Preventive Measures for the Protection of Architectural Heritage Structures against Flooding

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Vorbeugende Maßnahmen für den Schutz historischer Bauwerke und Anlagen gegen Hochwasser
Der Aufsatz erläutert typische konstruktive Methoden, die für historische Bauten, bauliche Anlagen und Kunstgegenstände im Hinblick auf ihre besondere Gefährdung durch Hochwasser entwickelt wurden. Das historische Bauerbe wird hierfür in fünf Kategorien eingeteilt: 0: Gegen Hochwasser widerstandfähige Strukturen, 1: Strukturen aus Materialien mit hoher Volumenausdehnung bei Feuchtigkeit, 2: Konstruktionen aus Materialien, die bei Feuchtigkeit erheblich an Festigkeit einbüßen (einschließlich Böden), 3: Konstruktionen, die für partielle Schäden bei Hochwasser anfällig sind, und schließlich 4: Konstruktionen und Elemente, bei denen die Gefahr des Einsturzes oder des Wegschwemmens durch Hochwasser besteht. Für jede Kategorie und ihre typischen Schadensphänomene werden geeignete präventive oder restaurative Maßnahmen benannt, einschließlich einiger Empfehlungen zum generellen Risikomanagement. Dabei werden der jeweilige Zustand historischer Strukturen, die häufig wiederholt von Hochwassern betroffen waren, und die Geschichte früherer Interventionen berücksichtigt, denn Erfahrungen bei den jüngsten Hochwasserfällen zeigen eine enge Abhängigkeit der Schadensbilanzen von früheren Restaurierungsmaßnahmen und vom Vorzustand der geschädigten Bauwerke. Schließlich werden Beispiele bewährter traditioneller Vorsorgemaßnahmen erwähnt. Der Bericht basiert auf den Ergebnissen des EU-geförderten Forschungsprojektes „CHEF – Cultural Heritage

