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Shahid Chamran University

Turbulent characteristics in flow subjected to bed suction and jet injection as a pier-scour countermeasure

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Abstract

The effect of a combined system of the bed suction and jet injection as a pier-scour countermeasure on the turbulent flow field is studied in a laboratory flume using an Acoustic Doppler Velocimeter (ADV). The three components of the velocities in the vertical symmetry plane in the equilibrium scour hole in front and rear of the pier under 3-jet injections and bed suction rate Q_s/Q_0 = 2% located between $0 < x/D < 2.4$, (where x and D are the horizontal distance along the streamwise direction between the suction source and the pier center and the pier diameter respectively); in clear-water scour condition were measured instantaneously. Also, characteristics of turbulence flow (the turbulence intensity, vorticity and turbulent kinetic energy) in the upstream of a circular pier were investigated. The results reveal that turbulence properties, such as turbulence intensities decrease with bed suction and jet injection. Over the entire water depth, they decrease more rapidly near the bed than those near the free surface. As a result, a system of jet injection and bed suction decrease scouring around the pier.

Keywords: *pier scour, jet, turbulence, bed suction, injection*

1 Introduction

Scour is a natural phenomenon caused by the flow of water in rivers and streams. It is the result of the erosive action of flowing water, removing and eroding material from the bed and banks of streams and also from the vicinity of bridge piers and abutments (Breusers et al., [2]). During the past decades, several methods were investigated to reduce local scour at bridge piers (e,g., Chiew [5] and [6]; Chiew [7]; Dey et al., [8]; Dey and Raikar [9]; Chiew and Chen [30]; Grimaldi et al., [14]; Zarrati et al., [26], [27] and [28]; Mashahir et al., [18]; Tafarojnoruz et al. [23] and [24]; Gaudio et al., [12]; Soltani-Gerdefaramarzi et al., [20] and [21]). The boundary layer separation and down flow produces the horseshoe vortex around the pier, resulting in increment of bed remove and causes local scour around the bridge piers. On the other hands, suction and blowing (injection) are useful methods to reduce boundary layer separation (Schlichting and Gersten, [27]). Prinos [19] studied the effects of bed suction on the structure of turbulent open-channel flow numerically by solving the Reynolds-averaged Navier-Stokes equations. He showed that the turbulence levels were greatly reduced with increasing suction rate but the near-bed velocities and bed shear stress were increased with increasing suction rate. Nezu [28] conducted measurements of mean velocity, turbulence intensity, and Reynolds stress of open channel flow with bed suction. He found that the dimensionless Reynolds stress subjected to suction decreases when compared to that without suction. Chen and Chiew [3] investigated theoretically and experimentally streamwise velocity distributions of turbulent open channel flow with bed suction. The velocity increased significantly in the near bed and reduced near the water surface, resulting in the formation of a more uniform velocity distribution. Chen and Chiew [4] studied the influence of bed suction on the characteristics of turbulent open channel flow in a laboratory flume. The experimental results showed that bed suction significantly affects the mean flow properties, turbulence levels, and Reynolds stress distributions and all these properties reduce with increasing relative suctions. Lu and Chiew [15] investigated the effect of bed suction on turbulence flow over an immobile, two-dimensional triangular dune. The measurements displayed that bed suction causes the flow within the boundary layer to be less turbulent because both the near-bed turbulence intensity and Reynolds shear stresses decreased with suction and the streamwise velocity profile became more uniform with suction. Also, it causes the flow to adhere to the bed,

Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

resulting in reduction of the separation length. Schlichting and Gersten [27], Maclean and Willetts [16], and Maclean [17] reported that bed suction increases the bed shear stress. Dey and Sarkar [10] studied the velocity and turbulence characteristics in an evolving scour hole downstream of an apron due to submerged jets issuing from a sluice opening detected by an acoustic Doppler velocimeter. Their results showed that the flow in the scour holes (intermediate and equilibrium) is found to be plausibly self-preserving. Ghodsian and Vaghefi [13] studied experimentally scour and flow field around a T-shape spur dike in a 90 degree channel bend. They showed that increasing the Froude number and length of spur dike the amount of scour increases and increasing the wing length of spur dike decreases the scour. Dey and Nath [11] measured turbulence characteristics in flows subjected to boundary injection and suction. Soltani-Gerdefaramarzi et al. [22] investigated experimentally the effect of jet injection on flow structure. The results showed that jet injection can decrease the vertical velocity, Reynolds stress and vorticiry within the scour hole resulting in a reduction of the pier scour and sediment entrainment. Jet injection has a similar effect with collar. For the region above the jet injection, the resulting flow acts as an obstacle to block the downflow from impingement onto the bed. For the region below the jet, the strength of the downflow and horseshoe vortex likely will also decrease. The efficacy of jets in reducing scour depends on its magnitude and location on the pier relative to the bed level [20]. The objective of present study is to investigate the characteristics of turbulence flow within an equilibrium scour hole around a circular pier submitted to bed suction and constant water jet injection from pier as a pier-scour countermeasure by weakening the downflow and horseshoe vortices.

