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COMPUTING EQUILIBRIUM FLOW STRUCTURES AT THREE INTERFERING SQUARE PIERS CAUSING RELATIVE SCOUR

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ABSTRACT

The hydrodynamic flow pattern at clear-water equilibrium scouring- condition around three staggered arranged identical square piers was analysed experimentally. Two piers were placed in line and other was set eccentrically in mid of in line square- piers. One side face of each pier was faced the flow perpendicularly. The detailed 3-D velocities were captured instantaneously after the equilibrium scour attained. Readings were taken at five different vertical azimuth sections and at two horizontal sections (near bed and middle depth). The contour profiles and distribution of velocity-components, kinetic energy k and intensities for turbulence were computed, analyzed and plotted in dimensionless form. Velocity vectors and absolute velocities hold detailed hydrodynamic flow characteristics. Vorticity and circulations are determined by computation. Mutual interferences caused by this square shaped pier group lead to enhance prolonged scour around eccentric- pier. Sand shifting was more toward flume-wall compared to single or two pier combinations. Vortices-strength near front-inline pier was less than that of eccentric and more than that of rear-inline pier.

KEYWORDS

Open-channel, Clear-water, Turbulent-flow, longitudinal-gap, Eccentricity, Vorticity, Circulation.

1. INTRODUCTION

The hydrodynamic flow characteristic around a pier group is a big problem. For hydraulicians it is an important topic to find the extent of scour near multiple piers. Nowadays arrangements of pier group are becoming more needed in bridge designing for its geotechnical and economic benefits. The mechanism of scour and flow characteristic for multi-piers arrangement is too complex and it is also very complicated to find out scour-depth from the single-pier experiment. Also, many laboratory flume based experiments were accomplished to accumulate more information on scour mechanism, flow behaviour and to compute scour depth with more precision. Many of the researchers gave stresses on velocity measurement and subsequent pattern of the turbulent flow field at different shaped piers (Melville and Raudkivi, 1977; Das et al., 2013a-c, 2014a-e, Raikar and Dey, 2008). Bridge designs oftentimes lead to a multiple- pier arrangement in which straight uses of the outcomes are copied only from single- pier preparation that may be problematical. Most of the multiple- pier experiments have been restricted to two pier arrangements, positioned either eccentric, inline or sidewise focusing on flow field, turbulent field and scouring geometry prediction (Das and Mazumdar, 2015a,b) and the consequences of pier spacing towards flow on kinematic characteristics and on scour-depth (Raudkivi, 1998; Graf, 2003; Das et al., 2016, 2018, 2019). Empirical equation to compute scour-depth around inline two circular-piers was recently proposed (Yilmaz et al., 2017). The hydrodynamic flow characteristics were studied around

three inline - eccentrically arranged identical circular piers (Das et al. 2017; Jaman et al., 2017a,b). On basis of previous scouring studies, the current study has been inspired on the topic of dealing with three identical square-shaped piers and how the scouring differs with it. Hardly there were any lab-flume experimental investigation done to find out the vortical flow type and characteristics at the three, equidistant towards flow, square piers having plan- view of (inline) two square front- square rear- piers and a square eccentric- pier arrangement. Here, the principal objective is to critically study the hydro dynamic interaction by computing three-dimensional turbulent velocity flow fields all over the square-piers.

2. EXPERIMENTAL PROCEDURE

For experimentation, perspex-sided re-circulating rectangular flume was used. Here, three identical hollow square-piers (Perspex-made) of 7 cm width (b) were placed centrally at effective working section of flume [Fig. 1]. Piers of 7 cm side was considered, for comparing the outcomes between present study and previous studies with two circular-piers (Das and Mazumdar, 2015b), two square-piers (Das and Mazumdar, 2018), and three circular-piers (Jaman et al., 2017a). Longitudinal-gap between square front and eccentric- piers (l) along flow was 66 cm (Das et al., 2016). After experiment, water drained out from scour-hole, max-scour-depth formed near up-stream zone of three square-piers [Fig. 2]. Thereafter, equilibrium max-scour-depth around the piers was measured with point-gauge. From the gauged data contour profile is determined. The

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three components of velocity were recorded instantaneously using a down facing VectrinoPlus probe (Das et al., 2015c). Vectrino output readings (.vno) were converted by VectrinoPlus software into .xls readings for filtering. A polar cylindrical axis coordination, given in Figs. 1 - 2, is developed to present non-dimensional velocity and following dimensionless flow fields for turbulence at five vertical azimuth-sections $\pm 90^\circ$, $\pm 45^\circ$, and 0° around the piers. The time- mean velocities in r , α , z are signified by u , v , and w , whose resulting instabilities are u' , v' , and w' . Positive direction of tangential - u , radial - v , and vertical - w , velocities are respectively counter clock-wise, out-ward and up-ward. To hold off solid section of piers in the plotted diagram, abscissa scale is taken by r_0/h , $[(r - 3.50b)/h]$, so $r_0/h = 0$ shows the square pier boundary.

