Water Science and Engineering 2019, 12(1): 62−72

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Water Science and Engineering

journal homepage: http://www.waterjournal.cn

Computational investigation of hydraulic performance variation with geometry in gabion stepped spillways

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Received 18 May 2018; accepted 3 January 2019
Available online 8 April 2019

Abstract

Over recent years, there has been a clear increase in the frequency of reported flooding events around the world. Gabion structures offer one means of flood mitigation in dam spillways. These types of structures provide an additional challenge to the computational modeller in that flow through the porous gabions must be simulated. We have used a computational model to investigate the flow over gabion stepped spillways. The model was first validated against published experimental results. Then, gabion stepped spillways with four different step geometries were tested under the same conditions in order to facilitate inter-comparisons and to choose the best option in terms of energy dissipation. The results show that normal gabion steps can dissipate more energy than overlap, inclined, and pooled steps. An intensive set of tests with varying slope, stone size, and porosity were undertaken. The location of the inception point and the water depth at this point obtained from this study were compared with those from existing formulae. Two new empirical equations have been derived, on the basis of a regression analysis, to provide improved results for gabion stepped spillways.

Keywords: Computational modelling; Energy dissipation; Gabion stepped spillways; Inception point location; Skimming flow

1. Introduction

Spillways can be defined as structures, located over dams, whose function is to release any excess water during the flooding seasons in order to reduce the probability of having an overtopping failure (Novak et al., 2001). Many materials can be used in the construction of spillways, including roller compact concrete and gabions. Each material has advantages and disadvantages (Boes and Hager, 2003). Energy dissipation can be considered one of the main design elements of stepped spillways because the high energy of the flow can cause many problems at the toe of the structure, such as the formation of scour holes, which can lead to structural failure in spillway foundations. Also, overtopping damage can occur, which can cause significant problems for people in the surrounding areas (Novak et al., 2010).

Chanson (2002) has defined two types of flow over stepped spillways: non-aerated flow and aerated flow. Normally, non-aerated flow takes place along the upper steps of spillways where there is no air entrainment, while aerated flow can be observed along the lower steps where air entrainment occurs (e.g. André and Schleiss, 2004; Chanson, 1994, 1995). For the same geometry, when the discharge increases, the length of the non-aerated zone also increases. Thus, the likelihood of generating cavitation will also increase. As noted by Husain et al. (2013), cavitation can be extremely damaging and even destroy spillways, leading to operational failure of the steps and spillways. The aerated zone can be determined by estimating the location of the inception point, which represents the endpoint for the non-aerated zone and the start of the aerated zone. The inception point is the location where the boundary layer intersects the free surface of the water

This work was supported by the Higher Committee for Education Development (HCED) in Iraq.
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Peer review under responsibility of Hohai University.

https://doi.org/10.1016/j.wse.2019.04.002

(Chanson, 1994, 1996). Flow over stepped spillways can be classified into three hydraulic regimes: nappe flow, transition flow, and skimming flow (Zhang and Chanson, 2016b).

Traditionally, spillways have been impermeable. However, the use of a permeable layer such as gabions offers a means to improve the hydraulic performance by enhancing energy dissipation. Gabions are containers that can be filled with gravel, cobbles, stones, and rocks, depending on the purpose of construction. Since 1879, gabions have been used in China and Egypt. Gabions have also been used for different purposes such as riverbed protection, bank stabilization, and retaining walls. There are three different types of gabions: basket, mattress, and sack. All of these may be filled with gravel and/or cobble materials (Zhang and Chanson, 2014). The choice of gabion type depends upon the application. For instance, basket gabions are commonly used for stability purposes and to protect river beds and stream banks (Freeman and Fischenich, 2000). A brief discussion of earlier studies conducted on gabion stepped spillways is provided below.

