Flood and post-flood performance of historic stone arch bridges

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ABSTRACT: The paper deals with specific problems of historic stone arch bridges during and after flood events. It is focused on vulnerability of such bridges to flood loading and action. It presents typical damages and failures experienced by the authors on this type of structures and those known from literature. Long term monitoring of post flood remedial works is also presented. Except of structural performance there are presented and analysed also other typical post-flood damages, namely problems of transport of salts and their efflorescence, and some specific features of biological attacks are briefly commented. Case examples of historic bridges in Central Europe damaged by floods – historic as well as recent ones – are given as illustrations. They represent medieval and baroque bridges. In the last part, the paper suggests strategies and measures mitigating adverse effects from flooding on stone arch bridges, which involves preventive measures, actions during the flood and post-flood activities.

1 INTRODUCTION

1.1 Historical remarks on medieval bridges

Stone arch bridges represent very durable structures. Regardless the fact that these structures suffer severely from floods, being usually built with quite low height above the water, we can admire numerous ancient examples throughout the Europe. The art of building stone arch bridges had been developed by Roman architects and their basic ideas and typology survived for many centuries, (see e.g. http://traianus.rediris.es). The Central European ancient bridges exhibit also the Roman bridge construction features, namely in foundation technologies of bridge pillars. Further, the arch construction was in medieval time strongly influenced by French constructors who, however, also had learned from Roman bridge building skills. Some examples are given bellow.

In medieval time only 27 European cities had a large stone bridge on its territory, (Velflík, 1921). Four of them had been built in Bohemia and the Prague Queen Judith's bridge built in 1169 was the 6th oldest stone bridge in Europe. A review of the oldest bridges and their typical parameters is given in Table 1.

1.2 Historical remarks on floods

The ancient stone bridges suffered from many floods and some vanished entirely except of remains of foundations in the river and usually also except of bank arches frequently embedded in cellars of more recent buildings.

Floods have been so impacting phenomena that they are well documented in written chronicles, mostly together with a detailed description of the societal and economy effects. Technological data are less descriptive but thanks to a rather simple bridge typology they can be interpreted more or less appropriately. Also the data on the height of water during the flood culmination are usually well documented in situ on different types of high water line records.

Table 1. Review of the oldest European medieval stone arch bridges (Velflík, 1921)

City	Years of construction	Number of arches	Comments on technical features and flood damages
Toledo	996	2	
Albi	1035-1178	7	
Palermo	1113	5	
Dresden	1119-1206	16	
Würzburg	1133		The bridge was heavily destroyed during 1342 flood.
Regensburg	1135-1146	15	The 336 m long bridge has never been substantially destroyed by high water, even though a massive ice block and flood in 1784 destroyed two timber bridges repairing damaged (built in 1633) or missing (built in 1499/1502) parts of the bridge.
Prague	1169-1171	23	The bridge had in the river 12 arches of span between 12,3 – 19,8 m. It was severely damaged during 1342 flood
Avignon	1177-1188		

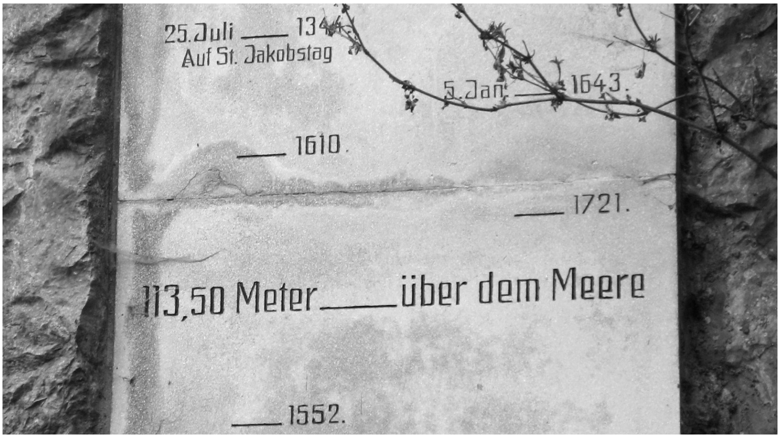

Figure 1: Historic high water line scale in Limburg (Germany) on the Lahn River. (Photo T.Drdácký)

Let us illustrate a typical life of a medieval bridge by several historical examples. An ancient bridge in Prague across Vltava (Moldau) river was built from timber (?in 795?) and it was destroyed by flood several times: in the 9th Century, in 935? (929?) "when the body of St. Wenceslas was transported across it" (Cristiane chronicle), in 1118 due to high water about 3 me above the bridge deck (Cosmas chronicle) and lastly in 1159, (then a stone masonry bridge was built by the Queen Judith).

