Journal of Hydro-environment Research xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hydro-environment Research

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

Research papers

Effect of unsteady flow conditions on scour features at low-head hydraulic structures

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Hydraulic models
Low-head structures
Scour process
Unsteady flow

ABSTRACT

The study of scour mechanism downstream of low-head control structures is a fundamental topic for hydraulic engineers. Generally, the analysis of the scour process is conducted under steady flow conditions, assuming that the maximum discharge is occurring for sufficient time to reach the equilibrium scour configuration. Nevertheless, in rivers the scour process generally occurs in correspondence with a flood event, which is characterized by discharge varying with time. This last condition is still less studied and analyzed in terms of effects on bed morphology. Researchers mainly focused on the maximum scour depth assuming that it occurs in correspondence with the peak discharge, but they rarely took into account the evolution of the scour process under unsteady flow conditions. The aim of the present paper is to analyze the evolution of scour morphology under unsteady flow conditions, and compare it with that obtained under steady flow conditions. In particular, three structure typologies were tested: a stepped gabion weir with upstream impermeable filtering layer, a straight rock sill, and a curved rock sill. The results showed that the scour phenomenon deeply depended on inflow conditions. Nevertheless, it was also shown that the equilibrium morphology of the downstream stilling basin is essentially the same under both unsteady and steady flow conditions if the duration of the unsteady event is enough long.

1. Introduction

The scour mechanism occurring downstream of low-head control structures is an important topic that has been widely analyzed in recent decades. In particular, the analysis mainly focused on the hydraulics and the scour characteristics in the stilling basin. Low-head structures have been found effective in controlling sediment transport and, at the same time, they are able to guarantee a reduced impact on the ecosystem. Therefore, many traditional structures have been re-converted into more eco-friendly anthropic works, such as block ramps, rock grade control structures, stepped gabion weirs, cross-vane, W-weirs, etc.

One of the first systematic studies investigating erosive process occurring in a movable stilling basin was conducted by Veronese (1937). The author analyzed the effect on the scour characteristics of the stilling basin geometry. Namely, he conducted a series of experimental tests in prototype channels to investigate the effect of symmetric enlargement of the stilling basin on scour morphology. More recently, Bormann and Julien (1991) analyzed several grade control structures configurations, varying both the model scale and the geometry of the structure itself. They concluded that the scour process depends on both the structure geometry and on the stilling basin characteristics. Based on the similarities between scour process due to plunging jets and downstream of grade control structures, Bormann and Julien (1991) and, successively, D'Agostino and Ferro (2004) showed that the diffusion length of the flow entering the stilling basin is a fundamental parameter. Furthermore, as it was also shown for scour due to plunging jets (see for example Rajaratnam, 1981; Rajaratnam and Macdougall, 1983; Breusers and Raudkivi, 1991; Hoffmans and Verheij, 1997; Hoffmans, 1998; Mason and Arumugam, 1985; Pagliara et al., 2010, 2012a, 2015), the geometry of the structure was found a significant parameter influencing the scour morphology because of the different entering flow inclinations. Among eco-friendly hydraulic structures, block ramps and rock chutes constitute a peculiar typology. Namely, they are characterized by a complex hydraulic behavior due to the rough sloped bed that contributes to dissipate an appreciable amount of energy (Pagliara and Palermo, 2011). In particular, these structure typologies exhibit some similarities with both stepped chutes and rock sills, in terms of both hydraulic behavior and dissipative mechanism. Nevertheless, the presence of a downstream mobile stilling basin contributes to amplify the energy dissipation, as a hydraulic jump

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http://dx.doi.org/10.1016/j.jher.2017.04.001
1570-6443/

generally occurs in correspondence with the structure. In general, eco-friendly structures exhibit substantial similarities in terms of scour process, due to their geometry that is characterized by relatively small dimensions (low height and/or mild surface slopes). In particular, a detailed analysis of the scour mechanism can be conducted in the case for which the structure is stable. Therefore, incipient movement conditions of the stones constituting the different eco-friendly structure typologies has received considerable attention (Parker et al., 1982; Whittaker and Jaggi, 1986; Robinson et al., 1997; Hoffmans, 2010). Furthermore, the main parameters influencing the scour phenomenon (tailwater, stilling basin material and geometry, protection sills, etc.) were carefully analyzed in order to understand the dynamics of the erosive mechanism both in clear water and live bed conditions (Pagliara and Palermo, 2011; Oertel et al., 2011; Pagliara et al., 2012b). The previously mentioned studies on block ramps were useful to understand the similarities and differences among other several low-head structures, as shown by Pagliara and Mahmoudi Kurdistani (2015) and Pagliara et al. (2016). In particular, stepped gabion weirs exhibit similarities with both stepped chutes and block ramp. They are characterized by different flow regimes: skimming, nappe and transition flow regimes. In addition, these different flow regimes deeply influence the scour mechanism in the downstream stilling basin. Pegram et al. (1999), Peyras et al. (1992) and Pagliara and Palermo (2013) analyzed this structure typology in detail. In particular, Pagliara and Palermo (2013) focused on the scour mechanism occurring downstream of stepped gabion weirs and rock grade control structures classifying the onset conditions of the different flow regimes (see also Rajaratnam, 1990; Essery and Horner, 1978; Peyras et al., 1992; Ohtsu et al., 2004). Namely, Pagliara and Palermo (2013) analyzed both the hydraulics and the scour process downstream of different stepped gabion weir configurations. They studied four structure configurations: permeable and impermeable isolated structures and structures with both permeable and impermeable upstream filtering layer having the same height of the stepped gabion weir. Their analysis was conducted for constant discharges up to the equilibrium scour conditions. Similarly, rock sills share similarities with other low-head hydraulic structures, including rock chutes, W-weirs, J-hook, etc. In particular, rock sills can assume different shapes according to their hydraulic functioning and the location in which they are inserted. Detailed studies on this type of structure were conducted by Bhuiyan et al. (2007) and Scurlock et al. (2012). They proved that 3D rock structures can substantially improve fish habitat and, at the same time, they can dissipate a relevant amount of flow energy. Therefore, in this study two different types of rock sills were taken into consideration, i.e., straight rock sills (which are common in river restoration projects) and curved rock sills (which can be considered representative of a larger variety of 3D low-head structures). The aim of the present paper is to analyze the hydraulics and the scour evolutions in the presence of both stepped gabion weirs and rock sills under unsteady flow conditions. In addition, this paper aims to answer to the following questions:

