since the end of 2004. In May 2005, the governor of the region proclaimed a state of emergency to protect the lives and property of inhabitants downstream from the dam.

The Mostiste reservoir normally serves as a source of drinking water for more than 70 000 inhabitants. Therefore, the remedial works concept design had to respect the requirement that water supply remained uninterrupted without any dramatic reduction.

This paper provides an analysis of the failure's initiation and gives information about the remedial measures accepted. The extra-operational procedure - the gradual filling of the reservoir accompanied by careful monitoring - should be carried out during the winter and spring of 2006 depending on hydrological conditions. The authors hope to be able to summarize the results of this test operation during the oral presentation at the conference.

BASIC INFORMATION ABOUT THE DAM

The Mostiště Dam on the Oslava River has served for more than 40 years as the water supply source for waterworks at the cities of Velké Meziříčí and Třebíč. Normally, the reservoir supplies the region with drinking water.

The dam is located on the Oslava River (Fig. 1), its backwater length is 5.385 km and the catchment area is about 223 km^2.

The dam was finished in 1960 as the first compacted rockfill dam in the Czech Republic. The dam sealing is made of a thin inclined loess core. The maximum dam height is 29 m and its crest length is 292 m.

Figure 1: A map of the Czech Republic with the Mostiště Dam

The reservoir volume division corresponds to the main purpose of the scheme – the supply of drinking water. The flood protection effect of the dam is relatively small; for bigger flood wave volumes it is practically negligible.

Figure 2: Aerial view of the dam

Total reservoir volume	11.9373 M m^3
Uncontrollable flood storage	0.9437 M m^3
Controllable flood storage	0.6094 M m^3
Live storage	9.3389 M m^3
Permanent storage	1.0453 M m^3

The dam site is located upon a moldanubium granite massif, and the dam sub-base is composed mostly of high quality granite rock.

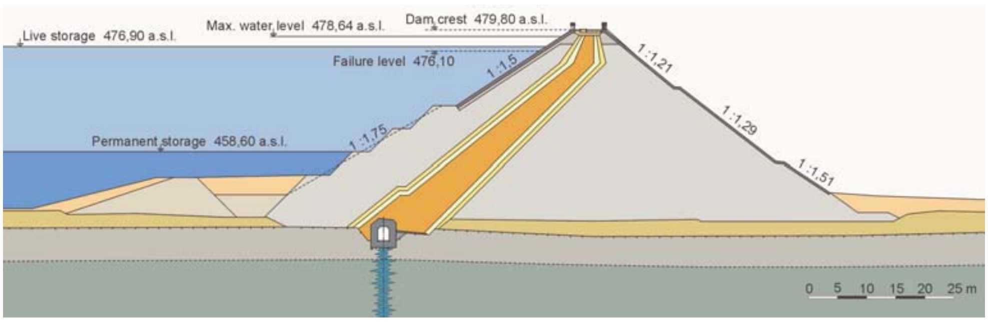

Figure 3: Typical cross section of the dam

The dam is composed of compacted quarry-rock fill with a thin loess soil core (Fig. 3). In the upper part the core is vertical; in the lower portion it is inclined close to the upstream face. The dam core is keyed to the sub-base by a grouting gallery. The sub-base was grouted along a single line of grout holes.

According to the dam safety classification system in the Czech Republic the Mostiště Dam is registered as category I, i.e. one of the most carefully observed hydraulic schemes. There are 26 such dams in the Czech Republic.

When compared with other rockfill dams in the Czech Republic, relatively small vertical and horizontal displacements have been observed at the dam during its service life. However, the set of critical comments addressed to the Mostiště Dam design concept deals with the recent state of the art in large dam engineering when compared with the state of knowledge in the 1950's. The dam has very steep slopes from 1:1.2 to 1: 1.7, meaning the reserve in dam stability is minimal. The impervious core is relatively thin; protective zones (filters) are made of crushed stone with gradation, not assuring resistance against contact suffosion. Moreover, the additional survey gave rise to doubts about the quality of the filters, their real extent and functionality. The transition zones between the "stiff" rock fill and the impervious core are completely missing. The dam was not equipped with any drainage system, which is a common feature in dams built in later periods. There is only one bypass bottom outlet (the recent Czech standards require at least 2 bottom outlets) and a small hydropower penstock.