The Queen Judith's bridge in Prague successfully survived heavy floods in 1180, 1257, 1259, 1264, 1273, 1311, 1315, 1316 and 1322 probably with minor damages only. But the high water on the 12th March 1272 with a lot of ice broke through the bridge in the middle of the river Moldau (Dobner). The damage had been so large that the bridge "managers" – the Knights of the Cross (Hospitaliers) monastery – had to collect a special tax approved by the King Přemysl Otakar II. throughout the kingdom, (Tomek, 1855). Eventually, an ultimately destroying flood had happened in night on the 3rd February 1342 when a large mass of ice had caused a collapse of about two thirds of the bridge that then never had been repaired and replaced later by the famous Charles Bridge.

The second oldest Bohemian bridge in Písek was built about the year 1265. Even though the bridge had been attacked several times with severe floods his six from seven originally erected piers and arches never collapsed. The 1342 disastrous flood destroyed the spandrel walls the top of which reached 5,5 meters above the normal water level. In February, 22nd 1768 ice floes partly destroyed cutwaters of three piers during a splash flood and one land pier with the adjacent vault collapsed. Few years later, 27th February 1784 two central piers were heavily damaged and undermined. Two other significant high water events in 1845 and 1890 when water entirely filled the profile of arches did not cause major damage.

The Charles bridge in Prague, (in the row of large medieval bridges being the fourth in Bohemia and the thirty first in Europe), was founded on July 9th 1357. Even the partially built bridge was damaged by large floods in 1359, 1367, 1370, 1373 and 1374. The most serious damage was caused by a catastrophic flood in 1432 (21st July) when the huge mass of floating material blocked all bridge arches with hay, timber and even wooden houses. The created dam obstructed free flow of water which substantially elevated the high water line and contributed to destructive undermining of five piers with a subsequent collapse. The damage increased another flood in January 28th 1496 when further pier with two adjacent arches had failed which was repairing till 1503. After another heavy damage in 1655 three bridge piers had to be partly rebuilt as a consequence of a strong flood on 28th February 1784, Figure 2. The last partial collapse of the Charles Bridge occurred in 1890 when again a huge amount of timber blocked the water way and after undermining of two other piers the bridge arches fell into water on three places. Thus only one pier and one arch from the original medieval Charles bridge structure have remained after the above mentioned damages and failures.

From these examples it follows that flooding is a natural and quite frequent loading situation for historic stone arch bridges. A detailed evaluation of the Lahn River water gauge shows that in the years 1255-1984 the bridges suffered 60 floods, 22 of them major, i.e. in average a flood in every 12 years. Naturally, the major and namely catastrophic floods represent exceptional loads for such bridges with specific features and a strongly destroying action.

The large stone bridges mostly sustained the static as well as dynamic pressure loads of water provided they were not combined with other loads (ice, timber) or with occurrence of dams and barriers piled up from floating material, which changed the water flow and caused problems to foundations. Small, usually timber or improperly maintained bridges inclined to collapse totally, which has been referred to in several cases. For example, the flood on Curych Lake in 1778 (July 8th) caused besides 63 fatalities also a total destruction of 15 houses and 8 bridges, (Swissworld, 2007)

However, the modern time changed the flood loads compared to the historic ones. First, there is practically no timber floating in large amounts in the rivers because of stopping the transport and water treatment of logs in rafts. Also the ice does not represent so high hazard as before due to increased temperature of water in most rivers, and thanks to a better control and tools for early removal of cumulating barriers. On the other hand, the floating cottages and garden houses are usual, and during the 2002 flood there occurred also lorries, containers and steel boats which all have a quite high mass and energy at impacting into a historic bridge, Fig.2. Further, the water has a higher chemical contamination which creates specific conditions for chemical degradation and biological attacks.

Figure 2: Floating lorry and a container at a foot bridge in Prague – Troja during the flood in 2002.

2 STRUCTURAL DAMAGE AND FAILURES DUE TO FLOODING

2.1 Failure of foundations

The undermining of foundations of piers inside a river as well as on the banks were the most recorded failures observed at large historic bridges during disastrous floods. They mostly occurred in situations when the water way under the arches was obstructed by floating barriers from ice, wood or other materials and objects. Then the stream along the river bed has a higher speed and turbulences which wash out the subsoil layers and undermine the piers. The bridges founded on piles or directly on rock usually have less heavy damages that those standing directly on gravel without piled grids, unless they were provided with protective walls which has been adopted for all recent repairs.