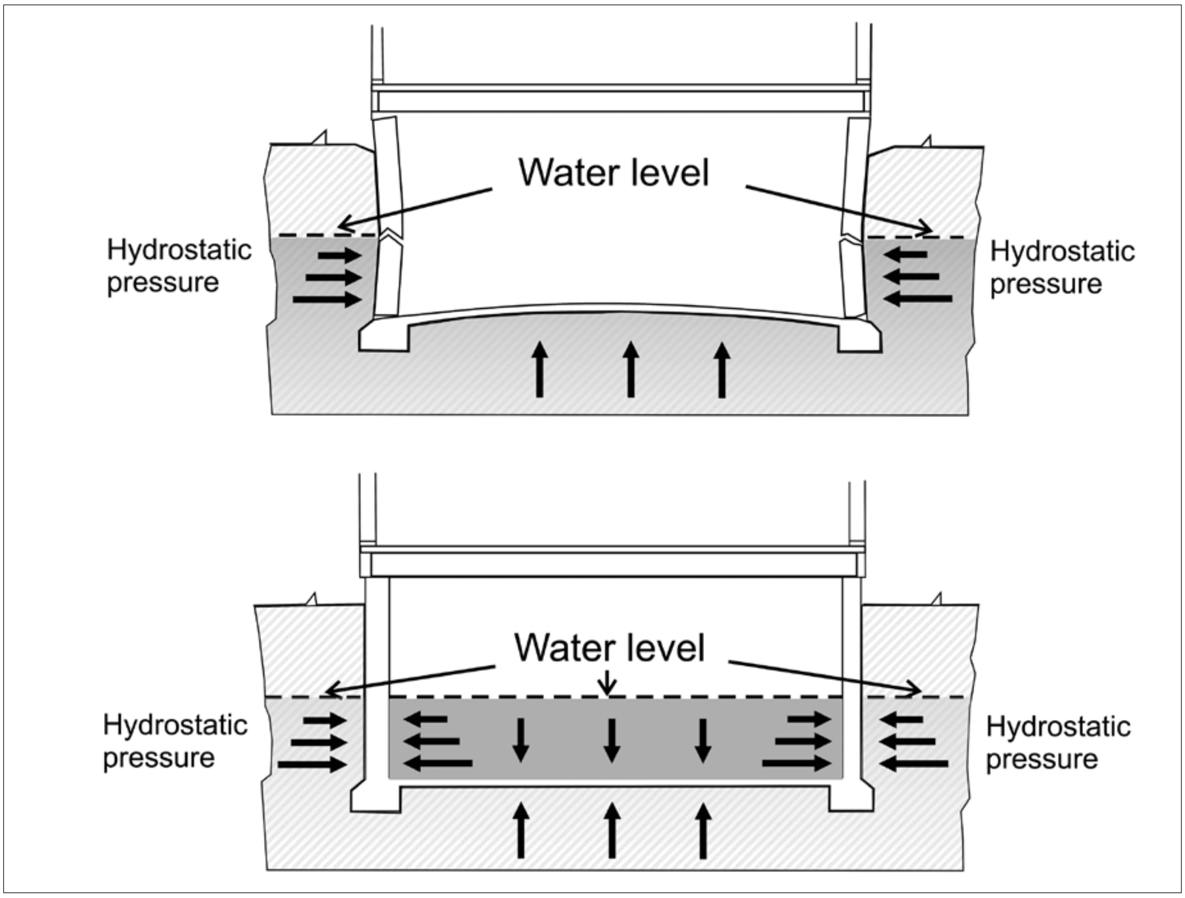

Fig. 1: Principle of preventing damage to basement floors and walls caused by external hydrostatic water pressure by means of balancing interior water flooding

Protection against Flood" (koordiniert von der Bundesanstalt für Materialprüfung Berlin), und auf den Erfahrungen, die die Autoren bei zahlreichen Begutachtungen historischer Baustrukturen sammeln konnten, die bei den zentraleuropäischen Hochwasserereignissen in den Jahren 2002 und 2013 beschädigt worden waren.

1. Approach

Preventive measures for the protection of built heritage are typically divided into two categories: structural and non-structural, i. e. more organizational or operational (Drdácký et al., 2007). Structural measures are sometimes difficult to implement in the case of cultural heritage protection, because they are mostly visible and disturbing, and often not cost-effective. The application of standards to protect cultural heritage from flooding leads to the problem that the originality, authenticity and aesthetic qualities and values of historic monuments should not be compromised. However, in practice no European standard is available for effective protection of cultural heritage against flooding. Nevertheless, standardization of some preventive processes and procedures, e. g. mapping and monitoring, would certainly bring positive results.

Best practice is usually difficult to generalize in a sufficiently informative way. Some basic principles which have proved to be efficient can be learnt in various forms and from various media (e. g. proceedings of specialized conferences). Let us summarize four pillars for the general mitigation of any adverse natural disaster effects on cultural heritage according to the World Institute for Disaster Risk Management (USA):

i) regular inspection and careful maintenance of the historic stock and improved land-use planning and management;
ii) raising awareness and regular coordinated training;
iii) international cooperation and availability of funding;
iv) legislative support.

Fig. 2: Protection of bridge piers' foundations against undermining by means of small islets with a paved upper surface – a historical example in Regensburg (Bavaria)

Structural strategies and measures reducing flood action are suggested and designed selectively according to the ranking of structures and elements vulnerable to flood effects, as defined by the author elsewhere (Drdácký et al., 2011). Let us summarize them again:

0 Flood-resistant objects and structures
1 Objects and structures of materials with high moisture volumetric change
  · Timber structures and elements
  · Combined structures of different moisture expansion materials
  · Some soils
2 Structures of materials whose strength is highly degrading under moisture
  · Dried brick (adobe) masonry
  · Masonry with clay (low lime or cement content) mortars
  · Decayed timber structures and elements
  · Infill subsoil and fine particle subsoil
3 Structures susceptible to partial damage due to flooding
  · Timber parts prone to uplifting and floating away
  · Large bridges
  · Pavements
4 Structures and elements vulnerable to overall collapse or displacement due to flooding
  · Small bridges and walkways
  · Free standing walls
  · Light improperly anchored objects (summer houses, etc)

2. Strategies and Measures

2.1 Historic Comments and Introduction

Guidelines or instructions how to behave during flood events are quite old and they mostly concern non-structural measures. In the Czech lands the first known case is from 1538 and is particularly focused on protection of ponds or lakes. The next governmental document is from the year 1542 and concerns river weirs which should be "opened during high water".