Figure 1: Top view for gauge and velocity measurements

Figure 2: Scoured zones around three square piers

3. VELOCITY FIELDS ANALYSES

3.1 Tangential Velocity

Around the three square-piers at five azimuth-sections $\pm 90^\circ$, $\pm 45^\circ$, and 0° contours of dimensionless time-mean tangential velocity (u/U) were plotted. Contour profiles depict the flow behavior near and around such three square-piers. On 0° azimuthal section, u/U is nearly nil and therefore is inconsiderable as was recorded by ADV. As azimuth- angle α increases, value of u/U increases and turns finite. At square front- pier close to scour hole - value of u/U is a bit lower than square eccentric- pier and square rear- pier. From the past (Jaman et al., 2017a) and current investigation max- u/U is 6.1 % and 4.3 %, respectively, at any location upstream of square front- pier and decreases while it moves down-ward and increases toward bed. Max- u/U near up-stream of scouring region around square front- pier, square eccentric- pier and square rear- pier are acquired approximately 5.4 %, 15 % and 21 %, correspondingly. In those zones, u/U varies with higher magnitudes for square front- pier and square eccentric- pier corresponding to the square rear- pier. In present study, at $\pm 45^\circ$ azimuth-sections of the three square-piers value of u/U is found greater than value on 0° azimuth- section of corresponding points of corresponding piers. For the three piers in the arrangement max- u/U on 45° are 104 %, 112 % and 101 % of the max- u/U on -45° , respectively. It proves that small sheltering effects occur between 45° section for square eccentric- pier and -45° section for square front- pier and between -45° section for square eccentric- pier and 45° section for square rear- pier.

For sheltering effects between front- and eccentric- piers, max- u/U on 90° azimuth- section for square front- pier, square eccentric- pier, and square rear- pier is 99 %, 98 % and 100.9 % of max- u/U on -90° azimuth- section for corresponding piers. The flow behavior of u/U for square front- pier, square eccentric- pier and square rear- pier on $\pm 90^\circ$ are similar. The u/U on $\pm 90^\circ$ sections, for the three square- pier, are always higher than u/U on

$\pm 45^\circ$ sections for corresponding piers, as aspects of scouring are small, however it progressively decreases. Also u/U on $\pm 90^\circ$ and $\pm 45^\circ$ is comparatively strong as aspects of scouring are small, but progressively decreases due to flow area increase as the scouring- depth increases. Due to the way of the downflow flux along the sides of the three square-piers, a significant increase in u/U near piers is found and then reduces as radial distance r_0 increases from each pier and all over the flatbed u/U remains almost constant. The u/U in downstream of three piers for $z/h = 4$ % is almost similar to the corresponding values of u/U for $z/h = 50$ % but a bit higher in magnitude. The eddies created from the square front- pier are then flowed downstream and comes to the 0° to -90° section of eccentric- pier and 0° - 90° of square rear- pier and concurrently eddies created from eccentric- pier come to 0° to -90° section of square rear- pier.

