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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 $\pm$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 $\alpha_1$ and $\alpha_2$ 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 axes and the original channel bed plane ($\varDelta$) varied from 6.22 cm to 18.66 cm, i.e., the non-dimensional intersection distance $\lambda = \varDelta / D_{\rm eq}$ ranged from 2 to 6, where $D_{\rm eq}$ is the diameter of the equivalent single jet. The equivalent diameter $D_{\rm eq}$ was defined to compare the obtained results with those from the equivalent single jet, characterized by the same total cross-sectional area of the two pipes of diameter $D$, i.e., $D_{\rm eq} = (2D^2)^{0.5}$. In other words, each tested configuration was compared, in terms of equilibrium morphology, with that obtained in the presence of a single plunging jet, characterized by an inclination angle $\alpha_{\rm v} = (\alpha_1 + \alpha_2)/2$. $D_{\rm eq}$ has already been adopted as the scale length factor in previous studies by the same researchers (Pagliara et al., 2011, 2012a). Preliminary tests conducted by Pagliara et al. (2012a) with two subvertical jets characterized by $\Delta\alpha = 0°$ (i.e., two jets with the same inclination angle) showed that the equilibrium morphology is essentially the same as that of a single plunging jet whose diameter is $D_{\rm eq}$, under identical hydraulic conditions and jet configurations (i.e., the same discharge, tailwater level, and inclination angle). Therefore, the choice of $D_{\rm eq}$ as a scale length factor results in the possibility of establishing more convenient hydraulic conditions for the design of a multiple-jet configuration. Furthermore, the jet velocities of both non-crossing jets and an equivalent single jet are exactly the same and can be expressed as $V = Q_{\rm w}/(\pi D_{\rm eq}^2/4)$. It can be easily observed that the densimetric Froude numbers $F_{d_{90}}$ of both the non-crossing jets and the equivalent single jet are the same, with $F_{d_{90}} = V/(g' d_{90})^{0.5}$, and $g' = [(\rho_{\rm s} - \rho)/\rho]g$, where $g'$ is the reduced gravitational acceleration, $g$ is the gravitational acceleration, and $\rho_{\rm s}$ and $\rho$ are sediment and water densities, respectively. Experimental tests were conducted with variations of $F_{d_{90}}$ between 8.61 and 14.47. In general, $F_{d_{90}}$ is adopted in the presence of non-uniform bed materials and the channel bed material non-uniformity is taken into account by introducing a non-uniformity parameter $\sigma$. This is mainly due to the fact that the superficial layer of the scour hole is made of a resulting material whose $d_{50}$ is both larger than the mean diameter of the original sediment mixture and closer to the $d_{90}$ of the original sediment mixture. Nevertheless, in the case of uniform stilling basin materials ($d_{90} \approx d_{50}$), $F_{d_{90}}$ is almost equal to $F_{d_{50}}$ and $\sigma \approx 1$. Therefore, no significant differences can be detected by adopting either $F_{d_{90}}$ or $F_{d_{50}}$. In this study, $F_{d_{90}}$ was adopted in order to remain consistent with the authors' previous studies.

The selected jet geometries were allowed to obtain different vertical distances $S$ of the virtual jet crossing point from the water surface. In particular, the non-dimensional vertical distance of the virtual crossing point of the jets $\delta = S/D_{\rm eq}$ varied between −2.9 and −21.27. Note that, according to Pagliara et al. (2011, 2012a), the non-dimensional vertical distance $\delta$ was assumed to be positive when the jets crossed above the water surface, whereas in the cases tested in this study, the virtual crossing point of the jets was below the water surface. Therefore, for the sake of consistency with previous studies, $\delta$ was assumed to be negative. Finally, tests were conducted with variation of the tailwater level $h_0$, i.e., the water level above the original channel bed level. In particular, tests were conducted with variation of the non-dimensional tailwater level $T_{\rm w} = h_0/D_{\rm eq}$ between 0.7 and 7.1.

