

Scour due to offset jets

1. Introduction

1.1 GENERAL

India's water resources become increasingly strained, as the population of India continues to expand. Discharge of untreated sewage is the single most important cause for pollution of surface and groundwater in India. Heavy pollution from open sewers is common place in urban areas and arsenic contamination of groundwater continues to threaten the health and well-being of local communities. India is defined as a 'water stressed' country and innovative methods to provide cost-effective water treatment to communities are a crucial requirement if growing populations are to be sustainable. Sewage are to be removed by applying different sewage treatments. A natural river continually picks up waste products from and drops them on its bed throughout its course. Knowledge of sediment transport can be applied extensively in civil engineering such as to plan how to control the flow of water in culverts, over spillways, below pipelines and around bridge piers and abutments, excess of which can damage the environment and failure of foundation of the structures. Moreover, when suspended load of sediment is substantial due to human activities, it can cause environmental hazards including filling up of the channels by siltation. Sediment transport is the movement of organic and inorganic particles by water. In general, the greater the flow, the more sediment will be conveyed. Water flow can be strong enough to suspend particles in the water column as they move downstream, or simply push them along the bottom of a waterway. Transported sediment may include mineral matter, chemicals and pollutants, and organic material. The total load includes all particles moving as bed load, suspended load, and wash load.

Turbidity, as an optical property of water, is one of the more difficult parameters to measure. Turbidity is caused by particles and coloured material in water. Total suspended

solids (TSS) are the main cause of turbidity. Turbidity currents are most typically underwater currents of usually rapidly moving, sediment-laden water moving down a slope. Turbidity currents can also occur in other fluids besides water. In the most typical case of oceanic turbidity currents, sediment laden waters situated over sloping ground flow down-hill because they have a higher density than the adjacent waters. The driving force behind a turbidity current is gravity acting on the high density of the sediments temporarily suspended within a fluid. As such currents flow, they often have a "snow-balling-effect", as they stir up the ground over which they flow, and gather even more sedimentary particles in their current. Their passage leaves the ground scoured and eroded. Once a turbidity current reaches the calmer waters of the flatter area, the particles borne by the current settle out of the water column. The sedimentary deposit of a turbidity current is called a turbidite. When sediment transport removes material from a streambed or bank, the erosion process is called scour. Scour can occur anywhere where there is water flow and erodible material. Local scour is an engineering term for the isolated removal of sediment at one location, such as the base of underwater structures, including bridge piers and abutments. This localized erosion can cause structural failure, as bridges and overwater constructions rely on the bed sediment to support them.

1.2 SCOPE OF THIS WORK

The objective of the present work is to understand the hydrodynamics of scouring process using offset jets. The sewage can be removed by offset jets.

2. Scour due to offset jets

2.1 GENERAL

The scour is a result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges. Such scour around pier and pile supported structures and abutments can result in structural collapse and loss of life and property. Local scour (also termed localized scour) is developed near the structures due to modification of the flow field as a result of obstruction to the flow by the structures.

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Scour within the contracted portion of rivers, scour downstream of structures, scour at bed sills, scour below horizontal pipelines, scour at bridge piers and abutments, and scour at other river training works are the examples of local scour. It is very important to reduce local scour caused by impacting jets. Scour downstream of an apron due to jet issuing from a sluice opening is important from the point of view of the stability of hydraulic structures. The scour phenomenon downstream of a sluice gate opening is complex in nature owing to the abrupt change of the flow characteristics on the sediment bed (Dey and Sarkar 2006a). Scouring of bed in the downstream of any hydraulic structure, spillways, downstream of spurs in a river, diffusors (very often multiple jets), and propeller jets of ships hydraulic structures is mainly caused by the freely falling jets. Scour due to jets occurs very rapidly, which causes danger to the stability of the channel bed, in addition to the devastating effects. At hydraulic structures, it is normally desirable to dissipate the energy of the jet in order to limit scour. Therefore, relatively high tailwater conditions often exist, together with hydraulic jump formation and jet discharge under submerged conditions.

A forceful stream of fluid (water or gas) discharged from a narrow opening or a nozzle is called a jet. Jet fluid has a higher momentum compared to the surrounding fluid medium. In the case where the surrounding medium is made up of same fluid as the jet and this fluid has a viscosity, than the surrounding fluid near the jet is assumed to be carried along with the jet by a process called entrainment. When excess water is

discharged from a reservoir into the downstream water body, it often flows in the form of a jet. This high energy water jet can pick up sediment particles and transport them downstream of the impinging area, thereby forming a scour hole that may affect the stability of the upstream structure.

Jet flow may be two-dimensional or three-dimensional, free or submerged depending on the tailwater depth (Chiew and Lim, 1996). Depending on the location of the jet relative to the undisturbed bed level, it can be a wall jet or an offset jet. Scour induced by submerged offset jets can be found near sewage outfall Fig.1(a) and the downstream sluiceway of dam Fig.1(b). Sluiceway of dams Fig.1(b).

An offset jet is a jet through which water falls from a certain height into the channel bed surrounded by the same fluid. Local scour downstream of a hydraulic structure is a common problem due to the impact of jet of water ejecting through the spillway. When excess water is discharged from a reservoir into the downstream water body, it often flows in the form of an offset jet. This high energy water jet can pick up sediment particles and transport them downstream of the impinging area, thereby forming a scour hole that may affect the stability of the upstream structure. An offset jet is formed when it flows into a downstream water body at a location above the bed level (Fig.1). The flow pattern of the offset jet is complex in nature where the fluid jet issuing from a certain height above the bed level follow a reattachment to the solid boundary. The reattaching offset jet (ROJ) is also known as the Coanda jet after the Romanian aerodynamicist Henri Marie Coanda (1886-1972). The high velocity flow from a sluice gate placed over an abrupt drop forms a reattached offset jet (Rajaratnam and Subramanya, 1968). This class of flows is important for various engineering applications such as stabilizing positions of hydraulic jumps for energy dissipation, environmental discharges including disposal of municipal or industrial wastewater, fluid injection systems, circulation controller, and modulated mixing.

