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SCOUR MECHANISM AROUND PIERS AT CLEAR WATER EQUILIBRIUM CONDITION

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Abstract *— This paper presents a review work of local scour mechanism around pier scour holes at clear water equilibrium conditions. Many researchers have carried out various studies to determine the velocity profiles around the scour holes. The contours and spatial distributions of the time-averaged (mean) velocities, turbulence intensities, turbulent kinetic energy and Reynolds stresses at different azimuthal planes were determined. Velocity vector plots of the flow field at azimuthal planes are used to explain further flow features. The vorticity and circulation of the horseshoe vortex are determined by using finite difference technique of computational hydrodynamics and Stokes theorem, respectively. Bed-shear stresses are also estimated from the Reynolds stress distributions. The flow and turbulence characteristics of the horseshoe vortex are discussed from the standpoint of similarity with velocity and turbulence intensity characteristic scales. These detailed measurements are obtained with a non-intrusive instrument, the acoustic Doppler velocimeter (ADV), which measures three-dimensional instantaneous velocities. This instrument is very practical for the measurements related to scour. This instrument can also be used as a tool during the investigation for enhancement of sediment transport as an alternative to dredging mechanism in future which is to be explored. It is therefore felt that more studies are still necessary to enhancement of sediment transport effectively for dredging purpose and also to measure the turbulence using ADV.*

Keywords*-open channel flow; clear water; scour; pier; vortex*

I. INTRODUCTION

Numerous studies have been carried out with the purpose of predicting scour and various equations have been developed by various researchers [1-7]. Selection of an appropriate design method to estimate equilibrium depths of local scour at bridge piers has perplexed designers for many years. There was a wide variety of formulas available, and no obvious similarity in either their appearance or their predictions. The apparent conflicts arising from earlier studies, some of which showed live-bed scour exceeding clear-water scour and others of which showed the reverse [8]. An attempt was made [9-10] to verify the entire characteristic (especially turbulent characteristic) of pre-jump and post-jump region of a hydraulic jump, and a theoretical model is developed based on the K-ε Model in the finite difference form.

An experimental investigation was presented [11] on clear water equilibrium scour around an equilateral triangular pier. The experiment is conducted for the approaching flow having undisturbed flow depth greater than the pier width and the depth-averaged approaching flow velocity about 68% of the critical velocity of the uniform bed sand of median diameter of 0.825m. The outcome of seven experimental studies was presented [12] on local clear-water scour. First an experiment was carried out with a circular pier of 5 cm diameter to see the nature of the equilibrium scour hole around the pier. The results obtained has leaded us to choose a pier of diameter 7 cm to run the following experiments where the piers were placed eccentrically with a distance three times the pier width (= 21cm) between them without the intervention of the *"wall effects"*. The eccentric pier was placed at varying longitudinal distance (from 25%, 37.5%, 50%, 62.5%, and 75% of the equilibrium scour depth of a single pier) to observe the nature of scour. All the experiments were carried out at an average inflow depth of 0.125m and a discharge of 0.025 m^3/sec, over a sand bed of 0.825 mm mean particle diameter.

A series of clear water scour experiments were conducted [1,3] in a tilting flume with a circular pier under different conditions of densimetric Froude number and inflow depths. Tests used a single pier of 50 mm diameter embedded in a sand bed of mean particle size d_{50} = 0.365 mm. It was observed that the entire scour geometry (scour depth, length, width, area and volume) depended on the densimetric Froude number and inflow depth. On the basis of the obtained results, empirical equations were proposed for scour depth, scour length, scour width, scour area and scour volume. Scour hole parameters calculated from the proposed equations have been compared with those obtained from experimental results and were found to be very close to each other.

Two numbers of piers of square and triangular shape of same width were used [13-15] to carry out experiments. The piers were located eccentrically along the middle portion of the tilting flume. The eccentricity is kept constant for all the experiments while the in-line distance (longitudinal spacing) along the flow direction between them was increased gradually by 25%, 37.5%, 50%, 62.5% and 75% to enhance the scour. All the experiments were conducted at same inflow depth, same discharge, same pier width, same Froude number. The only difference was the longitudinal spacing between the piers.