2 Experimental Setup and Measurements

Laboratory experiments were carried out in a horizontal re-circulating flume (Fig. 1) with glass walls in the Hydraulic Modeling Laboratory at the Nanyang Technological University, Singapore. The flume was 30 m long, 0.7 m wide and 0.6 m deep. The flow rate was controlled using a speed inverter and a valve and was monitored using an electromagnetic flow meter, and a tail gate located at the downstream end was used to control the water depth in the flume. At the entrance to the flume, pipe straighteners were installed to ensure uniform flow and to minimize circulations and large scale turbulence. The working section was filled with uniform sediments with median grain sizes d50 = 0.48 mm and geometric standard deviation $\sigma g = (d84/d16)0.5 = 1.33$ in the experiments. The uniform approach flow (Qo = 53.5 L/s, U = 0.27 m/s and h = 28 cm) was established and can be considered to be two-dimensional (W/h = 2.5), turbulent ($Re = \rho Uh/\mu = 88628$), and subcritical ($Fr = U/(gh)0.5 = 0.16$). In order to have clear water scouring condition the shear velocity (U*) was determined to be 0.81 U*c. Critical shear velocity was be get by trial and error method using the Shields Diagram and was 0.017 m/s. The diameter of the circular pier is D = 75 mm installing vertically at 17 m downstream of the channel entrance and was drilled with three 3-mm diameter holes located 1 cm above the bed materials level. The maximum angel of jets was selected 90o and individual the flow rate of jets was Qj = 0.015 L/s. Suction with rate Qs/Q0 = 2% located $0 < x/D < 2.4$ (where x and D are horizontal distance along the streamwise direction between the suction source and pier center and diameter of pier, Qs and Q0 are suction flow rate and undisturbed total flow rate, respectively). The seepage zone is located at a distance 16 m from the upstream end of the flume and is in the form of a recess with 2 m long, 0.7 m wide and 0.4 m deep. The depth of sand is 0.2 m was placed on top of a filter cloth. Water before being drained by 12 identical pipes, each with a value to control suction charge, is seeped through the sand layer, filter net, and perforated plate. The velocity measurements were implemented in the equilibrium scour hole (dse = 9.2 cm) under clear-water scour condition which had been previously established by performing a continuous run of 2 days under a constant water jet injection and bed suction . For measuring instantaneous velocities of flow in three directions was used Sontek's down-looking 3-dimensional MicroADV (Micro Acoustic Doppler Velocimeter) with sampling frequency 50 Hz and sampling volume 5 cm located below the probe. In order to obtain one velocity profile, for each point 240 seconds duration was typically done. More than 27 points were used to obtain the velocity profile at each of these x locations. The accuracy of velocity data collected by ADV was checked by the software WinADV (Wahl [29]) to filter and process the velocity and turbulence data. The method of SNR/correlation was used in this study for ADV data filtration, such data with an average correlation coefficient of less than 70% and average SNR of less than 15 dB was filtered out. The details of the equipment and experiment can be found in Soltani-Gerdefaramarzi et al. [20] and [21] paper and will not be repeated here however the Cartesian coordinate system with indicating 0 as the origin in the figure located at the centre of the pier.

Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

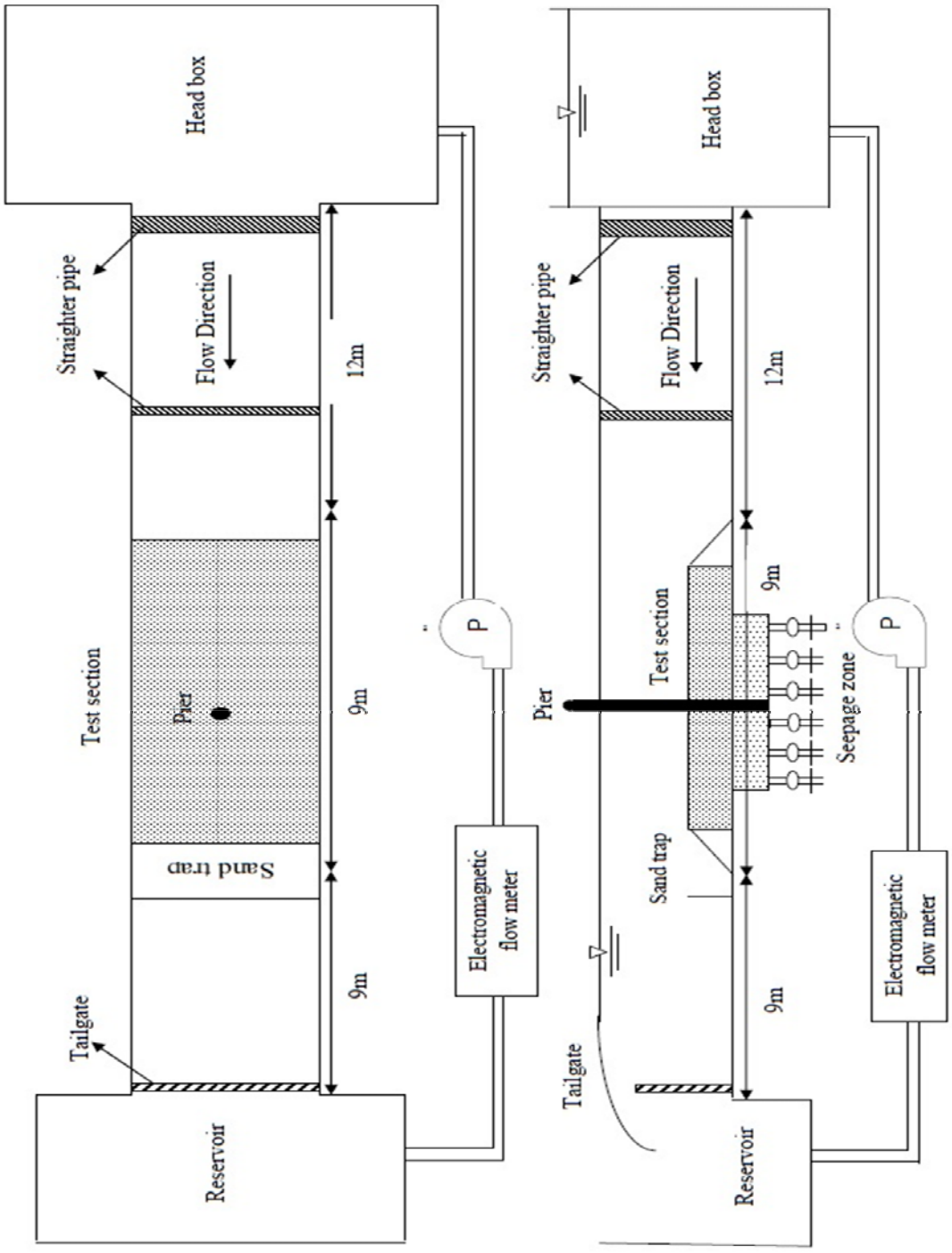


Fig. 1 Plane view and longitudinal profile of flume

Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

3 Results and Discussion

A three-dimensional Acoustic Doppler Velocimeter (ADV) was used to measure three-dimensional instantaneous velocities so that the turbulent properties of flows could be investigated. Two experiments, an unprotected experiment, a protected experiment with bed suction and 3-jet injection located 1cm above of bed material, were conducted to investigate changes to the velocity and turbulence flow characteristics around the bridge pier. Angel between jets and the individual flow rate of jets are 90° and 0.015 L/s respectively. Vertical distributions of the velocity ($u(z)$, $v(z)$, $w(z)$), of the normalized turbulence intensity ($\frac{\acute{u}}{u^*}$, $\frac{\acute{v}}{u^*}$, $\frac{\acute{w}}{u^*}$), and of the normalized vorticity ($\frac{(\acute{u}^2-\acute{w}^2)}{u_*^2}$) were obtained for any experiment at different vertical sections along central line of the flume at 6 positions in front of the pier ($0.67D \leq x \leq 3.33D$). Here only 3 vertical lines upstream of the pier in jet injection and suction condition and without jet and suction are shown to obtain the figures clearer for velocity, turbulence intensity and vorticity. Although the flow is three-dimensional near the pier, the magnitude of the lateral velocity (v-component) is rather low, so the data of lateral velocity are not shown in this paper.