Coanda effect is the phenomena in which a jet flow attaches itself to a nearby surface and remains attached even when the surface curves away from the initial jet direction. If an offset jet is discharged into a downstream pool, free shear layers are developed at the peripheral surface of the jet, and the entrainment of fluid occurs. In the case of a two-dimensional offset jet, there is reduced pressure from the bottom of the jet because of the presence of a solid boundary which results in the deflection of the jet towards that boundary. As the jet approaches the boundary, the flow decelerates, and pressure inside the jet rises. Eventually, the offset jet reattaches to the wall, enclosing a separated flow zone in which a reverse eddy is formed. Upon reattaching, the jet behaves like an impinging jet, and the pressure at the impinging zone becomes larger than hydrostatic attaining the maximum near the impinging point. The forward flow is accelerated because of the favourable pressure gradient set

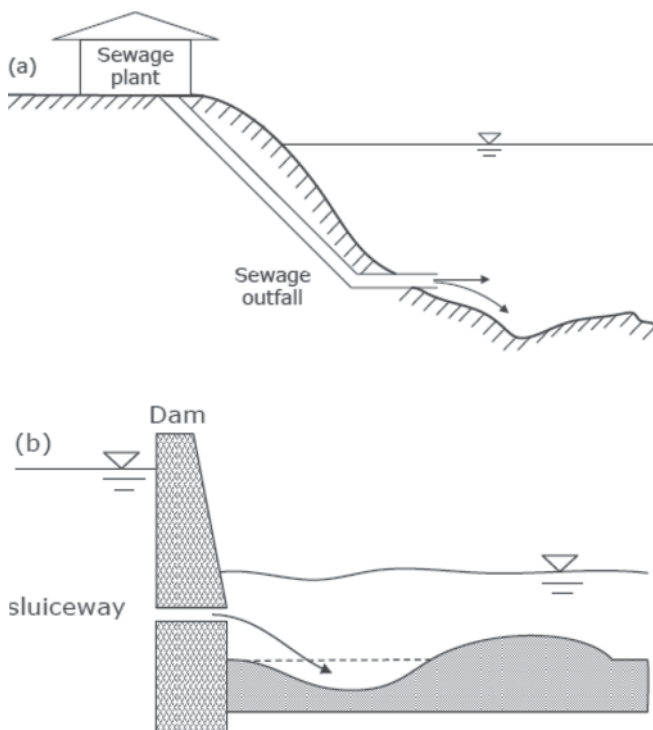


Fig.1 Examples for offset jets (a) schematic diagram of sewage outfall; (b) sluiceway of dam

by the reattachment. At the end of the impingement zone, the acceleration ceases, and a turbulent wall jet condition is established. A new internal boundary layer in the forward flow is developed in this developing wall jet region, which increases in thickness because of the presence of the solid boundary and turbulent diffusion. A mixing layer is established at the upper part of this jet, and a large reverse-flow region is created near the free surface, which is significantly affected by the shallow tailwater depth. Further downstream, the velocity distributions gradually recover to the normal subcritical open-channel flow.

2.2 REVIEW OF LITERATURE

Hydraulic structures are built in rivers for various purposes like for river training works, for water storage for future use or for producing electricity and sometimes to decrease the flow velocity or sometimes to provide passage to connect the opposite banks of rivers. Due to the river bed soil and flow characteristics, it is seen that sediment is eroded and deposited at a certain distance in bed and some of the sediment particles remain suspended. As a result scouring forms. A lot of experimental work and numerical simulations on scouring due to submerged horizontal jets have been done by various researchers before, however a few has been done considering offset jet and mathematical investigations. Here is a brief review on the work studied by them.

Rajaratnam (1981) presented the results of an experimental study on erosion caused by plane wall jets of air and water on beds of sand and polystyrene and also did the same for impinging plane jets of water and air on beds of sand. By using dimensional analysis, the characteristics features of the scoured bed in the asymptotic state were analysed. For the scour formed by wall jet, it was found that the asymptotic profile in the scour hole part is similar with the maximum depth of erosion and the distance of this section from the nozzle as the length scales. Moreover, the maximum erosion depth, its distance from the nozzle, height of the ridge formed in the downstream end of the scour hole and its distance from the nozzle in terms of the thickness of the jet are functions of densimetric Froude number. Ali and Neyshaboury (1991) studied local scour caused by deeply submerged 2D offset jets. They conducted various experiments to study the time variation of scour by changing sediment sizes, jet heights and flow velocity. They observed that the characteristics of scour depend on time, Froude number, and more importantly on sediment size and height of the jet above the bed. Moreover, at the asymptotic state, it was found that when the height of the offset jet is smaller, depth of the scour hole is more than that caused by a jet with a bigger height. They presented results of detailed experimental investigation on the behaviour of turbulent offset jet at asymptotic conditions of the scouring process but they did not perform any mathematical model to study the scour process. They measured the horizontal and vertical velocity distributions but

