APPLICATION AND FEEDBACKS OF GABION STRUCTURES IN FLOOD STORAGE PROJECTS FOR THE PROTECTION OF URBAN AREAS AND INFRASTRUCTURES

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Abstract*:*
The paper focuses on the application of gabion structures in river control and particularly on transversal gabion weirs and spillways in flood storage projects. Storage has the general effect of attenuating the flood hydrograph, reducing its peak flow rate and spreading the volume out over a longer time span; this effect may be natural or engineered as part of a flood alleviation scheme. Flood damage on a river can be significantly reduced by construction of one or more reservoirs: where a reservoir site immediately upstream from one damage center provides more economical protection than local protection works, reservoir flood storage should be considered. Flood storage works can be online: in which the water is temporarily stored within the river channel and its floodplain or offline: in which the water is diverted from the river channel, stored in a separate area (which may be part of the floodplain) and subsequently released back to the river or to another watercourse. In general, online storage works are normally located in the upper catchment (where the catchment area is modest) while offline storage works are more common on larger rivers with wide floodplains. The paper illustrates some applications of gabion structures in offline flood storage projects executed in Italy and France.

Keywords: gabions, spillway, flood storage

1. INTRODUCTION

There is a wide range of structural and non-structural measures available to designers and/or managers of the operating water authorities to reduce the probability of flooding, the magnitude of the flood itself or the impact level of the inundation [1]:

- Source control: measures that reduce the likelihood of high flows/water levels occurring (i.e. detention basins, permeable paving, wetlands)
- Pathway modifications: measures that modify or block the pathways taken by floodwater to a site (i.e. ground raising, construction of diversion channels)
- Receptor resilience: measures that reduce the vulnerability of receptors to the impacts of the flow (i.e. flood forecasting and warning)

Detention basins (also called storage reservoirs) offer one of the most reliable and effective methods of flood control: a certain volume of the reservoir is kept apart to absorb the incoming flood; further, the stored water is released in a controlled way over an extended time so that downstream channels do not get flooded.

There are two basic methods of storing flood water [2]:
● Online storage works: on the same alignment as the watercourse with a dam constructed across the river

● Offline Storage works: off the river alignment, with a bounded basin adjacent to the river or a tributary emptying into the river

1.1 On-line Storage Works

The components of on-line storage works include
· an impounding structure: generally an earth or concrete structure across the river and floodplain, behind which the water is stored;
· a flow control structure: generally set in the impounding structure, to control the outflow from the storage area.
The flow control structure can be a fixed throttle (such as a flume or orifice), sized to have little effect on normal flows, but requiring a significant rise in upstream water level to discharge flood flows. Such arrangements also require an overflow weir or spillway to cater for extreme events, which would otherwise lead to the safe water level upstream of the impounding structure being exceeded.
Often, the control structure incorporates gates, which are normally left open, but are operated during floods to ensure that downstream flows do not exceed the design flow of the downstream flood defences. Again, the operation rules need to cater for extreme events, which could overwhelm the impounding structure. If this is likely to occur, the normal response is to increase the outflow and accept that some damage may be caused downstream; this damage would generally be less than that caused if the impounding structure were to fail in a rapid and uncontrolled manner. This assumption, however, needs to be examined individually for each case.

1.2 Off-line Storage Works

Off-line storage works generally comprise (Fig. 1):
· an intake structure: diverting water to the storage area when the river flow or level exceeds a pre-determined value;
· a storage area: a reservoir separated from the river, formed either by low ground levels (natural or excavated) or by retaining structures (embankments and/or walls);
· an outlet structure: returning water from the storage area to the river after the flood peak is past.