3.1) Velocity fields in the upstream and downstream of pier

Streamwise velocity distributions

Figure 2 shows the vertical distributions of the longitudinal, u(z) at three locations: x = 0.67D, 2D, and 3.33D for both no-suction and no-injection and for suction rate 2% with 3-jet injection experiments upstream of the pier. In this figure, the bold symbols represent results of tests conducted without any protection while the dotted symbols show tests conducted with protection. The data were obtained dimensionless, using the undisturbed approach flow velocity, U and the approach flow depth, h. The u-component is dominant along the most part of the upstream and downstream of pier. Entering the scour-hole region, the u-component remains important up to close to the cylinder, notably within the upper layer, z/h ≥ 0. As expected, the measured longitudinal velocity, u(z), diminishes away from the water surface and approaching the pier beginning at z < 0 (within the scour hole) to become negative values, notably close to the bed layer in the cases without jet injection and bed suction (bold symbols). The nearest location to the pier (x = 0.67D) has the highest negative u-component (-0.6 cm/s) within the scour hole. The change is more apparent near the bed because of jet presence and it decreases gradually until little nearer the free surface in experiments with suction and injection. The measurements displays that bed suction causes the flow above the scour hole to be less turbulent therefore the streamwise velocity profile became more uniform with suction. The bed suction decreases the rate of longitudinal velocity increasing due to jet issuing of pier surface within the scour hole (from u/U = 0.385 to value 0.0023 at x/D = 0.67 in z/h = -0.17) and adjusts the jet effect but farther away from suction zone, the rate of velocity increasing, enhances and the effect of injection is more dominate, significantly close to the pier. At the downstream of pier, near and rear of the cylinder the longitudinal velocity is small and negative showing flow reversal towards the water surface. Moving from water surface, streamwise component velocity becomes positive and increases but decreases within the scour hole (Fig. 3).

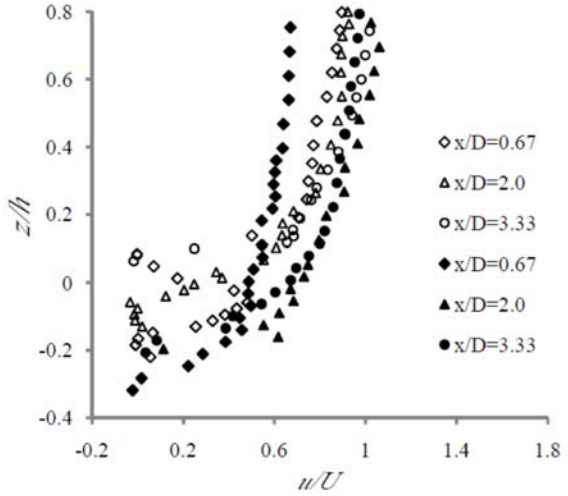


Fig. 2 Streamwise velocity profiles in the upstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

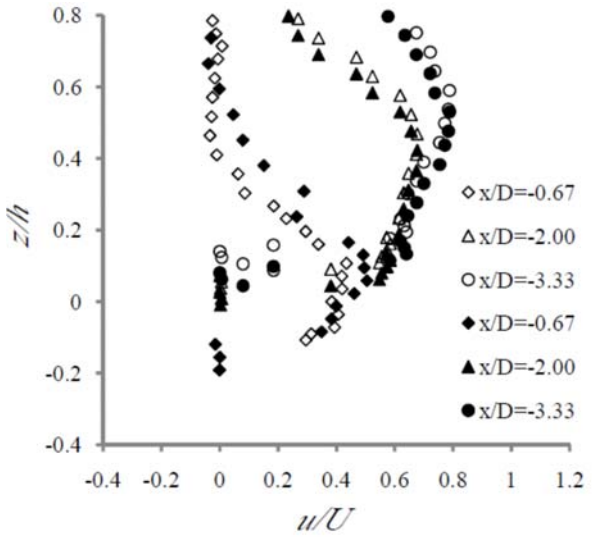


Fig. 3 Streamwise velocity profiles in the downstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