1) Under unsteady flow conditions, is it always correct to select the peak discharge to evaluate the maximum scour depth, using relationships valid for steady flow conditions?
2) If the answer to the previous question is negative (as it will be shown), is there a minimum duration of the unsteady flow event that can cause the same scour features of a steady event characterized by a constant discharge equal to the peak discharge? Equivalently, when should the peak discharge of the unsteady event occur to obtain the same maximum scour depth of a steady event with constant discharge equal to peak discharge?

To answer these two questions, experiments were conducted for different peak discharges varying both the time steps for the discharge increase/decrease and the total duration of the test. Furthermore, in order to minimize scale effects, experimental tests were conducted in two different channels and with different cohesionless materials. This analysis focused on the scour process evolution due to different flow conditions. It was experimentally proven that there is a significant similarity between the tested structures, i.e., it was shown that *for certain inflow conditions*, the non-dimensional time to reach the equilibrium configuration is essentially the same for all the low-head structure geometries tested in the present study. This implies that the answer to the first question is "no" (as it is valid *for certain inflow conditions* and not *always*), whereas the answer to the second question is "yes". Finally, an applicative example is provided in order to better illustrate the proposed methodology.

2. Experimental facilities

Two dedicated models were built at the hydraulic laboratory of the University of Pisa. Namely, experimental tests regarding stepped gabion weirs were conducted in channel 1, which is characterized by the following geometric characteristics: 0.30 m wide, 0.60 m deep and 6 m long. Whereas experimental tests with rock sills were conducted in channel 2 (0.50 m wide, 0.90 m deep and 8 m long). The stepped gabion weir was made of uniform rounded stones whose median diameter was D_{50} = 12 mm. Stones were kept together using a wide mesh (1 cm x 1 cm). The structure was built in layers (Fig. 1) with step width w_s and step height h_s equal to 51.3 mm. The total structure height was H = 154 mm. A filtering layer, having the same height of the structure, was located upstream and constructed using the same material as the downstream stilling basin in channel 1 (d_{50} = 4.78 mm, d_{90} = 5.7 mm, non-uniformity coefficient σ = 1.2 and density ρ_s = 2645 kg/m^3, with d_{xx} diameter of the stilling basin material for which xx% is finer). In addition, the upstream filtering layer was made impermeable by using a covering steel sheet in order to simulate a real configuration that usually occurs in rivers when an upstream sediment layer becomes impermeable due to the presence of silt and clay intrusion between grains. Furthermore, two rock sill typologies were tested, i.e., straight and curved rock sill. Rock sills were made of crushed stones layers and shaped in such a way that the final configuration was either straight or curved. Namely, the median diameter D_{50} of the stones constituting the sill was equal to 4.65 cm (non-uniformity coefficient σ = 1.3 and density ρ_s = 2450 kg/m^3), whereas the stilling basin material adopted in channel 2 was much finer that than of Channel 1 (d_{50} = 2 mm, non-uniformity coefficient σ = 1.22 and density ρ_s = 2214 kg/m^3). The choice to adopt two different stilling basin materials allowed to establish that there is no influence of the bed material size on the scour evolution. Furthermore, also scale effects can be considered negligible as the kinetics of the erosive process was found essentially the same in both the channels and for all of the different tested structures. The curved rock sill was characterized by a non-dimensional curvature R/B = 0.5, where R is the curvature radius of the sill and B the width of the channel. Fig. 2 illustrates the rock sills simulated in channel 2. Experimental tests were conducted for different hydraulic conditions, i.e., different discharges Q and different downstream tailwater levels h_0. In particular, the downstream tailwater level was not controlled, therefore for each discharge different tailwater levels occurred. Furthermore, the inflow discharges varied between 5 and 10 l/s for stepped gabion weirs and between 10 and 15 l/s for both curved and straight rock sills. Preliminary tests were conducted under constant discharge in

Please cite this article in press as: Palermo, M., Pagliara, S. Effect of unsteady flow conditions on scour features at low-head hydraulic structures. J Hydroenviron Res (2017), http://dx.doi.org/10.1016/j.jher.2017.04.001