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Hydraulics of Submerged Offset-jets

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ABSTRACT

This study presents an experimental investigation of hydraulic characteristics of submerged offset jets. The instantaneous velocity was captured by an acoustic Doppler velocimeter (ADV). A total of 20 runs were carried out by varying different parameters: Reynolds number (28475–80730), offset ratio (3.16–6.2), jet Froude number (1.9–3), submergence parameter (0.65–2.82) and sluice gate openings (3, 3.5, 4, 4.5 and 5 cm). It is observed that the length of the reattachment depends on the relative offset height and the tail water depth. A mathematical formulation is developed for the submerged offset jet assuming a submerged jump in a drop structure to find the back-up depth and subcritical sequent depth by applying the momentum and continuity equations at the inlet and at tail water depth respectively. A mathematical equation is also developed for the back-up depth at the efflux section, which is experimentally verified for the range of supercritical Froude numbers from 1.1 to 10 and submergence factor. The jet trajectories (lower layer of jet, upper layer of jet and maximum jet velocity layer) are also derived applying the boundary conditions. The computed jet trajectories of the submerged offset jet show a satisfactory agreement with the experimental data.

Keywords: offset jet, coanda effect, rough bed, recirculation region, open channel flow, boundary layer.

1. INTRODUCTION

The topic of submerged wall jets has been the focus of many investigators due to their engineering application in energy dissipation downstream of hydraulic structures including drop structures, spillways, barrages and weirs. The submerged jumps can be considered as a transitional phenomenon between wall jets and free jumps. A submerged offset jet is formed when a fluid jet is issued from an elevated opening. This high-velocity jet over an abrupt drop creates a complex flow pattern following reattachment to a solid boundary and, hence, is called a reattaching offset jet (ROJ). The flow consists of a deflecting free jet and the evolving wall jet past reattachment. Figure 1 shows the flow pattern in a reattached offset jet.

An offset jet is formed when a jet discharges into a medium above a wall that is parallel to the axis of the jet but offset by a certain height. The flow field of an offset jet is complex and is encountered in many engineering applications. As the fluid jet is issued from an elevated opening, it is deflected towards the solid boundary due to the reduced pressure from the bottom of the jet. This phenomenon is known as Coanda effect (Rajaratnam and Subramanya 1968; Miozzi et al 2010), and the reattaching offset jet is known as a Coanda jet after the Romanian aerodynamicist Henri Marie Coanda (1886–1972). The flow velocity reduces as the jet approaches the boundary, and, as a consequence, the pressure inside the jet increases.

The reattaching offset jet encloses a zone where a reverse eddy is formed. Upon reattaching, the jet behaves like an impinging jet, which results in the formation of pressure greater than hydrostatic pressure, with the maximum value at the impinging point. This provides the pressure gradient to accelerate the flow. As the impinging zone ends, the acceleration ceases establishing a turbulent wall jet condition. The thickness of the wall jet region increases due to the presence of solid boundary and turbulent diffusion. Surface rollers or large reverse flow regions are formed near the free surface, which is influenced by the tailwater depth conditions. Further downstream, the flow recovers the normal subcritical open channel flow.
2. THEORY OF SUBMERGED OFFSET JET