Vertical Velocity distributions

The vertical distributions of the vertical, w(z) velocity components at three locations for without any protection and with protection is shown in Fig. 4. In the plane upstream of pier, the vertical velocity (w-component) is consistently negative value (indicating down flow). As this figure display, the vertical velocity component becomes more negative when the flow is close to the pier in cases with suction as a result of local flow abstraction and out of the scour hole, $z/h \geq 0$, the w-components is practically negligible. From $x/D \leq 2.0$, at the lower layer and approaching the cylinder, the w-component, being a downward component, becomes important. It usually reaches a negative maximum value in the upper layer of the scour hole, $w/U \approx -0.27$ at $z/h = 0.014$ and tends towards zero or slightly positive values at the solid boundary of the scour hole. Close to the solid boundary of the scour hole and notably at the range of $2.0 \leq x/D \leq 3.33$, noticeable is a return flow formed by a negative u-component and a positive w-component. The data show that the negative values of vertical velocity diminishes (becoming close to zero) in $x/D = 2$ and 3.33 in cases with protection thereby reducing the downflow strength and moving it away from the bed. The sudden reduction of the vertical velocity is observed at $x = 0.67D$ (close to the suction and injection zone) which w-component decreased from $w/U = -0.244$ to a value of close to 0.004 for $z/h = 0.0125$ (jet issuing location). Additionally, the results indicate that the response of the vertical velocity to bed suction is more than that of the streamwise velocity. This behavior is not unexpected because suction has a more direct impact on vertical velocities than horizontal ones. Measurements by Chen and Chiew [3] and [4] show a rather similar trend. The vertical velocity (w-component) is always positive in the downstream of the pier and close the water surface reduces and gets reversals (Fig. 5). Accordingly, the formation of positive wake vortices at the rear of cylinder causes the bed material remove from the bed, deepening scour hole.

3.2) Turbulence intensities distribution at the upstream of pier

The vertical distributions of normalized turbulence intensity components where ú = fluctuation of u, v'= fluctuation of v and ẃ = fluctuation of w, are plotted in Figs 6 to 8 respectively. The fluctuating velocity components in the x, y and z directions, were obtained dimensionless, using the undisturbed approach shear velocity, u* and the approach flow depth, h. The results show that in the upstream of pier, the turbulence intensity values in the longitudinal and vertical in all tests increase away from the water surface and the distributions of these values are almost similar. In the experiment with bed suction and jet injection, changes to the turbulence intensities were similar to the trend observed from the tests without jet injection and suction significantly in bed upper position ($z/h \geq 0.2$). These figures indicate that the suction and jet together causes the turbulence intensity reduce within the scour hole (close to zero near the pier for both figures), but has not considerable effect on locations near the water surface. Bed suction decreases turbulent fluctuations in the flow field resulting in less momentum exchange between fluid particles. On the other words, suction causes the flow to be less turbulent, a phenomenon that is confirmed by the data in both Figs 9 and 10 as it is in agreement with the general expectation. Watters and Rao [25], Nezu [28] and Antonia and Zhu [1] reported that the flow in the boundary layer under suction condition changes from turbulent to laminar. Of course It should be attended that in location of jet issue ($z/h = 0.03$), the turbulence intensity increase in experiments with jet and suction. Generally, these results supported that a combined system of jet and suction as a pier-scour countermeasure can decrease turbulence at the upstream of pier.

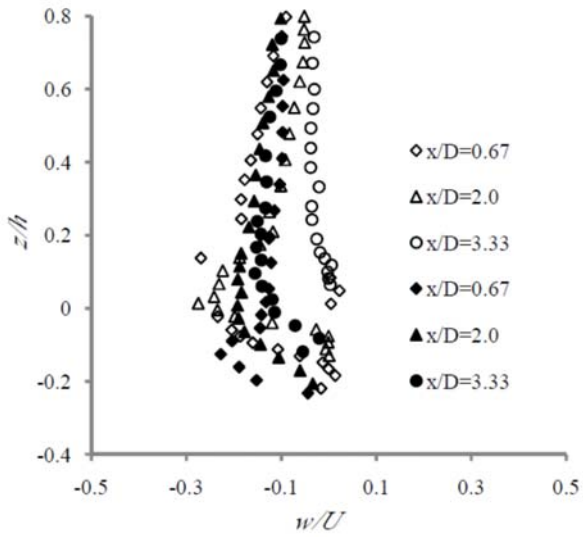


Fig. 4 Vertical velocity profiles in the upstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