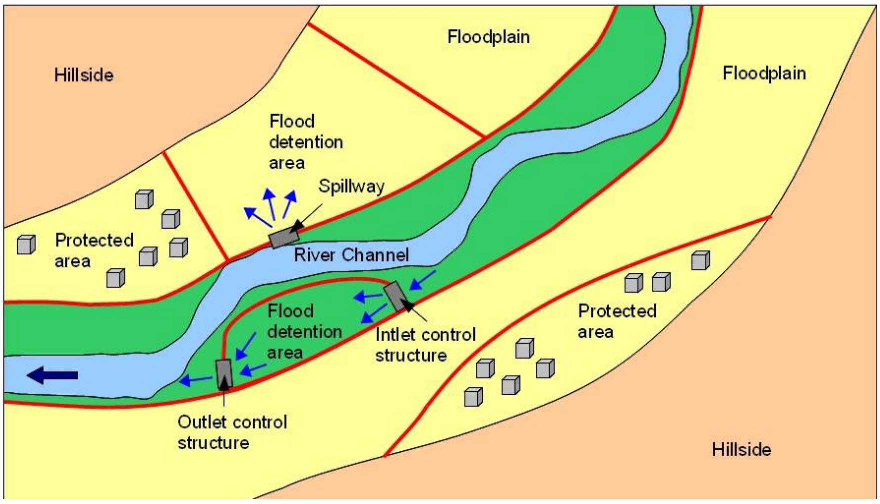

Figure 1 Flood retention scheme [1]

A gravity rather than pumped intake arrangement is normally adopted on economic grounds, as the inflow rates required are generally high and operation relatively infrequent. Weirs can

be used and have the advantage of beginning to operate whenever river levels rise above a given value. They provide no control over water levels in the storage area, however, and need to be long, if a significant discharge is required for a limited additional rise in river level. For this reason, a gated arrangement is often used.
The storage reservoir generally lies within the flood plain and is isolated from it by purpose built walls or embankments. Such storage areas are only used during floods events and are therefore normally empty for long periods of time The volume available for storage in the reservoir depends on the water depth that can be obtained, which is controlled by existing ground and peak flood levels; this depth is often limited, making it necessary for the reservoir to cover a large area. Choosing a site where the ground is low (either naturally or as a result of excavations, for example for gravel pits) increases the depth available but may mean that pumps are needed to empty the reservoir after the flood has passed. The outlet may be by gravity (generally using gates), pumped or by a combination of the two.

1.3 Spillway design

Spillway is an essential structure of a flood retention solution and it is used to provide a controlled release of water from one area to another either over the structure or through it [3]. It can be designed to derive water from the river or restore water to the river. Most often, spillways release floods to prevent overflow or damage to the dam or levee embankment. Except during high water events, water does not typically flow over the spillway. A spillway can be constructed as a low crest embankment protected against surface erosion that is linked to water flow velocity; the protection is usually made of concrete, built stone, rocks or gabions. Overflow spillways with significant head differentials will require properly shaped crests, energy dissipation structures and downstream channel protection.

1.4 Gabion diversion spillways

Diversion spillways are structures that discharge in a flood detention area or a secondary river channel. Their objective is to divert part of the flood from the main river channel in order to reduce downstream water level. The spillway is usually made of reinforced concrete, but the use of gabions and Reno mattresses is a solution which is very economical and can be used to create a resilient downstream slope; as gabions will produce an uneven crest, pre-cast concrete threshold is usually adopted to assure the required level of the spillway.
The main points to consider in the design phase are:
- to assure a waterproofing cut off in the body of the spillway;
- as with any permeable spillway surface there is a possibility that fine soil particles can be washed out of the underlying levee fill. A separation layer such as granular or geotextile filter should be always provided beneath the gabions.
- The resistance of the wire mesh units and their filling materials to high flows: according to the height of the structure and the unit flow discharged through the spillway, the water velocity at the base of the spillway can be relatively fast (several meters per second) and possibly lead to displacements of the filling stones and excessive deformations of the cages [4], [5];
- The possible abrasion and mechanical damage due to the passage of the floating objects.

