Experiences from the small historical dams failures during heavy floods

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Abstract. Roughly between 400 and 600 years ago many small earth dams were constructed mainly in the south part of the Czech Republic. They were used for fish production and flood protection. To our days roughly one third survived, which means about 25 000 of them. During catastrophic floods in 2002 many of them had some problems but less than 0.3% failed. Experiences gained from the failure evaluation are presented. Firstly from the view of limit states of failures, when limit states of internal erosion and surface erosion played most important role and were the main reason of failures. Secondly, from the view of so called domino effect of failure, when the most important dam on the catchment basin failed and after that the other ones, situated below, had limited chance to survive. The failures are described for catchment basin of the small river Lomnice in south part of the Czech Republic close to the town Blatna. The experiences obtained there led to the evaluation of other catchment basins where domino effect of failure can play also very important role. For the evaluation of potential risk, the numerical modelling was used to study the flood wave propagation below the critical dam, especially at the moment when this wave is reaching the dam situated below the critical one. Finally, the recommendations are specified, not only for individual dams but also for catchment basin, where the risk of domino effect failure is very high.

1. Introduction
During last two decades, floods caused many problems in the Czech Republic. Therefore, more attention is devoted to this problem, either with respect to their frequency, as to the environment protection with the help of different flood protection measures. During the last period the emphasis is directed on the information system, on the first signal about potential dike failure, on the recommended behaviour during floods, and on the actions which can play positive role from the safety point of view, etc.
In the Czech Republic, there are roughly 3 different types of floods:

- Regional – affecting one or more river-basins, coming usually in summer and is caused by long term heavy rainfall;
- Local – affecting small area. Caused by extremely high local rainfall (storm) – most difficult from the forecast point of view;
- Floods in foothills – during spring, when the soil is still frozen – caused by combination of snow melting and rain.

Very often during the last period, we are speaking about frequency of floods, as for example in the Czech Republic different floods were recorded, especially the regional ones, in 1997, 1998, 2002, 2006 and 2010. Figure 1 is showing the situation in Prague during the heavy floods in 2002. However, from the figure 2 – showing flood events in Prague during the period of 1825-2002 – it is clear that the flood in 2002 was strongest during the last 2 centuries; however, flood frequency during the last decade of the 19th century was also exceptional. The 2002 flood also heavily affected the Prague metro system [1].

Figure 1. View on River Vltava in Prague during heavy floods in 2002 (August 14, August 22).

Figure 2. Prague – floods during the period of 1825 – 2002.
Uniqueness of the flood in 2002 was that the heavy rainfalls causing the flood came in two peaks very close to each other. Nearly whole country was strongly affected by this flood with maximum rainfall in south part of the country. Since nearly all rivers are flowing in a northerly direction the highest flood wave reached on the river Labe (Elbe) boundary with Germany close to Dresden.

The highest concentration of failures of small earth historical dams during the 2002 flood were connected with small river Lomnice, (figure 3), where five dams failed and two others were damaged, [2] or [3].

![Figure 3. Little River Lomnice – situation and scheme of dams.](image)

Heavy rainfalls during 7th and 9th August 2002 did not cause any problems; pond reservoirs were nearly full and fulfilled their flood protection role. The situation was improved during Saturday and Sunday (10-11th August) and with the help of directed outlets, a certain reservoir volume was restored, for example in three cases water level was 0.3 – 0.6 m below normal level.

New heavy rainfalls started on Monday (12th August), which had very quick negative effect due to the full saturation of surrounding land. On Monday evening, the flow volume reached 100 years flow rate. But still all dams were able to catch all these volumes.

The critical situation started at around 4 am of the next day (Tuesday) when - due to overflowing - the first dam (Melin) on this river basin failed. Additional wave reached the crest of the next dam
“Metelský” in few minutes and very quickly, this dam failed as well. Relatively large volume from this reservoir (about 1 mil. m³), with the estimated (and recalculated) outlet more than 500 m³.s⁻¹ (which was much higher than 100 years flow rate – about 20 m³.s⁻¹), affected the villages Metly and Předmíř, where some houses failed and one man died. The embankment of the next pond “Veský” survived due to the very wide crest with asphalt pavement but was strongly eroded on the downstream side. The same situation was observed on the next pond “Zámecký”, the crest of which is also protected by asphalt pavement – European road E 49 is passing on top of the crest, figure 4.

![Figure 4. Crest of the dam Zamecky - European road E 49.](image)

![Figure 5. Town Blatná – on 13th August 2002 morning.](image)
Nevertheless all the other three dams (figure 3) situated below failed, and the village Tchořovice was strongly affected, many houses were destroyed. After the failure of the last one (Dolejší), the flood wave was getting flatter in much wider and flatter valley so that the impact on the town Blatná was diminished. Nevertheless, even there the damages were very high, figure 5, because on the brook, joining River Lomnice in Blatná, another three dams (Luh, Velky Belcicky and Pusty) failed as well.

