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# Effect of Jet Injection on Flow Structure in Local Pier Scour

**Somayeh Soltani-Gerdefaramarzi[1*], Hossein Afzalimehr[2], Yee-Meng Chiew[3] and Jacques Gallichand[4]**

*[1]Department of Agricalture and Natural Resources Engineering, Ardakan University, Iran.*
*[2]Department of Water Engineering, Isfahan University of Technology, Iran.*
*[3]School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.*
*[4]Département Des Sols et de Génie Agroalimentaire, Université Laval, St-Foy, QC, Canada.*

***Authors' contributions***

*This work was carried out in collaboration between all authors. The author SSG designed the study, conducted literature review, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors HA, YMC and JG managed the analyses of the study, read, edit, and approved the final manuscript.*

***Original Research Article***

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## ABSTRACT

This study investigates experimentally the effect of jet injection on the flow structure around a pier-scour hole. Experiments are conducted with 1-jet, 3-jets and without jet injection under clear-water scour conditions. The results show that the jet(s) alter(s) the turbulent characteristics and vertical component of the velocity, causing a reduction of the strength of the down flow. A quadrant analysis for the Reynolds shear stress values reveals that the sweeps and ejections have the main contributions on the Reynolds shear stress production in the near-bed flow. The third-order correlations of velocity fluctuations show an obvious distinction for the jet injection experiments in comparison to that without injections, especially inside the scour hole.

*Keywords: Jet injection; pier scour; quadrant analysis; Reynolds shear stress; third-order correlations.*

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**Corresponding author: E-mail: soltani@ag.iut.ac.ir;*

## 1. INTRODUCTION

The obstruction of flow by a pier in either a river or marine environment will change the local flow pattern in the vicinity of pier. The boundary layer separation combined with the down flow produces a horseshoe vortex wrapped around the base of the pier, entraining bed material and producing a local scour hole. Numerous studies of local scour at piers and pier countermeasure have been reported based on laboratory experiments over the past seven decades (e.g., Tafarojnoruz et al. [1]; Barbhuiya and Talukdar [2]; Chiew [3]). One of the reasons for the departure from traditional armoring countermeasures, such as dumping of riprap stone, sacrificial sill or piles in recent studies is associated with the recognition of other failure mechanisms related to the use of armoring countermeasures. One way of reducing pier scour is the utilization of jet injection issued from the pier as this will alter the shape of the velocity profile and the boundary layer. In their study, Soltani-Gerdefaramarzi et al. [4] have found that the jet acts as an obstacle against the down flow, causing it to lose its strength in impinging the bed. However, they did not show how the local turbulent flow field is affected by the jet, causing the method to be successful as a pier-scour countermeasure. Dey et al. [5] conducted an experimental study on turbulent flow characteristics in submerged plane wall jets subjected to injection (upward seepage) and suction (downward seepage) from the wall. The vertical distributions of time-averaged velocity components, turbulence intensity components and Reynolds shear stress at different horizontal distances are presented. It is a well-known fact that jet injection from a boundary layer will postpone flow separation. If the laboratory study confirms the potential of this technique as an effective countermeasure, it will be important to undertake a program in the field to verify its applicability in prototype scale. Therefore, the objectives of this study are to investigate the turbulence flow structure around a circular pier subjected to jet injections as a scour countermeasure and to apply the bursting analysis to identify the dominant events in Reynolds stress production under an equilibrium scour hole.

## 2. EXPERIMENTAL DETAILS

The uniform approach flow with flow rate, $Qo = 53.5\ Ls^{-1}$, depth-averaged velocity, $U = 0.27\ ms^{-1}$ and water depth, h = 28 cm was established in a glass-sided flume. Table 1 shows summary of the experiments and flow conditions. Uniform sediments were used in the tests with median diameter $d_{50}$ = 0.48 mm and geometric standard deviation $\sigma_g = (d_{84}/d_{16})^{0.5}$ =1.33. The instantaneous velocities of flow in three directions were measured using a Micro ADV in an equilibrium pier-scour hole with depth, $d_{se}$ = 12.5 cm for no-jet injection test around a circular bridge pier after 48 hour of starting any experiment. Three experimental runs were conducted to measure the turbulence flow characteristics, with one run without jet injection, and two runs with 1-jet and 3-jets injections located 1cm above the bed material. Normalized distributions of the velocity, turbulence intensities, three components of the Reynolds stress, and third-order correlations of the velocity fluctuations were obtained for each run at 6 vertical sections along the center of the flume upstream of the pier ($0.67D \le x \le 2.4D$) in which x is the distance upstream from the center of the pier and D = pier diameter. The details of experimental set-up can be found in Soltani-Gerdefaramarzi et al. [4,6]. Fig. 1 illustrates how the jet comes out from the pier.

**Table 1. Summary of experiments condition**

| Test series | *h* (cm) | $Q_0$ (Litr/s) | *U* (m/s) | *Re* | *Fr* | $Q_j$ (Litr/s) | *θ* | $U/U_c$ | Explanation |
|---|---|---|---|---|---|---|---|---|---|
| A | 28 | 53.5 | 0.273 | 88628 | 0.16 | - | - | 0.81 | Without jet injection |
| B | 28 | 53.5 | 0.273 | 88628 | 0.16 | 0.015 | - | 0.81 | 1-jet |
| C | 28 | 53.5 | 0.273 | 88628 | 0.16 | 0.015 | 45 | 0.81 | 3-jet |