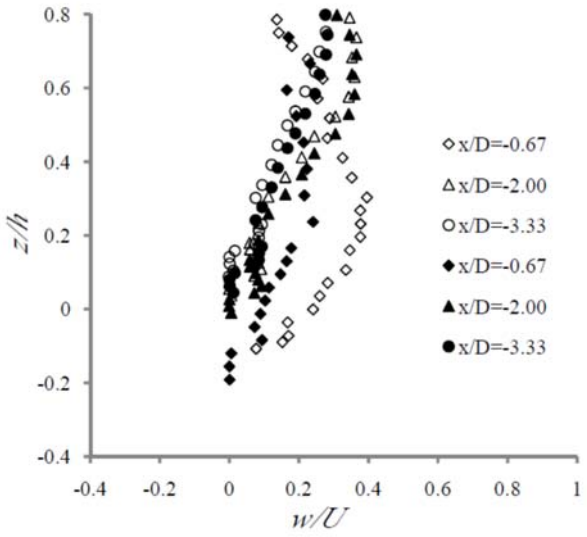


Fig. 5 Streamwise velocity profiles in the downstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

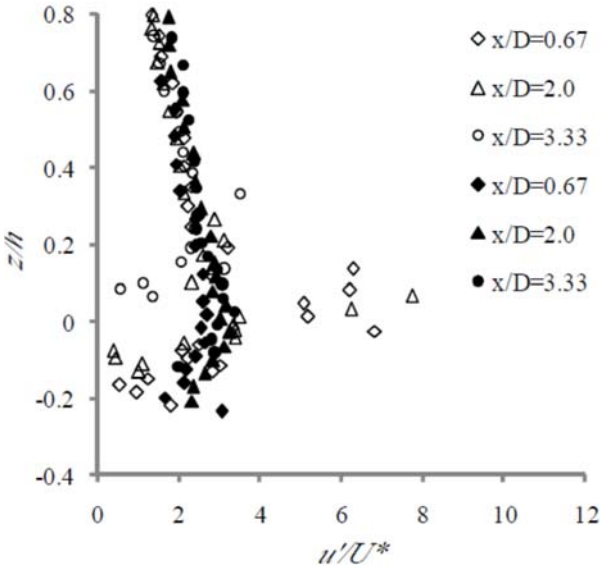


Fig. 6 Normalized streamwise turbulent intensity profiles in the upstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

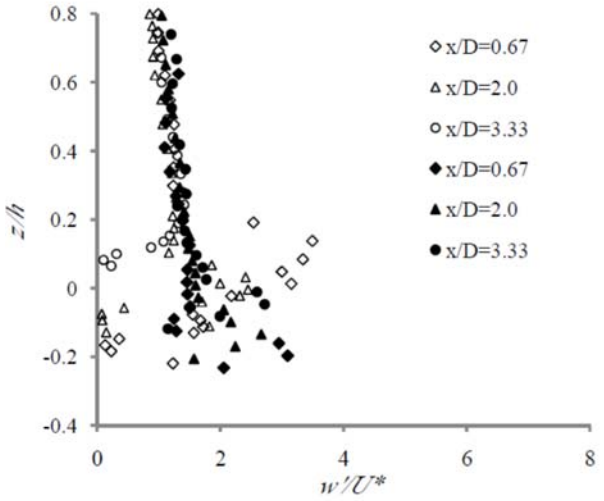


Fig. 7 Normalized vertical turbulent intensity profiles in the upstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

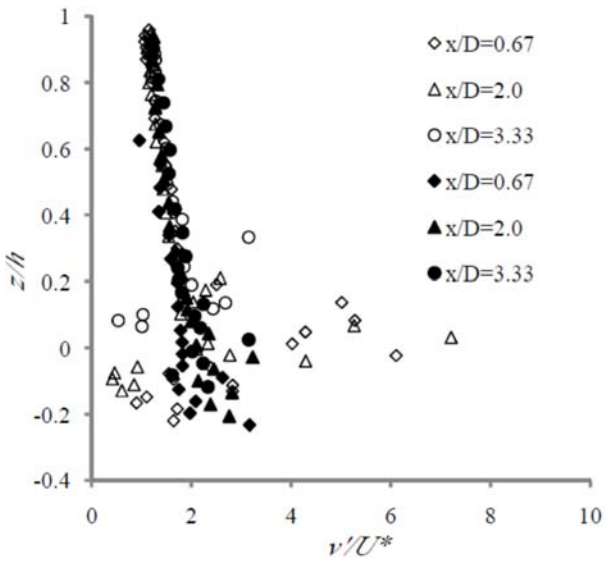


Fig. 8 Normalized lateral turbulent intensity profiles in the upstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