did not explore the characteristics of velocity and turbulence in an evolving scour hole. Chatterjee et al. (1994) studied the occurrence of local scour and sediment transport formed by horizontal jet of water coming out from sluice opening. They observed that the rate of scour is relatively high in the first few minutes and goes on decreasing as the scour continues. The scour profiles are time independent and also same in nature but dependent on the characteristics of bed grain-size. The scour characteristics have been described by the time to reach the equilibrium stage, the locations of the maximum scour depth, and the locations of the peak of the dune from the end of the rigid apron. Each of these variables has successfully been expressed in terms of flow parameters and sediment characteristics. Chiew and Lim (1996) used two types of circular jets, wall jet and offset jet, having air as well as water flowing through the jet, to study local scour in uniform cohesionless sediment bed. They performed various experiments with densimetric Froude number of 13.14 - 60.74 and offset ratio of 0.5 - 15.75. They found densimetric Froude number to be the main characteristic scouring parameter in relation with the maximum equilibrium scour dimension. They further noted that higher offset distance in an offset jet causes smaller scour hole, because the maximum flow from the jet is elevated farther away from the sediment bed, and most of the energy is diffused into the flow instead of being used to erode the sediment. They observed scouring in air jet to be sooner than that in the water jet. They did not explain the scour process by mathematical or analytical model. Sarkar and Dey (2005) experimentally studied the characteristics of scour holes downstream of an apron due to a submerged horizontal jet issuing from a sluice opening. They found that the scour profiles for scour holes downstream of the apron are nearly similar. They provided various guidelines to civil engineers for designing apron foundations and protective measures (such as launching aprons) for scour downstream of an apron in uniform and non-uniform sediments. The characteristic lengths of the scour hole were determined from the scour profiles. They found that for non-uniform sediments the horizontal distance of the dune crest from the edge of the apron, the dune height, the horizontal distance of maximum scour depth from the edge of the apron, the horizontal extension of scour hole from the edge of the apron and the maximum equilibrium scour depth all decrease with increases in geometric standard deviation of sediments and for uniform sediments, the horizontal distance of the dune crest from the edge of the apron, the horizontal distance of maximum scour depth from the edge of the apron, the horizontal extension of scour hole from the edge of the apron and the maximum equilibrium scour depth were all found to increase with increase in densimetric Froude number, whereas the dune height decreases with increase in densimetric Froude number.

Faruque et al. (2006) studied scour caused by three-dimensional jets issuing from a square cross-section nozzle on to a non-cohesive sand bed and performed experiments

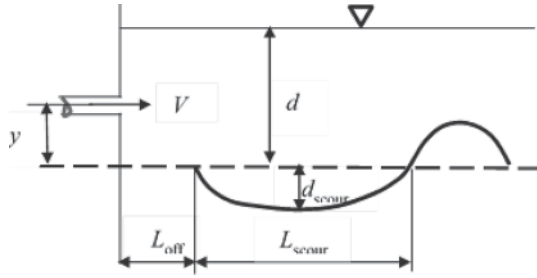


Fig.2 Scour by a deeply submerged circular offset jet. (Chiew and Lim, 1996)

using two different nozzles and three tailwater depths. The densimetric Froude number was maintained below 10, while the jet expansion ratio was held greater than 10. The results indicate that the densimetric Froude number, tailwater depth, and grain size-to-nozzle width ratio, all have an influence on the extent of scour and each parameter has a dominant influence at different flow conditions. They observed that at lower values of densimetric Froude numbers (<5), non-dimensional tailwater depth and grain size-to-nozzle width ratio have no effect on the maximum depth of scour whereas at higher densimetric Froude numbers, the effect of tailwater depth appears to be important at larger values of grain size-to-nozzle width ratio. A set of scaling parameters based on nozzle hydraulic radius, grain size, and densimetric Froude number provided a better scaling of the time variation of the scour parameters. Dey and Sarkar (2006) performed number of experiments on scour in uniform and non-uniform cohesionless sediment beds downstream of an apron by submerged horizontal jet discharging from a sluice opening, for various sluice openings, jet velocities, apron lengths, and tailwater depths. They found that the scour profiles follow a particular geometrical similarity at different times, and is expressed by a combination of two polynomials,

$$\hat{y}(\hat{y} \leq 0) = a_0 + a_1 \hat{x} + a_2 \hat{x}^2 + a_3 \hat{x}^3 \quad \dots (1)$$

$$\hat{y}(\hat{y} > 0) = b_0 + b_1 \hat{x} + b_2 \hat{x}^2 + b_3 \hat{x}^3 \quad \dots (2)$$

Where, a_{0-3} and b_{0-3} are coefficients obtained from scour profiles and boundary conditions. The time variation of scour depth increases linearly with densimetric Froude number. The equilibrium scour depth increases as apron length, sediment size and sluice opening decreases, and increases with increase in densimetric Froude number. Experiments were performed with various densimetric Froude number ranging from 5.7 to 12.61. The equilibrium scour time considered in this study is 12h. The maximum equilibrium scour depth as measured in this work lies in the range of $6.57 < \hat{h} \hat{h} < 13.85$ and $\hat{l} > 26$ where $\hat{h} \hat{h} = h/b$ and $\hat{l} = l/b$ and l = apron length and b = sluice gate opening. Dey and Raikar (2007) conducted various experiments and analysed the results on scour below a high vertical drop using uniform sand and gravel. They found that the parameters influencing the equilibrium scour

depth below a vertical drop are tailwater depth, jet thickness, and velocity of jet, mass density of water, mass density of sediments, gravitational acceleration, and kinematic viscosity of water. They observed that the equilibrium scour depth increases with increase in densimetric Froude number, whereas the scour depth decreases with increase in sediment size and tailwater depth. To represent the time variation of scour depth, the time scale that follows an exponential law is obtained. Karki, Faruque, and Balachandar (2007) used both square and 2D offset jet to perform experimental study of scour process. The square offset jet test is performed for densimetric Froude number 10 and deep tail water depth while the 2D offset jet test is conducted for 5.5 and 10 densimetric Froude number considering both shallow and deep tailwater depth conditions. They found that for both the types of jets for a given densimetric Froude number, depth of the scour hole decreases and total length increases as offset distance increases. Moreover, the time required for the initiation of significant scour increases with increase in offset distance for both types of offset jet. They observed that the offset distance is the most important factor affecting scour in addition to other geometric parameters for both jets. They did not perform mathematical model to study the scour process. They did not explore the characteristics of velocity and turbulence in an evolving scour hole. Dey and Sarkar (2008) using acoustic Doppler velocimeter performed an experimental investigation on the velocity and turbulence characteristics in a scour hole produced downstream of an apron caused by submerged jets emerging from a sluice opening. Experiments were carried out with jet Froude numbers ranging from 2.58 to 4.87 and submergence factors 0.96 to 1.85. The important interpretations they made about the flow characteristics in submerged jet are: the flow in the fully developed zone is self-preserving over apron and scoured bed, local maximum horizontal velocity decay rate increases with an increase in scour hole dimension, horizontal velocity's inner-layer thickness and turbulence intensity distributions increases due to bed roughness and scour hole, the decay rate of the local maximum Reynolds stress, horizontal, and vertical turbulent intensities over scoured beds are slower than those over the apron. They also found that the decay rate of local maximum horizontal velocity increases with an increase in scour hole dimension. Chiew et al. (2012) collected experimental data of offset and propeller jet scour from published literature to investigate the characteristics of the scour hole formed on a uniform cohesionless sediment bed and found that the densimetric Froude number F_0 and the offset height are the two primary parameters in affecting the scour hole dimensions. They found the dimensionless scour depth is directly proportional to densimetric Froude number and inversely proportional to dimensionless offset height, and dimensionless scour length and dimensionless scour width, both are directly proportional to Froude number and dimensionless offset height. Hong et