3.2 Radial Velocity

The contours of dimensionless time- mean velocity v/U on five azimuth-sections $\pm 90^\circ$, $\pm 45^\circ$, and 0° were plotted. On 0° azimuth- section, v/U changes its direction on both side of zero contour line $v/U = 0$ within the scour hole, at changed depths for square front- pier, square eccentric- pier and square rear- pier are around 60 %, 65 % and 71 % of consequent max- scouring- depth below non-scoured bed level ($z/h = 0$ %) for the corresponding pier, respectively. As published, for two square- pier experiment under same experimental clause, it is 65 % and 67 % of max scouring- depth under the non-scoured bed level for corresponding front square pier and eccentric square pier and for square single pier experiment under same experimental condition, these are 65 % and 62 % of max scouring -depth for $z/h \leq 0$ %, correspondingly. Therefore, it confirms the existence of powerful horseshoe-vortices within scouring - holes near upstream zone of three square- piers. The max-reversed v/U are seen upstream near beds of square front- pier, square eccentric- pier and square rear- pier are about 24 %, 35 % and 23 %, respectively whereas for two square-pier experiment [Das and Mazumdar, 2018] max- v/U occurs near bases of inline front- square pier and eccentric- square pier are around 21 % and 31 %, respectively and for single-pier experiment max- v/U near bases of pier is 20 % and 32 %. The v/U is found positive, due to the obstacle of pier structures and for back and uni-directional flow occurring near scouring bed. At $\pm 45^\circ$ azimuth-sections of the three-pier, v/U -distribution is nearly similar to v/U -distribution at 0° azimuth-section of corresponding piers. Presently v/U -distributions at 0° are greater than at $\pm 45^\circ$ at respective locations. For the three square-piers at $\pm 45^\circ$ flow-velocity separation line is shallower than at 0° . Flow-velocity at $\pm 90^\circ$ is out of phase than those at 0° and $\pm 45^\circ$. At $\pm 90^\circ$ azimuth-sections for the three square-piers within the scour-holes ($z/h \leq 0$ %), v/U acts towards each pier and a thin region of reversed flow-velocity exist just near the bed. At five azimuth- sections, max- v/U for square eccentric- pier is calculated convincingly higher than max- v/U for other two front- and rear- piers. At both horizontal sections, maximum v/U is spotted at up-stream of eccentric- pier contrasted with other two- piers. And v/U in down-stream of three square piers at $z/h = 4$ % section found very similar to that at $z/h = 50$ % section and also greater than that at $z/h = 50$ % section. At $z/h = 50$ % and near upstream zone of each pier structure v/U are bigger than individuals at $z/h = 4$ % section due to existence of soaring momentum-flow.

Contours of dimensionless time-mean vertical velocity w/U were plotted for five azimuth- sections $\pm 90^\circ$, $\pm 45^\circ$, and 0° and at two horizontal sections, $z/h = 50$ % and $z/h = 4$ % from zero bed level. The max- w/U values are observed near square front- pier, square eccentric- pier and square rear- pier at depth ranges of 20 % - 67 %, 6 % - 65 % and 50 % - 71 % of corresponding max non-dimensional scouring-depth under the non-scouring- bed level ($z/h = 0$), respectively, and decreases towards scouring- hole bed. Size and max- w/U of the core are higher for square eccentric- pier. For the three square-piers, square front- pier, square eccentric- pier and square rear- pier at 0° azimuth-sections max- w/U was measured as 67 % at $z/d_{sf} = 40$ %, 71 % at $z/d_{se} = 19$ % and 37 % at $z/d_{sr} = 64$ % from $z/h = 0$, respectively. Near-bed, gap between square front- pier and square rear- pier (for square rear- pier on 0°), between square front- pier and square eccentric- pier (on 90° for square eccentric- pier) and square eccentric- pier and square rear- piers (on 90° for square rear- pier), the reverse max- w/U are 5 %, 17 % and 19 %, respectively. Around three piers as α increases from 0° to $\pm 90^\circ$, w/U decreases gradually. A down-flow develops near up-stream of three square- piers owing to down-ward negative pressure grade at stagnation of varied approach- flow, and thus vortex pushes the down-flow. The moderate reducing character of v/U and

w/U with an increase in α were found, when decreasing character of horseshow vortices were also established. It confirms that these horseshoe vortices reduce its strength through down-stream flow.

On 45° , -45° , 90° and -90° sections around square front- pier, square eccentric- pier and square rear- pier, down-ward max- w/U are 72 %, 79 %, 52 %, 55 %; 84 %, 79 %, 66 %, 80 %; and 71 %, 65 %, 62 %, 46 % of down-ward max- w/U on 0° for corresponding pier locations, correspondingly. As studied by Das and Mazumdar, 2018, for two piers, it was 96 %, 89 %, 76 % and 67 % for square front- pier and 95 %, 66 %, 83 % and 72 % for square eccentric- pier and also for square single- pier experiment on 45° and 90° max- w/U was observed 80 % and 73 % of results and 81 % and 63 % of the results. From these observations, down-flows around square eccentric- pier are always greater than w/U around other two square-piers and around square front- pier w/U always bigger than around square rear- pier.

Maximum negative w/U was noticed at up-stream of square eccentric- pier. Hence, at up-stream of square eccentric- pier, it is understandable that maximum scouring- depth is found with strongest circulation. Vertical velocity at down-stream of three square-piers is noticed with their positive magnitude. Hence, flow is thereby directed up-wards. It specifies the flow firstly passes down-ward at the up-stream region of each pier forming horseshoe vortices, then moves from pier side and thereafter it goes up-ward at down-stream region of the three square-piers forming wake vortices. For $z/h = 4\%$ at the piers downstream, value of time- mean w/U is observed maximal. The max-value of w is found about 0.6-0.7 times of v/U . Now, by comparing the contours of w/U , it is clear that w in the upstream of piers for $z/h = 4\%$ section has more magnitude than that in $z/h = 50\%$ section and in piers downstream values of w/U for $z/h = 4\%$ section is more. At $z/h = 4\%$ section in wake region, velocity of higher value is observed as contrasted to $z/h = 50\%$ section. It confirms, flow moves up-ward producing stronger wake vortices at down-stream of piers. Thus, the wake-vortex effect is little at downstream of three square-piers.