**Fig. 1. Photo of a circular pier with a water jet injection on the pier surface**

## 3. RESULTS AND DISCUSSION

We are interested in determining the influence of the jet injection on the velocity profiles and flow field. To this end, three experiments, an unprotected experiment, a protected experiment with 1-jet and a protected experiment under 3-jet injections located 1cm above of bed material, were conducted to investigate changes to the turbulence flow characteristics around the bridge pier in the equilibrium scour hole. Angel between jets and the individual flow rate of jets were 45º and 0.015 L/s respectively. Vertical distributions of the velocity (u(z), v(z), w(z)), of the turbulence intensity, and of the Reynolds stress were obtained for any experiment at different vertical sections along central line of the flume at 6 positions in front of the cylinder (0.67D ≤ x ≤ 2.4D). Here only 3 vertical lines upstream of the pier in jet injection condition and without jet are shown to obtain the figures clearer for turbulence intensity, and Reynolds stress. For vertical distributions of the velocity, 5 positions at the behind of the cylinder (-0.67D ≤ x ≤ -3.3D) also was measured which cover the approach-flow region outside the scour hole and the scour-hole region. However the flow around of pier is three-dimensional, the magnitude of the lateral velocity (*v* component) is rather low, therefore the data of lateral velocity are not displayed in this paper.

### 3.1 Distribution of the Velocities at the Upstream of Pier

Fig. 2 shows the vertical distributions of the longitudinal, u(z), and vertical, w(z), velocity components for test conducted with no, 1 and 3 jet injections upstream of the pier. In the figure, the bold symbols represent the results for 1-jet or 3-jets injections, while the open symbols are those without a jet. The longitudinal velocity (u-component) decreases away from the water surface, and becomes negative in the scour hole (z < 0), notably close to the bed layer for the no jet injection run (Fig. 2a). The magnitude of u increases in the z direction and the vertical gradient ($\partial u/\partial z$) within the scour hole (z < 0) is larger than that above the hole (z > 0). In addition, the negative values of u increase toward the bottom of the scour hole, while far from the pier, (x = 0.67D to x = 2.4D) the positive values of u increase. The nearest location to the pier (x = 0.67D) presents the highest negative u value (-0.6 $cms^{-1}$) within the scour hole, showing the existence of a vortex system within the scour hole. Similar observations were reported by Dey et al. [7] and Ahmed and Rajaratnam [8]. Jet injection increases significantly the streamwise velocity (u) values near the bed (z/h < 0.2) close to the pier, but this is not observed far from the pier (e.g., x = 2.4D from the pier) due to weakening jet injection effect. Within the scour hole (z < 0) in presence of the jet, the u-values are close to zero; far from hole however, considerable larger values of u is observed near the bed and at the location of jet injection (z/h = 0.03). Accordingly, the magnitude of normalized longitudinal velocity increases from u/U = -0.155 to 0.405 for 1-jet (Fig. 2a) and from u/U = -0.01 to 0.48 for 3-jet injection at x/D = 0.67 (Fig. 2c). A change in the sign of u from the negative to positive indicates that jet injection generates sufficient kinetic energy in the boundary layer and weakens the flow separation near of bed.

The vertical velocity component illustrates the power of the down flow and plays an important role in the pier-scour process. Large negative values such as w = -7.39 $cms^{-1}$ are observed within the scour hole (z/h = -0.14) and close to the pier (x = 0.67D) for the no jet experiment. However, because of jet injection the value of this velocity component diminishes (close to zero) which indicated characteristics reduction of down flow as well as horseshoe vortex effect. For example, the vertical velocity at x = 0.67D decreased from w/U = -0.24 to a value of close to -0.05 in 1-jet and reduced to -0.16 in 3-jet injection at z/h ≈0. Within the scour hole 3-jet injection decreases w-component considerably and this reduction is greater than 1-jet injection. For example, the value of w/U = -0.27 in without jet test reduces to close zero with 3-jet while in 1-jet injection it reaches to -0.2 at x = 0.67D and z/h = -0.13. This result shows that the effect of 3-jet in scour reduction is more than 1-jet injection within scour hole because the 3-jet contains more energy thereby weakening the strength of down flow in front of pier and moving it away from the bed. Of course reducing in the magnitude of vertical velocity in the close of pier is more because jet is more effective in the near of pier. Thus it had a significant effect on the resulting scour hole.

### 3.2 Characteristics of Maximum Downflow

Fig. 3 shows that the maximum downflow velocity (vertical velocity upstream of the pier), $W_{max}$, and the location of occurrence, z/h are functions of x/D. For the test without jet, Fig. 3(a) shows that the value of $W_{max}$ increases almost linearly as it approaches the pier, with the smallest $W_{max}$ value (≈ 0.27U) at x = 0.6D. When x/D = 2.4, $W_{max}/U$ reaches -0.15. For the 3-jets experiment, Fig. 3(a) clearly shows that when x/D > 1.5, the 3-jets injections effected the largest $W_{max}$. Fig. 3(b) shows that the location of the maximum downflow moves from z/h < 0 to z/h ≈ 0.12 for 3-jets, showing that the location of $W_{max}$ moves away from the bed for x/D < 2 but jet injection has minimal influence when x/D ≥ 2.5. The reduction of downflow and its location of occurrence will affect the scour hole formation.