THE DAM'S FAILURE AND ITS PROGRESSION

Technical dam safety inspections and surveillance indicated increased seepage through the dam body since 1996. The defects could not be localised due to the lack of a drainage and seepage observation system. The uncertainties over future dam behaviour called for additional surveys, focused firstly on the probable locations of potential defects. The careful investigation of records from the building site during construction showed that the dam material used was very heterogeneous, and at some locations quite improper (wooden logs, steel rods, etc.). During the completion of the dam body, suitable loess material for the dam core was probably unavailable, and its upper portion contains sandy layers from the borrow pit. Moreover, the compaction technology used was not sufficiently developed at the time of construction in the 1950's.

The failure was assessed as being a complete hydraulic fracturing of the impervious core in at least two places above the level of 476.00 m above SWL. Further on, a geological survey indicated the potential for future damage to the thin vertical part of the core at any point in the dam. Nevertheless, the systematic location of hazardous places was not possible. At the same time, the geological survey showed that the impervious core thickness varies at its top significantly, and its level does not fit the requirements of present dam safety standards.

The failure was triggered by a combination of unfavourable factors. The most significant factor was the use of heterogeneous core materials, locally improper for the sealing zone, and also implicated was poor compaction of the impervious core. This was caused by the lack of suitable material at the end of construction, and the use of poor compacting equipment (ramming plate). One of the accompanying effects was the varying levels of moisture of the core material. Moreover, at some places transition zones (filters) are missing or do not fit non-suffosion criteria.

The complex analysis was carried out with the use of FEM stability analysis. The results of the modelling documented the significance of

- unsuitable construction methods, namely the non-uniform filling of the embankment body in the cross section,
- the development of differential settlement in the core and shoulders followed by "an arch effect" and corresponding stress redistribution. The accompanying effects of such a failure are a decrease in vertical stresses in the core, water penetration to the joints, and a successive increase of soil moisture at the affected zones.

It is evident that the failure development has been gradual and over a long period of time. The total hydraulic fracturing was undoubtedly preceded by a gradual increase in seepage through the core. A more accurate assessment of the reasons for the failure is however quite difficult due to a lack of reliable data.

The geological survey of the dam and thus additional knowledge obtained showed the necessity for the complete and systematic repair of the dam sealing.

FOLLOWING ACTIVITIES AND PROVISIONS

At the end of the year 2004 the findings mentioned above led to the statement that the dam did not fulfil elementary safety requirements and could not be operated without immediate measures being taken. The main goal of the dam owner was to avoid increasing risk for the inhabited area downstream of the dam. Based on the modified manipulation order, the water level in the reservoir was lowered by 13 metres. This enabled the routing of a 20-year flood through the reservoir without exceeding the critical water level of 476.00 m above SWL. Following operational decisions and proposed conditions for the remedial works a compromise was reached between contradictory demands for the maintenance of a tolerable level of risk in order to obtain increased dam safety, and for ensuring a continuous drinking water supply. If the summer months were dry the insufficient water storage capacity and impaired water quality could complicate raw water intake from the reservoir.

With respect to the extreme snow cover in the catchment area during spring 2005, a 7 m long section of side spillway wall was temporarily removed (Fig. 4). This part of the wall was blasted out in its entire height to release an additional discharge of 14 m^3/s without exceeding the critical water level in the reservoir.

Figure 4: Emergency spillway - partial removal of spillway wall

To partially increase dam safety, further provisional repairs were carried out at the evidently damaged parts of the dam sealing. These activities consisted of filling caverns in the core using low-pressure grouting and sand jetting into the drill holes directed to the transition zones (filters). These measures temporarily reduced the risk of dam failure to a tolerable level.