When a fluid jet is issued from an elevated opening, an offset jet is formed. The flow consists of a deflecting free jet and a submerged wall jet after reattachment to the solid boundary. The flow zones in a submerged offset jet are depicted in figure 1. The flow in the region below the maximum velocity point, characterized by a boundary layer flow, is called inner layer of shear flow. The problem of an offset jet interacting with an adjacent parallel boundary has been previously described along with the important flow parameters that must be considered. This particular problem is relatively new, the first reported study being that of Bourque and Newman (1960). Since then, several investigators attempted to study various aspects of the problem. Earlier work by Rajaratnam (1967) identified the effects of wall jets in a water channel. Bourque and Newman (1960) studied the effects of Reynolds number and offset ratio on the reattachment length and distribution of the wall static pressure in the recirculation region. They considered the offset ratios in the range 4–48.5 and Reynolds number in the range 2760–7750. The flow field solution of an offset jet in the presence of a free stream motion is provided by Hoch and Jiji (1981). They considered offset ratios in the range 3–8.7 and Reynolds number of 16,000. Pelfrey and Liburdy (1986) reported the mean flow characteristics for the offset ratio 7 and the Reynolds number 15,000 using Laser Doppler Anemometry (LDA). Later on, Holland and Liburdy (1990) experimentally investigated the thermal characteristics of the heated offset jet over adiabatic impingement surface. They considered the flow geometry similar to that of Pelfrey and Liburdy (1986) and three offset ratios viz. 3, 7 and 11. Yoon et al. (1995) investigated the flow characteristics of a two dimensional offset jet (offset ratio viz. 5) discharged parallel to a rough wall and the distributions of the mean velocity, and turbulent stresses in the flow field were obtained and compared with those of the wall attaching offset jet on a smooth wall. It has been observed that the reattachment region on the rough wall is longer than on the smooth wall for the same offset height and jet speed. Nasr and Lai (1997) studied the mean velocities and turbulence characteristics of a turbulent plane offset jet with a small offset ratio of 2.125 using LDA. The LDA results were used to examine the capability of three different turbulence models in predicting the velocity field of the jet. Dey and Sarkar (2008) investigated the conditions of submerged jumps having different submergence factors and jet Froude numbers over different rough beds. It was found that the rate of decay of jet velocity in a submerged jump increases with increase in bed roughness, the most important observation being the flow in fully developed zone is self-preserving in general. Dey et al. (2010) compared the flow field in the fully rough and smooth submerged wall jets and observed that the rate of decay of jet-velocity on fully rough walls is greater than that on smooth wall, but it is less than that on transitionally rough walls due to the presence of roughness sub-layer on the fully rough walls. Bhuiyan et al. (2011) studied the characteristics of reattached offset jets on rough beds under the influence of limited...
The influence of roughness on reattached offset jets was found to be less than that in submerged wall jets on a similar rough bed. Agelin-Chaab and Tachie (2011) experimentally investigated the three-dimensional offset jet using a particle image velocimetry technique. They have performed experiments for four different offset ratios viz. 0.5, 1.0, 2.0 and 4.0, and three nozzle exit Reynolds numbers of 5,000, 10,000 and 20,000. The reattachment lengths are independent of Reynolds number but increase with offset height.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experiments presented in this paper were performed in the Hydraulic and Water Resources Engineering laboratory, Department of Civil Engineering, Indian Institute of Technology Kharagpur, India.

Experiments were carried out in an open channel flume. Submerged offset jets were tested on a horizontal rigid rough bed. Figure 2 shows a schematic view of the experimental setup to study the hydraulic characteristics of submerged offset jets over rough bed. The flume was 0.6m wide, 0.71m deep, and 1.2m long. The sidewalls of the flume were made of transparent glass to facilitate optical access. A Perspex vertical sluice gate, which had a streamlined lip to produce a supercritical stream with a thickness equal to the gate opening, was fitted over the bed. Different sluice gate openings \(y_1\) (= 3.0, 3.5, 4.0, 4.5 and 5 cm) were achieved by adjusting the gate vertically. The water discharge at the inlet, controlled by an inlet valve, was measured by a calibrated V-notch weir. An adjustable tailgate downstream of the flume controlled the tailwater depth \(y_4\). The free-surface profile was measured by a point gauge. Table 1 furnishes the important experimental parameters of different runs for various combinations of jet Froude number \(F_1\) (= \(U_1/(gy_1)^{0.5}\)) where, \(U_1\) is the jet velocity, Reynolds number \(R\) (=\(U_1y_4/V\)), where \(V\) is the coefficient of kinematic viscosity and \(g\) acceleration due to gravity.

Velocity profiles were measured by a 4-beam down-looking Acoustic Doppler Velocimeter (ADV), named Vectrino, used to capture the instantaneous velocity components, which had a sampling rate and volume of 100 Hz and 0.09 cm\(^3\), respectively. The sampling duration was 4 min in order to have a statistically time-independent average velocity. Near the bed, the sampling durations were relatively long. The closest vertical spacing of the ADV measurements was 0.25 cm. The ADV measurements were taken in the central vertical plane (CVP), which is along the centerline of the flume in vertical lines at different streamwise distances from the sluice gate.