Fig. 1 shows a photo of the experimental apparatus. Fig. 2 shows the schematic diagram of the experimental apparatus, including the main hydraulic and geometric parameters, where $z_{\rm mnc}$ is the maximum scour hole depth; $l_0$ is the scour hole length; $z_{\rm Mnc}$ is the dune height; $B_{\rm nc}$ is the maximum scour width; $l_0'$ is the dune length; and $x$, $y$, and $z$ are the longitudinal, transversal, and vertical coordinates of the reference system, respectively. All the other symbols appearing in Fig. 1 have already been defined above.

Before starting each experimental test, the channel bed was carefully levelled and a constant water level was set. Then, the experimental test was carried out up to when equilibrium conditions were reached, i.e., when negligible differences in scour hole lengths were recorded. In general, the time duration to reach equilibrium conditions depends on both hydraulic and granulometric characteristics. For this study, preliminary tests showed that, approximately 1 h from the beginning, no more significant morphology variations were observed. It has to be noted that this duration is in agreement with that suggested by Dey and Sarkar (2006) for similar coarse materials, as they observed a very rapid developing phase. During each test, longitudinal scour profile readings were taken at different instants. In addition, when the dynamic equilibrium conditions were established, the scour geometry was completely surveyed, both longitudinally and transversally, in order to measure all the main geometric characteristics. In the tested range of parameters, $z_{\rm mnc}$ varied from 4.6 cm to 17.8 cm. Nevertheless, $z_{\rm mnc}$ was larger than 10 cm for most of experimental tests. Based on previous studies (Canepa and Hager, 2003; Pagliara et al., 2006, 2008), the sediment surface profile was recorded with a special point gauge with a reading accuracy of 0.5 mm, extended with a circular metal ring with a diameter of 0.02 m, allowing for a detailed and precise survey of the scour morphology.

Table 1 shows the ranges of variation of the main tested variables and measured scour geometric parameters.

Fig. 1. Photo of experimental setup.

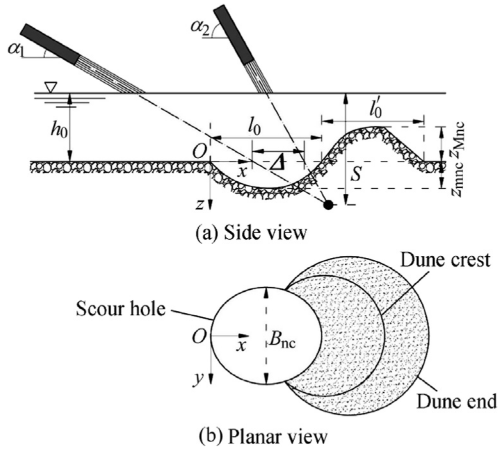


Fig. 2. Schematic diagram of experimental setup.

Table 1
Range of variation of tested variables and scour geometric characteristics.

| Extreme | $Q_w$ (L/s) | $F_{d_{90}}$ | $\Delta\alpha$ (°) | $\lambda$ | $\delta$ | $T_w$ | $z_{mnc}$ (cm) | $z_{Mnc}$ (cm) | $l_0$ (cm) |
|---|---|---|---|---|---|---|---|---|---|
| Min | 2.5 | 8.61 | 15 | 2 | −21.27 | 0.7 | 4.6 | 1.6 | 27.1 |
| Max | 4.2 | 14.47 | 55 | 6 | −2.90 | 7.1 | 17.8 | 12.6 | 79.0 |

## 3. Scour features analysis

The observation of the experimental tests and the relative equilibrium morphology allowed us to generalize both the hydraulics and the scour morphology characterizing the erosive mechanisms. According to tested geometric configurations and hydraulic conditions, the scour mechanisms show some similarities. In particular, both the scour hole shape and dune formation strongly depend on the jets' inclination angles and on the location of their virtual crossing point. Furthermore, experimental evidence showed that three main scour typologies, characterized by different hydrodynamic behaviors, can be distinguished and classified. The main parameters influencing the proposed classification were found to be $\Delta\alpha$, $F_{d_{90}}$, and $\lambda$. The last parameter is strictly connected to the parameter $\delta$, as both can describe the effect of the virtual crossing point location on the scour mechanism. Therefore, all experimental test data and morphologies were carefully analyzed and the scour typologies were classified and termed Type 1, Type 2, and Type 3.