A wide range of longitudinal velocity profile data was measured [16] for validating the Nortek acoustic Doppler current profiler (ADCP) compared with observed data collected from secondary source by using Aquadopp current profiler. The results of an experimental investigation on relative energy dissipation were conducted at chutes of different slopes with different contractions [10,17]. So the effects of contraction and bottom slope on relative energy dissipation were investigated. Experiments were carried out in channels, where chute slope was varied between 1V:10H to 1V:6H and chute contraction varying between 0° to 6°. It was found that the energy dissipation increases with increasing slope and decreases with increasing contraction and ratio between the critical water depth at section zero and the chute height.

A number of methods and devices were used to accurately measure volumetric flow rate in its open channel networks, most of which measure flow indirectly either by measuring velocity and area, or head (flow depth or pressure), and mathematical relationships are then applied to translate the measurement to the volumetric flow rate or discharge. Besides tracers methods were also used [18-19]. Many experiments were carried out in a re-circulating tilting flume with constant bed slope at an average inflow depth of 0.125 m and a discharge of 25 lps, over a sand bed of 0.825 mm mean particle diameter [8, 20-22]. Three circular piers and three square piers of same width were considered where two piers are arranged in-line along the flow direction and the other one is placed eccentrically in between them. The eccentric pier was placed at an increasing longitudinal distance of $2L/8$, $3L/8$, $4L/8$, $5L/8$, and $6L/8$ respectively, where L is the maximum length of sediment transportation for a single circular pier under equilibrium scour condition.

Scouring is a natural phenomenon caused by the flow of water in river and stream. It is the consequence of the erosive action of flowing water, which removes and erodes material from the bed and banks of stream and also from the vicinity of bridge piers and abutments. Scouring occurs naturally as part of the morphologic changes of rivers and as the result of man-made structures. Scour can either be caused by the normal flow and flood flow. Normal flow cannot make a big scour, but during a peak flow in which the flow velocity is higher the normal flow and make a big scour hole. Scour can occur under any flow condition. Due to scour, materials are washed away from the pier or abutment from the natural level of the bed. The scour that occurs near a pier, abutment, erosion control device, or other structure obstructing the flow is called local scour. These obstructions cause flow acceleration and create vortices that remove the surrounding sediments. Generally, depths of local scour are much larger than general or contraction scour depths, often by a factor of ten. Local scour can affect the stability of structures such as riprap revetments and lead to failures.

The depth of the scour is directly dependant on the width of obstruction. Thus, the wider the obstruction, the deeper is the scour. Though not addressed by most empirical relations, the ratio of obstruction width to channel width is probably a better measure of scour potential than is the obstruction width alone. Projected length of an obstruction into the stream affects the depth of scour. With an increase in the projected length of an abutment into the flow, there is an increase in scour.

However, there is a limit on the increase in scour depth with an increase in length. This limit is reached when the ratio of projected length into the stream to the depth of the approaching flow is about 25. The stream wise length of a structure has no appreciable effect on scour depth for straight sections; however, when the structure is at an angle to the flow, the length has a very large effect. At the same angle of attack, doubling the length of a structure increases scour depth by as much as 33%. Some equations take the length factor into account by using the ratio of structure length to depth of flow or structure width and the angle of attack of the flow to the structure. Others use the projected area of the structure to the flow in their equations.

II. LOCAL SCOUR MECHANISM

The boundary layer flow past a cylindrical pier undergoes a three-dimensional separation. This separated shear layer rolls up along the obstruction to form a vortex system in front of the element which is swept downstream by the river flow. Viewed from the top, this vortex system has the characteristic shape of a horseshoe and thus called a horseshoe vortex Figs (1-2). The formation of the horseshoe vortex and the associated down flow around the cylindrical pier results in increased shear stress and hence a local increase in sediment transport capacity of the flow. This leads to the development of a deep whole (scour hole) around the cylindrical pier, which in turn, changes the flow pattern causing a reduction in shear stress by the flow thus reducing its sediment transport capacity. The temporal variation of scour and the maximum depth of scour at bridge elements therefore mainly depend on the characteristics of flow, pier and river-bed material. The formation of the horseshoe vortex and the associated down flow cause scour at cylindrical pier, abutment and spur dike.

The mechanism of scour around bridge piers has been studied [23-29] whereas studies on the mechanism of sediment transport and scour at the reservoirs, rivers, pipes are addressed in [30-36]. Many studies were conducted on erosive process, both in clear water and live bed conditions.