4. TIME-AVERAGED FLOW FIELD

Figure 3 schematically illustrates the different flow zones in a submerged offset jet. The time-averaged velocity components in \((x, z)\) are represented by \((u, v)\). The origin of the coordinate axes is located at the junction of the sluice gate and the horizontal wall. Here, \(x\) and \(z\) are the horizontal and vertical distances, respectively. The flow characteristics are plotted on a nondimensional \(\hat{x}\) \(\hat{z}\)-plane, where \(\hat{x}\) is \(x/y_1\) and \(\hat{z}\) is \(z/y_1\). Velocity measurements
help to understand the flow field. Vertical profiles of horizontal velocities were measured at selected sections of the channel, covering pre-attached and attached part of and up to the section where the reversed velocity occurs. The jet is observed to curve down slowly through the first half of the recirculation region and then sharply downward to the attachment point. Jet velocity starts to recover slightly in the impingement region, and after attachment, the decay of maximum velocity with distance follows the same pattern as that of a wall jet.

Table 1. Experimental parameters

<table>
<thead>
<tr>
<th>Run. no</th>
<th>$y_1$ (m)</th>
<th>$U_1$ (m/s)</th>
<th>$y_4$ (m)</th>
<th>$\Delta Z$ (m)</th>
<th>$F_1$</th>
<th>$R$</th>
<th>OFFSET RATIO (OR) ($h_1/y_1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.025</td>
<td>1.139</td>
<td>0.540</td>
<td>0.10</td>
<td>2.3</td>
<td>28475</td>
<td>4.50</td>
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<td>2</td>
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<td>1.356</td>
<td>0.540</td>
<td>0.12</td>
<td>2.5</td>
<td>40680</td>
<td>4.50</td>
</tr>
<tr>
<td>3</td>
<td>0.045</td>
<td>1.328</td>
<td>0.555</td>
<td>0.12</td>
<td>2.0</td>
<td>59798</td>
<td>3.16</td>
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<tr>
<td>4</td>
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<td>1.400</td>
<td>0.550</td>
<td>0.14</td>
<td>2.0</td>
<td>70000</td>
<td>3.30</td>
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<td>1.566</td>
<td>0.495</td>
<td>0.15</td>
<td>2.5</td>
<td>62640</td>
<td>4.25</td>
</tr>
<tr>
<td>6</td>
<td>0.045</td>
<td>1.528</td>
<td>0.515</td>
<td>0.15</td>
<td>2.3</td>
<td>68767</td>
<td>3.83</td>
</tr>
<tr>
<td>7</td>
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<td>1.627</td>
<td>0.495</td>
<td>0.16</td>
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<td>47600</td>
<td>5.00</td>
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<td>1.758</td>
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<td>61525</td>
<td>6.20</td>
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<tr>
<td>10</td>
<td>0.045</td>
<td>1.794</td>
<td>0.480</td>
<td>0.20</td>
<td>2.7</td>
<td>80730</td>
<td>4.90</td>
</tr>
</tbody>
</table>

Figure 3. Vertical distribution of $\hat{u}$ (a) up to minimum jet thickness and (b) from minimum jet thickness to the wall jet region for $U_1 = 1.528$ m s$^{-1}$ and $y_1 = 0.045$ m in submerged offset jet subjected to offset ratio $h_1/y_1 = 3.83$
5. SUBMERGED JUMP AT DROP IN A RECTANGULAR CHANNEL

For a supercritical stream discharging from a slot with offset height $\Delta Z$, if a normal jump is to be formed at the efflux section where the depth is $y_1$ and the Froude number is $F_1$, the tail water depth $y_4$ should be equal to the subcritical sequent depth $y_2$ given by the momentum equation. If $y_4$ is less than $y_2$, the jump is swept downstream and is known as a repelled jump.

If, however, $y_4$ is greater than $y_2$, the jump gets submerged or drowned jump, simply called the submerged jump. Based on the experimental data obtained, a definition sketch for the submerged jump is presented in figures 4 & 5, which defines the average flow field of a submerged jump in a rectangular prismatic channel. Usually $y_1$ and $y_4$ are depths at the toe and at the end of jump, $y_3$ is the back up near the gate, and $y_2$ is the minimum flow depth.