All historic floods, including the most recent ones, ought to be carefully analysed in order to learn how to improve flood management and preventive as well as post-event measures. Such examples are reports by Thieken et al. (2005) or by Messner and Meyer (2005). A guide for the assessment of flood damage of cultural heritage properties has been suggested by Kelley (1994), based on the 1993 Mississippi flood experience. Some flood consequences on Norwegian cultural heritage were analysed by Mattsson and Oftedal (2004).

There were several projects on flood-risk management supported by the European Commission (EC), for example the very detailed project FLOODsite which contains some tasks focused on mitigation of flood damage, but without specific relation to cultural heritage. For instance, the damage evaluation systems and methods do not consider intangible cultural or environmental and natural heritage values. In fact, general non-structural measures mostly contribute to the protection of cultural heritage, too. This paper takes advantage of the EC joint international project CHEF (Cultural Heritage Protection Against Flooding, see Drdácký 2010a).

2.2 Regular Inspection of Structural Health

Regular inspection of structural health concerns all categories of cultural heritage objects endangered by possible flooding. Special attention is to be paid to the structural integrity of structures such as dams, namely in relation to historic water works (ponds and channels), and bridges, especially when they are small and of light or water-saturation-sensitive materials.

Defects and deficiencies identified during regular inspections must be repaired as soon as possible in order to keep historic objects well maintained and "healthy". In many cases maintenance requires restoration interventions involving consolidation or strengthening of materials and structures. Such works should be done appropriately, taking into account and assessing possible negative effects during emergency situations. The issue is discussed below in detail.

2.3 Emergency Plans and Guidelines

Emergency plans and guidelines – which must take into account all categories of cultural heritage objects including movable heritage – are the most important preventive measures, reducing the damage or loss substantially. In fact, in the last floods the majority of damages to cultural heritage was experienced in movable heritage, which could have been totally saved if proper evacuation plans had been elaborated (and the warning had functioned reliably).

In the case of the built environment, most guidelines are based on the principles of comprehensive flood-risk management which takes into account that absolute flood prevention is unachievable and unsustainable because of the high costs and inherent uncertainties. Thus management aims at controlling the hazard on the one hand and lowering the vulnerability on the other hand (e. g. Hooijer et al. 2002).

A very instructive guide, "Preparing for Floods", was issued by the UK Office of the Deputy Prime Minister in 2003. It focuses on ways to improve the flood resistance of domestic and small business properties. Examples of guidelines specifically oriented to cultural heritage in relation to natural disasters are the guide prepared by ICCROM or the more recent publication "Before and After Disasters" (FEMA 2005).

Flood guidelines usually give advice on how to save lives and property without taking into account cultural assets, especially when these are not in permanent use. This proved to be true during the recent flood in Bulgaria (Thieken et al. 2005).

All emergency plans must also contain maps of cultural heritage located in the flooding zone with clearly categorized vulnerability and needs for emergency measures. Relevant transport means must be ensured for evacuation of movable heritage and adequate storage facilities prepared.

Fig. 3: Preventive restoration impact on the damage of monuments in the Château Veltrusy Park, near Prague: a) an appropriately restored bridge and sculpture, b) incorrectly restored sculpture

2.4 Early Warning and Information Systems

As mentioned above, early warning and information systems represent the most important element of flood mitigation measures, as they affect all categories of cultural heritage objects. The majority of, if not all, flood damage to movable heritage in Prague and Central Bohemia in the year 2002 was a consequence of totally ineffective warning and information services.

2.5 Pre-prepared Technical Means against Flooding

Pre-prepared technical means against flooding are designed to prevent water inflow into the cultural heritage buildings or into the vicinity of such buildings. They are mostly a part of integral protection measures for a settlement and typically they encompass stable walls and dams with moving gates or temporary walls that can be easily installed. To this category also temporary barriers used for tightly closing door or window openings by means of special shutters or bags with sand belong. The technical means are generally applicable for all categories of objects. However, their appropriateness must be checked against concrete conditions and conservation requirements.