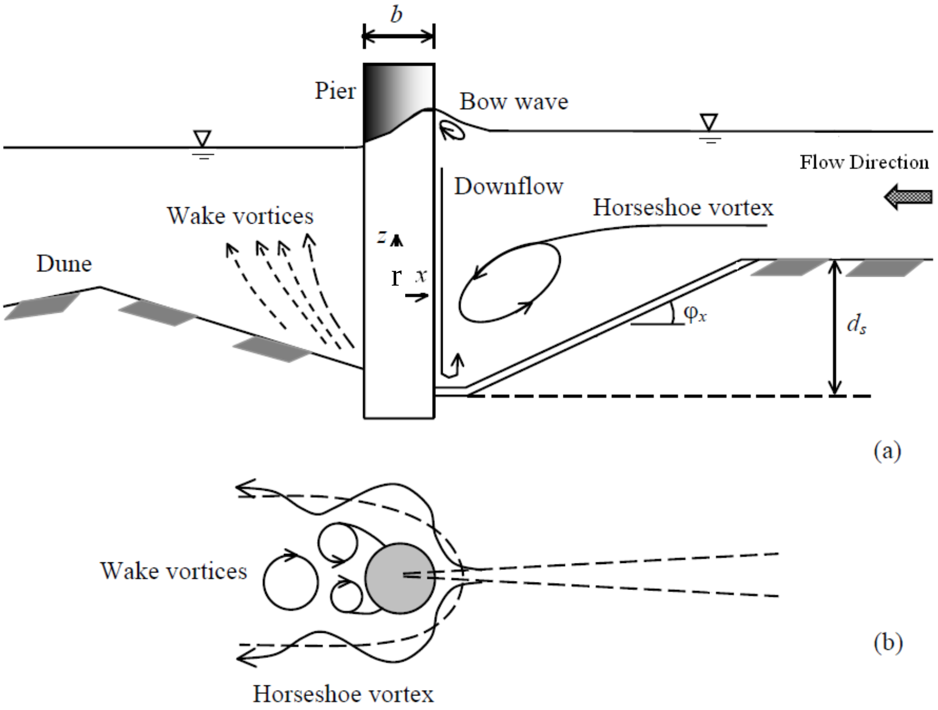

Fig. 1 Flow structure at cylindrical pier (*a*) side view (*b*) top view

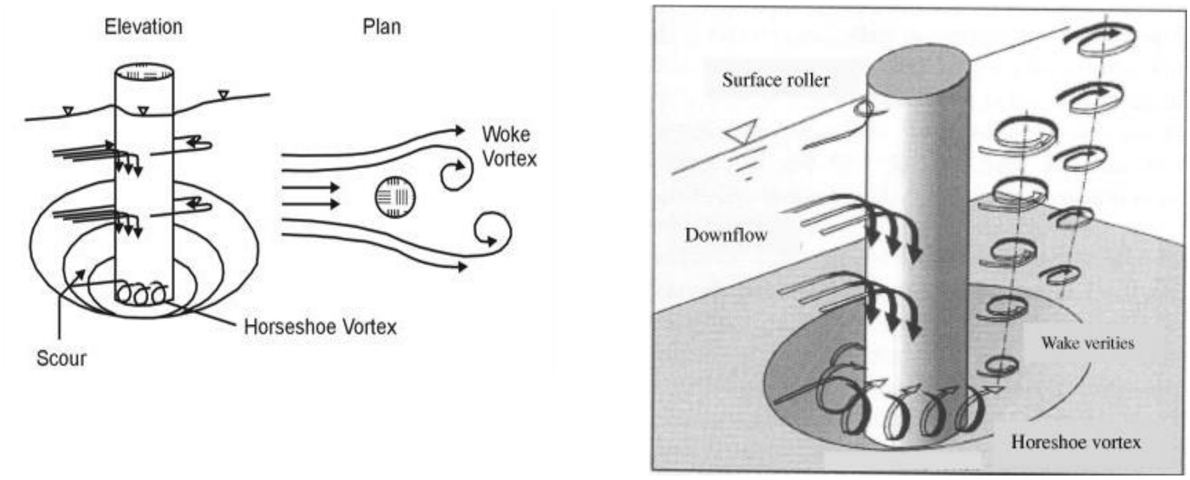

Fig. 2 Flow structure at cylindrical pier

III. HORSESHOE VORTEX AND DOWNFLOW

The flow deflected by sediment embedded bridge piers causes scour at its foundations. Scour may endanger the stability of the complete bridge structure. In bridge hydraulics circular-shaped pier foundations are commonly used. Due to the similar flow structures of airflow around circular bodies in wind tunnels, the basic researches concern flow visualization in aerodynamics. The main flow features involve a vertically deflected flow along the cylinder front, a horseshoe vortex system upstream of the cylinder, a flow separation beside the cylinder and a wake zone downstream of it shown in Fig. 1. The pressure distribution beneath the horseshoe vortex system was measured and the horseshoe vortex position was determined experimentally. For all flow conditions a horseshoe vortex system consisting of at least two vortices. Horseshoe vortex in front of the pier to be the prime agent causing scour and it is assuming a layer-by-layer scouring process. Near the upstream face of the pier there is an existence of downflow, which joins the separated flow to form the horseshoe vortex stretched around the pier.

IV. WAKE VORTEX

Wake vortices form at the downstream side of piers and are the result of flow separation at the sides of the pier Fig. 1. One vortex develops on one side, sheds away, and is convected downstream. Immediately, other forms on the other side, finally shedding also. The wake vortices dissipate as they move downstream. The frequency of vortex shedding is directly proportional to the approach velocity and inversely proportional to the pier diameter. Information on wake vortex scour at bridge piers is particularly scanty. As wake vortex scour occurs at the downstream of the pier, it has little or no destructive potential. Because the horseshoe vortex scour occurs at the face of the pier and threatens to undermine the pier, this type of scour has been given considerable theoretical thought and is well-documented with model studies by previous researchers. Knowledge about wake vortex scour due to bridge piers has come mainly from a few laboratory tests. To describe the scouring action, Melville wrote “each of the concentrated vortices acts with its low pressure center as a vacuum cleaner, picking up material from the bed, which is then transported downstream”.