For Maccaferri gabions and Reno Mattresses, based on research done at the Engineering Research Center in Fort Collins, Colorado [6], the relevant hydraulic roughness and the allowable shear stresses are shown in table 1:

	Unvegetated Roughness n	Unvegetated All. Shear N/m^2	Vegetated Roughness n	Vegetated All. Shear N/m^2
Gabions 0.50 m	0.0301	470	0.200	500
Gabions 1.00 m	0.0301	470	0.200	500
Reno mattress 0.17 m	0.0277	224	0.300	400
Reno mattress 0.23 m	0.0277	268	0.300	450
Reno mattress 0.30 m	0.0277	336	0.300	450

Table 1: Roughness and allowable shear stresses for gabions and Reno mattresses

2. DEVERSION GABION SPILLWAY ON THE SAMOGGIA RIVER, ITALY

The Reno river and its tributary Samoggia flow through a region rich in infrastructure and agricultural activities where safety problems of rivers are of fundamental importance. The Reno-Samoggia hydraulic system was often subjected to extraordinary floods such as that in November 1999 that caused the interruption of the Bologna-Milan railway line (Figure 1).

Figure 1: The Samoggia flooding in 1999

2.1 Characteristics of the basin flood control

Following to these dramatic events, a plan for the security of Samoggia river against the centennial flood was launched by the Emilia Romagna Region for the creation of a flood detention basin on an area of 90 ha and a storage capacity of 6.3 million m^3 [7]. The centennial flow is estimated at 350-400 m^3/s. Given the morphological characteristics of the Samoggia river and the hydraulic contribution from the Lavino creek downstream the structure, the hydraulic study led to limit the flow downstream the spillway to 180 m^3/s to ensure the safety of the river. To obtain this flow reduction, a selective weir has been designed for the maximum flow of 350-400m^3/s while the excess flow is laterally discharged into the basin through a lateral spillway.

The presence of the weir will raise the water level upstream allowing the spillway to be operational for 140-150 m^3/s flows, corresponding to a flood return period of 3-4 years. The weir has been designed on the basis of experimental tests carried out at the University of Florence (Figure 2). The spillway is 90 m long and allows centennial flows (350-400 m^3/s) to partially be diverted into the basin. In the area downstream of the reservoir, an outlet control structure provided with valves will return the accumulated water into the river. To avoid the risk of overflowing the basin's levees, an emergency spillway allows water to return to the Samoggia river once the maximum basin level has been reached.

Figure 2: Physical model of the weir/spillway system

The flood retention basin covers a surface of 90 ha on the left bank of the Samoggia river and has a variable depth between 6 and 10 m. The selected area is particularly suited for this type of work because it is characterized by the presence of a thick layer of clay close to the ground level which has allowed the creation of a quasi-impermeable reservoir bottom; the waterproofing of the banks was insured either by inserting an impermeable cement and bentonite diaphragm on the existing bank or by the construction of new clayey banks.

The Emilia Romagna Region has purchased all the land covered by the basin to develop the site from an environmental point of view with the creation of wetlands, recreational areas and pedestrian routes and will be partially used for irrigation.

2.2 Description of the structures

The weir will be made of reinforced concrete with a bank protection made of gabions with planting cuttings; foundations will be made of sheet piles to avoid any possibility of piping.

The perimetral dykes of the basin were made using clay materials for the core and sandy loam materials for the shell obtained by mixing the soil in situ with 25-30% sand to allow for an optimal compaction.

For the levees exceeding a height of 7 m, the connection between the clay core and the silty shell was provided by a soil reinforcement geogrids made by high fiber protected by a polyethylene sheath tenacity polyester. (Figures 3, 4).

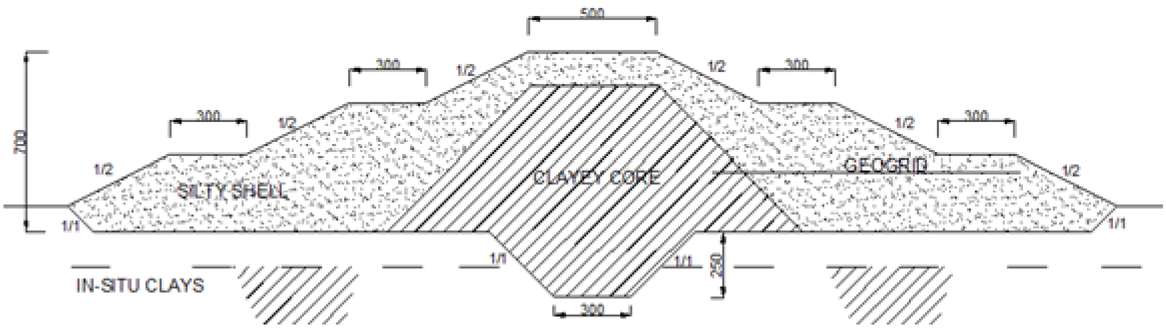

Figure 3: Cross section of the levees higher than 7 m reinforced with geogrids

Figure 4: Installation of the reinforcing geogrids

The existing banks of the Samoggia river have been reinforced and raised to the same height as the new peripheral levees; they were made with a central clay core drilled to a depth of about 2 m to be anchored to the existing clay layer below the foundation level to ensure their waterproofing.