3.4 Velocity Vector

Velocity vectors $\vec{V}$ contour profiles at $\pm 90^\circ$, $\pm 45^\circ$, and 0° sections for three square piers were plotted with magnitude of $\sqrt{v \cdot v + w \cdot w}$ and direction $\tan^{-1} w/v$ and also at $z/h = 50\%$ and $z/h = 4\%$ horizontal sections around such piers, whose scale and path are $\sqrt{u \cdot u + v \cdot v}$ and $\tan^{-1} v/u$ respectively. Plotting of vectors on $\pm 45^\circ$ and 0° , show the hydraulic flow behaviours of horseshoe vortices with down-flow moving toward up-stream of three square-piers. For three square-piers, height i.e. minor axes lengths of elliptical type vortices on 0° , is outsized than on both $\pm 45^\circ$. On 0° for three square-piers, vertical flow w/U is strongest and w/U decreases as α increases. Here, vortex core size for square eccentric-pier is bigger than the square front- pier and square rear- pier. On $\pm 90^\circ$ for separated-flow, the vertical-flows are indistinct. On $\pm 90^\circ$, also a close study of six vector fields near scoured bed for all piers shows the existence of weaker vertical-flow.

The velocity-flow characteristics are well described in the flow zone for $z/h = 50\%$ and $z/h = 4\%$ horizontal sections. To evade congested vector profile plotting, a few calculated points are deleted from vector plotting. From vectors plotting of, it is clear that in downstream zone of square front- pier, velocity decreases. It is also similar to square eccentric- pier and square rear- pier. Here, from the profile, wake zone's length is rather larger for square front- pier, compared with two other square- piers. And the length is larger for square eccentric-pier than square rear- pier. Wake zone length is larger at $z/h = 50\%$ than $z/h = 4\%$ horizontal section. Due to pier induced adverse pressure gradient near upstream of piers, boundary layer is separated and then shifts both sides of the piers, near the bed, towards down-stream. This occurrence results in larger wake at $z/h = 50\%$ horizontal sections in contrast with $z/h = 4\%$ horizontal section. This condition is caused by the effect of roughness on turbulence - amplify near bed.

3.5 Absolute Velocity

Contour of non-dimensional absolute time-mean velocity, $V/U = (u \cdot u + v \cdot v + w \cdot w)^{0.5}/U$ for equilibrium scour and under clear water state on five azimuth-sections 0° , 45° , -45° , 90° and -90° and at two $z/h = 50\%$ and z/h

$= 4\%$ horizontal sections around the three piers were plotted. The contour profiles of dimensionless V/U for the square front- pier, square eccentric- pier, and square rear- pier are almost similar. It shows lack of u/U on 0° and dominating nature of u/U on $\pm 90^\circ$. On 0° for all piers u/U is negligible; hence it is evident that there is the exclusive vertical-flow at azimuth-angle 0° for all the square-piers. On $\pm 45^\circ$ azimuth-sections starting from sharp pier-edge for the three-piers, flow-separation is observed which lead to decreasing natures of V/U near the piers. Also, on $\pm 90^\circ$, u/U is a main flow attribute. For all three square-piers near scouring-bed, V/U contour lines are concentrated, focusing rapid changes of velocity regions. On $\pm 90^\circ$ u/U and w/U are almost negligible near all square- piers because pier side faces and direction of flow are parallel with each other. From the dimensionless contour profiles, in wake regions at down-stream near piers have lower values of time-mean V/U . At x-y horizontal-section for $z/h = 50\%$ to 60% the V/U decreases its value near bed since flow is obstructed by deposited sediment i.e. dune at pier down-stream. At down-stream near piers (wake zones) has greater values of V/U at $z/h = 50\%$ section than that of $z/h = 4\%$ section.