There is concern that the holes may enlarge or move upstream endangering the piers and the bridges. We have made observations in the vicinity of the scour holes and have come to the conclusion that, in each case, the scour was caused by two streams of wake vortices from adjacent piers intersecting downstream. The vortices that result from the two conflicting velocity fields create local scour. At one bridge, the scour is enhanced by the vortices that occur at the confluence of the main channel and its side channel. This is known as confluence scour.

V. METHODOLOGY

The flow depth in the flume is adjusted by a tailgate. The approaching flow depth is maintained at desired depth by operating the tailgate. The bed slope is kept constant for all the experiments. The critical condition of the bed is checked before test run. The depth-averaged approaching flow velocity is estimated using Manning’s equation. From the sieve analysis test, median diameter of sand is determined. Considering steady uniform flow in a rectangular channel the expression for bed shear stress (τ_0) can be derived as $\tau_0 = \gamma_f R\sin\alpha$. Here the resistance between water-air interfaces is usually very small when the water surface is smooth and can be conveniently neglected. It is considered that $\sin\alpha \approx \tan\alpha = S$ as the bed slope is small. The critical bed shear stress (τ_{0c}) is determined by using the expression for critical Shields parameter, $\Theta_c \left(=\tau_{0c}/(\Delta\rho g d)\right)$. From van Rijn’s [37] empirical equations of the Shields curve the value of critical Shields parameter was calculated where particle parameter, D_* ($=d\sqrt[3]{\Delta g/\nu^2}$). Then critical shear velocity (u_{*c}) is calculated using $u_{*c}=\sqrt{\tau_0/\rho}$. Therefore u_c can be calculated from $u_c/u_{*c}=5.75\log\left(h/2d_{50}\right)+6$ where u_{*c}, h, d_{50} are already known. Finally the critical discharge is calculated using the continuity equation. Critical shear flow Reynolds number R_{*c} $\left(=u_{*c}R/\nu\right)$ is determined at 20^0C temperature of water.

The depth-averaged approaching flow velocity (U) is set as about 68-99% of the critical velocity (u_c) of the uniform sand bed considering side-wall effect to satisfy the clear water condition [25-27]. The depth averaged approaching flow velocity is determined from the measured vertical profile of the approaching flow velocity at 2 m upstream of the pier where the presence of the pier did not affect the approaching flow. Also to satisfy clear water scour condition, average bed shear stress must be less than or equal to critical bed shear stress.

