Designing and Building Gabion Check Dams in Burkina Faso

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Abstract

Gabion check dams (GCDs) are among the most diffused soil and water conservation practices in Burkina Faso, used to cope with soil loss and reservoir siltation. Specifically, CGDs are flexible, permeable structures built in gullies to create a sedimentation bench that decreases the average upstream slope. The consequent slowing-down of the flowing water limits flood-wave sediment transport capacity reducing soil loss upstream, reduces the amount of trapped sediment in reservoirs and promotes water infiltration into the soil. The present work provides concise guidelines for the design and implementation of GCDs in Burkina Faso. This was achieved gathering the experience developed in the frame of several cooperation and development projects led by the Italian non-governmental organization. The theoretical elements and procedural steps to perform an appropriate design and implementation of GCDs are described and discussed, including hydrological and hydraulic methods to assess stream flow characteristics, spillway functioning, siltation rate, dimensions and stability of the structure.

Keywords

Gabion check dams • Soil and water conservation • Sub-Saharan Africa • Soil erosion • Desertification

107.1 Introduction and Study Area

Soil and Water Conservation (SWC) techniques are widespread throughout Burkina Faso and are the outcome of a combination of traditional techniques to reduce soil erosion and the need to preserve reservoir storage capacity. Gabion check dams (GCDs) are semi-permeable stone bounds from 1 to a few meters high which are built in the gullies perpendicularly to the main stream-flow line (Vlaar 1992). In well-developed gullies, GCDs are weirs characterized by the presence of metallic gabions used to avoid the stone displacement caused by the high flow rates. Lying across the gully and valley bottom, the dams form an upstream retention basin that impounds flood water and traps the sediments (Grimaldi et al. 2013). The present work aims at the definition of general criteria for GCDs design and construction. In particular, it describes and discusses (i) the characteristics of the materials; (ii) the rules for an appropriate hydraulic

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verification (i.e. flow assessment, spillway functioning and stilling basin design); (iii) the static verification of the structure; (iv) the assessment of siltation rates; and (v) the construction and maintenance phases.

The region where the data were collected is situated in the Northern Burkina Faso (Province of Yatenga, Passore and Bam). The climate of the region is characterized by a rainy season from June to October (when crops are grown) and a long dry spell from November to May. The total rainfall measured at the available rain gauge stations over the last 30 years ranges from 500 to 600 mm. Data were collected between 2006 and 2012 in the framework of two European Union-funded development cooperation projects led by the Italian non-governmental organization (CISV, Comunità, Impegno, Servizio e Volontariato, Torino, Italy).

107.2 Methodological Description

A GCD is a broad-crested weir. As water passes over its spillway and down the chute to the stilling basin, potential energy converts into kinetic energy. Therefore, the spillway and the stilling basin are designed to create a controlled hydraulic jump and dissipate energy. Spillways are built using gabions while the dissipation basin is protected by rocks. The alignment of concatenate gabions ensures both permeability and structural resistance. Permeable structures can adequately cope with high internal stress and pressures while ensuring free drainage and energy dissipation. Their strength and effectiveness may increase with time as silt and vegetation fill the interstitial voids.

107.2.1 Characteristics of the Material

Galvanized steel wire, of 2.5 mm diameter, is the most commonly used material to build gabions. Gabion basket standard size is 0.5 m × 1.0 m × 2.0 m. To follow the design guidance reported in this paper, width, height and length of the standard gabions shall not vary more than 5 percent from the dimensions specified in these provisions. In Burkina Faso, locally collected stones have an average specific unit weight of 24 KN/m^3 and each basket is filled by stones with an upper boundary porosity value of 30 %. Although the stones are usually transported by means of a truck, GCDs are commonly constructed by hand.

107.2.2 Hydraulic Verification

Based on previous studies performed in the Sahel area (Gresillon and Herter 1979), a GCD must resist to the peak flow wave with a recurrence interval of 10 years. Among the methods developed in Western Africa for the assessment of the peak flow, we selected the easy-to-use approaches proposed by Rodier and Auvray (1965), and Rodier and Ribstein (1988). The former method refers to catchment areas ranging from 10 to 120 km^2, while the latter is applicable to catchment areas ranging from 2 to 10 km^2. Both methods are based on the evaluation of the discharge consequent to a maximum daily precipitation with a 10-years return period. The main parameters required are the area of the catchment, its average slope and the soil hydraulic permeability. Using these data, the duration and the volume of peak flow are estimated. In the model the peak flow of the 10-year return period is then expressed by Eq. (107.1):

$$Q_{r10} = A \cdot P_{10} \cdot \mathrm{k}_{r10} \cdot \alpha_{10} \cdot \mathrm{S}/T_{b10} \qquad (107.1)$$

where A is the peak coefficient, α_{10} and $\mathrm{T}_{\mathrm{b10}}$ are the dimensionless shape coefficient and the base time of the 10-year flow hydrograph, respectively, $\mathrm{k}_{\mathrm{r10}}$ is the overall runoff coefficient, P_{10} is the 10-year rainfall and S is the drainage area. Rainfall data series are used to estimate P_{10}, whilst for A, α_{10}, $\mathrm{T}_{\mathrm{b10}}$ and $\mathrm{k}_{\mathrm{r10}}$ were obtained from graphs and tabulations reported in Rodier and Auvray (1965) and in Rodier and Ribstein (1988).