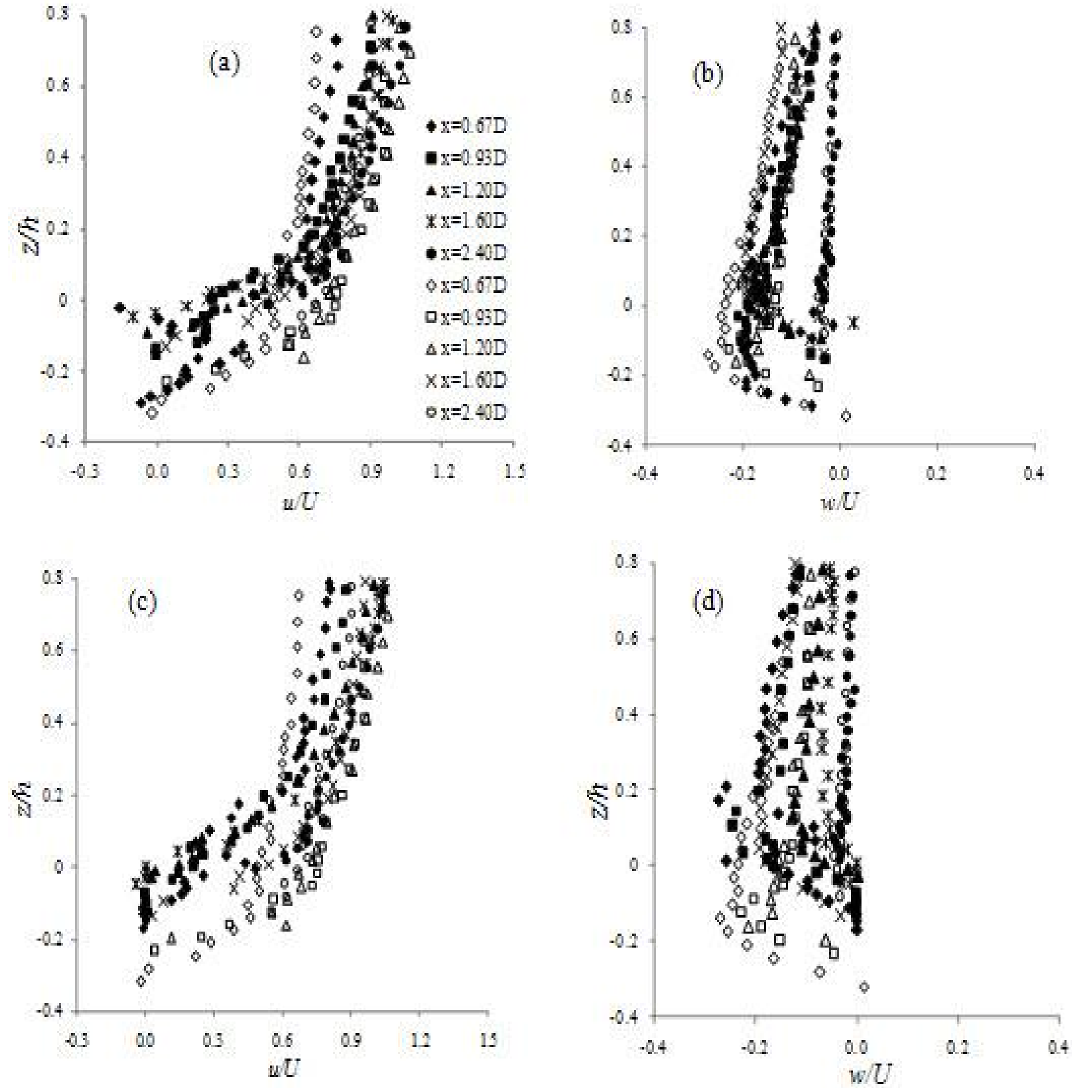


**Fig. 2. Distribution streamwise and vertical velocities in the upstream of pier for (a and b) 1-jet and (c and d) 3-jet; (Bold symbols: with 1-jet; open symbols: no jet)**

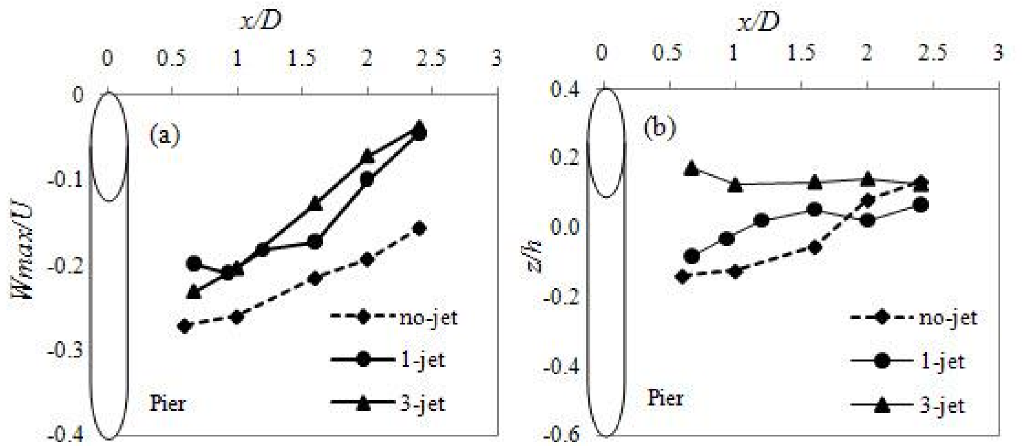


**Fig. 3. Characteristics of downflow along the center of flume (Flow from right to left)**

## 3.3 Turbulence Intensities

Figs. 4(a) and 4(b) show the distributions of turbulence intensities normalized by the shear velocity upstream of the pier for 1 and 3-jet injections, respectively in comparison with no jet injection data. The results reveal that without jet injection, the turbulence intensities in the longitudinal, lateral and vertical directions increase away from the water surface, displaying similar behavior. However, the experiments with jet injections show that the turbulence intensity increases with depth and reaches a peak, a behavior that is similar to that without the jet. However, beyond the peak values, they decrease with increased fluctuations within the scour hole for the 1-jet injection. For the 1-jet experiment, the turbulence intensities are significantly larger than those without the jet. For the 3-jet test, however, the turbulence intensities are rather small within the scour hole. Nevertheless, outside the scour hole ($z > 0$), they increase for both the 1-jet and 3-jets injections, especially at the location near the source of the jet. In summary, it may be inferred that the 3-jet injections cause less turbulence within the scour hole due to the reduction of flow separation, a phenomenon which is confirmed by the data presented in Fig. 4(b).