4. VORTICITY: CIRCULATION

Figure 3 exhibit vorticities contours $[\zeta = \partial v/\partial z - \partial w/\partial r]$ for equilibrium scouring on 0° , 45° , -45° , 90° and -90° r-z sections (azimuth- sections) around square front, square eccentric and square rear- piers. For computing vorticity contours using a technique of forward difference of computational hydrodynamics, differential equation is converted into an equation of finite difference. At a grid point, (m, n) vorticity equation (1) is expressed as

$$\zeta = \left(\frac{v_{m,n+1} - v_{m,n}}{\Delta z} \right) - \left(\frac{w_{m+1,n} - w_{m,n}}{\Delta r} \right) + O(\Delta z, \Delta r), \quad (1)$$

where index m and index n run towards "r" and "z" directions. Now, $O(\Delta z, \Delta r)$ is called 'expressions of order Δz and Δr '. The scale representation of above equation is given as

$$\zeta = (\partial v/\partial z) - (\partial w/\partial r) \quad (2)$$

Only at pier boundaries where there is a presence of pressure gradient, formation of vorticity occurs. When the pressure increases sufficiently strong, subsequently 3D- boundary layer goes through flow partition and system spins up front side near each pier, forming horseshoe vortex system at all the bases of piers. This type of vertical- flow is calculated particularly in r-z section, as its axis of revolution is erected to r-z section. Vorticities contours are calculated from v/U and w/U contours. Figure 3, contours of vorticities, confirm that the vorticities are concentrated inside scour holes. Further study of velocity vectors plotting and vorticities contours confirm existence of forced vortex. Near center of horseshoe vortices, a high vorticity concentration shows the vortices core. Vortices core sizes decrease as α increases, becoming relatively small at $\pm 90^\circ$ and thereby vorticity becomes significantly weaker. At up-stream of each pier, circulation of each horseshoe vortex is calculated from vorticities contours, using normalized Stokes' theorem.

$$\Omega = \oint_C \mathbf{V} \cdot d\mathbf{s} = \iint_A \zeta \, d(rz) \quad (3)$$

where, $\mathbf{V}$ is velocity vector, and $d\mathbf{s}$ is inter grid displacement vector. The circulation is calculated for each azimuth- section for each square pier positioning (Table 1).

On azimuth- sections 0° , 45° , -45° , 90° and -90° near upstream zone of the front square pier circulation are found 71 %, 83 %, 31 % and 35 % of respective circulation on 0° . Likewise on sections 0° , 45° , -45° , 90° and -90° , for square eccentric- pier and square rear- pier, Ω are calculated 73 %, 65 %, 37 %, 32 % and 83 %, 95 %, 34 %, 40 % of circulation on 0° of corresponding pier. The calculated values of Ω are in obedience with Raikar and Dey, 2008 and also affirms that Ω increases steadily from angles $\pm 45^\circ$ to 0° and similarly increases rapidly from $\pm 90^\circ$ to $\pm 45^\circ$. Therefore horseshoe-vortex core dimension becomes somewhat larger while shifts from $\pm 45^\circ$ to 0° and further becomes rapidly larger when shifts from for $\pm 90^\circ$ to $\pm 45^\circ$. Due to existence of square eccentric- pier, the separated streamline from square front- pier at -45° concurs with streamline and separated at 45° . In r- α section direction of resultant

velocity $\tan^{-1}u/v$ for square front- pier on 45° is apart from square eccentric- pier but on -45° it is along square eccentric- pier.

Table 1. Circulation magnitudes for five azimuthal sections.

Pier location	Circulation, Ω				
	$\alpha = 0^\circ$	$\alpha = 45^\circ$	$\alpha = -45^\circ$	$\alpha = 90^\circ$	$\alpha = -90^\circ$
Inline-front	18.75×10^{-3}	13.28×10^{-3}	15.62×10^{-3}	5.79×10^{-3}	6.56×10^{-3}
Eccentric-middle	28.62×10^{-3}	21.01×10^{-3}	18.65×10^{-3}	10.48×10^{-3}	9.44×10^{-3}
Inline-rear	15.26×10^{-3}	12.73×10^{-3}	14.44×10^{-3}	5.25×10^{-3}	6.13×10^{-3}

Figure 3: Contours of vorticity - ζ (in per second) for square-front, square-eccentric and square-rear piers for r - z sections