Foundations of light small bridges can suffer from uplift forces – that was the case of a short romantic stone arch bridge in the park of the castle at Veltrusy during the 2002 flood, Fig. 3. Here flooding destroyed a dike around a water channel which partially served also as a balancing ballast for the stability of a bridge-pavilion which partially collapsed.

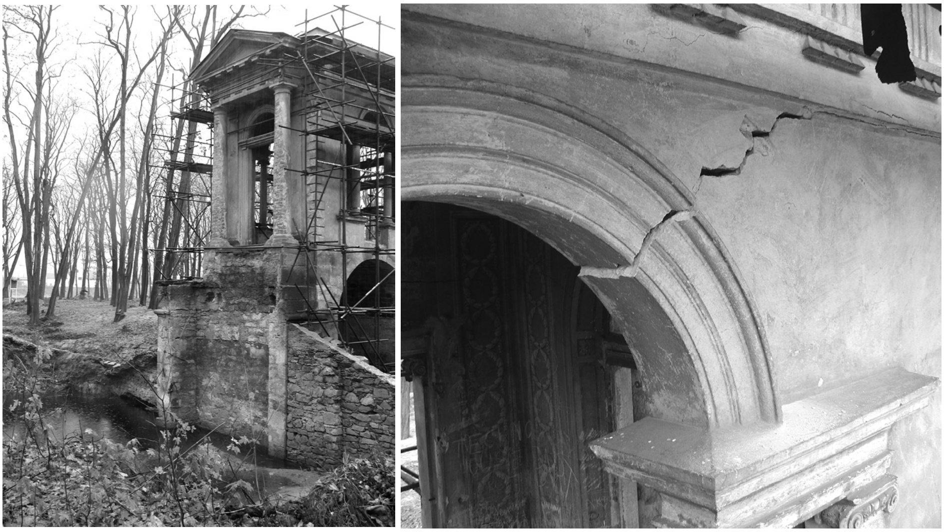

Figure 3: Left bridge pier was uplifted during flooding and damaged by wide cracks.

2.2 Typical damages on piers

The cutwaters were extremely loaded namely by ice friction. Even the ashlars mutually jointed with iron clamps were pulled-out from the structure and the cutwaters had to be repaired almost after all spring floods. There are recorded needs for a remedial walling up of a partially failed cutwater masonry, e.g. in Písek in 1768.

Failure of piers is closely connected with foundation subsidence or rotation due to the above mentioned undermining. They usually do not collapse entirely but their tilting might be so expressive that they have to be rebuilt in order to serve as a support to the arched vaults. A typical case is demonstrated in Fig. 4, (the Charles Bridge in Prague after the 1890 flood).

In some cases, water penetrates behind the bridge abatements and can cause failure of land piers, as happened in Písek in 1768 where the left land pier collapsed and caused a partial collapse of a bridge tower accompanied with fatal injuries.

2.3 Failure of arches

The arches have a quite high load carrying capacity for vertical loads but they are very sensitive to any support movement. The strength of arches is substantially influenced by the height of spandrel walls, which has been proved during full scale experiments on British arch bridges, (Harvey, 2007), namely when strengthened with sufficiently thick and integrated parapet walls. Therefore, under usual situations, the arches sustain very well even high vertical loads.

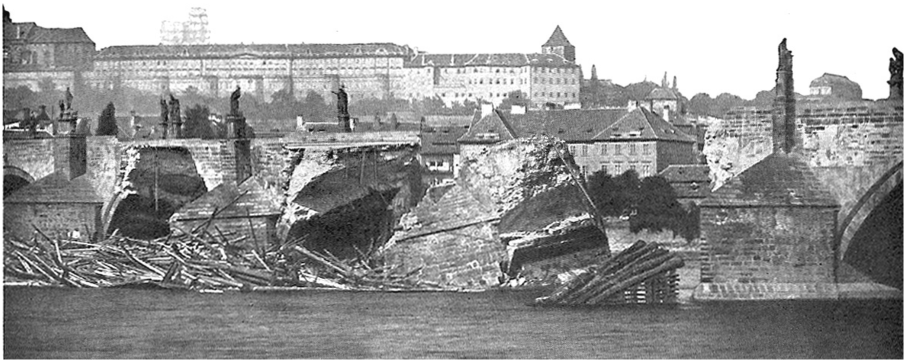

Figure 4: The Charles Bridge in Prague after a catastrophic flood in 1890 (photo J.Eckert).