The peak flow assessment provides information regarding the dimensions of the spillway and the dissipation basin, as well as water levels (y_i) at different locations. Based on hydraulic theory and practice, the width $\mathrm{L_s}$ of the crest of the spillway is computed using Eq. (107.2).

$$L_s = \frac{Q_{r10}}{dy_c^{1.5}} \qquad (107.2)$$

where y_c is the hydraulic head over the spillway and d is a discharge coefficient. Since GCDs are broad crested weirs, a commonly used value for d is 1.82. Infiltration flow through the porous structure is neglected and the total peak flow with 10 years return period Q_{r10} is conservatively assumed to be totally discharged by the weir.

The total water depth y_{tot} immediately upstream of the structure is obtained by summing up the hydraulic head y and the height z of the weir (Fig. 107.1). According to the hydraulic theory, the higher y_{tot} the larger the upstream extension $\mathrm{L_{up}}$ of the affected water profile. This latter can be assessed using the Eq. (107.3):

$$L_{up} = m(y_{tot} - y_{up})/i_f \qquad (107.3)$$

where y_{up} is the depth of the unaffected upstream water flow; i_f is the average river slope; and m is an empirical coefficient defined in Table 107.1.

The Northern Burkina Faso has a flat morphology and the average river slope ranges from 0.3 to 0.5 % (Grimaldi

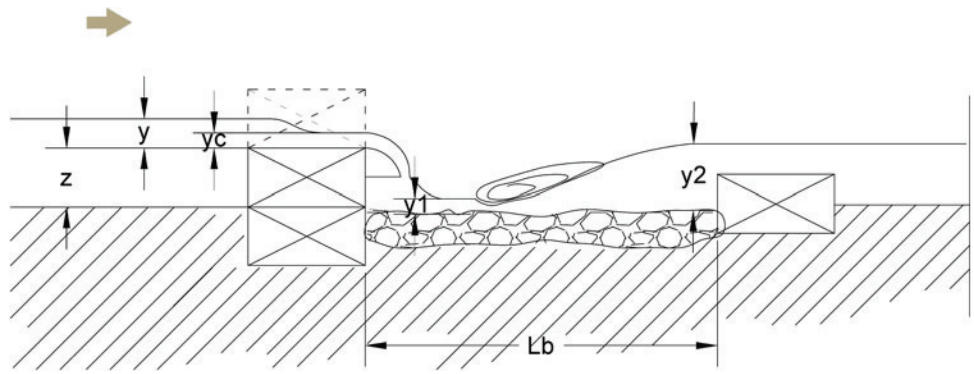

Fig. 107.1 General GCD schematization in Burkina Faso, showing water flowing on the weir spillway and the stilling basin formed by an end sill. For an explanation of hydraulic variables and abbreviations, please refer to equations in the text

Table 107.1 Empirical coefficient m related to different ratio y_{tot}/y_{up}

y_{tot}/y_u	1.1	1.2	1.4	1.6	1.8	2.0	3.0	5.0
m	6.5	4.5	3.0	2.4	2.1	1.9	1.5	1.25

et al. 2013). Nevertheless, gullies incision might be locally negligible thus allowing the frequent inundation of large floodplain areas. Consequently, limiting y_{tot} is a crucial measure to prevent the overflow or the by-passing of GCDs (Durand 1996). The crest width L_s and height z should be adjusted consequently. As a rule of thumb, L_s is approximated to the width of the river bed, whereas z may range from 0.5 m to 1 m to limit the upstream backwater effect.

The upstream subcritical flow experiences a critical state y_c over the weir thus becoming supercritical y_1 downstream (Fig. 107.1). Its potential energy is converted into kinetic energy and Eq. (107.4) can be used to compute the depth of the downstream flow. Hydraulics theory provides appropriate equations and abacus for y_c (UACE 1995; Geyik 1986).

$$\frac{y_1}{y_c} = \frac{2}{1.5 + \sqrt{2\left(\frac{z}{y_c} + \frac{3}{2}\right)}} \tag{107.4}$$

The *kinetic energy* subsequently *dissipates* in a turbulent *hydraulic jump* that provides an abrupt transition to downstream subcritical flow. Its depth y_2 is computed using Eq. (107.5):

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1 + 8Fr_1^2} - 1\right) \tag{107.5}$$

where Fr_1 is the Froude number of the downstream flow. To dissipate the water kinetic energy in the stilling basin, the total length of the basin L_{basin} can be computed using Eq. (107.6).

$$L_b = 6 \div 8(y_2 - y_1) \tag{107.6}$$

To limit the value of L_b, practical solutions are listed in literature (Geyik 1986; UACE 1995). The stilling basin must be protected by a layer of rocks in order to avoid scouring effects as a consequence of the hydraulic jump. Rocks displacement is avoided downstream by a sill, built aligning concatenate gabions.