al. (2012) experimentally investigated the evolution of scour caused by propeller jet. They observed that the equilibrium scour profile comprises three components - a small scour hole directly beneath the propeller; a primary scour hole downstream of the small scour hole; and a sand dune farther downstream of the primary scour hole and also examined the similarities and differences that exist in the equilibrium scour profile developed under different conditions. They proposed a semi-empirical formula based on the densimetric Froude number, offset height and a reference time scale, to simulate the temporal development of the maximum scour depth that showed good agreement with the experimental data. Hong, Chiew, and Cheng (2013) investigated the development of a scour hole with non-cohesive sediments due to the jet induced by a rotating propeller. They conducted experiments with sediment particles of median size 0.34 - 1.46, densimetric Froude number of 6.08 - 10.69 and offset ratio of 0.5 - 1 and tailwater depth of 0.45 m and 0.6 m for a time period of 64h. Dimensionless equation for the estimation of time dependent scour depth induced by a propeller wash is developed and its simulated results compared well with the experimental data used in the paper and those from the published literature. The time to initiate propeller scour decreases with decreasing densimetric Froude number and propeller diameter but increases with increasing sediment size and offset height. The densimetric Froude number and the offset ratio play the most important role in affecting the scour dimensions caused by both offset and propeller jet. The wall jet induces the deepest scour depth for the same value of densimetric Froude number than that of the offset jets and propeller jets. They developed an equation that can be used to account for the scour depth induced by an offset and a propeller jet and to deduce the critical condition for the initiation of scour.

$$13 \frac{d_{s,me}}{d_0} = 0.265 \left[F_0 - 4.114 \left(\frac{y_0}{d_0} \right) \right]^{0.955} \left(\frac{y_0}{d_0} \right)^{-0.022} \quad \dots (3)$$

$$\text{where } \left(\frac{y_0}{d_0} \right) \geq 0.5$$

$d_{s,me}/d_0$ = dimensionless scour depth; F_0 = densimetric Froude number; y_0/d_0 = offset ratio.

Melville and Lim (2014) analysed 309 known laboratory data for local scour depth developed by two-dimensional horizontal jets, which leads to development of a new comprehensive prediction equation that comprises a number of mutually independent multiplying factors, which account for the effects on local scour depth of the characteristics of the applied jet flow and the bed sediment, as well as the extent of a downstream protective apron. When utilized in terms of the jet thickness, the equation shows that the maximum possible dimensionless local scour depth is equal to three times the jet Froude number expressed in terms of jet velocity and jet thickness. The equation is compared to most of the

existing predictive equations by applying each equation to the existing data, the comparison indicating that the new method has superior performance. Indeed, many of the existing predictive equations are shown to perform poorly when judged against the known laboratory data. They gave the following equation for prediction of local scour depth due to 2D horizontal jets that performs better than existing predictive equations, when judged against the known laboratory data.

$$\frac{y_s}{y_j} = 3 F_j K_D K_{yt} K_\sigma K_L \quad \dots (4)$$

where F_j = strength of the applied flow; y_s = local scour depth; y_j = thickness of jet at vena-contracta; the K s are dimensionless multiplying factors expressing the influence on scour depth of sediment size (K_D), tail water depth (K_{yt}), sediment gradation (K^σ), and apron length (K_L).

Most of the researchers explained only the dependency of various parameters on the scour caused by the offset jet from visual observations and simple calculations. The results of detailed experimental investigation on the behaviour of offset jet at asymptotic conditions of the scouring process were investigated but they did not perform any mathematical model to study the scour process. The horizontal and vertical velocity distributions were measured at various locations but the characteristics of velocity and turbulence in an evolving scour hole were not explored.

2.3 PARAMETERS RELATED TO SCOUR

1. Bed sediment-median size (d_{50}), grain size distribution (S-curve), cohesiveness, relative density, angle of repose, thickness of the sediment bed (t).

TABLE 1: CHARACTERISTICS OF SEDIMENTS USED IN THE EXPERIMENTS

| Median size (d_{50}) | Angle of repose (°) | Relative density (s) | Geometric standard deviation |
|--------------------------|---------------------|----------------------|------------------------------|
| 1.81 mm | 31.9 | 2.65 | 1.28 |

where, d_{50} is the 50% finer sediment size.

2. Flow parameters

- Width of the flume at the sluice gate opening ($B = 6\text{cm}$),
- Offset height, h (variable),
- Sluice gate opening ($b = 4\text{cm}$),
- Jet Froude number [$F_r = U/(gb)^{0.5}$],
- Densimetric Froude number [$F_0 = U/(\Delta g d_{50})^{0.5}$],
- Velocity at the gate opening [$U = F_r \times (gb)^{0.5}$],
- Discharge [$Q = U \times B \times b$]
- Offset distance ratio = h/b
- Tailwater depth

3. Time of scour can be taken as an additional parameter ($T = 10\text{-}12\text{ hrs}$)

4. Fluid: Mass density (10^3kg m^{-3}), viscosity

(approximately $10^{-6} \text{ m}^2 \text{ s}^{-1}$ at 20°C), gravitational acceleration ($g = 9.81 \text{ m s}^{-2}$), and temperature