Unfortunately, during severe floods the parapet walls usually do not resist the load and fall on the bridge deck, which simultaneously increases the load and decreases the load carrying capacity of the arches. Altogether with the high water (and ice) loading a tilting and subsidence of the undermined piers mostly cause the collapse of vaults. The safety of arches is further decreased by their water uplift which reduces the stabilizing compressive stresses in the vaults.

The situation is worsen by many defects and namely cracks in the vaults due to long term cyclic deformations from moisture and temperature fluctuations, (Jäger & Witzany, 2005).

2.4 Failure of parapet walls

Historic parapet walls were usually quite high because they were used for defending activities, too. For example, the Queen Judith's bridge had parapet or "breast" walls of 2 meters high and 30 cm thick, the original Charles Bridge then of 160 cm high. At very heavy floods the water line reaches levels pretty high above the bridge deck and the parapet walls are too weak to sustain such a dynamic pressure. In Fig.5 we can follow a typical case of collapsed parapet walls, (bridge in Písek, 2007). Here the wall ashlars were saved after the flood from the river.

Figure 5: The medieval bridge in Písek during high water (left) and the view of destroyed parapet walls after the flood (right). (Photo Wikipedia)

3 NON-STRUCTURAL DAMAGE AFTER FLOODING

Non-structural damage of stone arch bridges after flood situations include mainly the increased moisture contents, problems of drying accompanied with efflorescence of salts and biological attack of wet surfaces, which is further influenced by high contamination of high water.

Biological colonization of stone bridges is very rich and divers owing to different nutrition conditions, environmental conditions and their fluctuations. The flooding temporarily changes these conditions and a study of history of biotic colonization of stone bridges after the 2002 flood has shown that real situations can substantially differ from the expected scenarios, (Wasserbauer, 2003). The predicted danger of a massive distribution of moulds was after the flood blocked and delayed by different species of bacteria that colonized the flooded materials within the earliest 24 hours. This bacterial microfilm on the surface was even resistant to majority of disinfection means aimed to extirpate higher organisms. As long as after remarkable decrease of moisture in materials the bacteria were gradually replaced by colonies of moulds and other organisms typical for wet environments.

A detailed analysis of salt efflorescence was carried out on a small sandstone ashlar bridge in the castle at Veltrusy. The efflorescence which appeared more than two years after the flood was intensive in thin cracks between the stone blocks and mortar joints, even though it covered also other parts of the masonry (Fig. 6). The salts have been analyzed by the semi-quantitative method XRD, and a mixture of the $Na_3H(CO_3)_2.2H_2O$ and the $Na_2CO_3.H_2O$ in an approximate ration of 1:1 has been mostly discovered. Further the salts $K_3Na\ (SO_4)_2$ and Na_2SO_4 have been identified in lesser concentrations in samples taken from the stone surface. During the flood the bridge building material was leached by the percolation and the salts crystallized from the mineralized water on the surface thanks to a slow drying of the bridge. The salts carbonated reacting with the aerial CO_2. Infill material above the vault, Portland cement in repair mortars and former conservation of masonry with water-glass are supposed to be possible sources of the identified alkali and sulfates. High crystallization pressures can damage building materials, therefore, the structure should dry slowly in order to accumulate salts on the surface from where they should be regularly removed. It is further recommended to check a subsurface salt content, and if appropriate to carry out desalination procedures on the masonry.

Figure 6: Salts effloresced on a bridge arch surface more than two years after the flood.

4 MONITORING OF DAMAGES AFTER FLOOD

The small pavilion-bridge shown in Fig. 3 exhibited wide cracks after the high water relief. The natural restitution of foundations as well as changes from remedial works have been monitored since 2002. Three independent quantitative measurement systems have been installed: i) a set of fixed point for mechanical extensometer measurements, ii) LVDT sensors for continuous measurement of temperature and crack movement, and iii) a geodetic measurements system.

Very classical gypsum brittle strips were also made across the cracks. The measured results help to decide about the proceedings of remedial works and checked the efficiency of adopted measures, Fig. 7.