Knowledge obtained from the provisional repair contributed to a more reliable description of the state of the dam body:

- The real geometrical shape of the impervious core does not correspond to that given in the original project documentation,
- The transition zones are locally missing or are of insufficient thickness and improper grain size, which does not protect the impervious core against contact suffosion.

To precisely map the extent of the potential dam-break floodplain, dam breach and flood routing modelling was used. The calculations considered the mechanism of dam failure to consist initially of hydraulic fracturing, piping and subsequent dam breaching at the documented points where weakened zones of the core lie. This analysis was the basis for the preparation of an early-warning system in the area below the dam.

In order to accelerate the tender and contractor selection process, the governor of the region proclaimed a state of emergency to protect the lives and property of the inhabitants living downstream from the dam according to the Emergency law. This enabled immediate design activities and the preparation of tender documentation with one principle target - to finish all necessary remedial works to increase the safety of the dam by the end of 2005.

THE DAM REPAIR DESIGN CONCEPT

The design concept for the remedial works was approved by the technical committee in March 2005. From that time on, intensive design and consultation work was carried out to prepare project documentation for the construction work. Conceptually, the remedial works at the Mostiště Dam were divided into two stages:

- 1st stage – urgent safeguarding work averting the emergency state, consisting of
  - reconstruction of the dam sealing - impervious core,
  - a system improving technical safety monitoring,
  - reconstruction of the water supply main,
  - additional grouting of bedrock.
- 2nd stage – reconstruction of the dam, which comprised
  - arrangement and remedial works at the dam crest,
  - verification and completion of a monitoring system.

The 1st stage included repair of the dam core over the entire extent of the dam’s length, and improvement and completion of technical safety instrumentation to enable verification of the results of reconstruction. This stage was required to be finished before the end of 2005 to enable the filling of the reservoir, and the provision of a continuous raw water supply to the waterworks and distribution network as soon as possible. However, the requirements of dam safety-related standards would be fully fulfilled after the completion of the 2nd stage of the remedial works.

IMPROVEMENTS IN RESERVOIRS

Reconstruction of the impervious core

The main goal of the works was the installation of a reliable sealing element in the core, which significantly decreased its permeability in damaged and degraded portions. The raising of the impervious core crest to the standard level is also a necessary condition for remedial activities planned in the 2nd stage of the remedial works.

The repair consists of the development of a continuous inclined sealing element (seepage barrier) along the entire length of the dam (292 m) to the depth of 7 m (to the level of 473.00 m above SWL - Baltic system), close to the upstream face of the impervious core (see Fig. 5). As the sealing membrane could not be vertical (due to the inclined part of the core), it was decided to use the technology of jet grouting from the dam crest (see below). The total area of the seepage barrier was about 1700 m^2.