![Definition sketch for the submerged jump at drop in a rectangular channel](image)

A supercritical stream of depth $y_1$ and Froude number $F_1$ comes out of a slot with parallel boundaries. As the tailwater depth $y_4$ is greater than $y_2$, the jump is submerged. At the inlet section, there is backing up, and the depth is $y_3$. From this section forward, there is a continuous increase in water surface up to tailwater depth $y_4$. The submergence factor $s$ for a submerged jump of supercritical depth $y_1$ and Froude number $F_1$ is defined as

$$s = \frac{y_4 - y_2}{y_2} \Rightarrow y_4 = (s + 1)y_2 \quad (1)$$

Referring to the definition sketch, the ratio of the backed-up depth $y_3$ to the supercritical depth $y_1$, found using the principles of continuity and momentum equation $y_3/y_1$, can be shown to be a function of only $F_1$ and $s$. Applying the momentum equation to the efflux section and the end of jump,

$$Q = U_1 y_1 = U_4 y_4 \quad (2a)$$

$$\frac{\rho g}{2} y_3^2 - \frac{\rho g}{2} y_4^2 = \rho Q(U_4 - U_1) = \rho U_1^2 y_1 \left( \frac{y_1}{y_4} - 1 \right) \quad (2b)$$

Substituting Eq. (1) into Eq. (2) using equation of continuity and simplifying,
\[
\left( \frac{y_3}{y_1} \right)^2 - \left( \frac{y_2}{y_1} \right)^2 (s+1)^2 = 2F_1^2 \left( \frac{y_1}{y_4} - 1 \right)
\]  

(3a)

\[
\frac{y_3}{y_1} = \left[ (s+1)^2 \left( \frac{y_2}{y_1} \right)^2 - 2F_1^2 + \frac{2F_1^2}{(s+1)} \left( \frac{y_2}{y_1} \right)^{-1} \right]^{0.5}
\]

(3b)

The free surface profiles of submerged offset jets were measured by a point gauge with a Vernier least count of ±0.1 mm. The flow rate at the flume inlet controlled by an inlet valve was measured by a calibrated V-notch weir. In Table 2, the submergence ratio \(s\) and the jet Froude number \(F_1\) are defined. In this study, the \(y_4\) was measured at the location where the free surface profile became parallel to the flume bottom. The sequent depth \(y_2\) of a B-jump is obtained from Eq. (6).

The theoretical equation above is developed for the back-up depth at the efflux section; Table 2 shows calculated and experimental values of back-up depth.

Table 2. Calculated and experimental values of back-up depth, submergence factor and sequent depth

<table>
<thead>
<tr>
<th>Run no</th>
<th>(F_1)</th>
<th>(\Delta Z) (m)</th>
<th>(y_1) (m)</th>
<th>(U_1) (m/s)</th>
<th>OR</th>
<th>(y_4) (m)</th>
<th>(y_2) (m)</th>
<th>(s)</th>
<th>(y_3) (Cal)</th>
<th>(y_3) (Exp)</th>
<th>(\Delta y) (Cal)</th>
<th>(\Delta y) (Exp)</th>
</tr>
</thead>
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<td>1</td>
<td>2.3</td>
<td>0.10</td>
<td>0.025</td>
<td>1.139</td>
<td>4.50</td>
<td>0.555</td>
<td>0.144</td>
<td>2.82</td>
<td>0.5490</td>
<td>0.5500</td>
<td>0.00571</td>
<td>0.0050</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>0.12</td>
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<td>0.540</td>
<td>0.176</td>
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<td>1.328</td>
<td>3.16</td>
<td>0.555</td>
<td>0.199</td>
<td>1.78</td>
<td>0.5414</td>
<td>0.5360</td>
<td>0.01357</td>
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<tr>
<td>4</td>
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<td>0.4512</td>
<td>0.4550</td>
<td>0.02873</td>
<td>0.0250</td>
</tr>
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</table>

5.1. Hydraulic Jump in Drop Structure

![Figure 5. Sequent depth at drop structure in a rectangular channel](image)

