Comparison of Vortex Induced Velocity Kinematics around Underwater Horizontal Cylinder with Vertical End Plate

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Abstract. Electrical energy is harnessed from various natural sources to protect the environment and ecology which is termed as green energy sources. When vortex is induced on a cylinder, it starts vibrating according to the formation of vortex. The vibration is so strong that it can destroy any structure wherever alternating vortex is induced. Currently Vortex Induced Vibration is used to harness electrical energy from ocean, river and shallow water channel. In this paper, experimental investigations were conducted in flume to analyse the behaviour of underwater flow structures around a 5 cm horizontal cylinder placed transversely to the flow at 60% and 70% depths from water surface and simultaneously a 5 cm wide vertical end plate set at 8 cm downstream from cylinder. Fluctuating 3D velocity components around such plate cylinder combination were measured. From subsequent plotted contours, changing flow patterns in presence of vertical plate are analysed. Hydrodynamic flow features are shown by plotting absolute velocity fields and velocity vectors. It visualizes that streamlines separate first and then passes over the periphery of horizontal cylinder. The contour of turbulence kinetic energy confirms the presence of strong vortex in between horizontal cylinder and vertical plate. The horseshoe vortex at the upstream of cylinder becomes stronger due to the presence of vertical plate. The results from these two experiments are compared with the results observed in previous researches. With the increase in cylinder depth from water surface, the horseshoe vortices strength becomes stronger.

1. Introduction

Analysis of vortex induced flow fields around a cylinder is an interesting subject to the hydraulicians. The vortex induced flow field analysis around a cylinder or any structure on an erodible ocean bed or river bed was done by many researchers to find out the flow kinematics. Many researchers had shown that a vertically mounted cylinder on an erodible bed causes scouring and develops horseshoe vortex and thereby eroded sediments are transported downstream from the scour hole [1, 2]. From the visualization of flow fields by capturing real data using measuring instruments it confirms that when such flow is moved closer to a structure - the turbulent boundary layer separates and a whirl develops commonly known as horseshoe vortex and the subsequent circulation on such structure decreases due decrease in the water depth [3]. The nature of turbulent Kinetic Energy (KE) was depicted on a combination of three circular structure arranged eccentrically on a horizontal plane to understand the
vortex induced sediment transport [4]. An important phenomenon like the underwater unsupported cylinder when faces flow induced oscillation by wake vortex shedding due to which pipeline is encountered fatigue failure as proven both numerically [5, 6] and experientially [7, 8].

Vortex can be induced on a structure mounted either vertically or horizontally and that structure will vibrate due to vortex induction on the structure. The vibration will be destructive when the natural frequency of such structure and corresponding induced frequency become synchronized. In previous researches, this interaction between water and structure was attempted to suppress the effect of Vortex-Induced-Vibration (VIV) but there is another scope of VIV which is to generate energy to produce electricity [9, 10]. When a vertical or horizontal cylinder is set under submerge condition then vortex is induced on that cylinder. The cylinder will immediately start vibrating due to induction of such vortex. If the natural frequency of the underwater cylinder and the alternating vortex frequency are very close then such a cylinder immediately begins to oscillate on a constant Strouhal number. Such oscillation can sustain over an extended range of velocity by changing the Reynolds number along with vortex shedding on cylinder [11, 12]. Here the vortex induced flow fields were examined and discussed after measuring velocity profiles around horizontal cylinder placed under submerged condition and a vertical plate placed as an obstruction to the downward of such cylinder. Only the flow fields around the cylinders were measured by most investigators [13]. In some investigations a horizontal cylinder was placed to separate flow at the turbulent boundary layer and to visualize the flow contours along with vortices profiles surrounding the cylinder [14]. In shallow water channels, if the formed horseshoe vortices surrounding a cylinder are obstructed by a vertical end plate located downstream of that cylinder within a considerable spacing then it immediately affects the vortex shedding over such cylinder which causes its oscillation [15]. The disturbed turbulent KE due to this interaction between the vertical end plate and the horizontal cylinder ultimately increases the lifting force with a significant impact on the hydrokinetic energy device [12].