2. Character of failure
In all observed cases, the surface erosion played the most important role, but in two cases, the internal erosion probably also participated in the final collapse.

With respect to the internal erosion two different reasons were recorded. For example in one place of failure – gash – of the embankment of the pond Metly, the part of the old wooden outlet was found. From the historical records, this old outlet was left there roughly in seventeenth century, because from these days a new place for the new outlet was selected. In this profile on the downstream side, the place with higher humectation (moisture content) was observed for last decades, probably as the result of higher permeability in this profile. Due to the higher hydraulic gradient, the clogging of this old outlet failed and internal erosion started, leading to the complete collapse of the dam. The second case was observed for the pond Podhajsky, the embankment of which was reconstructed only 13 years before the event. Sealing wall formed by jet grouting was applied in one part of the dam embankment. At the same place dam completely collapsed, with high probability as the result of the combination of high hydraulic gradient and bad connection of this wall with dam bedrock, where large granite boulders were disclosed.

With respect to the surface erosion, the significant role played the dam crest arrangement. For the asphalt pavement, the erosion was strongly limited, protecting against total collapse – see also figure 4. The uniformity of the crest level played also important role, as in this case water overflow and the crest erosion happened throughout the whole length (figure 6) and dam collapsed in the place with minimum erosion resistivity, in one case two water gaps occurred at the same moment at two different places.

![Figure 6](image)

**Figure 6.** Dam Dolejší – Downstream slope eroded along the entire crest before the dam failed in two places.
3. Reconstruction
The basic question connected with reconstruction was connected with the type of soil, which has to be used. In Middle Ages the granite eluvium was used, as the bedrock in this region is composed by granite rock. However, grain size distribution curve was on the boundary, which is now accepted from the permeability point of view. Nevertheless, as this eluvium contains high percentage of mica the measured properties were sufficient:

- Percentage of fine particles – between 10 and 35%,
- Liquid limit 30-37%
- Plasticity limit 23-28% (but in some cases not detectable due to high sandy content);
- Optimum moisture content (Proctor standard) 12.5 – 17.0 %
- Coefficient of permeability after compaction in the range of $10^{-8} – 10^{-10}$ m.s$^{-1}$

Special care was devoted to the connection of the new part of the dam body with the older one. Contact was done with the help of cut-off, the same method was applied for the connection of the new part of the dam with subsoil. In the case of direct connection of the reconstructed part with boulders in the bedrock, either in the bottom or on the side slopes, bentonite slurry was applied on these boulders to obtain good connection and to restrict the development of preferential paths for the seepage.

As the old dams had no toe drain on the downstream side, the great care during reconstruction was devoted also to this drain to affect flow net in the positive way.

Nevertheless during the reconstruction the main attention was devoted to the protection against potential surface erosion in the future. For long crest of the earth dam or for dikes the first step is connected with unification of the crest height along all of its length, as surface overflowing starts in lowest point followed by erosion. The second step is coming out from the same principle. We recommend to select the place where overflowing below the dam (dike) can cause minimum problems and at this place to construct new additional spillway, the crest of which is few decimetres below of the main crest. This principle was proposed and realized during the reconstruction of small dams on the River Lomnice, however the crest of this additional spillway was reinforced. Firstly by concrete slab, later on the principle of the reinforced embankment was recommended. As reinforcing layer the new material was used, so called brick-fiber-concrete. This material is similar to concrete, however it is using demolition waste, mostly old bricks, instead of aggregates with addition of short synthetic fibers, randomly distributed in the mix. The high erosion resistivity of such reinforced embankment was approved by field test in the scale close to 1:1. The advantage of such additional spillway is not only in reduction of amount of water which overflow the main crest, but also as first signal, that the critical situation can start. This approach, which can be called as robustness approach, is now preferred in civil engineering generally.

For shorter length of the crest the reinforcement can be applied along the whole length. Cheaper and environmentally friendlier is solution recommended for dry dam, the main aim of which is to decrease flood wave during floods. Bottom outlet has limited capacity enabling to pass through only the flow equal let say to $Q_{10}$ – $Q_{30}$. For higher inflow rates the water level in the reservoir is increasing followed by overflowing along the whole crest length. In this case we recommended only crest reinforcement with the help of anti-erosion geosynthetic mattress which is very well connected with the subsoil, not only at the crest, but also with the help of long spins on the downstream face of the dam. After seeding with grass the root system help to improve this connection. Practical experience with this method is very good, as after two crest overflowing no damage was observed.

Some aspects influencing internal and surface erosion can be found in rather large range of literature, e.g. Sherard [5], Vaníček [6], Briaud et al [7], Dyer, Utili and Zielinski [8] or Utili et al [9].

4. Catchment basin evaluation – potential of the domino effect of failure
The reason for higher concentration of small dam failures on the small River Lomnice we attributed to the so-called domino effect of failure [2]. This effect can be typical for the small catchment basin, where the most important dam is situated on its beginning. In our case, it was pond Metelsky with
highest volume of water in the reservoir. After the failure of this dam the others situated below had limited chance to survive. Therefore the main experience obtained from the described case is connected with closer specification of this domino effect of failure.