2.4 EXPERIMENTAL SETUP AND PROCEDURE

The laboratory experiments were carried out in a flume, having cross section of 0.6 m wide, 0.71 m deep and 10 m long, at the Hydraulic and Water Resources Engineering Laboratory, Department of Civil Engineering, Indian Institute of Technology, Kharagpur, India as shown in Fig.3. The transparent sidewalls of the flume allowed optical access. A sediment recess of 0.6 m width and 2 m long and depth 0.3 m was prepared based on a few trial runs and levelled to the required offset distance. The test section was located 5 m from the upstream end of the flume. Two small holes were provided at the bottom of the downstream wall of the sediment recess to drain out water at the end of the experiment. A sediment trap was constructed adjacent to the downstream wall of the sediment recess to prevent the scoured sediments to go into the underground reservoir. There was an inclined concrete stilling basin consisting of one baffle wall and two vertical steel screens at the inlet of the flume through which water entered into the flume. The apron of height 0.3 m was made of perspex sheet over which vertical sluice gate was fixed. A perspex vertical sluice gate, which had a streamlined lip to produce a supercritical flow with a thickness equal to the gate opening, was fitted over the bed. Sediments samples of median size $d_{50} = 1.81 \text{ mm}$ was prepared for using in the experiments. The Indian Standard sieves were used for the preparation of different samples. The data of sieve analysis were plotted to draw the particle size distribution curves and d_{50} was obtained from the curves for the sediment sample. The properties of sands and gravels used in the experiments are summarized in Table 2.1. The depth of sediment recess was adjusted depending on the required offset ratio. A vernier point gauge with an accuracy of $\pm 0.1 \text{ mm}$ was used to measure the flow depths. An adjustable tailgate in the downstream of the flume controlled the tailwater depth in the flume. The water supply system consists of a constant head reservoir, an inlet tank, pumps and a large underground reservoir. A valve was fitted at the junction of constant head reservoir and inlet tank regulated the water supply in the inlet tank. The water discharge at the inlet, controlled by an inlet valve, was measured by a calibrated V-notch weir. A few experiments were carried out to investigate the effect of various parameters on the equilibrium scour depth.

The sluice gate was placed over the apron and was adjusted to have the required gate opening of 0.02 m and

different sluice gate openings can be changed by adjusting the gate vertically over the smooth apron. The sediment bed was levelled properly with sediment size of $d_{50} = 1.81 \text{ mm}$ and was checked by using a vernier point gauge before starting the experiments. The final bed level was also checked by flooding the sediment recess. The point gauge was attached to the instrument carriage which could be moved horizontally and transversely. The flume was initially filled with water at a low rate in order to avoid too much scouring of the sediment bed by the sudden action of the offset jet issuing from the sluice gate opening. The densimetric Froude number was fixed by conducting many trial experiments using different sediment sizes, different tailwater depths and various offset ratio. The experiment was then started by adjusting the discharge to the desired value after the water level reached the desired depth. Discharge was measured using a V-notch weir and expressed as a function of head of water H above the sill level of the V-notch as:

$$Q = 0.9174H^{2.159} \quad \dots (5)$$

The discharge into the flume was regulated by a valve fitted at the junction of the constant head reservoir and the inlet tank. The water level was measured by a vernier point

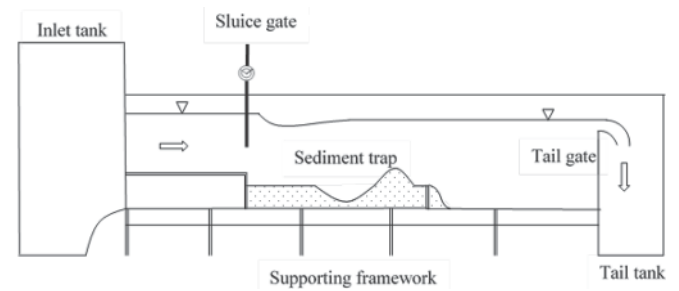


Fig.3 Experimental set up

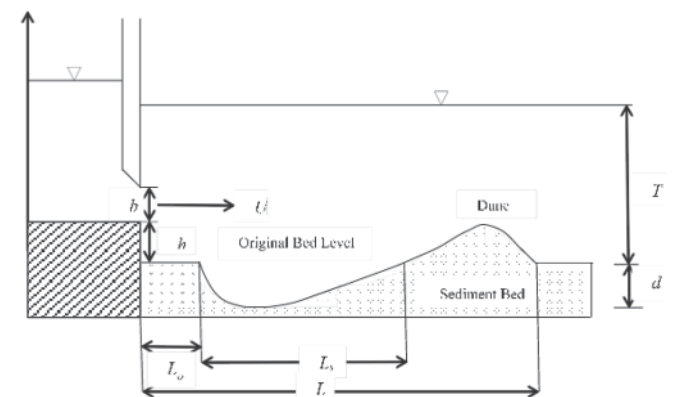


Fig.4 Schematic diagram of scour hole due to offset jet

TABLE 2: EXPERIMENTAL PARAMETERS FOR SEDIMENT SIZE 1.81MM

| No. | $B(\text{cm})$ | $t(\text{cm})$ | $l(\text{cm})$ | OR | OR_m | F_u | $U(\text{m/s})$ | $Q(\text{m}^3/\text{s})$ | $H(\text{cm})$ | $d_{50}(\text{mm})$ | F_0 | $T(\text{cm})$ |
|-----|----------------|----------------|----------------|------|--------|-------|-----------------|--------------------------|----------------|---------------------|-------|----------------|
| 1 | 2 | 17.5 | 12.5 | 6.25 | 6.75 | 2.62 | 1.165 | 0.0139 | 30 | 1.81 | 6.81 | 61.5 |
| 2 | 2 | 17.5 | 12.5 | 6.25 | 6.75 | 2 | 0.886 | 0.0106 | 30 | 1.81 | 5.17 | 61.5 |
| 3 | 2 | 17.5 | 12.5 | 6.25 | 6.75 | 2.3 | 1.018 | 0.0122 | 30 | 1.81 | 5.95 | 61.5 |

gauge having an accuracy of ± 0.1 mm, placed at the inlet tank. The scour profiles at regular intervals of time were traced on a transparent perspex sheet attached to the outside glass wall. The perspex sheet had square grids of size $1\text{cm} \times 1\text{cm}$, facilitating reproduction of scour profiles. The runs were taken for a period of 10 to 12 h when the equilibrium scour depth was obtained. Finally, water was drained out slowly by opening the holes at the bottom of the downstream wall of sediment recess, sediment trap and tail gate.

