Advances in Water Resources 66 (2014) 52–69

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Investigation of pressure variations over stepped spillways using smooth particle hydrodynamics ☆

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ARTICLE INFO

Article history:
Received 19 October 2012
Received in revised form 25 November 2013
Accepted 30 November 2013
Available online 23 December 2013

Keywords:
SPH
Stepped spillways
Mathematical modeling
Skimming flow
Cavitation

ABSTRACT

In this paper the smoothed particle hydrodynamics, (SPH), technique is used to investigate the pressure distribution on steps located in the non-aerated flow region of a stepped spillway for different discharges typical of skimming flow conditions. The open source code 2D SPHysics has been employed after being validated against the laboratory model studies of flow over broad crested weirs and flow over stepped spillways. The numerical results, in terms of the water surface and velocity profiles at different sections, are in good agreement with the corresponding experimental results. The code is then applied to determine the pressure distribution on the vertical and horizontal step faces. Also, the aspects of the pressure pattern are described and the positions/magnitudes of the maximum and minimum pressure values are presented.

1. Introduction

The use of stepped spillways can be traced back more than 3500 years to ancient structures found in Akarnania, Greece [9]. The continued popularity of this type of structure is due mainly to its simplicity in design, ease of construction and the recent advances in the design technology of construction materials such as roller compacted concrete [5]. Steps of different dimensions, shapes and arrangements are introduced into the surface of the conventional smooth spillway and designed in such a way so as to provide a staircase shape to its profile from top to bottom. These steps play a dual role: (1) they generate high levels of turbulence which increases the energy dissipation rate of the overflowing water, thereby reducing the need for a large basin at the end of the spillway; (2) they increase the surface roughness which then accelerates the growth of the turbulent boundary layer. This accelerates the initiation of self-aeration which effectively protects the spillway surface from cavitation damage.

Depending on the discharge and step geometry, flow over stepped spillways has been classified into three regimes: nappe flow which occurs with low flow rates; skimming flow dealing with relatively high discharges; and transition flow with moderate discharges. Although, air plays a vital role in protecting the surface of such structures against cavitation damage, it may be entirely absent over the upstream reach of the chute especially when water flows with high rates, typical of skimming flow conditions, over low dams. This reach of a spillway is termed the non-aerated flow region. It starts at some distance from the spillway crest and extends to where the turbulent boundary layer intersects the free surface at a point on the free surface known as the inception point of air entrainment [10]. The reach downstream of this point until the toe of the spillway is called the aerated region which is less prone to cavitation damage due to the entrained air bubbles. Fig. 1 shows the non-aerated and aerated flow regions corresponding to the skimming flow condition over a stepped spillway.

To date, only a small number of studies have been conducted to investigate the pressure behavior in the non-aerated flow region on moderate slopes. Understanding the pressure pattern on the step faces under severe conditions is therefore an important aspect of improving the design of said structures. The current work is a numerical investigation which presents and describes the features of pressure flow field on the horizontal and vertical faces of steps situated in the non-aerated flow region. The coordinates of the inception point, free water surface level over the steps along the chute slope and velocity profile at the outer edge of steps are also predicted and compared with the existing experimental results. These are examined under a range of flow rates typical of the

☆ A version of the paper was prematurely made available online from December 23, 2013. The accepted and final approved version of the paper was published online only on March 5, 2014.

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http://dx.doi.org/10.1016/j.advwatres.2013.11.013
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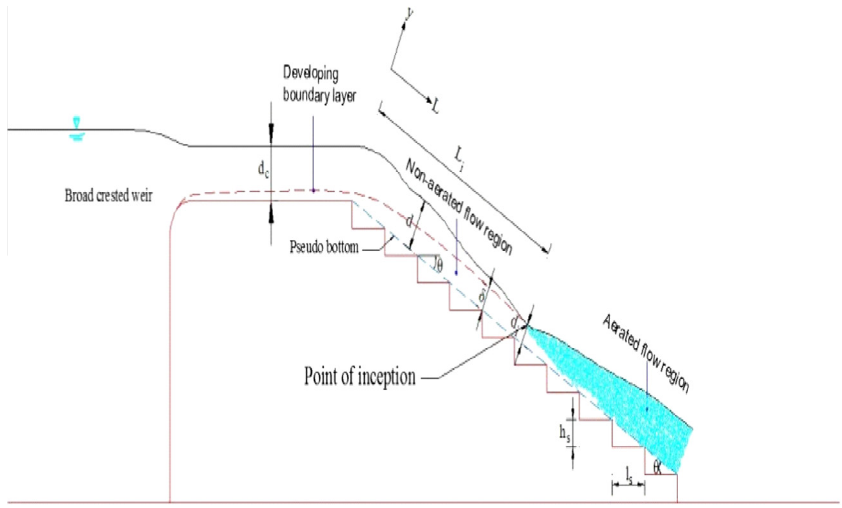