When negligible (1 mm or less) difference of scour depth was observed at an interval of 2 hours after 80 hours, it is considered that an equilibrium stage of the scour hole is attained. However, total duration of each experiment is 72-155 hours that is adequate for achieving the equilibrium scour [25-27] for single pier. After the run is stopped, the maximum equilibrium scour depths are observed at the upstream base of the piers. Then the maximum scour depth at an equilibrium state is carefully measured by a Vernier point gauge. The contour lines of the scour holes at the equilateral triangular piers are plotted by Surfer software.

VI. EXPERIMENTAL TECHNIQUE

The experiments are carried out in a recirculating flume (Fig. 3), is filled with sand to a uniform thickness. The sand bed is located at the upstream from the flume inlet. The recirculating flow system is served by a centrifugal pump which is located at the upstream end of the tilting flume. The water discharge is measured by a flow meter connected to the upstream pipe at the inlet of the flume. Water flows through a pipe line which runs directly into the flume. The flow depth in the flume was adjusted by operating a tailgate. The depth averaged approaching flow velocity is found out from the measured vertical profile of the approaching flow velocity at minimum 2 m upstream of the pier where the presence of the pier did not affect the approaching flow. Froude number, flow Reynolds number and pier Reynolds number for all the experiments are calculated.

The pier is first installed in the flume at the desired location. Before each test, care is taken to level the sand bed throughout the entire length of the flume and perpendicular in the around a pier structure. First of all we have to produce a sand bed having a smooth, uniform surface, so we used a spirit level to check the uniformity of the bed surface. Uneven bed surface are leveled using a hand trowel. After that we have to measure the bed level by point gauge randomly and to check the leveling of the flume. The sand bed preparation is very key as for as the experiment is concerned. Unevenness or defect in the channel bed can cause the damage the experiment. Piers are constructed in eccentrically with different condition with the help of single pier total scour length.

Fig. 3 Working section of a flume

During the experiment it is kept in mind that the width of the experimental flume is more than seven times of the pier width to avoid the wall friction factor. The minimum value of the ratio between flume width and pier width is 6.25 that could be used without a measurable effect from the side walls on the local scour at the pier. To start the test, the flume is slowly filled with water to the required depth from downstream. It should be noted that extra care is required when filling the flume with water, especially for test of this nature where no sediment movement is allowed. Any deformity in the bed surface may develop of ripples or dunes and general movement of the sand if the shear stress on the smooth bed is close to the critical shear stress. The pump is then turned on and desired flow rate has been achieved by controlling the control valve and a bypass valve. Concurrent with getting the pump up to speed, the tailgate is adjusted so as to maintain the correct depth of flow in the flume. Throughout the test period, the location and magnitude of the point of maximum scour depth are around the upstream of the pier. The frequency of the scour depth varied throughout the test period. Rate of scouring is maximum in the period of 1st to 12th hour and then less frequently thereafter. Here we have used the fiber transferring pier model. The run duration for all the experiments is in between 72 to 155 hours. After that the pump is stopped to allow the flume to slowly drain without disturbing the scour topography. The flume bed is then allowed to dry, during which time photo of the scour topography around the pier are taken.

After the run is ended, the maximum equilibrium scour depths are observed at the upstream base of the piers. Then the maximum scour depth at an equilibrium state is carefully measured by a Vernier point gauge which is attached with a movable trolley. The contour lines of the scour holes at the triangular piers are plotted by Golden software Surfer 8 version.

VI. CONCLUDING REMARKS

On the sand bed piers are placed. The change in equilibrium scour geometry that is the scour length, scour depth, scour depth, scour area and scour volume were studied under fixed flow conditions and same bed material by varying the longitudinal spacing between the piers. Relations have been found between the maximum equilibrium scour depth, length, and width with respect to the longitudinal spacing. The variations of planner surface area and the volume of the equilibrium scour holes were also observed relative to the change of longitudinal spacing. From these observations it can be predicted that how by using the energy of a flow and by arranging multiple piers the bed material can be transported by using a pier like obstruction. And in future this technique may be further evolved to provide a very cost effective method of sediment removal or siltation in a stream channel.