Velocity and turbulence profiles were measured by a SonTek 5 cm down looking acoustic Doppler velocimeter (ADV), which had a sampling rate and volume of 50 Hz and 0.09 cm^3 respectively. A spike removal algorithm filtered the output data from the ADV. The ADV measurements were taken in the vertical plane of symmetry (VPS) along vertical lines at different streamwise distances. In order to check the two-dimensionality of the flow, the ADV measurements were also taken in other vertical planes at a transverse distance of 10 cm from either side of the VPS. The velocity profiles in these planes revealed that in the central part of the flume, the flow was reasonably two-dimensional. The acoustic beams were sent out with a frequency of 16 MHz from the transmitting transducer traveling through the water arriving at the measuring point 5 cm below the transducer, where they were reflected by the ambient particles within the flow and received by the receiving transducers. Since the measuring location was 5 cm below the ADV probe, the captured data were free from an artifact of the ADV. In the near-bed region, the recorded velocities might contain spikes are possibly due to the interference between incident and reflected pulses. The measurement by the ADV probe was not feasible in the zone located 5cm below the free surface. Depending on the turbulence intensity, the sampling durations was 4 minutes in order to have a statistically time-independent average velocity. Near the bed, the sampling durations were relatively long. An inbuilt acoustic device of the ADV indicated the vertical locations of the ADV measurements with respect to the bed. The closest vertical spacing of the ADV measurements was 0.2 cm. It was mainly maintained from the bed to the point of flow reversal in the fully developed zone. On the other hand, the closest horizontal spacing of the ADV measurements was 2 cm from the sluice opening to the junction of the fully developed zone and the recovering zone.