The scour morphology termed Type 1 is characterized by a flat-elliptical dune almost surrounding the entire scour hole. It occurs for very low $\lambda$ values and for $\alpha_1 \geq 45°$, i.e., it was observed that this typology never takes place when $\alpha_1 = 30°$. The maximum scour depth generally occurs in correspondence with the virtual location of the crossing point of the two jets. Therefore, the scour hole shape is characterized by a relatively mild upstream scour hole slope and a prominent downstream scour hole slope. In addition, the resulting flow spreads radially, thus removing and depositing sediment material all around the scour hole. Fig. 3(a) shows a photo of the resulting equilibrium morphology, and Fig. 4(a) shows a typical non-dimensional longitudinal profile, from which it is evident that the maximum scour depth occurs in the downstream part of the scour hole ($x/l_0 > 0.5$).

Experimental observations showed that this typology takes place for the following combinations of hydraulic and geometric parameters: (1) $\Delta\alpha = 25°$, $T_w \geq 3.5$, and all tested $F_{d_{90}}$;

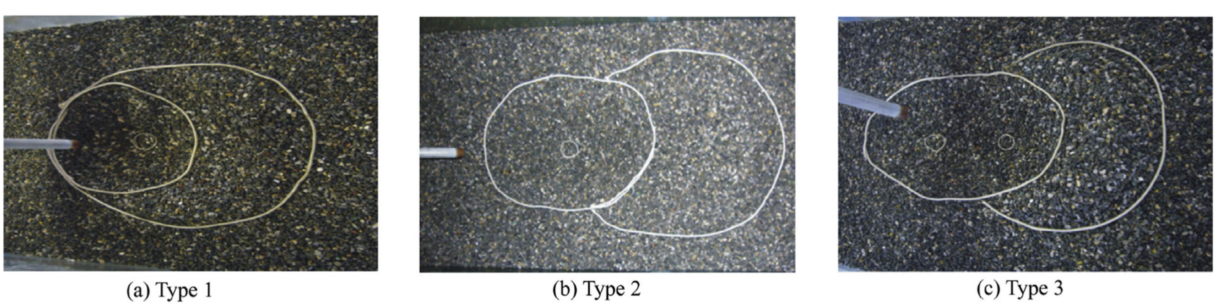


Fig. 3. Photos of equilibrium morphology for three scour types.

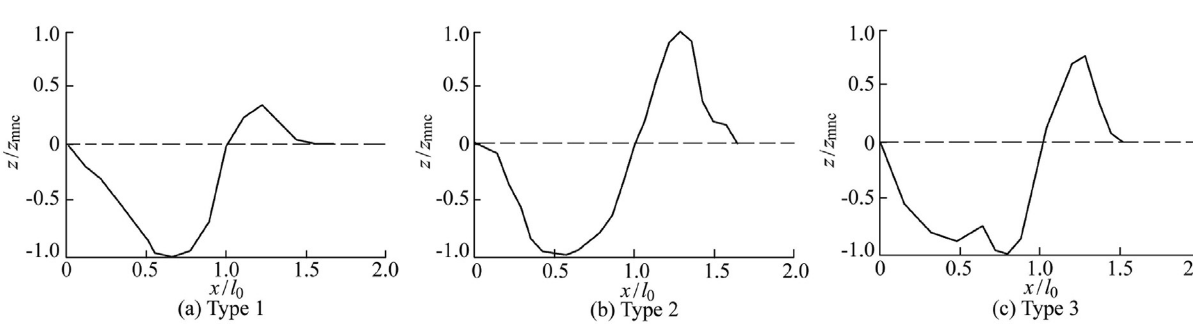


Fig. 4. Typical non-dimensional longitudinal (axial) profiles for three scour types.