2.6 Temporary Strengthening and Additional Supports

Temporary strengthening and additional supports may be required in cases of free standing sculptures or walls. In the latter case such measures should be combined with the execution of new inlet openings which help to balance the water pressure along both sides of a wall as well as with emptying the space behind the wall. The additional supports must not promote the creation of dams caused by floating objects. Strengthening is used to increase the resistance of existing doors or light walls.

Among the measures in this category we also consider surface protection of materials vulnerable to effects of washing out, e. g. adobe walls or bricks, infill layers and earth dams, as well as frescoes and similar surfaces. Such protection is of importance also for stone walls with clay mortars, especially if used as retaining walls, where usually additional support is needed.

2.7 Decreasing Load

Measures decreasing the load of water pressure, both static and dynamic, are applied to protect mainly bridges, free-standing walls, and floors. It is recommended to dismantle parapet walls or rails as well as to remove sculptures on bridges in order to decrease the surface acting against the water flow. This helps not only to save the parapet walls and sculptures but also the bridge itself. In free-standing walls the above mentioned temporary openings allow the balancing of water pressure. This measure is also useful for protecting the ground floor walls of buildings if they are highly or fully flooded (Fig. 1). Here, also openings into the floor structure may be recommended in order to decrease the uplift forces which may damage not only the floor but the whole object.

Significant forces can be generated by volumetric changes of water-soaking materials, namely by timber elements. This can be prevented by cutting sufficient dilatation gaps on the ends of timber beams or floors in order to allow their expansion without damaging the surrounding masonry.

Among the measures in this category we should also mention the necessity to remove from attics and floors all materials which are susceptible to water and could increase the load of ceilings after the high water relief, e. g. high layers of hay or insulation mats capable of trapping fine mud. It is also recommended to temporarily support massive timber ceilings which may exhibit excessive deformations due to water saturation of wood and infill.

2.8 Improved Anchoring

Improved anchoring of sensitive structural parts in supporting structures protects objects which may flow away, such as light bridges and walkways, timber roofs, small timber structures and houses.

2.9 Removal of Floating Objects

Floating objects are very dangerous for bridges and should be removed from the stream. They may damage bridges as well as other objects in the water by impact and they can accumulate before a bridge or other obstacle, thereby creating "dams" that increase the water pressure and can even elevate the water level.

3. Permanent and Temporary Structural Measures for Immovable Heritage

3.1 Flood-resistant Objects and Structures (category 0)

Even flood-resistant objects and structures require specific preventive or temporary measures. If located at sites with a high probability of inundation they presumably have had to survive several historic floods and the best way to protect them seems to be keeping them as much as possible in the state which has proved to be flood resistant. This is valid especially in the cases of very high water when it is not possible to avoid the flooding of the interior.

However, such objects may be immersed in shallow water during flood situations, too, and their external as well as interior structures, materials and artistic decorations are then in danger of watering. Protective measures start with attempts of tightening all inlets with temporary or built-in shutters for doors and windows. They may need to be combined with the strengthening of glazing and the erection of sandbag barriers. Floor structures are to be temporarily reinforced and supported against water pressure uplift forces.

Further, it is absolutely necessary to reduce the pollution of flooding water to a minimum. Therefore, all openings in the sewer system must be closed and tightened; this may be supported by automatic one-way pipe valves.

However, all these objects may carry important cultural heritage details or information which could be seriously damaged or lost due to flood action. Artistic details, wooden floors, surface paints or frescoes as well as just a naked surface of natural stone may suffer from physical, chemical or biological attack during and after flooding. If acceptable, the surfaces of sensitive artistic objects can be pre-treated by hydrophobic agents or prevented from direct action of the high water by means of wrapping them into tight plastic foils.

In the case of full flooding, it is recommended to open, unhinge and store the doors; otherwise high water will do it and the floating door wings may block other openings during the water decline.

The objects must be guarded and protected against vandalism and theft during flood situations, because the flooded objects are often easily accessible by boats and through windows on levels of higher, usually inaccessible floors.

Evacuation of furniture and other moveable objects, e. g. books from cellar and ground floor spaces, must be planned and controlled in a way which prevents possible overloading of floor structures due to an inappropriate increase of live load in the upper parts of a building.