By applying a momentum equation and continuity equation at the inlet \(y_1\) and at sequent depth \(y_2\), we get a depressed cubic equation, as follows:
\[
\frac{\rho g}{2} (y_1 + \Delta Z)^2 - \frac{\rho g}{2} y_2^2 = \rho Q (U_2 - U_1) = \rho U_1^2 y_1 \left( \frac{y_1}{y_2} - 1 \right)
\]  
(4a)

\[
(\Delta Z + y_1)^2 - y_2^2 = 2 \frac{U_1^2}{g y_1} y_1 \left( \frac{y_1}{y_2} - 1 \right) = 2 F_1^2 y_1^2 \left( \frac{y_1}{y_2} - 1 \right)
\]  
(4b)

\[
\left( \frac{y_2}{y_1} \right)^3 + \left[ -2 F_1^2 - \left( \frac{\Delta Z}{y_1} + 1 \right) \right]^2 \left( \frac{y_2}{y_1} \right) + 2 F_1^2 = 0
\]

\[I_j = S_j + \sigma j \]

\[Y^3 + a Y + b = 0, \text{ Where, } y_2 / y_1 = Y \text{ and } C = (a^3 / 27 + b^2 / 4)\]

\[Y = 2 \left( \frac{-a}{3} \right)^{0.5} \cos \left( \frac{\theta + 2k \pi}{3} \right) \]  
(6)

where \( k = 0, 1, 2 \) and \( \theta = \arccos \left( \frac{3b}{2a}(-3a/a) \right) \), was adopted in the present study with three real roots \( y_2 / y_1 = 2(-a/3)^{0.5} \cos \left( \theta / 3 \right) \). Hence, Eq. (3) and (5) have been used to give a chart for \( \Delta y / y_1 \) for values of \( F_1 \) to 10 and values of \( s \) to 5 as shown in Figure 6. Using this chart, the back-up depth for any particular case could easily be obtained.

Figure 6. Back-up depth with Froude number 1.1 to 10 and submergence factor at different \( \Delta Z / y_1 \)
5.2. Trajectories of Offset Jet

Theoretical equations are also developed for jet trajectories (lower layer of jet, upper layer of jet and maximum jet velocity layer) based on the boundary conditions by taking the input values of reattachment length \( L_o \), horizontal distance at minimum jet thickness \( L_o \), and the vertical distances \( \delta_u \) and \( \delta_0 \) at minimum jet thickness from experimental data as shown in figure 4.

\[
Z = a + bx + cx^2 + dx^3
\]

(7)

Applying the boundary conditions: (i) \( Z(x = 0) = \Delta Z \), (ii) \( dZ/dx (x = 0) = 0 \) (iii) \( Z(x = L_o) = 0 \) and \( d^2Z/dx^2 (x = L_o) = 0 \), we get

\[
\frac{Z}{\Delta Z} = 1 - \frac{3}{2} \left( \frac{x}{L_o} \right)^2 + \frac{1}{2} \left( \frac{x}{L_o} \right)^3
\]

(8)

Similarly for maximum velocity layer, let

\[
Z = a + bx + cx^2 + dx^3 + ex^4
\]

(9)

By applying the boundary conditions (i) \( Z(x = 0) = \Delta Z + y_1/2 \), (ii) \( dZ/dx (x = 0) = 0 \) (iii) \( d^2Z/dx^2 (x = L_o) = 0 \) (iv) \( Z(x = L_o) = \delta_0 \) and \( dZ/dx (x = L_o) = 0 \), we get

\[
\frac{Z}{\Delta Z + \gamma_1/2} = 1 - \frac{\delta_0 + \delta_u}{1 - 6 \frac{L_o}{L_o} + 6 \left( \frac{L_o}{L_o} \right)^2} \left[ \frac{x}{L_o} \right]^2 \left\{ 6 \frac{L_o}{L_o} \left( 2 - 3 \frac{L_o}{L_o} \right) + 4 \left[ 3 \left( \frac{L_o}{L_o} \right)^2 - 1 \right] \left( \frac{x}{L_o} \right) + 3 \left[ 1 - 2 \frac{L_o}{L_o} \right] \left( \frac{x}{L_o} \right)^2 \right\}
\]

(10)