As a result for square front- pier, a strong pressure gradient occurs on azimuth- sections -45° than 45° . On -45° azimuth- section of square front- pier, separated streamline adds with separated streamline near azimuth- section 45° of square eccentric- pier and also for square eccentric- pier separated streamline at azimuth- section 45° coincides with separated streamline near azimuth- section -45° of square rear- pier. Hence, Ω at square eccentric- pier on 45° is greater than Ω on -45° azimuth- section and at square rear- pier, Ω on -45° azimuth- section is greater than on 45° azimuth- section. As a result, co-shedding regime effect, grows in wake part of square front- pier, for square eccentric- pier on 90° azimuth- section is slightly higher than Ω on -90° and for square rear- pier on -90° is slightly higher than on 90° . This study confirms that Ω at five azimuth- sections around square eccentric- pier is constantly greater than Ω at corresponding five azimuth- section around square front- pier and square rear- pier. Around square front- pier, circulation is measured greater than at corresponding azimuth-angle around square rear- pier. On the five - sections 0° , 45° , 90° , -45° and -90° around square eccentric- pier, circulation are 53 %, 58 %, 19 %, 81 %, 43 % and 87 %, 65 %, 29 %, 99 %, 53 % greater than circulation at corresponding α around square front- pier and square rear- pier, respectively.

5. TURBULENCE FIELDS ANALYSES

At turbulence, the tangential intensity u^+ , radial intensity v^+ and vertical intensity w^+ , which are RMS values of three velocity fluctuations of flow u , v and w , correspondingly. The dimensionless tangential intensity u^+/U , dimensionless radial intensity v^+/U and dimensionless vertical intensity

w^+/U at an azimuth-section 0° and at two ($z/h = 50\%$ and $z/h = 4\%$) horizontal sections around the three square-piers were drawn. The distribution nature of u^+/U , v^+/U and w^+/U are almost identical both at corresponding r - z section and x - y section. Here, at square front- pier on azimuth- section 0° , the max-turbulent intensities are found around 1.33 to 1.70 of b from pier-centre. Whereas, in a experiment with two-piers at square front- pier on 0° those are found about 1.35 to 1.50 of b from pier-centre [Das and Mazumdar, 2018] and for single-pier experiment, those are found around 0.85 of b and 1.50 of b from pier-axis.

Generally, within scour-holes, a high turbulence intensity core is found thus, separation of flow and turbulence intensities decreases as r_0 and z increases. With the greater scour hole around the square eccentric- pier, high turbulence- intensity cores are found. With the change in α , there is a minor modification in distribution nature of u^+/U , v^+/U and w^+/U (not shown in present study).

Here, for square front- pier max- u^+/U and max- v^+/U are found 1.75 and 1.95 times of max- w^+/U , while for square single- pier experiment mean max- u^+/U and mean max- v^+/U are 2.04 and 2.29 times of mean max- w^+/U [Raikar and Dey, 2008] and for two square pier experiment for square front- pier, mean max- u^+/U and mean max- v^+/U are 211 % and 255 % of mean max- w^+/U [Das and Mazumdar, 2018]. In present study for square eccentric- pier and square rear- pier at 0° , max- u^+/U and max- v^+/U are found higher than max- u^+/U and max- v^+/U of square rear- pier on 0° . On 0° for square eccentric- pier and square rear- pier max- u^+/U , max- v^+/U and max- w^+/U are 116 %, 146 %, 132 % and 111 %, 110 %, 134 % times of max- u^+/U , max- v^+/U and max- w^+/U for square front- pier on 0° , respectively.

Consequently of shed vortices, observed from down-stream section of square front- pier and from down-stream zone of square front- pier and square eccentric- piers, associated with horseshoe vortices close to up-stream section of square eccentric- and up-stream section of square rear-piers, higher values of u^+/U , v^+/U and w^+/U for square eccentric- and square rear- piers are found. As such shed-vortices mix with outsized tangential fluctuations, max- v^+/U is 114 % greater than max- v^+/U on 0° for square eccentric- pier. Also approaching shed-vortices from square front- pier and square eccentric- pier was directly clogged by square rear- pier; hence max- v^+/U is 115 % greater than max- v^+/U on 0° for square rear- pier. Analogous investigation was noticed for piers in tandem where v^+/U was nearly double of u^+/U . The w^+/U on 0° for square eccentric- pier was slightly lesser and for square rear- pier was slightly greater than w^+/U on 0° for square front- pier. This occurrence is responsible for reducing and increasing nature of down-flow near the up-stream region of square eccentric- pier and rear square- pier, correspondingly, for the existence of up-flow in reattachment regime (gap between three piers) [Jaman et al., 2017a]. Values of max- u^+/U , max- v^+/U and max- w^+/U are observed next to up-stream of square front- piers, square eccentric- pier and square rear- pier with values of 90 %, 80 % and 35 %, correspondingly. Overall value of longitudinal intensity u^+/U is noticed about high at every consequent locations around three square piers (at two different horizontal sections, $z/h = 50\%$, and $z/h = 4\%$) than transverse intensity v^+/U and vertical intensity w^+/U .