Fig. 1. Non-aerated and aerated flow regions due to skimming flow over a stepped spillway of broad crested weir.

skimming flow regime on a stepped spillway with a 1 V:2H bottom slope. The numerical investigation is based on a code that uses the smoothed particle hydrodynamics (SPH) method. SPH has specific advantages in modeling free surface flows as it is meshless and not constrained by any numerical grid geometry. The code employed is the serial version of the 2D SPHysics [25] open source code.

2. Background

The primary design constraint of modern stepped spillways is its performance under the skimming flow regime which often occurs with relatively high discharges. The flow in this situation can be divided into two parts: (1) a main part which skims coherently over the pseudo bottom formed by step outer edges; and (2) a secondary part representing the reverse flow as the main flow impacts onto the horizontal step face. The reverse flow will cause vortices to form which rotate in a triangular area inside the step cavities below the pseudo bottom [2,13].

Different empirical equations have been proposed to define the onset of skimming flow regime. The following two equations are presented by Chanson [8] and Boes and Minor [4] respectively:

$$\frac{h_c}{h_s} = 1.057 - 0.465\frac{h_s}{l_s} \tag{1}$$

$$\frac{h_c}{h_s} = 0.91 - 0.14\frac{h_s}{l_s} \tag{2}$$

where h_c is the critical flow depth above the spillway crest, h_s and l_s are the height and length of the step respectively.

Peterka [50] documented that air content of 7% in the vicinity of the spillway surface may be sufficient to prevent cavitation formation. Although, the flow over stepped spillways is characterized by fully aerated flow downstream of the inception point of air entrainment, the amount of air content upstream to this point may be lower than that recommended by Peterka [50] to resist such damage. Despite this fact less attention has been paid to this issue, especially spillways of moderate slopes.

There have been several attempts to investigate pressure on moderately sloped stepped spillways using laboratory experiments. Frizell and Mefford [19] investigated whether cavitation can occur, due to the drop of pressure to the subatomspheric value, in flow over stepped spillways. Their experiments were performed on two stepped spillway models built on 1 V:2H and 0.8 V:1H sloping flumes under various heads. They concluded that the region close to the top of the return eddy may be prone to cavitation damage if cavitation occurs. However, the location of potential cavitation in relation to the inception point of air entrainment was not specified.

Ohtsu and Yasuda [47] conducted a systematic series of experiments on a wide range of sloping stepped spillways. Their study focused mainly on the characterization of the flow conditions, including nappe, transition and skimming flow, based on the pressure measurements at the step corners. They described the skimming flow based on their experimental results of the pressure on the step face as the condition of eddy formation inside the step cavity upstream to where the main flow touches the horizontal step face. Also, they observed that the pressure is not constant at the step corner.

André [2] studied the characteristics of the pressure field on two laboratory model stepped spillways having moderate slopes of 1 V:2H and 1 V:3H. Pressure transducers were used to measure the pressure on the horizontal and vertical step faces to study the effect of mirco roughness elements on the development of the pressure due to various discharges typical of the nappe, transition and skimming flow regime. The author revealed that no significant negative pressure values were recorded by the pressure instrument used in the experiments. It should be noted that in this work the steps, in which the pressure measurements were taken, were located at the uniform flow region where the flow is fully aerated.

Frizell et al. [20] carried out laboratory experiments to study the potential of cavitation damage on stepped spillways of two different slopes; one was typical of moderate slopes, 1 V:2.48H and the other corresponded to steep slopes 2.48 V:1H. The roughness height in both cases was 0.05 m. In their study, they used the cavitation index to characterize the potential of cavitation along the chute slope. From the fluid mechanics the cavitation index number, which is also called the special form of the Euler number or pressure coefficient as discussed in Rouse [55] and used by Falvey [16], can be defined by the following equation:

$$\sigma = \frac{2(P_o - P_v)}{\rho V_o^2} \tag{3}$$

where σ is the cavitation index, P_o and P_v are respectively the reference pressure and the vapor pressure of water at a given temperature, ρ is the density of water and V_o is the reference velocity.

Their results, collected at the low ambient pressure chamber on a moderately slopped spillway revealed that cavitation is likely to form in the absence of aeration; with cavitation index of 0.6–0.7,