REFERENCES

[1] P. Khwairakpam, S.S. Ray, S. Das, R. Das, and A. Mazumdar, “Scour hole characteristics around a vertical pier under clear water scour conditions”, *ARPN J. Eng. Appl. Sci.*, vol. 7, pp. 649-654, 2012

[2] S. Das, Study of the Impact of Sediment Transport Dynamics on Clear Water Scour. *PhD Thesis*, School of Water Resources Engineering: Jadavpur University, 2014.

[3] R. Das, P. Khwairakpam, S. Das, and A. Mazumdar, “Clear-Water Local Scour around Eccentric Multiple Piers to shift the Line of Sediment Deposition”, *Asian J. Water Env. Pollut.*, vol. 11, pp. 47-54, 2014.

[4] S. Das, R. Ghosh, R. Das, and A. Mazumdar, “Clear Water Scour Geometry around Circular Piers”, *Eco. Env. Cons.*, vol. 20, pp. 479-492, 2014.

[5] S. Das, R. Das, and A. Mazumdar, “Variations of clear water scour geometry at piers of different effective width”, *Turkish J. Eng. Env. Sci.*, vol. 38, pp. 97-111 ,doi: 10.3906/muh-1308-11, 2014.

[6] S. Das, R. Das, and A. Mazumdar, “Vorticity and Circulation of Horseshoe Vortex in Equilibrium Scour Holes at Different Piers”, *J. Inst. Eng. India Ser. A*, vol. 95, pp. 109-115, 2014.

[7] S. Das, R. Midya, B. Chatterjee, R. Ghosh, R. Das, and A. Mazumdar, "Bed Shear Stresses past a Flat Plate under Clear Water Equilibrium Scour State", *J. Assoc. Eng. India*, vol. 84, pp. 27-36, 2014.

[8] A. Kuila, Analysis of Clear Water Scour and Horseshoe Vortex Flow Field around Eccentric Circular Piers arranged in Tandem, *ME Thesis*, School of Water Resources Engineering: Jadavpur University, 2013.

[9] A. Chakraborty, A Brief Study of the Turbulent Flow Characteristics of Classical Hydraulic Jump, *ME Thesis*. School of Water Resources Engineering: Jadavpur University, Kolkata, India, 2009.

[10] R. Das, D. Pal, S. Das, and A. Mazumdar, "Study of Energy Dissipation on Inclined Rectangular Contracted Chute, *Arab. J. Sci. Eng.*, vol. 39, pp. 6995-7002.

[11] S. Das, S. Ghosh, and A. Mazumdar, "Flow field past a Triangular Pier due to Sediment Transportation at Clear Water Equilibrium Scour Hole", *Int. J. Emerg. Trends Eng. Dev.*, vol. 7, pp. 380-388, 2012.

[12] S. Ghosh, Analysis of turbulent flow field and scour hole geometry around two eccentric circular piers. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2012.

[13] D. Mondal, Analysis of scour hole geometry and turbulent flow field around two eccentric square and triangular piers. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2012.

[14] S.Das, R. Das, A. Kuila, and A. Mazumdar, Analysis of clear-water equilibrium scour around two eccentric circular piers to increase self dredging, *Proc. of the Sem. on Dredging: Equipment and Applications*, EADA, Kolkata, pp. 1-10, 2014.

[15] S. Das, S. Ghosh, and A. Mazumdar, "Kinematics of Horseshoe Vortex in a Scour Hole around Two Eccentric Triangular Piers", *Int. J. Fluid Mech. Res.*, vol. 41, pp. 296-317, 2014.

[16] I. Roy, Study of the Performance and Operational Procedure of Acoustic Doppler Current Profiler in a Tidal River. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2012.

[17] D. Pal, Study of Energy Dissipation on inclined Rectangular contracted Chute. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2012.

[18] P. Dutta, Design and analysis of 0.127 Metre (5") Parshall flume and long-throat flume. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2013.

[19] M. Nayek, Design and analysis of 0.127 METRE (5") cut-throat flume and long-throat flume. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2013.

[20] S. Thakurta, Analysis of Clear Water Scour and Wake Vortex Flow Field around Eccentric Circular Piers arranged in Tandem. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2013.