(2) $\Delta\alpha = 15°$ and 30°, very low $T_w$, and all tested $F_{d_{90}}$; and (3) $\Delta\alpha = 40°$, $T_w < 3.5$, and all tested $F_{d_{90}}$.

This typology does not occur for $\alpha_1 = 30°$, because in this configuration the lower jet exerts a prominent momentum quantity directed horizontally, thus contributing to transport of all the scoured material downstream of the scour hole. Therefore, the resulting ridge does not confine the entire scour hole and the resulting jet does not spread radially.

The second scour typology that was distinguished is termed Type 2. Its shape is characterized by an almost circular scour hole and the ridge is mainly located downstream, i.e., it does not surround the scour hole. The height of the ridge is significant and it contributes to substantially confining the scour depth evolution. In other words, the scour hole appears quite short, but it can be characterized by a significant scour depth, due to a strong vortex formation inside the scour hole.

The absence of a surrounding dune results in a flow that is mainly directed downstream. Also in this case, the maximum scour depth takes place close to the virtual crossing point of the jets. Experimental evidence showed that this typology occurs for all tested $\lambda$. Nevertheless, some specifications can be given. Specifically, for low $\lambda$, Type 2 takes place under the following conditions: (1) $\Delta\alpha = 25°$, very low $T_w$, and all tested $F_{d_{90}}$; (2) $\Delta\alpha = 15°$, 30°, and 55°, $T_w \geq 3.5$, and all tested $F_{d_{90}}$; and (3) $\Delta\alpha = 40°$, high $T_w$, and $F_{d_{90}} > 12$. Conversely, for medium to high $\lambda$ values, Type 2 takes place under the following conditions: (1) $\Delta\alpha = 15°$ and all tested $T_w$ and $F_{d_{90}}$; and (2) $\Delta\alpha = 25°$, 30°, and 40°, high $T_w$, and all tested $F_{d_{90}}$.

Fig. 3(b) shows a photo of the resulting equilibrium morphology, and Fig. 4(b) shows a typical non-dimensional longitudinal profile, from which it is evident that the ridge is prominent and it is playing a significant role in scour hole confinement.

The third scour typology that was distinguished is termed Type 3. Its shape is characterized by a longitudinally extended scour hole. In addition, two different scouring areas are clearly detectable, i.e., two different and comparable scour depth peaks occur in correspondence with the two jet impact points located on the sediment bed. It is evident that, in this case, the longitudinal distance between the jet impact points on the original channel bed level is significant, i.e., this scour typology can take place only for very high $\lambda$ values. Furthermore, the ridge is almost entirely located downstream of the scour hole formation and it contributes to further amplifying vortex formation. Finally, due to the significant longitudinal distance between the jet impact points, the scour hole length is prominent.

As mentioned above, experimental evidence showed that this scour type occurs only for very high $\lambda$ values and for the following geometric and hydraulic conditions: (1) $\Delta\alpha = 25°$, 30°, and 40°, high $T_w$, and low $F_{d_{90}}$; (2) $\Delta\alpha = 25°$, 30°, and 40°, low $T_w$, and all tested $F_{d_{90}}$; and (3) $\Delta\alpha = 55°$, low $T_w$, and $F_{d_{90}} > 12$.

Fig. 3(c) shows a photo of the resulting equilibrium morphology, and Fig. 4(c) shows a typical non-dimensional longitudinal profile, from which it is evident that two comparable peaks of the maximum scour depth occur. It is also evident that the dune height is significant and comparable to the maximum scour depth.