Non-dimensional turbulent kinetic energy k/U^2 at an azimuth-section 0° and at two ($z/h = 50\%$, and $z/h = 4\%$) horizontal sections around three square-piers were calculated and plotted, using the equation (4).

$$k/U^2 = 0.5(u^+ \times u^+ + v^+ \times v^+ + w^+ \times w^+)/U^2 \quad (4)$$

The profiles of k/U^2 are almost same with the profiles of non-dimensional turbulence intensities. For square eccentric- pier and square rear- pier on 0° , max- k are 140 % and 133 % of max- k for square front- pier, respectively. For two square- piers experiment [Jaman et al., 2017b], on 0° it is calculated for square eccentric- pier 127 % of max- k for square front- pier. On 0° for square eccentric- pier and square rear- pier, max- u^+/U , max- v^+/U are greater than max- w^+/U , max- v^+/U for square front- pier on 0° , respectively. Also on 0° for square eccentric- pier and square rear- pier, max- k are higher than max- k for square front- pier at 0° azimuth- section. Magnitude wise non-dimensional k just near bed at $z/h = 4\%$, max- k was found around square eccentric- pier, then square front- pier and square rear- pier, respectively. Whereas at $z/h = 50\%$, magnitude

wise max- k was found around square eccentric- pier, then square rear- pier and square front- pier correspondingly. Hence, it is clear that vortices of strongest strength and circulation will occur at square eccentric- pier. As a result of vortex shedding formation (very powerful rollers), higher magnitude core of k is found at wake-zone of square eccentric- pier, whereas values of k are found lesser in up-stream region of pier. At $z/h = 50\%$, max- k are always higher than those at $z/h = 4\%$. The distributed nature of turbulence k is analogous to high-valued cores of turbulent intensities, found within scouring region.

6. CONCLUSIONS

Here, flow fields around three identical square piers were determined experimentally. Max-equilibrium scour-depth gauged at square front- pier, square eccentrically positioned pier and square rear- pier are about 1.5, 3.1 and 1.4 times larger than single-pier max-equilibrium scour-depth. Also, these max-depths at three- piers are more than two- piers experiment with in line - eccentric positioning. The dune formation was more on the eccentric square- pier side (away from symmetry line). The sediment diversion was seen more on square eccentric- pier side. Shifted sediment further deposited downstream tilting towards square eccentric- pier side. On 0° section, for eccentric- pier and rear- pier, max- u are found 117 % and 244 % of max- u on 0° for square front- pier. As azimuth-angle α increases, u increases and turns finite. On 0° , upstream region of square eccentric- pier max- w 105 % and 189 % of max- w at corresponding locations of square front- pier and square rear- pier respectively. This validates the clear existence of coshedding-regime formed within the three square- piers (at downstream of square front- pier and square eccentric- pier). The velocity vectors' plots depict the size of horseshoe-vortex core for square eccentric- pier is larger than other two square-piers. Here, wake zone length is larger for square front- pier, then square eccentric- and then square rear- pier in order.

The vortex circulation " Ω " increases as α decreases and moreover increases for an analogous increase in scouring- depth. The Ω on 0° , 45° , 90° , -45° and -90° around square eccentric- pier is constantly greater than Ω at corresponding azimuth-angles around square front- pier and square rear- pier. Strongest vortices and circulation found at square eccentric- pier. For square front- pier and square rear- pier, for -45° angle, Ω is constantly recorded greater than Ω for 45° angle for the existence of strong pressure grade. Whereas, the Ω for square eccentric- pier for -90° angle is fewer than for 90° angle as the presence of co-shedding establishment that grows near wake section of square front- pier. The three non-dimensional turbulence intensities - u^*/U , v^*/U , w^*/U and turbulence kinetic-energy k/U , above scouring- holes, are found greater than their max-scales within scouring- holes. The turbulence u^*/U , v^*/U and k/U for square eccentric- pier are consistently seen greater than square rear- pier and square front- pier. Whereas the w^*/U for square eccentric- pier at 0° was slightly lesser and for square rear- pier was slightly greater than w^*/U at 0° for square front- pier due to reducing and increasing nature of down-flow near the up-stream zone for square eccentric- pier and square rear- pier, respectively, for the existence of up-flow in reattachment regime. Also, u^*/U , v^*/U , w^*/U and k/U at 0° square rear- pier are greater than for square rear- pier. Vortices within the three square-piers may increase scouring- holes size of square eccentrically positioned pier while transporting sediments far-off from the symmetry line.