The spillway is constituted by a compacted clay core covered by 1 m thick gabions filled with stones grading range of 100/200 mm. The lid of gabions is a three-dimensional geomat reinforced by double twisted wire mesh (Macmat-R), which has the double function to close the units and to allow for the vegetation growth, eventually increasing its resistance to hydraulic actions

The spillway is 90 m long (Figures 5, 6, 7), has a trapezoidal cross 4 m with a 2H/1V slope on both sides, with a unit flow of 2.2 m3/s/ml corresponding to a water depth of 0.25 m and a water velocity of almost 8 m/s. To dissipate the hydraulic energy a gabion stilling 6 m long was realised at the toe of the spillway.

The outlet control structure is made by reinforced concrete box culverts 2x2 m inserted in the left bank with a double gates system. The additional safety spillway security, which has to return the water of the retention basin to the Samoggia river if the basin reaches its maximum level has been realised on the existing bank and it is protected by a lining made with 50 cm thick gabions.

Figures 5, 6: the gabion spillway during construction and today

The spillway and the perimetral levees were realised in 2011 (fig. 8), the other works, which allow for the effective operation of the flood retention basin are scheduled for 2015.

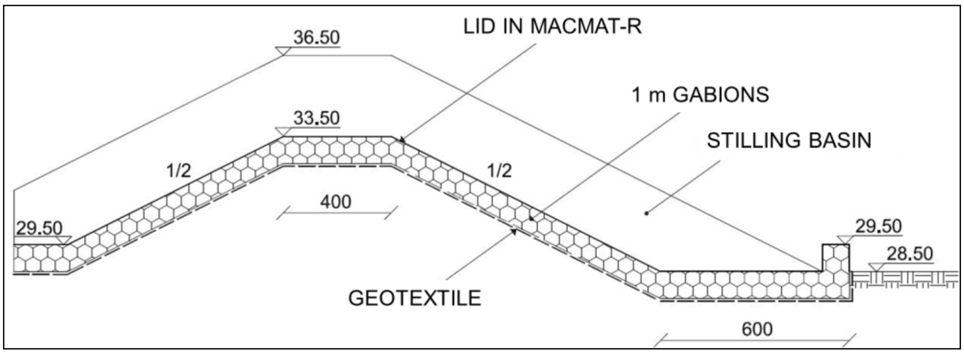

Figure 7: cross section of the gabion spillway

Figure 8: The Samoggia flood retention basin in 2012

3. GABION SPILLWAY IN LUNEL (FRANCE)

3.1 Problems and needs

As the Vidourle watershed is located in the Mediterranean climatic context, it is regularly subject to stormy rains occurring under the combined effect of warm, moist air lifts due to the presence of mountains (Massif Central) stopping clouds. These rainfall events are characterized by a very high intensity which may exceed 80 mm/h.

On 8 and 9 September 2002, during the centennial flood recorded on the Vidourle, this rainfall intensity reached between 200 and 600 mm in two days on the watershed, locally causing locally a rising water level of 2 meters in 5 hours, flooding homes and seriously affecting all municipalities in the basin (infrastructure, housing, shops ...). During this event, peak flows were evaluated up to 2400 m^3/s while the average flow of Vidourle is 20 m^3/s. These extreme events killed 23 people and caused thirty breaches on 85 km of the river basin flooding an area of 1,335 km² where 110,000 people live.

Since these events a series of measures have been taken including the action plan for the Vidourle flood prevention, based on three main measures:

- The realization of small dams for water retention in the upper part of the watershed to store the water upstream and protecting the dense urban centers against large floods
- The strengthening of the existing primary levees in order to delineate flow zones
- The creation of secondary levees with spillways to protect urban areas and housings.