[21] P. Ghosh, Horizontal Turbulent Circular Water Jet Entrainment in Quiescent Ambient Water. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2014.

[22] S. Chakraborty, Analysis of Clear Water Scour around Eccentric Triangular Piers Arranged in Tandem. *ME Thesis*. School of Water Resources Engineering: Jadavpur University, 2014.

[23] S. Das, R. Das, and A. Mazumdar, Vortex flow field past a cylinder under clear water scour regime, *Proc. International Conference on Applications of Fluid Engineering (CAFÉ-2012)*. G. L. Bajaj Inst. of Tech. & Management, Greater Noida, UP, 2012.

[24] S. Das, P.K. Roy, and A. Mazumdar, "A Plan for the Enhancement of Backwater for Irrigation for Sustainable Livelihood of Rural Communities At Magrahat Basin, South 24 Parganas, West Bengal", *REASON- A Tech. Mag.*, vol. XI, pp. 29-38, 2012.

[25] S. Das, R. Das, and A. Mazumdar, "Circulation characteristics of horseshoe vortex in scour region around circular piers", *Water Sci. Eng.*, vol. 6, pp. 59-77, 2013.

[26] S. Das, R. Midya, R. Das, and A. Mazumdar, "A Study of Wake Vortex in the Scour Region around a Circular Pier", *Int. J. Fluid Mech. Res.*, vol. 40, pp. 42-59, 2013.

[27] S. Das, R. Das, and A. Mazumdar, "Comparison of characteristics of horseshoe vortex at circular and square piers", *Res. J. Appl. Sci. Eng. Technol.*, vol. 5, pp. 4373-4387, 2013.

[28] S. Das, S. Thakurta, R. Das, and A. Mazumdar, "Turbulent Flow Field in Clear Water Equilibrium Scour Hole at Triangular Pier", *Proc. International Symposium on Sustainable Infrastructure Development (SID)*, IIT Bhubaneswar, Odisha, pp. 401-411, Feb., 2013.

[29] S. Das, B. Majumder, A. Chakraborty, B. Mandal, P.K. Roy, and A. Mazumdar, "Aquifer Characteristics of the Intake Wells on Damodar River near Raniganj, West Bengal, India", *Reason-A Tech. J.*, vol. XII, pp. 19-29, 2013.

[30] B. Mukherjee, S. Das, and A. Mazumdar, "Mathematical Analysis for the Loss of Future Storage Capacity at Maithon Reservoir, India", *ARPN J. Eng. Appl. Sci.*, vol. 8, pp. 841-845, 2013.

[31] S. Das, D. Roy, A. Mazumdar, S. Chowdhury, and M. Majumder, "Hydrological feasibility of a mini hydropower plant on Tiljuga River, Bihar, India", *Water Energ. Intl.*, vol. 69, pp. 30-37, 2012.

[32] M. Chatterjee, R. De, D. Roy, S. Das, and A. Mazumdar, "Hydrological Modeling Studies with HEC-HMS for Damodar Basin, India", *World Appl. Sci. J.*, vol. 31, pp. 2148-2154, 2014.

[33] B. Mukherjee, S. Das, and A. Mazumdar, "Comparison of Pipeline Hydraulic Analysis between EPANET and HAMMER Softwares", *Int. J. Adv. Sci. Tech.*, vol. 4, pp. 52-63, 2012.

[34] S. Das, B. Mukherjee, and A. Mazumdar, "Analysis of hammer head at increased flow demand in pipe networks: A case study", *Int. Rev. Mech. Eng.*, vol. 7, pp. 757-766, 2013.

[35] A. Mazumdar, H. Jaman, and S. Das, “Modification of Hunter's Curve in the Perspective of Water Conservation”, *J. Pipeline Syst. Eng. Pract.*, vol. 5, pp. 04013007, 2014.

[36] S. Das, P.K. Roy, and A. Mazumdar, “Analysis of pipe flow & head loss of a modeled network based on EPANET in a Water Treatment Plant at Raipur, West Bengal”, *J. Inst. Public Health Eng. India*, 2008-09(3), pp. 21-28, 2008.

[37] L.C. van Rijn, “Sediment Transport, Part I: bed load transport”, *J. Hydraul. Eng.*, vol. 110, pp. 1431-1456, 1984.