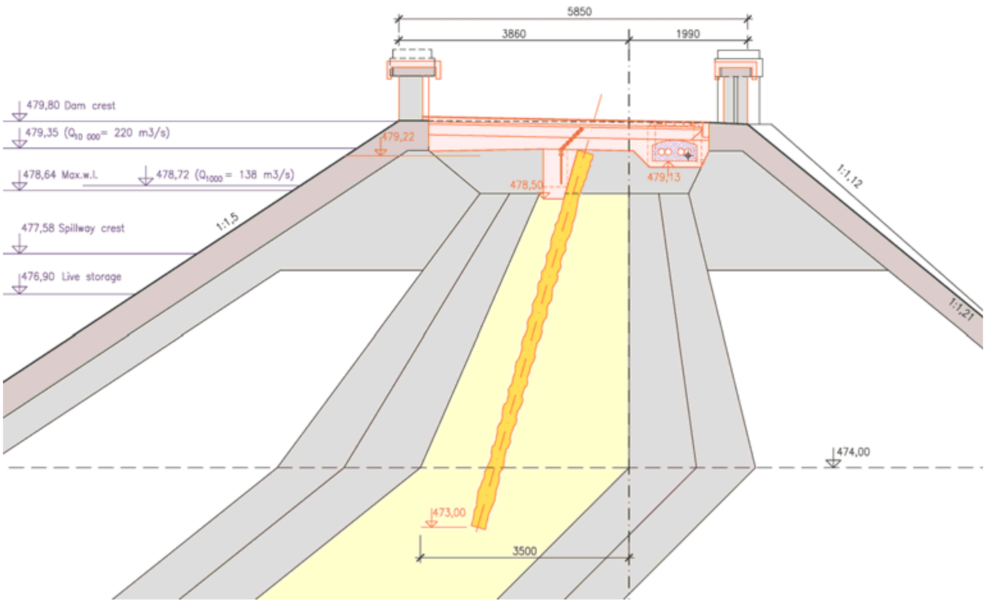

Figure 5: The sealing element in the dam core made by jet grouting technology

The system of technical safety monitoring

In the 1950's, during the construction of the dam, no drain was built at the downstream toe. Because of this, it has not been possible to reliably identify seepages and thus localise eventual failure zones. To improve this situation a new drainage system has been designed and installed at the downstream toe of the dam. This will stabilise the groundwater level and enable sensitive pressure, groundwater level and seepage measurements. The new drain is subdivided into sections to enable the spatial identification of possible increased seepages in potential failure zones. Moreover, the right bank abutment has been drained into the grouting gallery. Two automatic gauges have also been set up inside the grouting gallery to measure leakage. After the revision of the system of observation boreholes in the grouting gallery, it was decided to replace them with new ones, and the system was extended and automated. The newly installed devices give much accurate and frequently measured data, which provides the dam operator with better information as a basis for decision making within the early warning system. The automated system contains both outer and inner observation boreholes. For remote data collection new cable lines were installed in the grouting gallery and outside of the dam body. A conceptually new monitoring system will be gradually integrated into the system serving for the operation of the scheme.

The water supply main

The 45 year old water main taking water from the reservoir to the waterworks interfered with the newly designed toe drain. Therefore, the pipeline was preventively replaced by a new one.

Additional grouting

The grout curtain was finished at the beginning of the 1960s. Due to its age, it is showing local degradation, and so new grouting of the most exposed bedrock was performed as a part of the activities at the 1st stage of the reconstruction scheme. The locally damaged parts of the concrete structure of the grouting gallery (caused by the concentrated leakages) were repaired. In the right-bank part of the gallery along the downstream side, four separately controlled sections were developed by local grouting of the back side of the wall. The "closed" sections created in this way were drained to the gallery and thus enabled localisation of potential increased seepages through the dam's impervious core.

Recently, the 1st stage of the reconstruction was finished, and the trial filling procedure was started at the beginning of December 2005. During this procedure the detailed and frequent observation of dam behaviour will be carried out using the newly installed monitoring system.

The 2nd stage of the reconstruction is planned for the year 2006. It comprises dam crest repairs and the completion of the monitoring system. These arrangements will place the scheme in accordance with current standards and enable adequate control over any uncertain factors specified during the preparation works.

IMPROVEMENTS IN RESERVOIRS

THE REPAIR OF THE IMPERVIOUS CORE

Peculiarities of the impervious core repair process

Various technical methods were originally presupposed when choosing an appropriate reconstruction method. A range of international experience from ICOLD documentation was reviewed and analysed. Finally, three possible methods were assessed in more detail, namely:

- Removal of the upper portion of the dam and replacing the impervious core with appropriate material.
- Construction of a standard vertical slurry wall.
- An inclined curtain constructed using jet grouting technology.

Finally, the relatively "young" method of jet grouting was selected using the formalised multi-criterial optimisation method. It must be stated that this method is generally used for the improvement of subsoil properties (namely bearing capacity) and that its use to such an extent in the repair of an impervious core was probably a world first.