3.2 Objects and Structures of Materials with a High Moisture-Induced Volumetric Change (category 1)

Timber structures and elements

When wetted, massive timber elements, such as joists or logs, expand differently in all directions. If such elements are freely supported this geometrical change is more or less reversible and after drying the massive elements regain almost the same form as before wetting. On the other hand, plated wooden elements not only expand but usually distort. They never return to their original shape by simple drying. Therefore, such structures are to be evacuated, if possible. The floors represent a special case, being usually composed of wooden elements assembled frequently in several layers of non-coincident wood-fibre orientation, which helps to prevent severe distortion. The floors tend to bow; this can be prevented by means of creating sufficient dilation gaps along the perimeter of the floor between the floor structure and the walls.

Combined structures of materials with different moisture expansion

The floor between masonry walls is an example of a combined structure in terms of flood behaviour. In fact, any structure combining timber elements with masonry is subject to different moisture expansion. Wetting causes expansion and if this is constrained an excessive deformation or even a failure occurs. Thus the only possible preventive measure consists of creating dilation gaps and free supports. The forces created by expanding wood can reach quite high values which may easily destroy masonry. Therefore, this type of risk must be carefully evaluated and adequately dealt with.

Soils

Expandable soils, e. g. clays, may cause defects to building foundations and/or damage geotechnical structures. They usually react slowly and the adverse effects occur with delay; so in this case a fast drainage during and after the flood helps to control the soil behaviour. Relevant preventive measures are suggested below.

3.3 Structures of Materials whose Strength is Highly Degrading under Moisture (category 2)

Dried brick (adobe) masonry
Water saturation of dried brick has a detrimental effect on their mechanical characteristics so that adobe structures may fail very quickly, especially in situations when the wetting is accompanied by mechanical action of a water stream. The experience of recent floods shows that adobe masonry covered with water-resistant plaster, e. g. lime mortar, sustains flooding without serious defects. Therefore, it might be recommendable to strengthen adobe masonry by temporary confining jacketing together with a surface protection against direct contact of the dried brick with water. Further, recent studies on adobe consolidation (Ferron 2007) showed positive effects of surface treatment by gelatine and ethyl silicates on wet-dry cycling. This indicates that in dangerous areas the adobe could be chemically protected, too.

Masonry with clay mortars
Brick or stone masonry built using clay mortars with low lime or cement contents is also very sensitive to flood action. Especially irregular stone multiple leaf masonry may easily lose its load-carrying capacity in flood situations. Preventive measures include the same treatment as in the case of adobe masonry.

Brick or stone masonry
Even regular burnt brick or some water-sensitive stone masonries decrease their strength due to water saturation. This loss of load-carrying capacity may reach up to about 50 % of the capacity in dry condition (Siedel 2010). Therefore, all masonry buildings in possibly inundated areas should be inspected and examined with respect to possible degradation when flooded. Particularly the load-carrying capacity of wet pillars should be assessed, and in cases of their insufficient strength they must be temporarily strengthened or additional supports must be installed. Such required measures must be included in the inundation maps and emergency plans.

Decayed timber structures and elements
Decayed timber (regardless of the biodegrading agent – fungi or insects) has typically a lower density and higher water absorption. Moreover, its strength is decreased, too. Such timber soaks quite high amounts of water, its dead load increases and the structure or structural element tends to break and collapse. It is recommended to temporarily support ceiling joists and girders. This measure also reduces excessive deflections.

Infill subsoil and fine particle subsoil
Subsoil and foundation instabilities represent one of the major threats to architectural heritage during flood situations. Here controlled and rather slow pumping of water from cellars reduces the danger of washing out fine particles and prevents considerable damage by soil packing and subsidence (Drdácký 2010b). The shallow foundation of partition walls on infill, which frequently occurs in historic architecture, can be strengthened only by underpinning or by an improvement of the infill by means of grouting.

3.4 Structures Susceptible to Partial Damage due to Flooding (category 3)

Timber parts prone to uplifting and floating away
Timber roofs, sculptures, free-standing stairs, platforms and similar objects are under threat of being uplifted and floating away. Their anchoring should be inspected, well maintained and repaired in time or even strengthened against flood effects.