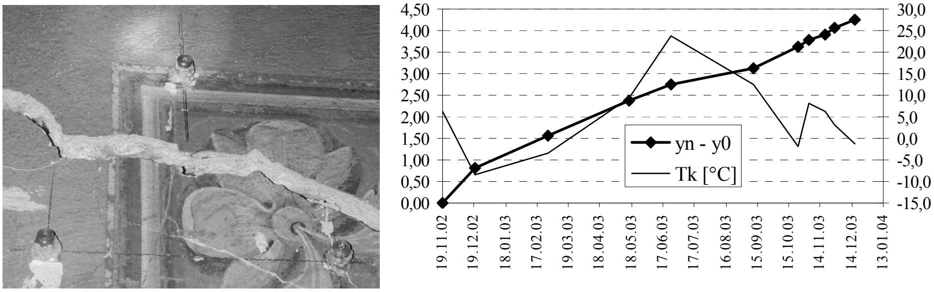

Figure 7: Fixed-points base for extensometer measurements and results after one year monitoring (differential vertical movement (closing) of the measured crack and relevant temperatures).

5 LESSONS & MITIGATION MEASURES

The most danger threat for historic stone arch bridges represented huge floating piles of material which created barriers with consequent hydraulic problems causing undermining of foundations. Even though this danger decreased due to above mentioned reasons, it is still necessary to be prepared for fighting with floating objects and ice which might block free flow through the bridges. In modern times the ice barriers are blasted if necessary and the floating objects are removed from the water by means of mechanical excavators.

The impact of floating objects on the bridge structure can be softened by ice breakers installed in a distance in front of the stone cutwater edges of the bridge piers.

The historically most damaging undermining of foundations has been mitigated for long by means of various protective structures surrounding the foundations and the piers. In addition to those which had been introduced during the construction of a bridge, improving and protecting measures involve mainly caisson collar walls around the foundation and the bottom masonry layers of piers. In some bridges the walls extend above the water and the whole structure creates small islands around the piers, e.g. in Regensburg, Fig. 8. Here the historic islands' perimeter walls are from oak piles and the space between them and the masonry is filled with stone material covered on the top with stone ashlars. This structure has been now protected with sheet piles and reinforced concrete.

The piers are protected with cutwaters which were frequently jointed together by means of iron cramps, (seen in the Fig.8). The outer stone ashlars of cutwaters were damaged or even extracted by ice friction, especially when the bridge was not maintained and the stones were released by growing vegetation. Therefore, a regular and proper maintenance belongs among the basic and most important mitigation measures protecting bridges from flood adverse effects.

A typical foundation of stone bridges used timber grids from massive beams jointed together with carpentry joints, usually extended with timber boxes from squared logs, which were sealed with clay and emptied by pumping water with bucket wheels. The piers were then built directly on river bed gravel with a layer of lime mortar or clay (Cihla & Panáček, 2006).

Recent catastrophic flood in 2002 tested the resistance of the oldest medieval bridges against dynamic forces of high water. The bridges of a quite low height survived successfully, even though they were frequently over-flown. It seems that the height of bridge above the water level was not so important as the quality of foundations and the subsoil conditions. However, the bridge in Písek (see Fig. 5) that resisted in the 2002 flood high water reaching 2 meters above the bridge deck was substantially restored in nineties. During those work the piers were anchored into the rock and, therefore, its original strength cannot be assessed. Let us only remind that this bridge had not exhibited any large extent failure during his nearly seven hundred years of function. Similarly, the bridge in Regensburg which is not founded on the rock but its foundations have been very well protected had never failed (except of at forced events during wars when some arches were blown up). On the other hand, the both historic Prague bridges mentioned above suffered very much during high water disasters because i.a. the foundation situation in Prague is not very favourable.

Figure 8: The medieval bridge in Regensburg with protective islands, stone cladding and iron cramps.

In contemporary management of high water situations the most endangered elements of historic bridges are their parapet walls (and sculptures standing on piers). Their early dismantling before the flood seems to be the most effective protection of these structures. It requires a perfect documentation for subsequent restoration works.

From the non-structural protection point of view, a suitable hydrophobic surface treatment helps to reduce a deep wetting of the structural material, and a deposition of harmful substances and biological agents. Possible salt problems are to be treated as has been mentioned above.

6 CONCLUSION

Historic stone arch bridges document a very high technological level of our historical periods which we are sometimes inclined to underestimate. Their partial failures during natural disasters, namely flood help to acquire a deeper knowledge into their materials, structure and behaviour, which supports development and adoption of adequate protecting measures in order to safeguard these admirable engineering works to future generations.

ACKNOWLEDGMENT

The authors gratefully acknowledge support from the Institutional Research Plan AV0Z20710524 and the EC 6th FP grant CHEF.

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