3.3) Vorticity distribution at the upstream of pier

Figure 9 indicates that the lateral vorticity is rather weak and close to zero in near water surface. But apart from this location, it increases and becomes strong significantly near jet location and reaches to the maximum value 56.4 at x = 2D and to 41.8 at x = 0.67D in z/h = -0.02 (within the scour hole). As shown these figures, in presence of the jet and bed

Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

suction, vorticity diminishes rather little within the scour hole indicating horseshoe vortex which forms at the base of the pier aids the scouring phenomenon.

3.4) Turbulent kinetic energy distribution at the upstream of pier

The turbulent kinetic energy is defined as:

$$k = \frac{1}{2}(\overline{\acute{u}\acute{u}} + \overline{\acute{v}\acute{v}} + \overline{\acute{w}\acute{w}}) \quad (1)$$

Figure 10 illustrates the distribution of turbulent kinetic energy of the flow at the upstream of pier for experiments.

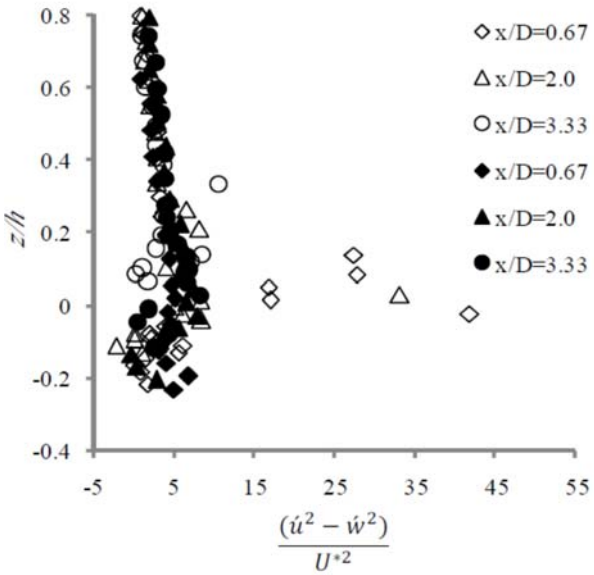


Fig. 9 Normalized vorticity in the upstream of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

These results showed that turbulent energy profiles were approximately linear and changed rather insignificantly in the upper part flow depth close to water surface. Approaching the pier (where down flow occurs), the turbulent energy became increasingly strong, especially at the location jet issue. The profiles of the turbulent kinetic energy were characterized by bulges below the original bed level. Similar profiles were observed for the Reynolds stresses profiles. Also, within the scour hole, turbulent kinetic energy decreased due to bed suction and jet injection through the pier, showing a strong anisotropy pattern at the bottom of pier in this region. The turbulent kinetic energy does not show any especial trend for the injection and bed suction tests. Compared to the results of Soltani-Gerdefaramarzi et al. [20] using only jet injection through the pier, it seems that bed suction affect on effectiveness of jet injection and modifies the turbulence flow structure within the scour hole due to significant turbulence anisotropy.

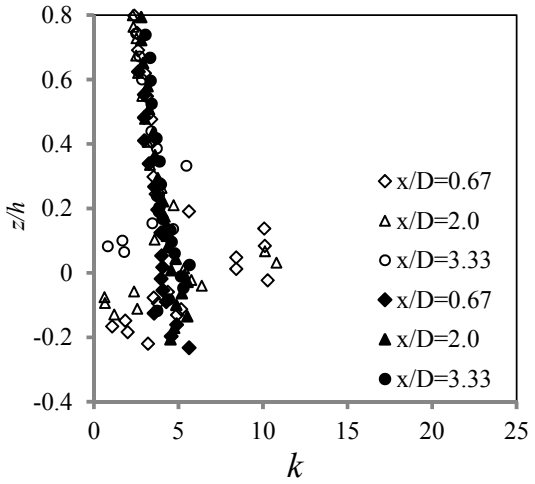


Fig. 10 Turbulent kinetic energy in the upstream plane of pier

3.5) Reynolds-stresses distribution at the upstream of pier

Figure 11 illustrates the distribution of Reynolds stress in the plane upstream of pier for without jet injection and suction and with suction and 3-jet injection. This figure represents that the Reynolds stress, $-u'w'$, are linear and change little in the upper part, $z > 0$, and show significant bulges in the lower part, $z < 0$, moving downstream and downwards towards the foot of the pier and increase significantly within the scour hole due to the turbulent mixing of fluid as a result of vertical flow. Also, these results display that the Reynolds stress reduce significantly due to 3-jet injection and suction within and out of scour hole. The significant reduction of Reynolds stress had an important effect on the resulting scour hole and sediment transport. For example, the value of $\frac{-\acute{u}\acute{w}}{u_*^2}$ reaches from 3.15 to 0.68 at $z/h = 0.2$ in $x = 2D$. Close to the jet location these values increase in cases of jet protection due to jet injection.