With the help of water-resources maps (in the scale 1: 50 000 covering all country), it was possible to specify other catchment basins in the Czech Republic, which are sensitive to this effect. Very quickly, it was recognized that the River Lomnice is not an exceptional case. Therefore, it was recommended to increase the care about dams, which can play initial role to this domino effect of failure. This recommendation is in accordance with Water law as this law specifies demands on technical-security control for different category of dams. In addition, for selected dams this category can be after the evaluation increased. Nevertheless, before the final specification of the dam category we recommend the numerical modelling of the propagation of this additional flood wave below this critical dam.

5. Flood wave propagation modelling
The numerical modelling, with which the specificity for selected catchment basin and dam can be defined, is based on two phases. For the first step, we have used software BossBreach, version 2.0 – [4] which is able to model the size of the breach of the dam and outlet from the failed dam as function of time. This software of the erosion of the earth dam is based on hydraulic, erosion and transportation equations, which take into account the geometry and material characteristics of the dam. Although this software is simple, can be useful as is giving the first estimation about the peak of the wave leaving the profile of the failed dam.

For the simulation of the range of flooded area below failed dam and for the gradual decrease of the flood wave peak (flood wave transformation) in individual profiles and namely for the profile of the next dam, software HEC-RAS 4.0 (Hydrologic Engineering Can ters River Analysis System) was used. Detailed parametric study was done and very good experiences were obtained for specific dam Brevnice. Cao et al (2014) discuss a similar problem – [10]. Morphological map for the river basin with dam Brevnice in digital form was the first condition of the study, followed by the information about vegetation, about different interaction with transport infrastructure in this inundation area. Subsequent parametric study helped us very much to estimate the impact of the potential engineered measures to flatten flood wave peak. Nevertheless the final result for the profile of the dam situated below the critical one is most important for further evaluation and recommendation.

6. Conclusion
Very careful evaluation of the reasons of great concentration of failed small historic dams during the heavy floods in 2002 helped to improve our knowledge about individual aspects having strongest negative impact. Limit state of surface erosion followed by limit state of internal erosion are playing most important role during the phase of dam crest overflowing. The reconstruction (and newly constructed dams or dikes) should fully exploit this knowledge and therefore some of them were presented. Nevertheless, the main reason for higher concentration of small dam’s failures was attributed to the domino effect of failure, especially for the case where the dam with highest reservoir volume is situated at the start of the catchment basin. After the failure of such critical dam the other dams situated below have limited chance to survive. After the specification of this type of domino effect of failure the subsequent study showed that similar situation can happen for many other catchment basins, as there is still a very high number of old historical small earth dams – about 25 000. Therefore, new conditions for monitoring of these dams with higher potential risk for the individual catchment basins were specified in laws updated following the described event evaluation. Numerical modelling can be very useful tool for more detailed evaluation of the potential risk of failure or about potential safety measures.
References

[1] Soga K, Vaníček I, Gens 2011 *Micro-Measurement and Monitoring System for Ageing Underground Infrastructures* (Prague: CTU Press)

[2] Vaníček I, Vaníček J 2004 *Rehabilitation of old earth dams failed during heavy floods in 2002 Proc. New Developments in Dam Engineering* (Balkema) pp 889-898

[3] Vaníček I, Vaníček M 2008 *Earth Structures in Transpoort, Water and Environmental Engineering* (Berlin: Springer)

[4] Pecival T, 2015 *Research of frequency and types of failures for small earth dams – domino effect* PhD thesis, (Czech Technical University in Prague, in Czech)

[5] Sherard JL, 1973 *Embankment Dam Cracking* Embankment Dam Engineering Casagrande Volume (New York: Willey) pp 271-353

[6] Vaníček I, 1988 *Creation and behaviour of cracks in clay core of earth and rockfill dams* (Praha: SNTL – Publishing house of technical literature in Czech) 168 p.

[7] Briaud JL, Chen HC, Govindasamy AV, Storesund R, 2008 *Levee Erosion by Overtopping in New Orleans during the Katrina Hurricane*, Vol. 134, No. 5, May 2008, *Journal of Geotechnical and Geoenvironmental Engineering*, (Reston Virginia USA: ASCE)

[8] Dyer MR, Utili S, Zielinski M, 2009 *Field survey of desiccation fissuring of flood embankments*. (London: ICE Proc. Water Management, 162(3)) pp 221-232

[9] Utili S, Castellanza R, Galli A, Sentenac P, 2015 *Novel approach for health monitoring of earthen embankments*. Journal of Geotechnical and Geoenvironmental Engineering (ASCE, 141(3): 04014111)

[10] Cao Z, Huang W, Pender G, Liu X, 2014 *Cascade dam break floods*, J. Flood Risk Management, 7(4) pp 357-373