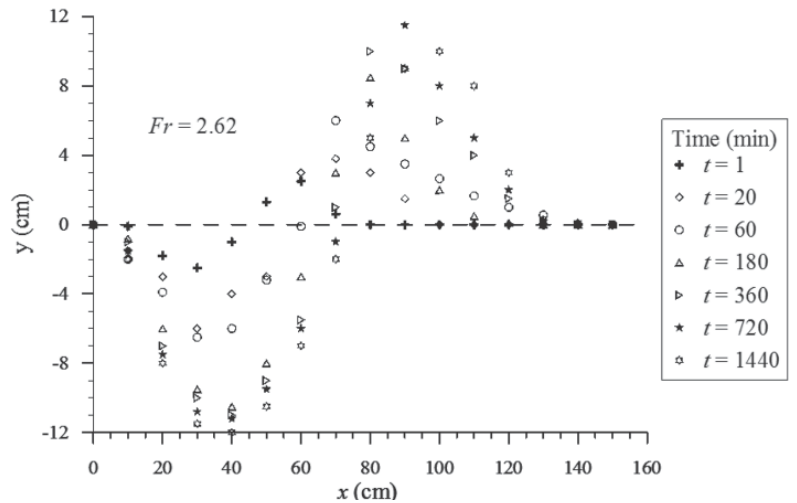


Fig.5 Scour profiles at different times for Froude number 2.62

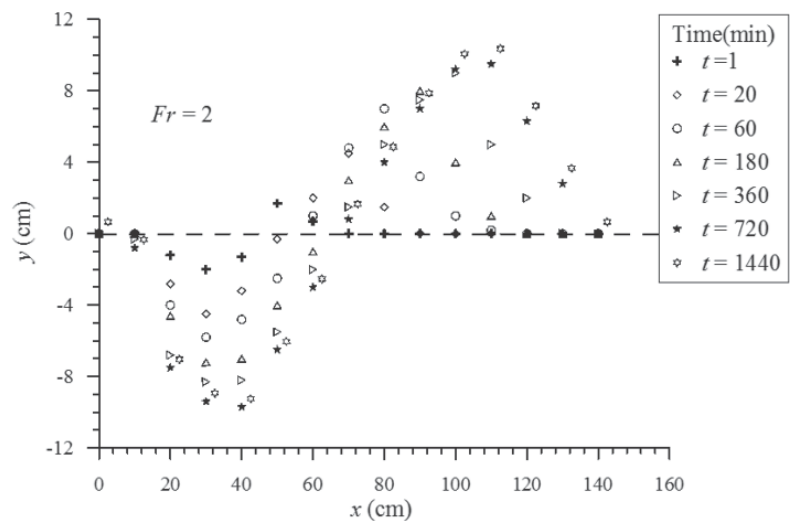


Fig.6 Scour profiles at different times for Froude number 2

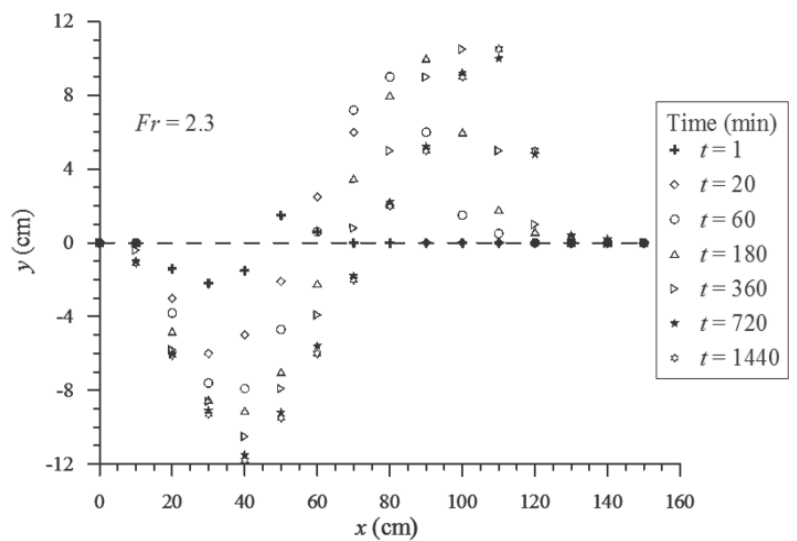


Fig.7 Scour profiles at different times for Froude number 2.3

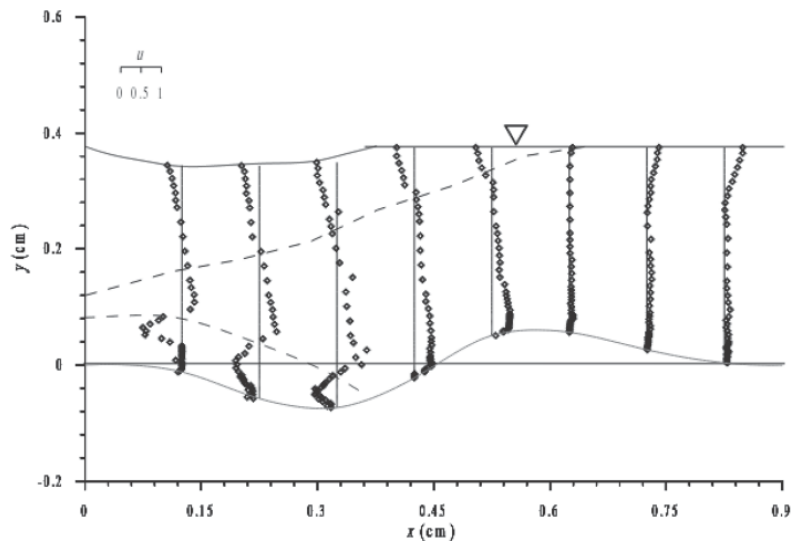


Fig.8 Vertical distributions of u for intermediate scour hole of $0.3d_{se}$

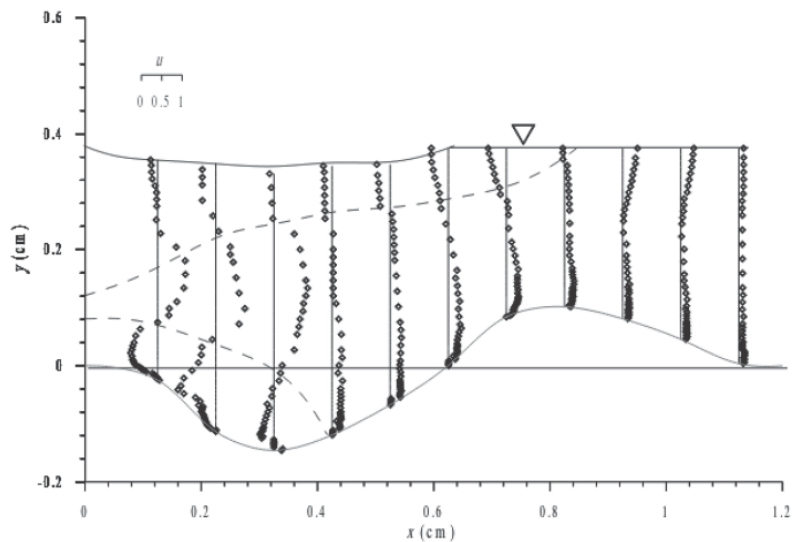


Fig.9 Vertical distributions of u for intermediate scour hole of $0.7d_{se}$

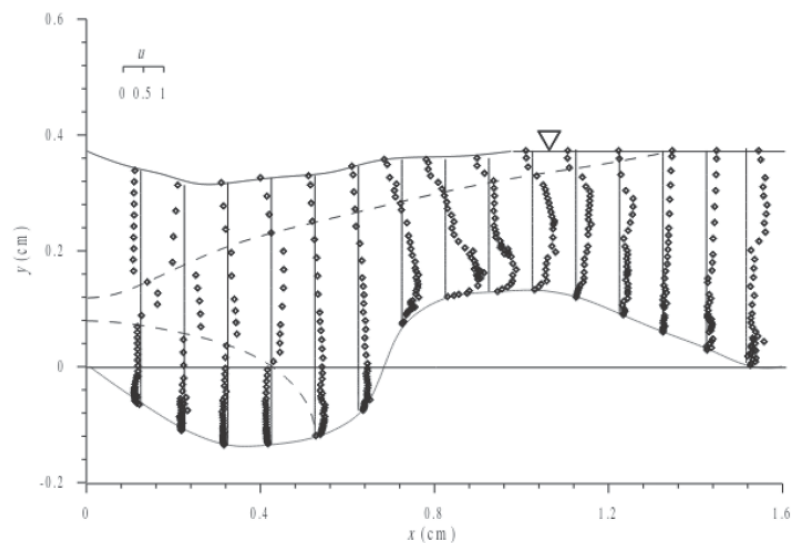


Fig.10 Vertical distributions of u for equilibrium scour depth

2.5 SCOURING PROCESS

The scouring process due to offset jet is complex, owing to the interaction between the jet and the resistance of the bed sediment. The evolution of a typical scouring profile along the longitudinal direction may be divided into four stages:

1. Initial stage: During the initial stage, as flow started a main or primary scour hole is formed downstream of the apron. The scour hole grew longitudinally with the formation of a small dune or deposition overlaid by smaller ripples. At this stage the finer particles moved away from the bed as suspended load.
2. Developing stage: During the developing stage, the size of the primary scour hole increased with time. As the flow separation took place at the edge of the apron having a reattachment of flow at the deepest point of the scour hole, the movement of the sediment particles was divided into two parts. Some amount of sediments moved along the downstream slope of the scour hole and ultimately went out of the scour hole. The other part was moved back along the upstream slope of the scour hole by the reversed flow and a second small dune is formed. The larger dune moved horizontally downwards away from the apron with the passage of time and the size of dune also increased.
3. Stabilization stage: During the stage of stabilization, the size scour holes and dunes slowly increased with time with the movement of very few sediment particles.
4. Asymptotic stage: After 24h of testing, scour hole and dunes reached the asymptotic stage where no particles were in suspension. Beyond this time, the dimension of the scour hole essentially remains unchanged.