In this research, the vortex induced flow fields are analyzed around a horizontally placed cylinder (diameter of 4 cm) positioned 6 cm above the bed surface and a flow facing vertical end plate having 5 cm width placed at 5.5 cm downstream from such cylinder curvature. Thereafter, the flow fields are compared with the results of another experiment with same horizontal cylinder fixing at 8 cm above the bed surface and with the same downstream end plate. The distance of the vertical end plate from the cylinder outer curvature was kept adjusted to 5.5 cm.

2. Experimental Arrangement
A hydrokinetic structure was suspended in a laboratory shown in figures 1-2. A structure of 5 cm smooth surface cylinder was used. The horizontal hollow cylinder was fixed with two rods attached with it at its end sides. The cylinder was fixed 6 cm above the bed area with an aid clamp. A vertical end plate of 5 cm wide was fixed 5.5 cm away from the cylinder outer curvature. The complete structure was suspended on a re-circulating flume made of clear Plexiglas sheet on both sides.

The size of the flume is about 700 cm long, 350 cm internal wide and 450 cm deep. The redistribution of 50 lps output was done using two 10 hp pumps each having 30 lps capacity. The desired water depth 20 cm was maintained constant at the upstream of cylinder by means of two gate valves clamped with pump delivery pipes. An average velocity of 0.72 m/s was maintained throughout the study. The structure was suspended at a distance of 400 cm from the flume entrance so a great commotion would not affect the flow kinematics around it. The complete structure was built at the Fluvial Hydraulics Laboratory of School of Water Resources Engineering in Jadavpur University.

![Figure 1. Schema of the experimental set up.](image-url)
Fast velocity segments on the three Cartesian sides were measured and maintained with the Nortek made Vectrino® probe of forming an acoustic-Doppler-velocimeter holding four signal receivers. It collects information 5 cm away from the investigation tip. Doppler effects are used worldwide as a system for measuring such underwater velocity components. These velocity components have been recorded at 100 Hz sampling rate capacity, 6 cm sampling height distance and 2 to 5 mm adjusting sampling volume range of Vectrino®. All gauge data using Vectrino® was converted and sorted with minimum signal-to-noise-ratio of 16 and minimum correlation value of 70%.

The three dimensional velocity data are arranged in a contour manner to visualize the flow structure surrounding the horizontal cylinder in x-z plane where the x axis indicates the direction along the flow and z axis indicates the direction vertical to the flow. The contour of time averaging longitudinal velocity (u), time averaging transverse velocity (v), time averaging vertical velocity (w) are plotted by using OriginLab software. The time averaging absolute velocity (V), vectors, turbulent intensities, and turbulent KE are derived from three-dimensionally gauged velocity components and subsequently plotted in contour form to analyze the flow effect around the two structures. With respect to vertical end plate, the x coordinate at the upstream is considered as negative and it’s downstream as positive.

**Figure 3.** Time averaging velocity vector.

3. **Results and Analysis**

Here the experimental results are illustrated in a vertical plane chosen between the transversely positioned horizontal cylinder and vertical end plate. Estimated time averaging longitudinal, transverse, vertical gauge velocities are abbreviated as u, v, w respectively and the other fluctuation components like absolute velocity, turbulent intensities at longitudinal, transverse, vertical direction and turbulent KE are abbreviated as V, u*, v*, w* and K respectively. From a fraction of the velocity corresponding to its variability, all line drawings are arranged with an x-z plane.

3.1. **Velocity vector**

The velocity vector’s magnitude is determined by the formula by $\sqrt{(u,u+w,w)}$ and the corresponding direction is determined by the formula $\tan^{-1}(w/u)$. The magnitude obtained and the directions for this velocity vector are graphically shown in figure 3. At the stagnation point where the flow is zero and the flow is separated due to a negative pressure slope which means the flow losses its momentum near the cylinder surface and the flow reverses its direction by increasing the pressure slope. The stagnation point is not shown in the image as the
stagnation point is on the cylinder surface and cannot be measured due to the Vectrino* limit. However, the decrease in velocity near stagnation point is shown in the figure where the flow moves to the ±z directions and the magnitude is also increased. The velocity reduction is about 14-19% of the free stream velocity. The stagnation point is also moved 35° towards the water surface. After separation, the flow passes over the cylinder tangentially and meets 3 cm away from the cylinder outer curvature. The flow pattern alters to the rear side of the cylinder as the pressure slope is almost the same. The magnitude of the longitudinal velocity just next to the cylinder is approximately 1-2% of free stream velocity and thereafter increases slightly as the flow continues from the cylinder to the bottom. The results are compared with previous researches [16-18]. The stagnation point is found to be shifted -17.3° near the bed surface for the 2 cm gap between bed and cylinder curvature. The stagnation point is shifted further by -9.2°, 26.7° and 44.6° towards the water surface with the increase in gap from 2 to 8 cm with an equal interval of 2 cm, respectively between the cylinder and the bed.