## 4. Results and discussion

One of the most important parameters, in terms of practical applications, is the maximum scour depth. The possibility of predicting the geometric characteristics of the scour morphology results in a reduction of the failure risk and, at the same time, contributes to optimizing the geometric configuration of the jet spillways. As mentioned above, crossing jets have already been studied by Pagliara et al. (2012a) in the case in which the crossing point of the jets is located above the water surface. It is evident that, for this configuration, the phenomenon appears to be quite complex, due to the fact that a huge splash occurs and the characteristics of the resulting jet are deeply modified. Pagliara et al. (2012a) stated that the maximum non-dimensional scour depth can be expressed by the following functional relationship:

$$Z_{mc} = f_1(F_{d_{90}}, \Delta\alpha) f_2(\delta, T_w) f_3(\alpha_1, T_w) \quad (1)$$

where $Z_{mc} = z_{mc}/D_{eq}$, in which $z_{mc}$ is the maximum scour depth in the case in which the jets cross above the water surface, and

$$f_1(F_{d_{90}}, \Delta\alpha) = 0.500 F_{d_{90}} - 0.002\Delta\alpha^2 + 0.134\Delta\alpha - 3.800 \quad (2)$$

$$f_2(\delta, T_w) = (-0.017 T_w + 0.022)\delta + 1 \quad (3)$$

$$f_3(\alpha_1, T_w) = (0.003 T_w - 0.010)(\alpha_1 - 30°) + 1 \quad (4)$$

It has to be noted that, for jets crossing at the water surface, $\delta$ is equal to 0. Therefore, $f_2(\delta, T_w) = 1$. In the case in which the (virtual) crossing point is located below the water surface, $\delta$ is negative. In addition, depending on the tailwater level, if the virtual crossing point is located far from the water surface, the interference between the two jets is reduced and the erosive phenomenon appears to be similar to that caused by two different single jets, as scour Type 3 occurs. Therefore, it appears evident that $\delta$ is one of the most influential parameters, because of its effect on the equilibrium morphology shape. Nevertheless, a prominent role is also played by $\Delta\alpha$. In fact, especially for lower $\delta$ values, the increase of the variable $\Delta\alpha$ results in a significant effect on the scour characteristics, because of the increase of the jet velocity components in the opposite directions. Furthermore, the tailwater level $T_w$ also assumes a fundamental importance. In fact, an increase of the tailwater level results in an increase of the jet diffusion lengths, causing a higher degree of interference between the two single jets and, thus, contributing to the significantly modified flow pattern inside the water body.

Based on these observations, experimental data of the variable $Z_{mnc}$ (non-dimensional maximum scour depth when jets do not cross above the water surface) were compared with those calculated with Eq. (1). This comparison allowed the

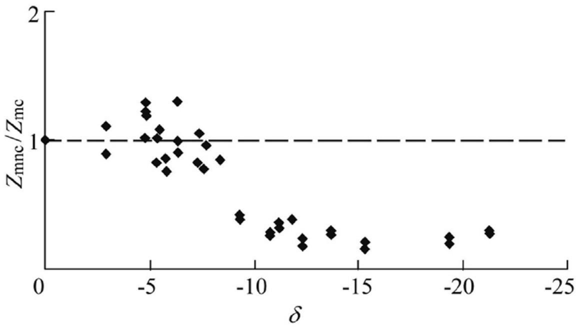


Fig. 5. $Z_{mnc}/Z_{mc}$ as function of $\delta$.