This large project, initiated by improving the safety of the existing urban levees, also affected the town of Lunel either by reinforcing the existing banks and by constructing a lateral spillway on the right bank downstream the Lunel bridge.

3.2 Description of the solution

The project was aimed to strengthen the right levee between the Bas-Rhône Languedoc canal and the Lunel bridge on a length of 1.9 km, including a 500 m long spillway feeding a floodplain. The hydraulic study has allowed to calibrate the geometry of the spillway needed for a design flood of Vidourle river equal to 3,000 m^3/s; the downstream slope of the spillway has been set to 2H/1V; the total length is 500 m and the longitudinal profile presents a notch 60 cm deep and 60 m in length (Figure 9) to assure the spillway starts to function with annual floods (Q=1000 m^3/s); for flow in between 1000 and 2400 m^3/s the diverting flow is confined to the notch; for exceptional flows (> 3000 m^3/s) the spillway has been designed to globally allow the passage of 180 m^3/s, of which 90 m^3/s to the notch. The details of the unit flows along the spillway are shown at Table 2.

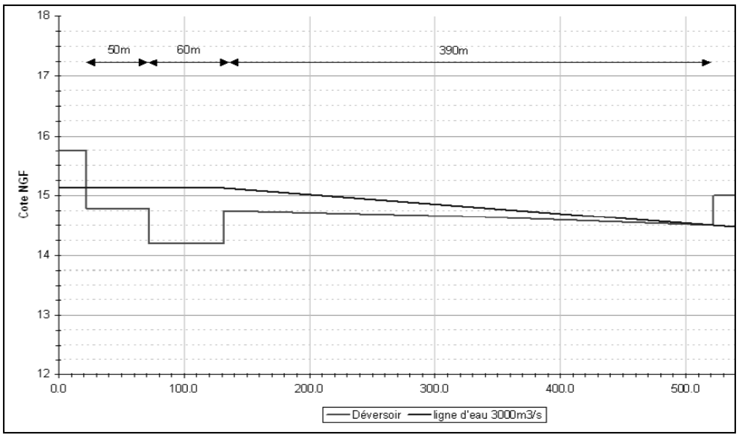

Figure 9: Longitudinal profile of the Lunel spillway for Q=3000 m3/s

Exceptional flood: 3000 m^3/s	Unit flow
Before the notch - Chainage 50	0,35 m^3/s/ml
At the notch – Chainage 100	1,51 m^3/s/ml
Immediately after the notch – Chainage 160	0,41 m^3/s/ml
After the notch – Chainage 260	0,21 m^3/s/ml
After the notch – Chainage 360	0,11m^3/s/ml

Table 2: Unit flows along the spillway

The project consists of a dam made of compacted fill, sealed on the top with a concrete anchor 1.20 m deep and 2.5m wide. On the crest, the outlet level is provided by a concrete sill to ensure the transition between the upstream and the downstream protection of the spillway. In order to protect the spillway against the shear stresses due to water, the original solution was designed with a cemented riprap revetment 1.50 m thick made of 400/800 kg along the spillway. As an alternative to this solution, France Maccaferri, on the basis of the allowable shear stresses of gabions and mattresses defined in Table 1, proposed the revetment of the spillway by wire mesh products whose thickness vary with the actual hydraulic loads: from 1 m thick gabion in correspondence of the notch to the 23 cm Reno mattresses at the end of the spillway (table 3). For the stepped spillway reference to Peyras testing [8] was done in order to determine the energy of the flow as a function of the drop height and the steps geometry. This solution has reduced the volumes of stones to be installed and to reduce earthworks to be undertaken (Figures 10, 11). The final cost of this solution, including both supply and installation, is about 40-50 €/m² for Reno mattresses and 180-200 €/m^3 for gabions, excluding the preparatory earthworks. This solution has been eventually adopted for its technical, aesthetic, environmental and economical advantages to the original riprap solution (Figure 12).