## 3.4 Reynolds Shear Stress and Bed Shear Stress

Fig. 5 illustrates the distribution of the three components of the Reynolds shear stress in the upstream plane of the pier subjected to no jet, 1 and 3-jets injections. The results show that the Reynolds shear stress distributions are linear and change little in the upper part of the scour hole ($z > 0$), but significantly bulges in the lower portion of the hole ($z < 0$). Moving downstream and toward the bottom of the pier, the Reynolds shear stresses increase significantly within the scour hole due to turbulent mixing of the fluid in this region. Graf and Istiarto [9] also reported a similar trend in their works. It should be mentioned that the Reynolds shear stress increases at the location of the source of the jet and out of the scour hole, but it reduces significantly due to the 3-jets injections within the scour hole. The significant reduction of the Reynolds shear stress considerably affects the developing scour hole. For example, the value of the normalized Reynolds shear stress, changes from 4 to 1.5 at $z/h = 0.2$ for the 1-jet experiment. Close to the jet location the Reynolds stress values increase, showing greater values for the 3-jet injections than those without and with 1-jet injection.

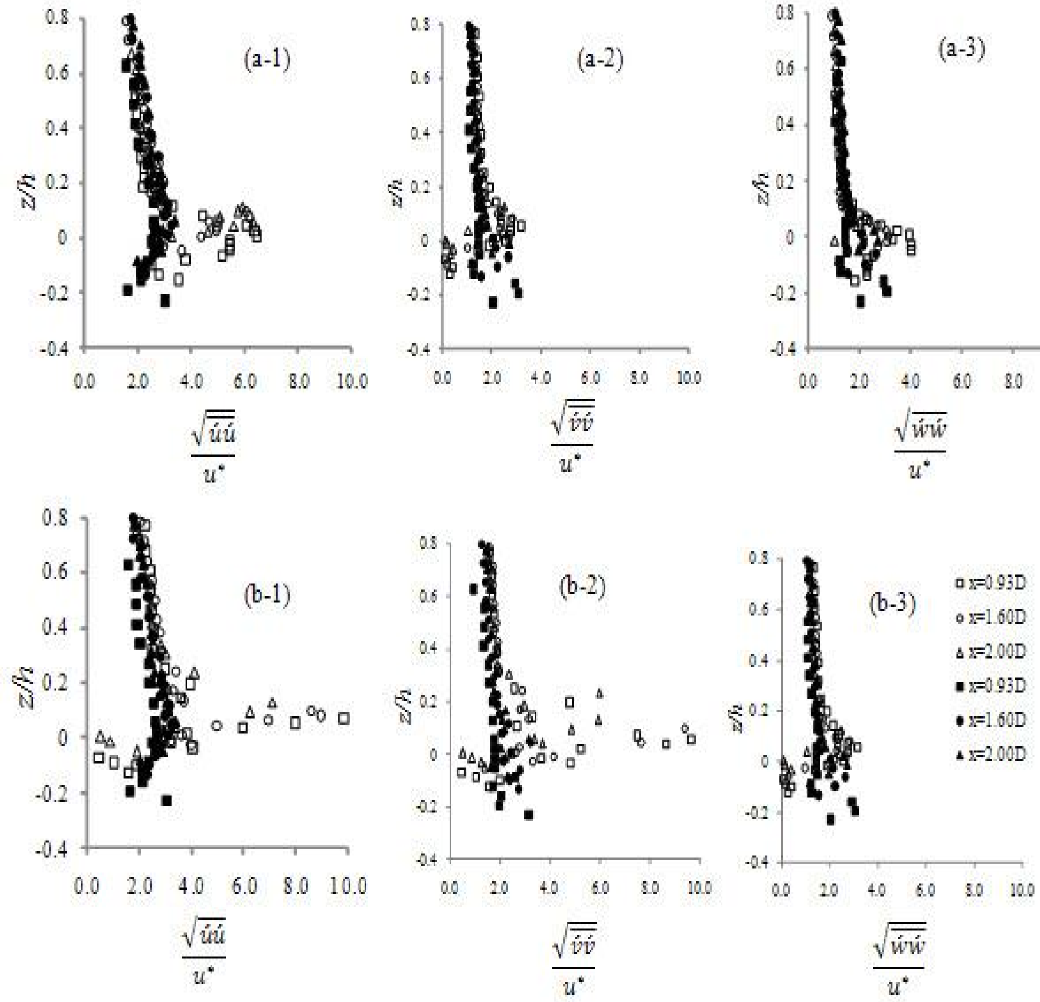


**Fig. 4. Distribution turbulence intensities in the upstream of pier for (a) 1-jet and (b) 3-jet; (open symbols: with 1-jet and 3-jet; Bold symbols: no injection)**

The bed-shear stress, $\tau_b$, is estimated using the distribution of the velocity as follows (Graf and Altinakar [10]):

$$\tau_b = \rho(u_*)^2 = \rho(U\sqrt{\frac{g}{C^2}})^2 = \rho(0.07U)^2 = \rho(0.07((u^2+v^2+w^2)^{0.5})^2 \quad (1)$$

Where g, U and ρ are gravitational acceleration, local depth-averaged flow velocity and density of water respectively, and C is the Chezy coefficient taken as C = 44 (m $^{½}$ s$^{-1}$). Fig. 6 shows the distribution of the computed bed shear stress in front of the pier with the distance, x for 1-jet, 3-jets and no jet injection. The data show that the bed shear-stress increases with distance from the pier, reaching the maximum value in the middle portion of the scour hole before gradually decreasing outside the hole, with the minimum value of $\tau_b$ on the flat bed. Graf and Istiarto [9] also reported a similar trend. However, far from the scour hole (x > 20), the bed shear-stress increases, probably coinciding with the reattachment of the jet at this location. The bed shear stress variation is negligible inside the scour hole for 1-jet injection, However, 3-jet injection reduces the bed shear stress, especially in region within the scour hole and close to the pier. The reduction in the bed shear stress enhances the stability of the bed sediment particle and thus reduction in rate of scouring.