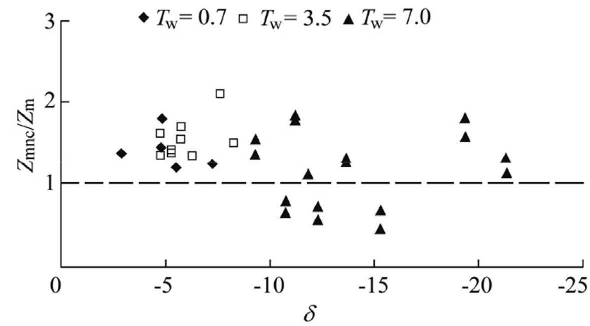


Fig. 6. $Z_{mnc}/Z_m$ as function of $\delta$ for different tested $T_w$ values.

establishment of the effect of $\delta$ on the parameter $Z_{mnc}/Z_{mc}$. Fig. 5 shows the comparison.

It can be observed that for $0 > \delta > -5$, there is generally a slight increase of the maximum scour depth, compared with that predicted by Eq. (1), for the same hydraulic and geometric conditions. This means that the location of the virtual crossing point below the water surface causes a slight increase of the scour depth, which is mainly due to the fact that jets do not cross in the atmosphere. Therefore, no jet splashing occurs. In such a configuration, energy dissipation decreases, resulting in an increase of the erosive action exerted by the jets on the bed material. If $\delta < -5$, both the distance of the virtual crossing point from the water surface and the distance $\Delta$ of the two impact points on the channel bed increase, and scour hole formation is caused by the combined action of the two jets. Nevertheless, the interference between the two jets results in a partial replenishment of the scour hole, as the bed material is transported both downstream by the lower jet and upstream by the upper jet. These opposite sediment movement dynamics contribute to the decrease of the maximum scour depth and are amplified when $\delta$ decreases.

The scour dynamics due to multiple non-crossing jets can also be compared with what is obtained in the presence of an equivalent single jet, which is characterized by the same densimetric Froude number and an inclination angle equal to $\alpha_v = (\alpha_1 + \alpha_2)/2$. For identical hydraulic conditions, the ratio $Z_{mnc}/Z_m$ is significantly influenced by the non-dimensional distance $\delta$, as shown in Fig. 6, where $Z_m = z_m/D_{eq}$ is the maximum non-dimensional scour depth estimated using the following relationships proposed by Pagliara et al. (2008) and valid for a single unsubmerged jet, black water conditions, uniform stilling basin material, and an absence of upstream flow in the channel:

$$Z_m = f_1(F_{d_{90}}) f_2(\alpha) f_3(T_w) f_4(\mu) \tag{5}$$

where $\mu$ is the relative scour hole width (a parameter indicating whether the scour hole shape is 3D or 2D) and

$$f_1(F_{d_{90}}) = F_{d_{90}} \tag{6}$$

$$f_2(\alpha) = -0.38 \sin\left(\alpha + 22.5^{\circ}\right)(1.360 - 0.012\alpha) \tag{7}$$

$$f_3(T_w) = \frac{1}{0.30}\left(0.12 \ln\frac{1}{T_w} + 0.45\right)(4 + T_w) \tag{8}$$

$$f_4(\mu) = 0.140 \tag{9}$$

Note that in the tested range of parameters, the scour morphology was always 3D, according to the definition given by Pagliara et al. (2008). Therefore, $f_4(\mu)$ is constant and equal to 0.140. It can be easily observed that for otherwise identical hydraulic conditions, the non-crossing jets cause an increase of the maximum scour depth for approximately $0 > \delta > -10$. This behavior can be explained considering that, for $0 > \delta > -10$, the virtual crossing point is generally located inside the scour hole. Therefore, the resulting jet behaves similarly to a submerged jet, for which an increase of the scour depth should be expected. Nevertheless, if $\delta$ decreases, ranging approximately between $-10$ and $-20$, the scour depth decreases.

It is worth noting that in this case the longitudinal distance between the two impact points of the jets on the stilling basin increases. Therefore, the two jets cause a huge interference of the scour processes. In particular, as described above, the bed material is transported both downstream by the lower jet and upstream by the upper jet, thus contributing to a decrease of the maximum depth of the equilibrium scour morphology. Nevertheless, if $\delta$ further decreases ($\delta < -20$), the scour depth becomes similar to that originated by a single jet. This is due to the fact that scour Type 3 occurs. Therefore, the interference between the two jets decreases and the maximum scour depth depends on the characteristics of the single non-crossing jets, whose behavior, in terms of scour mechanism, is similar to that of a single isolated jet.

