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Scour process caused by multiple subvertical non-crossing jets

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Abstract

The scour process induced by plunging jets is an important topic for hydraulic engineers. In recent decades, several researchers have developed new strategies and methodologies to control the scour morphology, including different jet arrangements and structures located in the stilling basin. It has been found that multiple jets can cause less scouring than single plunging jets. Based on this evidence, this study aimed to investigate the equilibrium morphology caused by multiple non-crossing jets. A dedicated laboratory model was built and experimental tests were carried out under different combinations of jet inclination angles, by varying the tailwater level and the virtual crossing point location, which was set below the original channel bed level. It was experimentally shown that the equilibrium scour morphology depends on the jet discharge, the differences in non-crossing jet inclination angles, the downstream water level, and the distance of the virtual crossing point from the original channel bed level. In particular, the last parameter was found to be one of the most influential parameters, because of the resulting flow patterns inside the water body. Furthermore, the analysis of experimental evidence allowed for a complete and detailed classification of the scour hole typologies. Three different scour typologies were distinguished and classified. Finally, based on previous studies, two novel relationships have been proposed to predict both the maximum scour depth and length within a large range of hydraulic and geometric parameters.

Keywords: Multiple subvertical jets; Plunge pool; Scour; Spillway; Tailwater

1. Introduction

One of the main problems for dam engineers is the prediction of scour features occurring downstream of hydraulic structures. High-speed water jets originating from spillways can have an impact on the downstream water body and can cause huge scour holes, involving potential structural risks. The scour process caused by plunging jets is a complex phenomenon, as it depends on several parameters. In particular, the erosive action of the jets mainly depends on the discharge, tailwater level, granulometric characteristics of the stilling basin, jet inclination angle on the stilling basin, and jet geometric configuration (Pagliara et al., 2008).

Many studies have been conducted on this topic and they have mostly focused on the scour hole geometric characteristics caused by single (isolated) plunging jets. Some relevant studies were conducted by Rajaratnam and Berry (1977), providing a complete and detailed analysis on the scour mechanism in the presence of both sand and polystyrene beds. Further studies were conducted to investigate the main parameters involved in the scour process (Rajaratnam, 1981; Mih, 1982; Mih and Kabir, 1983; Aderibigbe and Rajaratnam, 1996; Chiew and Lim, 1996; Ade and Rajaratnam, 1998; Pagliara et al., 2006, 2008, 2015; Faruque et al., 2006; Sarkar and Dey, 2007). In particular, Pagliara et al. (2006) analyzed the scour mechanism caused by plane plunging jets, resulting in a two-dimensional scour hole geometry, whose equilibrium characteristics are mainly influenced by tailwater level, channel bed granulometry, jet inclination angle, and discharge. Researchers have proven that

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air entrainment also plays a major role in the scour hole formation. This aspect was further developed by Pagliara and Palermo (2013), who conducted a comprehensive and detailed analysis of the scour evolution by varying the air-water inflow characteristics. Pagliara et al. (2008) proposed useful empirical relationships in order to predict the main geometric characteristics of the scour hole in the presence of a three-dimensional (3D) equilibrium morphology. They also established a criterion to classify and distinguish a two-dimensional (2D) scour process from a 3D one. As mentioned above, the scour geometric characteristics were found to mainly depend on the jet discharge, water level in the downstream water body (tailwater), jet inclination angle, and submergence condition of the jet. These results have been confirmed by Hoffmans (1998), who conducted a theoretical investigation and, by applying the momentum equation, derived a general predictive relationship valid for a 2D scour morphology. Furthermore, several studies have proposed effective countermeasures to reduce and control the scour evolution. Rajaratnam and Aderibigbe (1993) proposed a methodology to reduce the scour depth involving the use of horizontal protection screens located in the stilling basin. Pagliara and Palermo (2008) and Pagliara et al. (2010b) investigated the use of vertical walls characterized by different permeabilities in order to control both the maximum scour depth and length of the scour hole. They concluded that, if opportunely located, the vertical walls can significantly reduce the maximum scour depth (up to 40%).

While there is ample literature on single plunging jets, analysis of the scour features in the presence of multiple jets is still an under-investigated topic. The presence of multiple jets substantially increases the complexity of the phenomenon, as it is influenced by many other parameters, whose estimation is not always easy. In particular, a few very recent studies deal with multiple crossing jets and relatively fewer practical applications of this geometric configuration exist (Li et al., 2006).