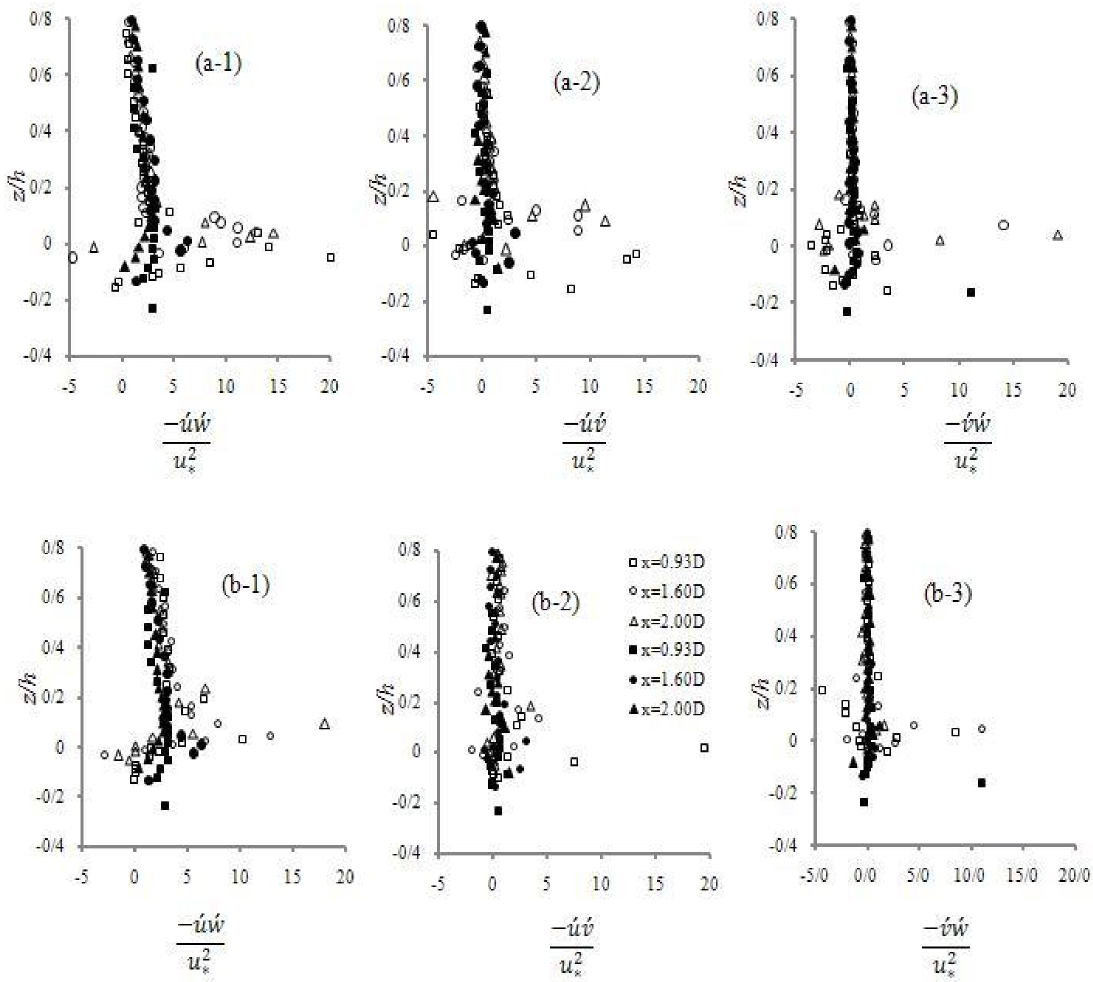


**Fig. 5. Distribution of the three components of the Reynolds stress in the upstream of pier for (a) 1-jet and (b) 3-jet; (open symbols: with jet; bold symbols: no jet)**

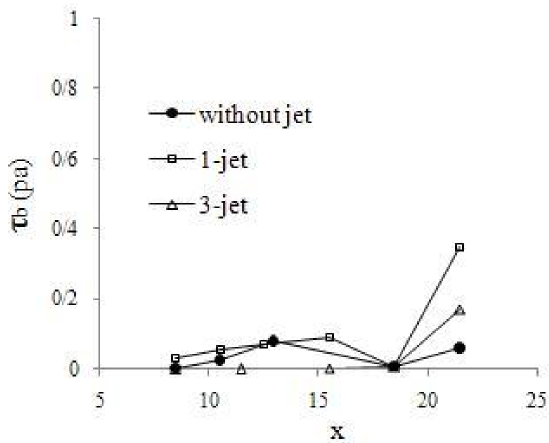


**Fig. 6. Estimated bed shear stress in front of the pier (Flow from right to left)**

### 3.5 Third-Order Correlations of Velocity Fluctuations

Third-order correlations give essential information on the turbulence stresses and the temporal characteristics of the velocity fluctuations. The virtual responses of bursting events are reasonably identified by the third-order correlations. The set of third order correlations Mjk is expressed as:

$$M_{jk} = \overline{\overline{u^j}\,\overline{w^k}} \qquad (2)$$

Where j + k = 3. More details of Eq. (2) can be found in Dey and Nath [11]. Fig. 7 presents profiles of third-order correlations of u' and w' in the upstream of pier. In the figure, $M_{30}$ defines the flux of the streamwise Reynolds normal stress $\overline{\acute{u}\acute{u}}$, $M_{21}$ corresponds to the turbulent advection of $\overline{\acute{u}\acute{u}}$ in the z-direction, $M_{12}$ refers to the turbulent advection of the vertical Reynolds normal stress $\overline{\acute{w}\acute{w}}$ in the x-direction and $M_{03}$ characterizes the vertical flux of $\overline{\acute{w}\acute{w}}$. As shown in these figures, distributions are simply somewhat changed by the influence of jet injection. Also, the mean trends of $M_{21}$ and $M_{03}$ are positive, while those of $M_{12}$ and $M_{30}$ are negative showing deceleration of the streamwise flux of $\overline{\acute{u}\acute{u}}$.