2.6 SCOUR PROFILES

The evolving scour hole at any time follows a particular profile as given in Fig.4. Typical scour profiles at different times during the development of the scour hole for different Froude numbers are shown in Figs.5, 6 and 7. It is observed that an existence of a similarity of the scour profiles can be established by plotting the profiles in dimensional coordinates xy , where x is the horizontal distance; y = vertical distance; and d_{se} is the maximum scour depth at any time t . It is found that the maximum scour depth increases with increase in Froude number.

2.7 DISTRIBUTIONS OF VELOCITY PROFILES

Fig.3 describes a schematic diagram of scour downstream of an apron due to submerged offset jet issuing from a sluice opening. The velocity distribution in the region from the starting of scour hole to the end of dune was investigated for different times at different longitudinal distances using ADV. The velocity measurements were obtained at eight different locations downstream of the nozzle along the centreline of the nozzle. Figs.8, 9 and 10 shows the velocity distributions at different stages of scour process. Fig.8 shows the vertical distributions of streamwise velocity u for intermediate scour hole of $0.3d_{se}$, Fig.9 shows the vertical distributions of u for intermediate scour hole of $0.7d_{se}$ and Fig.10 the vertical distributions of u for equilibrium scour depth. The maximum scour depth, d_{se} is 12.5cm, 30% of scour depth is 3.75cm and 70% of the scour depth is 8.75cm. There is a negative velocities or the reverse-velocity in the surface. The presence of a solid boundary results in the deflection of the jet towards that boundary, thus the offset jet reattaches to the wall, enclosing a separated flow zone in which a reverse eddy is formed. At the end of the recirculation region is the reattachment region where the pressure becomes larger than hydrostatic attaining the maximum near the reattached point. The forward flow is accelerated because of the favourable pressure gradient set by the reattachment. At the end of the reattached zone, the acceleration decreases, and a turbulent wall jet condition is established. Further downstream, the velocity distributions gradually recover to the normal subcritical open-channel flow.

2.8 Conclusions

1. The maximum depth of scour increases with increase in densimetric Froude number.
2. The maximum width of the scour hole was wider and its location was closer to the nozzle with decreasing offset distance.
3. The depth of scour hole decreases with increase in sluice gate opening.
4. The scour profiles at different time follow a geometrical similarity.
5. The vertical distributions of time-averaged velocity components, at different streamwise distances from the sluice opening have been presented. The flow is found to be self-preserving in general. The decay rate of local maximum horizontal velocity increases due to bed roughness.

References

1. Adduce, C. and Sciortino, G. (2006): Scour due to a horizontal turbulent jet: Numerical and experimental investigation. *Journal of Hydraulic Research*, 44 (5), 663–673.
2. Bhuiyan, F., Habibzadeh, A., Rajaratnam, N. and Zhu,

- D. Z. (2011): Reattached Turbulent Submerged Offset Jets on Rough Beds with Shallow Tailwater. *Journal of Hydraulic Engineering*, 137, 1636–1648.
3. Rajaratnam, N. (1981): Erosion by plain turbulent jets. *Journal of Hydraulic Research*, Delft, The Netherlands, 19 (4), 339-358.
4. Ali, K.H.M. and Salehi Neyshaboury, A.A. (1991): Localized scour downstream of a deeply submerged horizontal jet. *Proceedings of Institution of Civil Engineers*, Part 2, 91 (1), 1-18.
5. Chiew, Y.M. and Lim, S.Y. (1996): Local scour by a deeply submerged horizontal circular jet. *Journal of hydraulic Engineering*, A.S.C.E., 122 (9), 529-532.
6. Chatterjee, S. S., Ghosh, S. N. and Chatterjee, M. (1994): Submerged horizontal jet over erodible bed. *Journal of Hydraulic Division*, 106 (11), 1765-1782.
7. Dey, S. (2014): Fluvial Hydrodynamics: Hydrodynamic and Sediment Transport Phenomena, *Springer*, Berlin.
8. Dey, S. and Sarkar, A. (2006): Scour downstream of an apron due to submerged horizontal jets. *Journal of Hydraulic Engineering*, A.S.C.E., 132 (3), 246-257.
9. Dey, S. and Raikar, R.V. (2007b): Scour below a high vertical drop. *Journal of Hydraulic Engineering*. 133 (5), 564–568.
10. Dey, S. and Sarkar, A. (2008): Characteristics of Submerged Jets in Evolving Scour Hole Downstream of an Apron. *Journal of Engineering Mechanics*, 134 (11), 927-936.
11. Faruque, M. A. A., Sarathi, P. and Balachandar, R. (2006): Clear Water Local Scour by Submerged Three-Dimensional Wall Jets/: Effect of Tailwater Depth. *Journal of Hydraulic Engineering*, 132 (6), 575-580.
12. Hong, J.H., Chiew, Y.M., Susanto, I. and Cheng, N.S. (2012): Evolution of scour induced by propeller wash. Submitted to the 6th International Conference on Scour and Erosion, Paris.
13. Hong, J.H., Chiew, Y.M. and Cheng, N.S. (2013). Scour Caused by a Propeller Jet. *Journal of Hydraulic Engineering*, 139(9), 1003-1012.
14. Karki, M.A.A., Faruque, M.A.A. and Balachandar, R. (2007): Local scour by submerged offset jets. *Proceedings of Institution of Civil. Engineers, Water Maritime and Energy*, 160 (3), 169-179.
15. Melville, B. W. and Lim, S.Y. (2014): Scour Caused by 2D Horizontal Jets. *Journal of Hydraulic Engineering*, 140 (2), 149–155.
16. Metcalf, L., Eddy, H. P. (1922): *Sewerage and Sewage Disposal: A Textbook*. New York: McGraw-Hill.
17. Sarkar, A. and Dey, S. (2005): Scour downstream of aprons caused by sluices. *Proceedings of Institution of Civil Engineers, Waters. Maritime Energy*, 1582, 55–64.