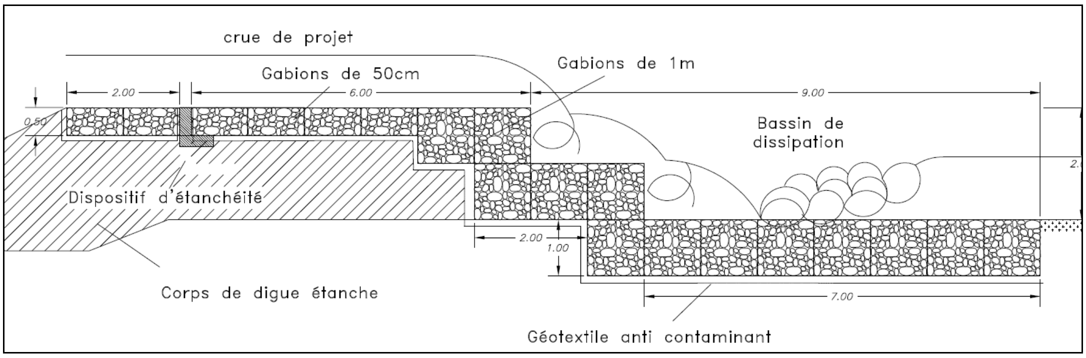

Figure 10: Cross section of the stepped gabion spillway

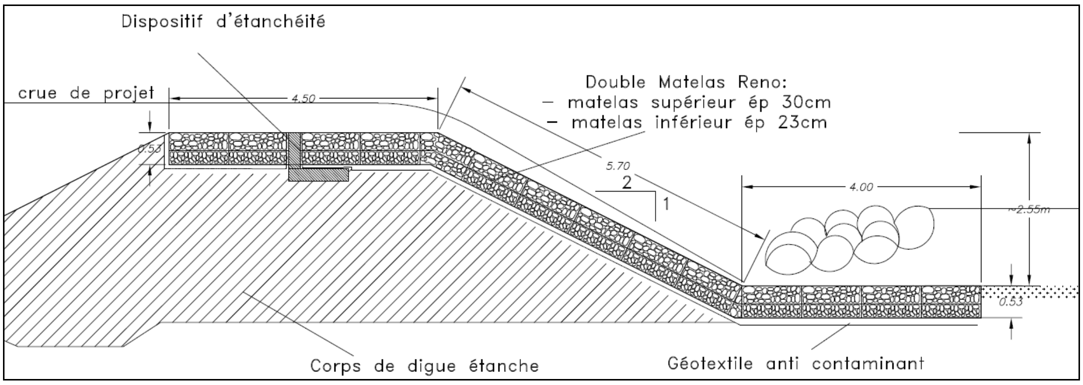

Figure 11: Cross section of the inclined Reno mattress spillway

	Water velocity at the toe of the spillway (m/s)	Height of the water at the toe of the spillway (m)	Type and thickness of the revetment	Active shear stress (N/m²)	Allowable shear stress (N/m²)
CH. 50	4,31	0,081	2 Reno mattress 30+23= 53 cm	325	357
CH. 100	4,73	0,319	Gabions 100 cm	294	500
CH. 160	4,55	0,090	2 Reno mattress 30+23= 53 cm	349	357
CH. 260	3,67	0,058	2 Reno mattress 17+17= 34 cm	256	273
CH. 360	2,85	0,039	1 Reno mattress 23 cm	175	192

Table 3: water velocities, water depths and shear stresses on the spillway for Q=3000 m^3/s

Figure 12: The completed Lunel spillway

CONCLUSIONS

The two examples illustrate the use of large sized gabion spillways for the creation of flood retention basins to assure the protection against floods of housings and infrastructures.
The use of this type of structures has allowed the use of local stone with a much smaller diameter and total volume than the equivalent solution made with riprap, always assuring the required safety of the spillway with respect to water velocities as high as 5 m/s and active shear stress up to 350 N/m^2.
Furthermore gabions and Reno mattresses have an extraordinary capability for regeneration of the natural environment, providing favorable developmental conditions: these structures act as shelter during the initial growth phase, thus allowing these solutions to provide adequate structural and hydraulic performances even when plants are not fully developed yet.

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