Buildings of insufficient robustness
It has been observed that in particular a lack of structural robustness may have led to failures of historic or just old buildings. For example, in masonry structures such a lack of robustness is represented by missing collar beams. Structural robustness may be improved adequately by: i) a system of horizontal and vertical ties, ii) increasing the resistance of key members (member essentially important for the structural robustness in the way that failure of these members implies a failure of a whole structure or significant parts of it), iii) secondary protection of key members, and iv) invulnerable structural detailing.

Large bridges
Large bridges usually sustain floods quite well. However, they are under threat of partial damage, in particular their foundations and parapet walls (see free-standing walls). Only the foundations of bridge piers are extremely vulnerable. The undermining of foundations is a very frequent occurrence, which may cause collapse of some parts of a bridge. Undermining is prevented by improving soil characteristics under the foundations, and traditionally by means of deep barriers around piers and by creating small islets with a paved upper surface. (Fig. 2) Light chain or suspension bridges should be protected by decreasing potential water-stream loads; therefore the rails should be temporarily removed.

Pavements
The local failure of the street and river bank pavement mainly involves surface erosion caused by the water stream, infill or fine soil compacting, suffusion or internal erosion usually in areas of insufficiently compacted infill after construction activities or distribution line digging. Here again the sub-

soil characteristics may be improved by means of grouting (silicate or polymer based). Grouting may be combined with the application of grouting tubes drilled into the ground and left there as strengthening “scaffolding” after their use for grouting. Polyurethane resins are frequently used for such a preventive or remedial work. It is very important to keep the pavement surface and area in perfect condition, which is based on regular inspection and early repair or regular maintenance.

3.5 Structures and Elements Vulnerable to Overall Collapse or Displacement due to Flooding (category 4)

Small bridges and walkways
Small bridges and walkways can be preventively protected in the same way as large bridges, i.e. by measures decreasing their load (dismantling the rails and/or parapet panels). If possible, some temporary measures reducing the direct water stream actions can be taken, as well as systems built that catch floating objects. However, this category of objects is usually severely damaged or lost, therefore any precious elements or objects of art should be removed and placed in temporary stores.

Free-standing walls
In the case of free-standing walls balancing water pressure is necessary. This is usually achieved by openings allowing water to flow behind a wall. Short walls, namely the walls in lower floors of buildings can be temporarily strengthened in an effective way.

Walls built with an axis perpendicular to the main water stream direction are to sustain pressure loads which are higher than the pressure from simple immersion not only due to the dynamic action of the mass of water. The water depth is increased by the backwater effect which may substantially contribute to the water pressure and must be taken into account when designing the strengthening of temporary cellar or ground floor walls.

Parapet walls on bridges may be dismantled and after the flood built up again. In any case, a detailed documentation and even the marking of individual stones are useful for an easier assembling after a possible failure.

Light improperly anchored objects
Light objects such as summer or garden-houses should be properly anchored to their foundations. In the case of flooding they are very likely to be swept away and it is recommended to evacuate all moveable objects of art and architectural details which could otherwise be lost.

4. Effects of Inappropriate Conservation and Neglected Maintenance

Several examples of recent damage to cultural heritage monuments due to natural disaster effects clearly show a very close dependence of the extent of damage on previous restoration interventions and on the healthy condition of the damaged monument (Drdácký et al., 2007).

Z. Slížková analysed damage to historic objects in the Château Veltrusy Park near Prague which were severely damaged by the flood in 2002. There was a remarkable difference between objects which had been properly restored before the flood, e.g. a stone bridge with Sphinx (Fig. 3a), and objects which were neglected or incorrectly restored, e. g. sculptures on the Château’s monumental stairs (Fig. 3b). Even though the bridge was totally immersed in a high water stream, it only needed to be cleaned with water and low pressure steam. In 2004, some hair cracks and slight mortar disintegration were visible in masonry joints. After the next flood in 2006 the bridge was only slightly restored (colour retouching, plaster repair).

On the other hand, the sculptures were repaired long before the 2002 flood by applying Portland cement and polyvinyl-acetate consolidation, which substantially decreased the water and vapour permeability and kept the water inside the material. This increased the contamination with salts, biocolonization, surface detachment, and disintegration patterns up to a height of three metres. Freezing, moisture dilation and crystallization damage required a very substantial restoration intervention after the flood.

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