For upper layer of jet trajectory, replace \( \Delta Z + y_1/2 \) with \( \Delta Z + y_1 \) and \( \Delta Z + y_1/2 \) with \( \Delta Z + y_1 \)

\[
\frac{Z}{\Delta Z + y_1} = 1 - \frac{\delta_0 + \delta_u}{1 - 6 \frac{L_o}{L_o} + 6 \left( \frac{L_o}{L_o} \right)^2} \left[ \frac{x}{L_o} \right]^2 \left\{ 6 \frac{L_o}{L_o} \left( 2 - 3 \frac{L_o}{L_o} \right) + 4 \left[ 3 \left( \frac{L_o}{L_o} \right)^2 - 1 \right] \left( \frac{x}{L_o} \right) + 3 \left[ 1 - 2 \frac{L_o}{L_o} \right] \left( \frac{x}{L_o} \right)^2 \right\}
\]

(11)

Pre-attachment length \( L_o \) is one of the important parameters of offset jet. Experimental data of \( L_o \) is a function of offset ratio (OR). Importantly, the \( L_o \) remains almost independent of jet Froude number \( F_1 \) and submergence ratio \( s \). Another important parameter is the length \( L_o (= L_o + L_o) \) required for the initiation of a wall jet region. It can be expressed as a function of \( F_1, OR, \) and \( s \). The vertical distance \( \delta_0 \) of the occurrence of jet velocity at \( x = L_o \) and the thicknesses \( \delta_0 \) of the upper layer at \( x = L_o \) were important for performing a multiple regression analysis, which showed regression coefficients as 0.99, 0.97, 0.75 and 0.95.

It is important to determine the trajectories of the submerged offset jet and the jet velocity. The submerged offset jet in the pre-attachment region is bounded by the inner and the outer separation lines forming the lower and upper profiles of the jet (figure 1). Note that for Run 6, the experimental analysis is shown in figure 7. The computed lower profile of the submerged offset jet in the pre-attachment region corresponds with the experimental profiles more in flow zone toward the boundary than toward the issuing jet, where the experimental profiles are underestimated as shown in figure 7(a). On the other hand, the computed upper profiles of submerged offset jets in
the pre-attachment region have satisfactory agreement with the experimental profiles in the falling portion but underestimate the experimental profiles near the issuing zone of the jet. The reason of this discrepancy is attributed to the fact that the jet near the issuing zone spreads over a short horizontal distance due to its abounding momentum before it curves down as shown in figure 7(c). Lastly, the trajectory of maximum jet velocity layer in the pre-attachment region show a good agreement with the experimental profiles as shown in figure 7(b).

Figure 7. (a) Trajectory of lower null velocity, (b) Trajectory of maximum velocity and (c) Trajectory of upper null velocity

6. CONCLUSIONS

The streamwise velocity profiles in the submerged offset jet were measured at different sections to study the jet characteristics. The vertical position of the upper null streamwise velocity point goes down initially but moves upward as soon as the reattachment of the deflected jet occurs. It meets the water surface as the flow changes to the normal subcritical open channel flow. The maximum horizontal velocity occurring within the jet layer has been found to decrease along the flow direction. The limited tailwater depth and surface roughness can accelerate the decay. The vertical position of maximum streamwise jet velocity moves down almost abruptly until the offset jet reattaches to the wall and then gradually along the reattachment region until the wall jet is developed. After that, the boundary layer grows upward as the jet thickness increases. After attachment, the jet centreline velocity drops to its lowest value due to pressure increase resulting from impingement where the slope of the curve changes its sign and the jet velocity starts to recover slightly and the decay of maximum velocity with distance follows the same pattern as that of a wall jet. A theoretical equation is developed for the back-up depth at the efflux section, which is experimentally verified for the range of supercritical Froude numbers and submergence factor. Experimental results agree well with the mathematical predictions. Theoretical equations are also developed for jet trajectories (lower layer of jet, upper layer of jet and maximum jet velocity layer) based on the boundary conditions by taking the input values of reattachment length, horizontal distance at minimum jet thickness and the vertical distances at minimum
jet thickness from experimental data. The predicted jet trajectories of submerged offset jet are in good agreement with the experimental results.

7. REFERENCES