3.2. Time averaging longitudinal velocity
The proximity of free flow is called the longitudinal flow (u) measured in cm/s and is shown in figure 4 (a). The main core of longitudinal velocity is located in the upper part of the cylinder. The upper core of the longitudinal velocity is located 12.54 cm above the bed surface and 5.28 cm in front of the vertical plate. About 1.375 times the free stream flow is 0.72 m/s. A velocity core of 1.319 times the free stream velocity is located under the cylinder and next to the bed surface. The lower core of the longitudinal velocity is located 2.46 cm above the bed surface and 5.94 cm in front of the vertical plate. When the gap between the cylinder surface and the bed surface increases the longitudinal velocity also increases below the cylinder. The longitudinal velocity separation is obtained when the gap between the cylinder and the bed surface is 8 cm. The high magnitude of longitudinal velocity core is developed due to the presence of vertical end plate only. The presence of vertical end plate creates a high horseshoe vortex in front of the vertical end plate under the cylinder. The time averaging longitudinal velocity is worsened by its low size found behind the cylinder outer curvature in the wake area at both cylinder positions 6 cm and 8 cm above the bed surfaces. The longitudinal velocity is observed negative due to the excessive loss in adverse pressure slope. The magnitude of flow below the cylinder is smaller than the flow above the cylinder with a gap of 2 cm and the magnitude of the flow below the cylinder increases with increasing gap. The magnitude of u is 0.94, 1.07, 1.15 and 1.293 times the upstream flow velocity for the gap of 2 to 8 cm with gap interval of 2 cm, respectively.

3.3. Time averaging transverse velocity
Figure 4(b) shows the time averaging transverse velocity v in cm/s. The range of time averaging transverse velocity is found at 5 cm/s to -4 cm/s in either direction. The time averaging transverse velocity is most commonly found near the cylinder surface. When the free stream flow hits the surface of the cylinder surface - a high turbulence is produced and this high turbulence effect ensures the presence of transverse velocity. The transverse velocity is 0.07 times the free stream velocity which is very small compared to longitudinal and vertical velocities. As a result the effect of transverse velocity in the cylinder is not significant for low velocity. If the cylinder position is changed from 6 cm to 8 cm away from the bed surface, the magnitude of transverse velocity becomes decreases for same reason as previously described.

3.4. Time averaging vertical velocity
At any point the time averaging vertical velocity (w) that moves upward is considered positive and in the opposite direction it is considered negative. The flow paths point up and down the directions from the upstream side of stagnation point of the cylinder which is clearly observable from the vertical velocity line shown in figure 4(c). After the stagnation point, the core of vertical upward flow is located in the vicinity of the cylinder 9.99 cm from the top of the bed surface and 6 cm from the vertical plate. The upward vertical flow is higher than the vertical downward flow. The upward vertical flow is 1.9 times the downward vertical flow. The upward vertical flow is found 0.56 times the free stream time averaging velocity. When the gap between the underwater cylinder and the bed surface increases then this upward vertical flow decreases and the downward vertical flow increases.
This occurs when the cylinder outer curvature is placed at a gap of 8 cm from the bed surface. The vertical velocity for 8 cm gap is 1.25 times the vertical velocity for 6 cm gap. The stagnation point shifts downwards as the gap between the cylinder outer curvature and the bed surface increases. From the stagnation point where the longitudinal velocity becomes zero and is divided into a vertical upward flow that takes the tangential path along the cylinder curvature and descends as it crosses rear side of the cylinder. This is achieved with a change in the direction of the vertical flow. Similarly, negatively downward flow changes its direction after crossing stagnation point to positively upward direction when the flow exceeds the cylinder. This flow direction change is clearly shown in $w$ contour diagram.