All third-order correlations tend to be zero in the inner layer (z/h < 0.2). Also, variations of $M_{21}$ and $M_{12}$ imply turbulent advection of the Reynolds normal stresses. In the inner layer (z/h < 0.2), the advection is negligible, increasing with z/h. The profiles of Mjk show that there exists an obvious distinction in Mjk for both tests with and without injection, especially within the scour hole. Jet injection appears to decrease the streamwise flux and advection of $\overline{\acute{w}\acute{w}}$ and increases the upward flux and the vertical advection of $\overline{\acute{u}\acute{u}}$. The maximum values are $M_{21}$ (z/h = -0.05) = $-M_{12}$ (z/h = 0.57) = 0.31 for jet injection and $M_{03}$ (z/h = 0.57) = 0.34 for without jet injection.

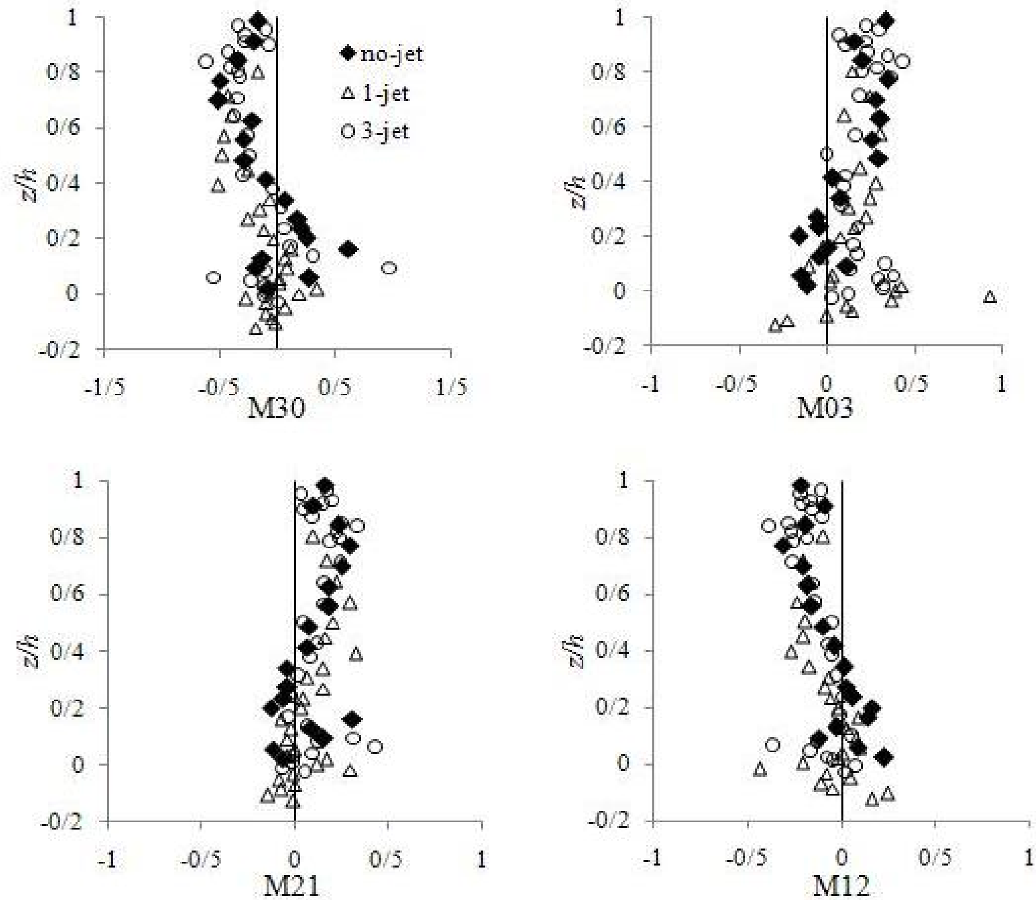


**Fig. 7. Profiles of third-order correlations of *u'* and *w'* in the upstream of pier**

### 3.6 Bursting Analysis

The quadrant analysis first introduced by Lu and Willmarth [12] to quantify the contribution to the Reynolds shear stress production by the coherent eddies during the events involved near-bed bursting in the turbulent boundary layer. The streamwise and vertical velocity fluctuations (u' and w') are divided into four quadrants for estimation the contributions of ejections and sweeps to Reynolds stress. The definition of 'sweeps' (u'>0, w'<0), 'ejections' (u'<0, w'>0), inward interaction (u'<0, w'<0), and outward interaction (u'>0, w'>0) is then applied systematically. Fig. 8(a-c) displays the percentage of velocity fluctuations (u' and w') and the fractional contributions of different events at each point over the entire flow depth under the no-jet, 1-jet and 3-jets injections at x/D = 0.67 upstream of the pier, respectively.

The results for case x/D = 1.2 and x/D = 2.4 (not presented here) show similar behavior. As shown in Figs, the dominant event is sweep (Q4), followed by ejection (Q2), then outward (Q1) and inward (Q3) in the entire flow depth except at some point in close to the bed level and within the scour hole (z/h < 0) where the contribution of ejection is more important than that of the sweep and Q2 events gradually exceed Q4 events with an increase in z. This difference between Q2 and Q4 events is associated with the increase in eddy size with vertical distance. Also, the contribution of sweep and ejection event diminishes away from the bed level and in contrast, the contribution of outward and inward (Q1 and Q3 events) continued to have insignificant contributions and increase in close to water surface becoming approximately equal in the water level. Furthermore, it is also found that the difference in distances from the pier have no significant effect on contributions of events but in percent of jet in experiments with 1-jet and 3-jet injection it cannot be seen any particular trend especially within the scour hole and close to pier. However, it is perfectly explicit that Q3 and Q1 events gradually exceed Q2 and Q4 events within the scour hole.