4 Conclusions

This study presented the experimental measurements conducted in open channel flow with a combined system of bed suction and jet injection through the pier body as a pier-scour countermeasure. The results show that the suction and injection together affects the velocity profiles, the rms values of velocity fluctuations, vorticity of the flow and the turbulent kinetic energy. Results of measured characteristics for turbulence flow show that the flow around the pier subjected to the jet injection from pier and bed suction can be encompassed into three regions: (1) a decelerating flow region near the bed within the scour hole, $z/h < 0.1$, (2) an

Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

acceleration region in the district of water depth middle region and out of scour hole, $0.1 \leq z/h \leq 0.2$, and (3) a reversion region in the outer layer, $z/h > 0.2$.

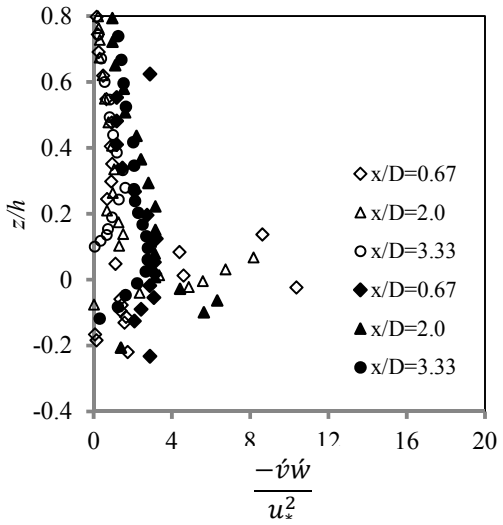


Fig. 11 Normalized Reynolds stress in the upstream plane of pier (Bold symbol = no jet and suction; Dotted symbol = with jet and suction)

The turbulent intensities magnitudes, vorticity decreased in the deceleration region, increased in the acceleration region and reverted to that of the unprotected condition in the reversion region in comparison with case of without jet injection and bed suction. Also, a combined system of jet injection and bed suction decreased the values of vertical component of velocity (w) in front of pier, weakening the down flow strength, moving it away from the bed thereby decrease scouring process. In summary this study confirms that bed suction and jet injection causes the flow within the boundary layer to be less turbulent. Suction may also result in significant turbulence anisotropy, which plays an important role in turbulence production. Soltani-Gerdefaramarzi et al. [21] showed that the equilibrium depth in the presence of bed suction and jet injection was considerably lower than that without any protection, with a minimum percentage reduction of 50%. Also, the obtained results of this study confirmed that jet injection and bed suction may be an effective countermeasure against local scouring at bridge piers.

5 Acknowledgments

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Notations

The following symbols are used in this paper:

d_{50} = median size of the sediment particles
d_{16} = sediment size which 16% of sediment is finer
d_{84} = sediment size which 84% of sediment is finer
d_{se} = equilibrium depth of local scour
D = pier diameter
Fr = Froude number
h = mean approach flow depth
Q_0 = flow rate
Q_j = individual injection flow rate
Q_s = suction flow rate
Re = Reynolds number
U = mean approach flow velocity
U_c = critical mean approach flow velocity for entrainment of bed sediment
U^* = shear velocity
U^*_c = critical share velocity
u, v, w = cartesian velocity components in the x, y, and z directions, respectively
u', v', w' = fluctuating velocity components in the x, y, and z directions, respectively
W = width of flume
x, y, z = cartesian coordinate in the longitudinal, lateral, and vertical directions, respectively
σ_g = geometric standard deviation of the sediment particle size distribution
θ = angel between jets
ω_y = lateral vorticity

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Scientific Professional Quarterly

http://Jhs.scu.ac.ir

Spring 2013

Volume 1, Issue 1, Pages 1-9

Hydraulic Structures

Shahid Chamran University

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