In the impervious core, the technology of jet grouting could not be applied in the usual manner. Besides a sufficient level of impermeability, the deformation characteristics had to follow the properties of the original core material to assure the appropriate deformation behaviour of the resulting improved sealing element. Thus, the target was not a high degree of strength and stiffness for the new element, but rather long-term deformation properties fitting the deformations of the original dam core.

The whole reconstruction process has been influenced by the low stability reserves of the dam, where the safety factor along critical failure surfaces reached values of about SF = 1.275. As it was feared that the jet grouting technology could impair the stability of the dam, the detailed 3D finite element model was set up to simulate the sealing element construction process. The results of the numerical solution served as a recipe for the technological procedure, which was based on the gradual development of the seepage barrier in a set of sequences, and a permanent check on strength acquirement in individual runs. The aim was to avoid worsening the stability conditions of the dam during construction.

As there is only limited experience with jet grouting technology being applied to the impervious cores of dams, the contractor was obliged to prove the method before the start of reconstruction at the test field in the right abutment. The test showed that the technology is vital in the creation of a core-sealing curtain of the required parameters.

<u>Experience with impervious core repair using jet grouting technology</u>
Jet grouting technology was applied in five sequences with reference to the restricting requirements based on the results of stability calculations (Fig. 6).

Figure 6: Procedure of jet grouting in five sequences

Furthermore, the technology had to avoid damaging the impervious core, so the grouting boreholes were inclined by 16 degrees in the direction of the inclined core so as to be sufficiently far from its faces. The procedure was based on the modified single jet method proposed by Soletanche.

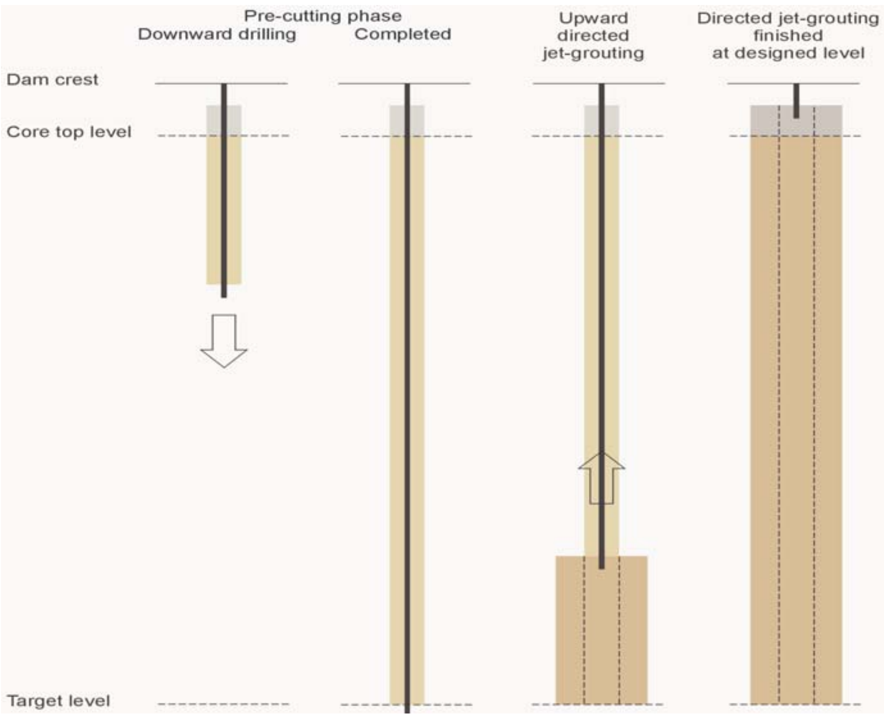

Figure 7: The scheme of jet grouting

The grouting in individual boreholes was carried out in two steps. The first one was the pre-cutting phase, which was done in a downward direction. Pre-cutting with the grouting suspension during drilling ensured a pillar diameter of approx. 0.3 m to the depth of 7 m from the dam crest. The second - upward phase was performed by directed jetting, creating butterfly–shaped lamellae with 0.4 m long “wings” in the direction of the longitudinal dam axis.