The high core of 0.55 m/s vertical downward flow is located 10 cm from the bed surface and 2.64 cm from the vertical plate because the vertical flow due to the aid of vertical plate with vertical flow when the flow exceeds the cylinder. The $u$ and $w$ contours confirm the conversions in velocity components which mean that first the longitudinal velocity is converted into vertical velocity at stagnation point and when it exceeds the cylinder the point comes where the vertical velocity becomes zero but simultaneously the longitudinal velocity becomes very high. Finally in the rear part of the cylinder, the longitudinal velocity decreases gradually and the vertical velocity increases. The same thing happens when the flow shifts downward at the stagnation point and follows the path below the cylinder. On the rear side of the cylinder, the up and down flow meets 3 cm away from the cylinder surface. The area between the cylinder surface and the contact point of up and down flow, the vertical velocity is almost ignored. This location depends on the Reynolds number. As the Reynolds number increases the length of that area, it increases affecting the formation of vortices behind the cylinder.

The downward flow from the stagnation point is small at a gap of 2 cm and gradually increases with increasing gap. The magnitude of upward vertical velocity is found -0.138, -0.264, -0.319 and -0.403 times the upstream velocity for the gap of 2 to 8 cm with an equal interval of 2 cm, respectively. The flow moves under the cylinder and rises to the top of the wake region of the cylinder. The magnitude of the upward vertical velocity is 0.152, 0.222, 0.263 and 0.319 times the upstream velocity for the gap of 2 to 8 cm with an equal interval of 2 cm, respectively.
3.5. Time averaging absolute velocity

Contour of subsequent time averaging absolute velocity is shown in figure 5 where the absolute velocity is calculated using the formula $V = (u^2 + v^2 + w^2)^{0.5}$. The absolute velocity indicates the total velocity intensity and scalar magnitude. Higher core of $V$ is located 7.5 cm away towards upstream from the vertical plate and 10.5 cm above from the bed surface. The time averaging absolute velocity is 142% higher than time averaging free stream velocity because in that area longitudinal velocity and vertical velocity are mutually supportive and the effect of transverse velocity is not significant.

3.6. Turbulence intensity

Contour of the time averaging turbulence intensities $u^+$, $v^+$ and $w^+$ having magnitudes equal to mean($u'\times u'$), mean($v'\times v'$) and mean($w'\times w'$), respectively acting in three Cartesian directions are shown in the figure 6 where $u'$ is deviation of $u$, $v'$ is deviation of $v$ and $w'$ is deviation of $w$ at the region between the vertical plate and horizontal cylinder. The magnitude of the turbulence rate is measured by the square root of its velocity fluctuations which means that the turbulence intensities increase when the fluctuations at that time are high.

Vortex shedding frequency which is dependent on Strouhal number is a function of longitudinal turbulence intensity. The longitudinal turbulence intensity increases as the vortex shedding increases. Turbulence in the approaching flow depends on Reynolds’ number as well.

The longitudinal; transversal and vertical intensities – all are located at the edge of the cylinder and the approximate size behind the outer bend of the cylinder. The magnitudes of the longitudinal and vertical turbulence intensities are found higher than the magnitude of transverse turbulence intensity. The core of the longitudinal turbulence intensity is located 10.56 cm from bed surface and 4 cm from the vertical plate. The turbulence intensity gradually diminishes toward the water surface and above the bed surface. The magnitude of the longitudinal turbulence intensity is 1.292, 1.222, 0.972 and 0.917 times the free steam velocity for the gap of 2 to 8 cm with an equal interval of 2 cm, respectively.