Based on previous studies (Pagliara et al., 2012a) and observations, it is evident that for non-crossing multiple jets, Eq. (1) can be modified as follows:

$$Z_{mnc} = f_1(F_{d_{90}}, \Delta\alpha) f_2(\delta, T_w) f_3(\alpha_1, T_w) f_4(\delta) \tag{10}$$

The analysis of experimental data allowed us to derive the following expression for the multiplicative term $f_4(\delta)$:

$$f_4(\delta) = 0.0068\delta^2 + 0.2224\delta + 1.9484 \tag{11}$$

Therefore, combining Eqs. (1)−(4) and (11), the maximum scour depth for non-crossing multiple jets can be easily estimated, within the following range of parameters:

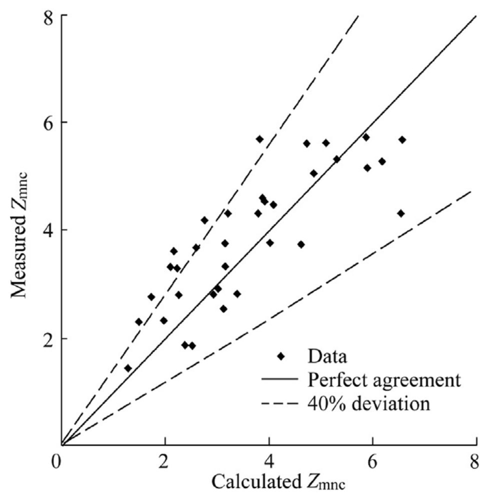


Fig. 7. Comparison between measured and calculated values of $Z_{mnc}$.

$-21.27 < \delta < -2.90$, $0.7 < T_w < 7.1$, and $8.61 < F_{d_{90}} < 14.47$. Fig. 7 shows the comparison between measured and calculated (with Eq. (10)) values of the variable $Z_{mnc}$.

From a practical point of view, the previous analysis shows that when $\delta$ approximately ranges between −10 and −20, non-crossing multiple jets should be preferred to both crossing and single jets, in order to reduce the maximum scour depth for the same hydraulic conditions.

Another important parameter, in terms of practical applications, is the maximum scour length. In general, this parameter is strictly connected to the maximum scour depth, i.e., for two-dimensional scour phenomena the scour length increases with the scour depth. Nevertheless, for complex jet configurations and a wide range of hydraulic conditions, Pagliara et al. (2012a) showed that the non-dimensional scour length cannot be expressed as only a function of the non-dimensional scour depth, even if it essentially depends on the same base parameters. Pagliara et al. (2012a) showed that in the case in which the crossing point of the jets is located above the water surface, the maximum non-dimensional scour length can be expressed by the following functional relationship:

$$L_c = f_1(F_{d_{90}}, \Delta\alpha) f_2(\delta) f_3(T_w) f_4(\alpha_1) \quad (12)$$

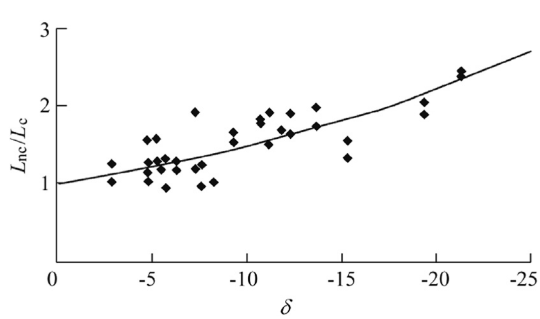


Fig. 8. $L_{nc}/L_c$ as function of $\delta$.