107.2.3 Static Verification

The appropriate design of a GCD requires static verifications to be performed referring to both the initial (i.e. empty) and steady (i.e. filled with sediments) scenarios. All the forces acting on the structure (e.g. gravity, hydraulic load, soil load) must be computed in order to verify the state limit conditions against (i) sliding; (ii) overturning; (iii) bearing; and (iv) piping failure (Geyik 1986). Since GCDs in Burkina Faso have small dimensions and high mass moment of inertia, they are mainly threatened by piping failure. For brevity the piping failure test for small GCDs is herein reported.

The seepage phenomenon can provoke the formation of springs downstream of the structure. Substantial spring flow transports particles of soil, creating cavities underneath the foundations. In order to test the weir against this possibility of piping failure, the seepage flow net has to be empirically determined. The test against piping failure can be generally accomplished using the simplified Bligh-Lane method (USBR 1987). Specifically, the structure is safe when the relationship reported in Eq. (107.7) is verified.

$$L_{tot} > c \times \Delta h \tag{107.7}$$

where, L_{tot} is the seepage path below the structure (in which the length of horizontal segments is divided by three), c is a coefficient depending on soil characteristics (Table 107.2), and Δh is the water level difference between upstream and downstream the weir. If the above mentioned relation is not

Table 107.2 Values of the Bligh-Lane coefficient (c)

Typo of soil	Coefficient c	Size of particle (mm)
Fine silt and sand	8.5	<0.125
Fine sand	7.0	0.125 ÷ 0.250
Sand	6.0	0.250 ÷ 0.5
Coarse sand	5.0	0.5 ÷ 2.0
Fine gravel	4.0	2 ÷ 8
Gravel	3.5	8 ÷ 16
Coarse gravel with cobbles	3.0	16 ÷ 130
Cobbles with gravel	2.5	130 ÷ 250
Plastic clay	3.0	<0.005
Compact clay	2.0	<0.005
Hard clay	1.8	<0.005

verified, then the CGD section should be modified by lengthening of the seepage path (i.e. possible solutions include building a gabions' apron downstream or a cut-off below the structure).

107.2.4 Siltation Rate and Design of SWC Interventions

The statistical analysis, carried out in Grimaldi et al. (2013), assessed the averaged annual siltation rate (ΔV) of a single GCD as reported in Eq. (107.8):

$$\Delta V = \alpha \times A_v \times if_0 \times d_{50} \tag{107.8}$$

where α is the constant term related to the area of interest; A_v is the vertical area of the SWC work; if_0 is the average original slope of the riverbed; and d_{50} is the mean value of the grain size distribution. Referring to Northern Burkina Faso, field data analysis pointed out $\alpha = 2{,}500$, for which A_v is expressed in square meters and d_{50} in millimeters (Grimaldi et al. 2013). This result can be useful to assess the effectiveness of SWC works to design land management plans at a catchment scale for both preventing soil erosion and reducing reservoir siltation.

107.2.5 Construction Phases and Maintenance

The work construction phases include the involvement of local communities, the choice and the organization of the worksite, and the maintenance planning. Stones are collected and piled up by villagers and the amount of labor invested in constructing GCDs is mainly determined by the shape of the valley bottom. The average cost per square meter of frontal vertical area A_v was estimated by Grimaldi et al. (2013) equal to 15 €/m^2, calculated including: (i) the worksite preparation, (ii) the mechanical transport of the stones from the quarries to the worksites, (iii) the locally produced cages made of galvanized iron, (iv) the labor cost, and (v) the tools used for the work construction and maintenance.

107.3 Discussion

If implemented at a large scale, GCDs exert a stabilizing effect not only on the structurally treated sites, but also on a wider, neighboring area influencing the whole catchment sediment budget. A proper design must be performed by local technicians and this paper aims at pointing out the most important procedural steps and challenges. In particular, the accurate design of the spillway and the stilling basin, based on the computation of the peak discharge of the 10-year flow (Rodier and Auvray 1965; Rodier and Ribstein 1988), is very important to fix the maximum water level upstream the structure. Adequate GCD dimensions and components insure the evacuation of the design discharge and prevent detrimental water overflow and lateral scouring. For the sake of simplicity, the main procedures for designing GCDs were only briefly illustrated here. The overall procedure obviously rely on rigorous hydrological, hydraulic and structural theories, and, for an in-depth treatment of these theories, readers should refer to specific publications (UACE 1995; Geyik 1986; USBR 1987).

The long-term maintenance of GCDs is still an important issue in Burkina Faso, particularly for medium/large structures and considering the short project cycles (3 years on average) of international cooperation projects. Moreover, the local strong wish of harvesting sensible amounts of water and soil often lead to the implementation of high weirs (up to 2–3 m) that are eventually by-passed due to the upstream backwater effect. Limiting the height of the weir (from 0.5 to 1 m) can generally avoid the by-passing of the GCD and promote the development of SWC works at a larger spatial scale. Small GCDs are easier to design, build and maintain, and promote the development of the upstream sedimentation wedge through gradual, successive steps. The accurate design and positive impacts of GCDs encourage farmers to implement SWC measures, and a participatory approach offers the best guarantee to succeed in managing land degradation.

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