REFERENCES

- Das, R., Das, S., Jaman, H., Mazumdar, A. 2019. Impact of Upstream Bridge Pier on the Scouring Around Adjacent Downstream Bridge Pier. *Arabian Journal for Science and Engineering*, 44(5), 4359-4372.
- Das, R., Khwairakpam, P., Das, S., Mazumdar, A. 2014d. Clear-water local scour around eccentric multiple piers to shift the line of sediment deposition. *Asian Journal of Water, Environment and Pollution*, 11(3), 47-54.
- Das, S., Das, R., Mazumdar, A. 2013a. Circulation characteristics of horseshoe vortex in the scour region around circular piers. *Water Science and Engineering*, 6(1), 59-77.
- Das, S., Das, R., Mazumdar, A. 2013c. Comparison of Characteristics of Horseshoe Vortex at Circular and Square Piers. *Research Journal of Applied Sciences, Engineering and Technology*, 5(17), 4373-4387.
- Das, S., Das, R., Mazumdar, A. 2014a. Variations of clear water scour geometry at piers of different effective widths. *Turkish Journal of Engineering and Environmental Sciences*, 38(1), 97-111.
- Das, S., Das, R., Mazumdar, A. 2014e. Vorticity and Circulation of Horseshoe Vortex in Equilibrium Scour Holes at Different Piers. *Journal of The Institution of Engineers (India): Series A*, 95(2), 109-115.
- Das, S., Das, R., Mazumdar, A. 2015c. Velocity profile measurement technique for scour using ADV. In: *Proc. International Conference on Testing and Measurement: Techniques and Applications, TMTA 2015*. Taylor & Francis Group, London, 249-252.
- Das, S., Das, R., Mazumdar, A. 2016. Comparison of local scour characteristics around two eccentric piers of different shapes. *Arabian Journal for Science and Engineering*, 41(4), 1193-1213.
- Das, S., Ghosh, R., Das, R., Mazumdar, A. 2014b. Clear water scour geometry around circular piers. *Ecology, Environment and Conservation*, 20(2), 479-492.
- Das, S., Ghosh, S., Mazumdar, A. 2014c. Kinematics of horseshoe vortex in a scour hole around two eccentric triangular piers. *International Journal of Fluid Mechanics Research*, 41(4), 296-317.
- Das, S., Jaman, H., Chatterjee, A., Das, R., Mazumdar, A. 2017. Hydrodynamic behaviour of flow past three typically arranged circular piers on different horizontal planes. *International Journal of Fluid Mechanics Research*, 44(5), 457-468.
- Das, S., Mazumdar, A. 2015b. Turbulence flow field around two eccentric circular piers in scour hole. *International Journal of River Basin Management*, 13(3), 343-361.
- Das, S., Mazumdar, A. 2018. Evaluation of Hydrodynamic Consequences for Horseshoe Vortex System developing around two eccentrically arranged Identical Piers of Diverse Shapes. *KSCE Journal of Civil Engineering*, 22(7), 2300-2314.
- Das, S., Mazumdar, A., 2015a. Comparison of kinematics of horseshoe vortex at a flat plate and different shaped piers. *International Journal of Fluid Mechanics Research*, 42(5), 418-448.
- Das, S., Midya, R., Das, R., Mazumdar, A. 2013b. A study of wake vortex in the scour region around a circular pier. *International Journal of Fluid Mechanics Research*, 40(1), 42-59.
- Graf, W.H. 2003. *Fluvial Hydraulics, Flow and Transport Processes in Channels of Simple Geometry*. Wiley, London.
- Jaman, H., Das, S., Das, R., Mazumdar, A. 2017b. Hydrodynamics of flow obstructed by inline and eccentrically-arranged circular piers on a horizontal bed surface. *Journal of The Institution of Engineers (India): Series A*, 98(1-2), 77-83.
- Jaman, H., Das, S., Kuila, A., Mazumdar, A. 2017a. Hydrodynamic Flow Patterns Around Three Inline Eccentrically Arranged Circular Piers. *Arabian Journal for Science and Engineering*, 42(9), 3973-3990.
- Melville, B.W., Raudkivi, A.J. 1977. Flow characteristics in local scour at bridge piers. *Journal of Hydraulic Research*, 15, 373-380.
- Raikaar, R.V., Dey, S. 2008. Kinematics of horseshoe vortex development in an evolving scour hole at a square cylinder. *Journal of Hydraulic Research*, 46(2), 247-264.
- Raudkivi, A.J. 1998. *Loose Boundary Hydraulics*, A. A. Balkama, Rotterdam.
- Yilmaz, M., Yanmaz, A.M., Koken, M. 2017. Clear-water scour evolution at dual bridge piers. *Canadian Journal of Civil Engineering*, 44(4), 298-307.