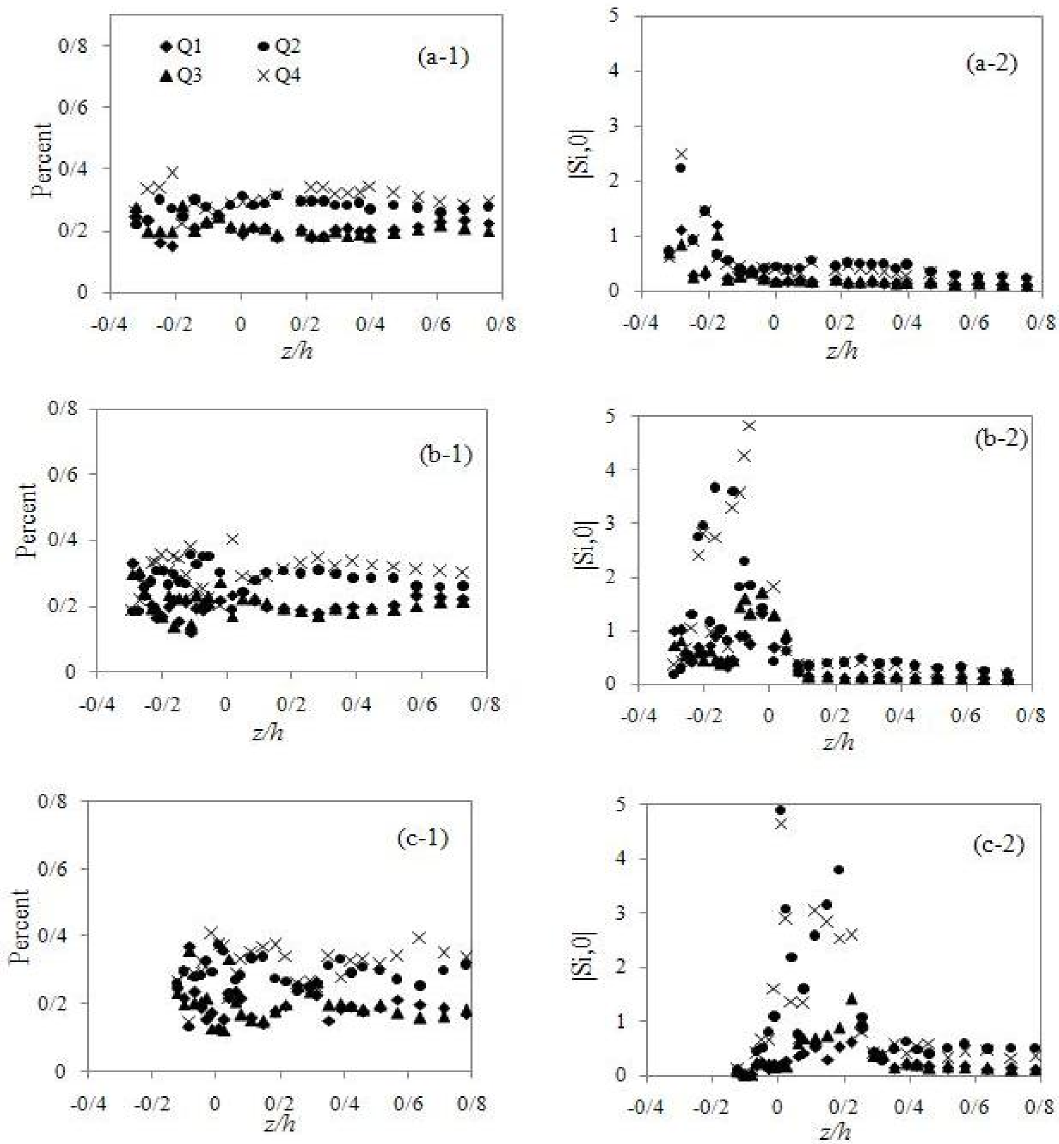


**Fig. 8. Percentage of velocity fluctuations (u' and w') and Stress fraction contributed for each quadrant (i= 1, 2, 3 and 4) in the upstream of pier for x/D = 0.67; (a) no-jet, (b) 1-jet; and (c) 3-jet**

The fractional contribution $S_{i,H}$ to the total Reynolds shear stress to each event is:

$$S_{i,H} = \frac{\overline{\acute{u}\acute{w}}^{i,H}}{\overline{\acute{u}\acute{w}}} \qquad (3)$$

To study the fractional contributions Reynolds shear stress production from different events for no-jet, 1-jet and 3-jet injection in the plane upstream of cylinder, the fractional contributions $|S_{i,H}|$ are plotted for the hole size H = 0 in Fig. 8 (a, b, and c-2) respectively. Here, $S_{i,H} > 0$ is for the first and the third quadrant, and $S_{i,H} < 0$ is for the second and the forth quadrant. In these figures, for the entire flow depth, the magnitudes of ejection and sweep motion behave in similar ways, also the magnitudes of outward and inward, regardless of the jet coming out location and within the scour hole.

Fig. 9 presents the joint frequency distribution at the normalized water depth z/h = 0.2 at the central axis of flume. The quadrant diagrams display a pseudo-elliptical shape with a tilting of the joint frequency distribution toward the second and fourth quadrants. Also, it is observed that the contributions of ejections (Q2) and the inwards (Q3) are dominant for different normalized flow depth (z/h) in the presence of the 3-jet injection, but the contributions of Q1 and Q4 in 3-jets injections are smaller than those without jet injection.