Although the magnitude of the transverse velocity is very small as compared to free stream velocity but the turbulence intensity of transversal velocity is very strong. The core of the turbulence intensity of transversal velocity is located 4.62 cm from the bed surface and 5 cm from the vertical plate. The high density of transverse turbulence intensity means the flow is trying to go to the wall. When the gap of the upper cylinder surface and bed increases from 6 cm to 8 cm, the transverse turbulence intensity decreases to 0.875 times the transverse turbulence intensity of 6 cm gap between the cylinder surface and the bed surface. The longitudinal turbulence intensity is found maximum at 8 cm from the bed surface and 3.33 cm from the vertical plate to the cylinder. The core of longitudinal turbulence intensity is high because of the presence of vertical plate in which the downward flow and upward flow after crossing the cylinder mix together and producing an adverse gradient of extreme pressure. When the cylinder is at 8 cm above the bed surface, vertical turbulence intensity is 0.66 times lower than that of the vertical intensity for the cylinder position 6 cm above the bed because it is found that the flow below
the cylinder is more when the gap is 8 cm from the bed. The magnitude of the vertical turbulence intensity is 0.902, 1.014, 0.791 and 0.708 times of the free stream velocity for the gap of 2 to 8 cm with an equal interval of 2 cm, respectively.

![Figure 6](image1.png)

**Figure 6.** Contours of time averaging (a) longitudinal (b) transverse (c) vertical turbulence intensities.

3.7. Turbulent KE

The contour of turbulent kinetic energy $K = \frac{1}{2}(u'^2 + v'^2 + w'^2)$ in x-z plane shown in figure 7. The turbulence kinetic energy is the function of the variation of velocity components. The KE depends on the severity of each component of the longitudinal, transverse, vertical velocity. The turbulent kinetic energy is located in the centre of cylinder area and facing the vertical plate which is obtained in the case of cylinder position of 8 cm from bed surface. It is observed that the turbulent kinetic energy is highest above the cylinder outer surface and decreases towards the water surface. When the cylinder is located 8 cm above the bed surface, the maximum turbulent kinetic energy is found under the cylinder surface. The turbulence kinetic energy is 0.951, 0.898, 0.705 and 0.729 times the square of the upstream free velocity for the gap of 2 to 8 cm with an equal interval of 2 cm, respectively. This high values of turbulent kinetic energy indicates that the presence of strong vortex shedding in the wake zone of the cylinder in both cases. The turbulent kinetic energy decreases gradually from the either side of the cylinder showing a slight inclination of turbulence intensities indicating a decrease in flow fluctuations.

![Figure 7](image2.png)

**Figure 7.** Contour of time averaging turbulent KE.

4. Conclusions

The main aspect of this study is to observe the complex flow kinematics around a horizontal cylinder transversely placed next to the flow in presence of a vertical end plate located downstream of it. This structure can be used for harvesting energy at shallow water based on the vortex vibration principle. To conduct experiment, a 5 cm cylinder was placed 6 cm above the bed surface with a vertical end plate positioning 5.5 cm away from the cylinder outer curvature and the kinematic results were compared with the result of another experiment with the same cylinder placed at 8 cm above the bed surface keeping the vertical end plate at same position.

It is illustrated that the contours of time averaging longitudinal, transverse and vertical velocities; the flow separation feature; and the development of vortices is similar in nature regardless of whether the cylinder area is upright on the bed surface. At different cylinder position it is found that there is a flow of water down near the plate which can be described as the beginning of the horseshoe vortex.
development. A separation of the flow is also visible near the upstream of the cylinder. The stagnation point appears to rise as the gap between the cylinder bottom surface and bed is shifted from 6 cm to 8 cm. A reverse flow is also observed at the back of the cylinder at both positions of the cylinder. The contours of time averaging longitudinal, transversal, vertical turbulence intensities are obtained with the same pattern. The magnitude of vertical turbulence intensity is perceived to be higher than that of the longitudinal and transverse velocities. The pattern of turbulent kinetic energy is the same in both positions of the cylinder. It is found that contour line of highest magnitude is over the cylinder outer curvature when cylinder is 6 cm above the bed surface. But when it is 8 cm above the bed surface then the contour line of highest magnitude is found below the cylinder outer curvature and found to be reduced towards the bed surface. Although the flow kinematics has been explored when the cylinder is kept suspended at different heights from the bed surface to understand and visualize the flow surrounding it but in practice the cylinders are used as movable structures along the transverse direction of the flow.

5. References

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