The grouting procedure was carefully monitored and maintained so as not to exceed maximum prescribed displacements of the dam crest. Those were originally assumed to be the values of 4 mm vertically and 4 mm horizontally (widening of the dam crest).

Unfortunately, the prescribed displacements were not gained during construction, and the measured deformations, both vertical and horizontal, exceeded 45 mm in some observation profiles (Fig. 8). The following stability analysis indicated higher pressures in the drills, which in combination with weakened zones in the dam core were the reason for the relatively high displacements. The additional calculations showed that the safety factor of the repaired dam could, at certain locations, have been slightly decreased to the value SF = 1.25!

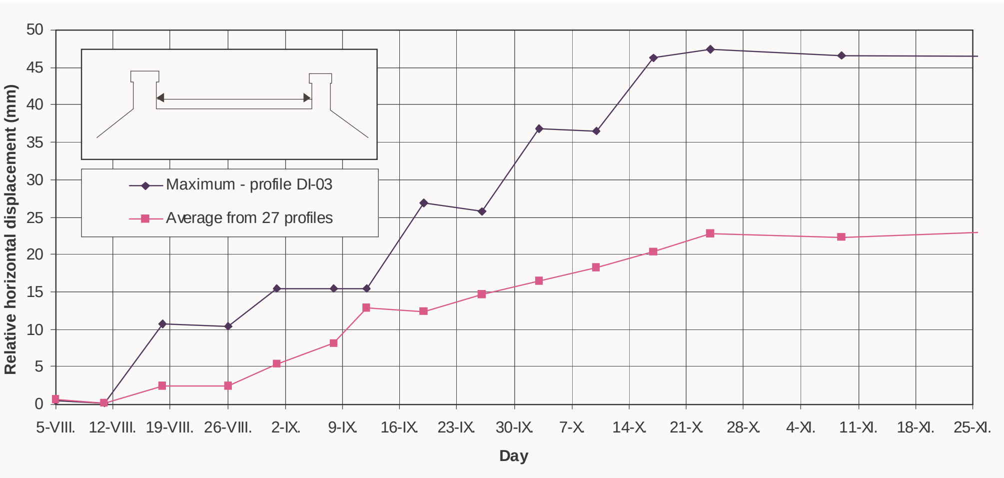

Figure 8: The development of horizontal displacements of the dam crest in individual sequences

Therefore, the recommendations for the trial reservoir filling procedure and parallel careful monitoring of displacements and seepage were set up by consulting engineers. The effect of the trial filling and the consequent sudden drop of reservoir water level on dam stability was numerically modelled in advance before the repair procedure. The modelling results enable the dam owner to control displacements and check if they are within the expected range.

CONCLUSIONS

Recently, the 1st stage of the remedial works has been finished, and, at the time of writing, the project documentation has been completed for the 2nd stage of the reconstruction. At the beginning of December 2005 the filling of the reservoir was slowly begun according to the plan for the trial procedure. Unfortunately, the filling stagnated during December due to the lack of water in the catchment.

Careful continuous monitoring was carried out from the beginning of December, when the first reference readings of all observation devices were completed. No significant displacements and seepage has appeared by January 2006. However, it is still too early to conclude and proclaim the effect and success of the dam reconstruction at the time of writing. It is hoped that an update on the Mostiště Dam's behaviour will be provided at the conference meeting.

ACKNOWLEDGEMENTS

The contents of this paper are a part of the research supported by the Grant Agency of the Czech Republic, project No.103/05/2391.

The authors wish to thank the dam owner – the Morava River Basin Agency, for providing the valuable data published in the paper.

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