where $L_c = l_c/D_{eq}$, in which $l_c$ is the maximum scour length and

$$f_1(F_{d_{90}}, \Delta\alpha) = (-0.014\Delta\alpha + 1.500)F_{d_{90}} + 0.087\Delta\alpha - 2.770 \quad (13)$$

$$f_2(\delta) = 0.017\delta + 1 \quad (14)$$

$$f_3(T_w) = -0.035T_w^2 + 0.290T_w + 0.798 \quad (15)$$

$$f_4(\alpha_1) = -0.011(\alpha_1 - 30) + 1 \quad (16)$$

In the case in which the two jets do not cross, the scour dynamics become even more complex, as the scour process caused by the two jets mainly depends on the parameter $\delta$. In fact, if $\delta$ decreases, two scour holes can occur and generally the scour length becomes more prominent. In particular, it was experimentally noted that, when $\delta$ is varied and all the other hydraulic parameters are kept constant, the ratio $L_{nc}/L_c$ becomes a monotonic decreasing function of $\delta$, in which $L_{nc} = l_0/D_{eq}$ is the non-dimensional scour length for non-crossing jets. Fig. 8 shows $L_{nc}/L_c$ as a function of the relative distance of the virtual crossing point from the water surface. It is worth noting that the mentioned ratio decreases with the magnitude of $\delta$, tending toward 1 for $\delta = 0$, as should be expected, i.e., $L_{nc} \approx L_c$ for $\delta = 0$.

Based on previous experimental evidence, the following empirical relationship ($R^2 = 0.87$, where $R^2$ is the coefficient of determination) was proposed in order to estimate $L_{nc}$:

$$L_{nc} = \exp(-0.04\delta)L_c \quad (17)$$

Fig. 9 shows the comparison between measured and calculated (with Eq. (17)) values of the variable $L_{nc}$. From a practical point of view, the analysis mentioned above shows that non-crossing multiple jets always cause an increase of the maximum scour length compared with crossing jets for the same hydraulic conditions.

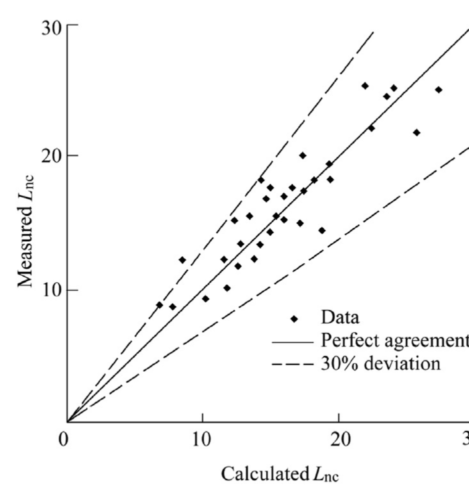


Fig. 9. Comparison between measured and calculated values of $L_{nc}$.

## 5. Conclusions

In this study an analysis of the scour mechanism caused by multiple non-crossing jets was performed. It was observed that the main parameters influencing the scour process are the following: the densimetric Froude number, the tailwater level, the inclination angles of both non-crossing jets, and the distance from the water surface to the virtual crossing point of the jets. The last parameter assumes the greatest importance. According to the non-dimensional vertical distance of the virtual crossing point of the jets, $\delta$, different behaviors can be detected resulting in different scour hole morphologies and hydrodynamics. In particular, three different scour types were distinguished and classified. In addition, an empirical relationship was derived to predict the maximum scour depth. From a practical point of view, it was observed that, in general, a reduction of the maximum scour depth occurs when $-20 < \delta < -10$. Therefore, for identical hydraulic conditions, multiple non-crossing jets, with $\delta$ varying between $-10$ and $-20$, are preferable to both multiple crossing jets and single jets with regard to minimizing the maximum scour depth. On the other hand, multiple non-crossing jets always cause a longer scour hole under the same hydraulic conditions.

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