Gabions are one common construction element for spillways in the African Sahel (Peyras et al., 1992). Gabions have been used widely for water structures like small earth dams, retaining walls, intakes, and soil conservation work. Salmasi et al. (2012) stated that there are many benefits from using gabions, such as ease of construction, structural stability, flexibility, and resistance to water load. The resistance to water load is likely to be related to flow through porous media. Porosity can help the water to drain faster and reduce the water load behind the structure (Zhang and Chanson, 2016a). Permeability is known to affect the flow properties of the free surface in many cases (Manes et al., 2009). It has been suggested that related flow mechanisms can play a vital role in increasing or decreasing friction factors, thereby affecting the shear penetration within the permeable bed, which can in turn affect the boundary layer. Hence, increasing the flow resistance may increase energy dissipation due to the momentum exchange between the surface and subsurface flows.

Stephenson (1979) performed a study on energy dissipation over stepped gabions. Different configurations were examined, such as stepped gabions with two to four steps and with four different slopes: 1:1, 1:2, 1:3, and 2:3. The energy dissipation was calculated using the differences in depths between the areas upstream and downstream. The results showed that the relative energy dissipation ranged from 25% to 85%. They also showed that the energy dissipation increased as the number of steps increased to three, but then decreased as the number of steps increased further. Concerns about the ability of gabion steps to resist damage under high flows were addressed by the experimental study of Peyras et al. (1992), who showed that gabion stepped weirs can withstand floods up to 3 $m^3/(m\cdot s)$ without any damage. Kells (1994) studied the energy dissipation over a gabion stepped weir as a function of the critical depth at and discharge over the crest. This experimental study used two downstream slopes of 1:1 and 1:2, and the main finding was that 20% of the energy can be dissipated due to the through-flow. Moreover, no significant differences were noticed in the energy dissipation when the slopes changed. It is important to note that the number of the steps in the previous studies affected the energy dissipation results more than the spillway slope. Therefore, more research is required to investigate the impact of the number of steps.

The sensitivity of the hydraulic performance to the characteristics of the material contained in gabions was investigated experimentally by Chinnarasri et al. (2008). They used three stone types: (1) crushed stone of about 25−35 mm in diameter; (2) rounded stone of about 25−35 mm in diameter; and (3) crushed stone of about 50−70 mm in diameter. The results showed that the energy dissipation ratios over gabion stepped weirs were greater than those over the corresponding impermeable stepped weirs by nearly 7%, 10%, and 14% for weir slopes of 30°, 45°, and 60°, respectively. Consequently, the outlet velocity was lower. Moreover, the results showed that both the stone size and stone shape had a small effect on the energy loss and flow velocity compared to the weir slope. The pressure on the step face of gabion stepped weirs was less than that on the horizontal step due to the dampening influence of filled stones. The average pressure difference was approximately 29%. More recently, Wüthrich and Chanson (2014) carried out a laboratory study to investigate the hydraulic characteristics of flow, such as flow patterns, air-water flow properties, and energy dissipation over normal and gabion stepped spillways with a 1:2 slope and a 0.1-m step height. This study was conducted with a wide range of flow rates in order to investigate nappe, transition, and skimming flows. They found that large velocities could be observed at the downstream end of gabion stepped spillways, as well as low rates of energy dissipation over gabion steps in comparison to smooth impervious steps. It can be concluded that there are many parameters with impacts on the performance of gabion stepped spillways, such as the size of stones, water flow conditions, and the air-flow entrainment. However, at present, there is no clear picture of which of these parameters has the strongest influence on the efficiency of gabion stepped spillways. Thus, further investigations are needed to determine the essential controlling factors.

It is well established that stepped spillways (gabion or other) have an advantage over non-stepped spillways in terms of reducing cavitation damage due to air entrainment and by improving energy dissipation performance (Husain, 2013). Although there is a well-developed understanding of the performance of normal stepped spillways, the same level of understanding has not been developed for gabion stepped chutes with more complex designs. Moreover, even though stepped spillways have been extensively studied using computational models, detailed numerical modelling studies on gabion stepped spillways have not been recorded. Also, gabion porosity and gabion stone size, both of which affect the flow, need to be investigated in detail in order to demonstrate their impacts on other important parameters, such as the location of the inception point. Finally, finding an optimum gabion stepped spillway design can improve performance and offer an alternative for stepped spillway construction.

In this study, we used a computational model as a *numerical flume* to investigate the performance of gabion stepped