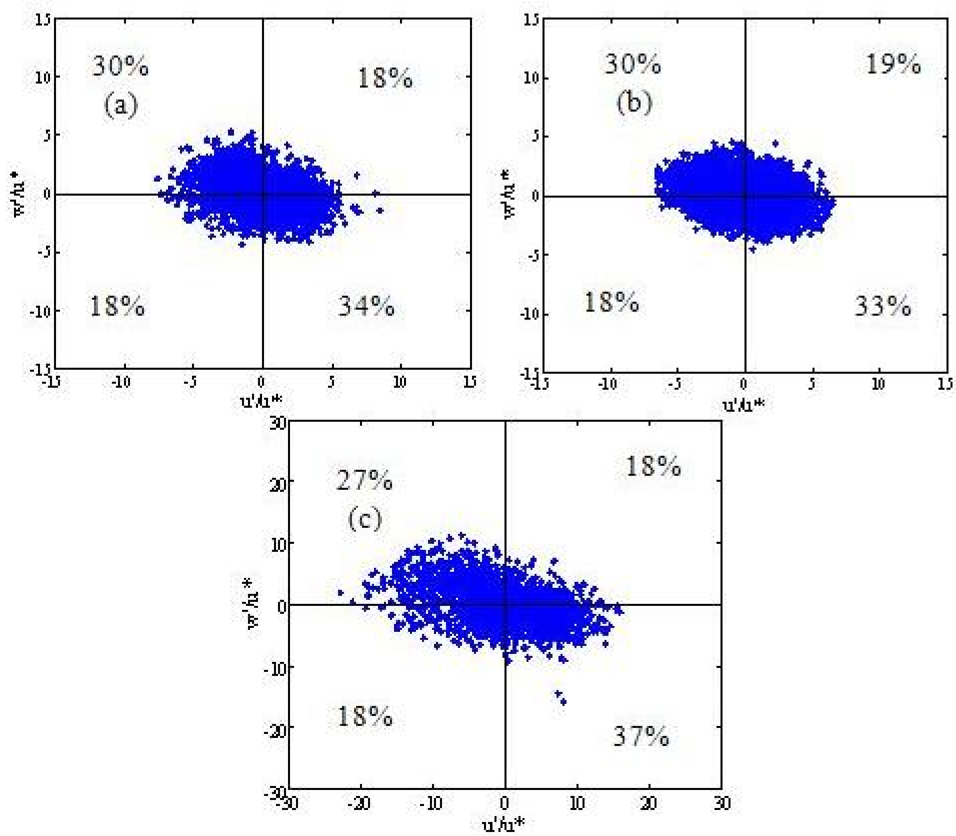


**Fig. 9. Joint probability distribution of u' and w' at water depths in the upstream of pier at x/D = 0.67 and z/h = 0.2; (a) no-jet; (b) 1-jet; and (c) 3-jet**

## 4. CONCLUSION

This paper presents the results obtained from an experimental study, in which the effectiveness of applying jet injection as a pier-scour countermeasure has been investigated by measuring the velocity around the pier, turbulence intensity fields, and Reynolds stress, in front of the pier with 1-jet injection, 3-jet injections and without jet injection protection in clear-water scour condition. Results of measured characteristics for turbulence flow showed that the flow around the pier subjected to the jet injection had a deceleration region near the sediment bed within the scour hole. The Reynolds stress magnitudes and turbulent intensities decreased in this region. This region had a significant influence on the formation of the pier-scour hole. Also, jet injection decreased the values of w-components in front of pier thereby decreasing the down flow strength. Within the scour hole 3-jet injection decreases w-component considerably and this reduction is greater than 1-jet injection. Also, Reynolds stress were reduced significantly due to 1-jet injection within and out of scour hole while 3-jet cause decreasing Reynolds stress in $z < 0$. Jet injection affects Mjk profiles particularly within the scour hole region where the strength of ejection (Q2) events increases, but sweep (Q4) effect decreases, resulting more negative and positive values for M30 and M03, respectively. Third-order correlations of velocity fluctuations show that jet injection decrease the streamwise flux and advection of $\overline{w'w'}$ but increases the upward flux and the vertical advection of $\overline{u'u'}$.

As a result, the presence of jet decreased the vertical velocity, and Reynolds stress within the scour hole and thus, all these phenomena result in a reduction of the pier scour and sediment entrainment. Also, a quadrant analysis for the Reynolds stresses shows that the sweeps and ejections are the important contributions towards the Reynolds shear stress production in the near-bed level and within the scour hole. In attention to the obtained results of Soltani-Gerdefaramarzi et al. [4] showing the jet efficiency in reduction of the scour depth, area and volume of scour hole and then the effect of jet on flow structure in this paper, it seems that jet may be an effective countermeasure against local scouring at bridge piers.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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## APPENDIX

*D* = pier diameter [m]

*Fr* = Froude number

*h* = mean approach flow depth [m]

$Q_0$ = flow rate [$m^3s^{-1}$]

$Q_j$ = individual injection flow rate [$m^3s^{-1}$]

*Re* = Reynolds number

*U* = mean approach flow velocity [$ms^{-1}$]

*u, v, w* = Cartesian velocity components in the *x*, *y*, and *z* directions, respectively [$ms^{-1}$]

$u', v', w'$ = fluctuating velocity components in the *x*, *y*, and *z* directions, respectively [$ms^{-1}$]

$u^*$ = shear velocity [$ms^{-1}$]

*x, y, z* = Cartesian coordinate in the longitudinal, lateral, and vertical directions, respectively [m]

$\tau_b$ = bed shear stress [$Nm^{-2}$]

$\theta$= Angle between jets.



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