When two jets cross before plunging into the stilling basin, the scour process becomes much more complex due to the huge amount of air entrainment that can occur. In addition, depending on the crossing angles, a huge splash effect can be observed. Therefore, it is also important to take into consideration other aspects during the design process, such as the presence of eventual buildings downstream of the dam (e.g., hydropower stations). Furthermore, the splashed water can hit the lateral walls, resulting in significant scour, endangering their stability.

Recently, Pagliara et al. (2010a, 2011, 2012a) and Pagliara and Palermo (2013) investigated the scour characteristics caused by crossing jets, whose crossing point is located above the water surface. Pagliara et al. (2012a) investigated the scour features induced by two subvertical crossing jets, and proposed some useful relationships to predict the maximum scour depth and the maximum scour length. In addition, they classified the scour hole typologies according to the main hydraulic and geometric parameters. Furthermore, Pagliara et al. (2011, 2012b) and Pagliara and Palermo (2013) conducted experimental investigations on horizontal crossing jets, by varying both the vertical and horizontal crossing angles of the jets. They also analyzed the effect of air entrainment in jets and proposed design relationships to evaluate the main geometric parameters of scour holes, including both the scour volume and planar surface extension. Based on previous studies, the present paper focuses on the scour hole characteristics caused by multiple subvertical non-crossing jets. Experimental tests were conducted using a laboratory model to simulate the scour process caused by two subvertical non-crossing jets with a non-cohesive stilling basin material. The jets were simulated using two pipes of the same diameter, with variation of the vertical angle combinations and the tailwater level.

The analysis of experimental data has shown that the scour depth in the case of a low tailwater level is prominent, due to reduced interference between the jets. In addition, if the distance between the projections of jet axes increases, two scour holes can occur. Therefore, the scour phenomenon appears to be more similar to that caused by single isolated jets. For a higher tailwater level, the diffusion length of the jets increases. Significant interference between the two jets occurs inside the water column, causing the formation of prominent vortexes. In this case, the inclination angles of the jets play a significant role. Namely, higher inclination angles of the lower jet reduce the interference between the jets, thus resulting in an increase of the scour hole dimensions. Finally, useful design suggestions are proposed in order to minimize the structural risks.

2. Experimental setup

Experimental tests were conducted in a channel 6 m long, 0.8 m wide, and 0.9 m deep. The granulometric characteristics of the channel bed material were $d_{90} = 10.26$ mm, $d_{84} = 10.02$ mm, $d_{50} = 9.5$ mm, $d_{16} = 7.49$ mm, and $\sigma = (d_{84}/d_{16})^{0.5} = 1.17$, where d_x is the characteristic diameter, for which x% of the material is finer. The non-crossing multiple jets were simulated using two pipes, whose diameter D was 0.022 m. The water with a discharge Q_{w} was equally subdivided into two jets and was measured using two flow meters with ±0.1 L/s precision. Experimental tests were conducted by varying the total discharge Q_{w} between 2.5 L/s and 4.2 L/s. Jets were located in the same vertical plane and the following angle combinations were tested: $\alpha_1 = 30°$ and $\alpha_2 = 45°$; $\alpha_1 = 30°$ and $\alpha_2 = 60°$; $\alpha_1 = 30°$ and $\alpha_2 = 85°$; $\alpha_1 = 45°$ and $\alpha_2 = 60°$; $\alpha_1 = 45°$ and $\alpha_2 = 85°$; and $\alpha_1 = 60°$ and $\alpha_2 = 85°$, where α_1 and α_2 are, respectively, the inclination angles of the lower and upper jets with respect to the horizontal plane. Therefore, $\Delta\alpha = \alpha_2 - \alpha_1$ varied between 15° and 55°. It should be noted that scale effects are negligible if the jet velocity is larger than 1 m/s and the minimum sediment size is 1 mm (Canepa and Hager, 2003; Pagliara et al., 2008). Therefore, in the present study, the d_{50} value of the bed material was set to be much larger than 1 mm and the minimum tested jet velocity was 3.3 m/s.

The geometric configuration of the jets was set in such a way that the distance between the two intersections of their