Chapter – 2

Literature review

2.1 General

A state-of-the-art review on various aspects of flow behavior around structures and consequent effect on channel morphology is presented. Over the past few decades, extensive experimental, analytical and numerical studies have been carried out to understand the flow characteristics around the structure to establish certain parametric relationship with erosion and deposition process in channel section. In order to bring out the gradual development in the study of flow characteristics around the slender structure and its influence on channel morphology, relevant literature has been reviewed chronologically under major categories as follows.

The states of art in this field are sub categorized as follow.

1. Experimental work related to scouring around hydraulic structure
2. Analytical and numerical approach to study fluid flow characteristics around structure
3. Energy loss in channel
4. Preventive measurement of scouring

2.2 Experimental work related to scouring around hydraulic structure

True understandings of flows are based on actual data which is still obscure. To get the better of this situation, studies have conducted in the laboratory using flumes. Experimentally a lot of assumptions have been made during steady state flow conditions and simple geometry of the flume. The understanding of three dimensional flood flows is important for natural and engineering point of view. The inclusion of sediments in the flowing water makes the situation very complex. This water-sediment mixture exhibits a three dimensional, unsteady behavior and is subjected to turbulence. A lot of semi-empirical work as well as numerical techniques have been exploited in understanding these multiphase flows in compound channel and still much is needed to get a full grip of the flow mechanism. Before the advent of computational fluid dynamics approaches, the direct field measurements and physical model studies of rivers were conducted. However field measurements are not so simple and little work had been done on it. Therefore major focus was on experimental studies. A number of hurdles were there in applying these experimental results to the actual flow problems. A summary of various experimental works are as follows.

Sellin (1964) conducted experiments in the laboratory for straight rectangular channels with straight floodplains. In straight channels the shearing stresses exists at the interface of main channel and floodplain although reduces the conveyance capacity of main channel still to a lesser extent. The reduction in conveyance must be considered in discharge of carrying capacity of the compound channel. The fast movement in main channel when interacts with slow moving floodplain flow begun the main channel flow retarded by floodplain flows and a transfer of momentum also happens among the two. This momentum transfer takes place through main channel to floodplain. It roots a reduction in the flow velocity in the main channel and an increment in flow velocity and in consequence the discharge carrying capacity of flanked floodplains. Altogether this is to keep the total discharge to a constant value. This momentum transfer from main channel to floodplains possesses till a certain depth of water in floodplain. However in the due course of time it gradually reduces to zero while that particular depth is reached on the floodplains.

Shen et al. (1966, 1969) conducted 21 experiments using a single cylinder diameter and sediment size by varying the hydraulic conditions (water depth and the depth averaged flow velocity) to include both clear water and live bed conditions. Experiment allowed scour to occur around a six-inch cylinder in a flume. They closed the experiment at some desired depth and fixed the entire flume bed with an adhesive solution. At that point re-established the flow and measured the velocity distributions with a small pitot tube and yarn streamers to establish direction. After experiments, they derived the empirical equation for scour depth as a function of time for a pile of diameter, D, in a flow with a depth-averaged velocity, V, and an upstream water depth, y_0. The complete absence of sediment size as a factor makes it difficult in any application of the model to satisfy conditions in his experiments. Generally, experiments examining scour time histories notices multiple time scales exists however this model has single time scale.

Breusers et al. (1977) summarized the important experiments on local scour around piers. The systematic experimental study of local scour around cylinders in cohesive soils is presented here. Remolded natural clays used in experiments and found that the equilibrium scour depth in cohesive soils is considerably less than that in non-cohesive soils and a small percent of clay (around 10% or more) dominates the properties of soil mixture. It proposed the equation to estimate the equilibrium scour depth in cohesive soil in terms of the flow Froude number, compaction, initial water content and cylinder diameter.

***Melville et al.** (1977)* studied the changing flow patterns at a cylindrical pier throughout the development of a local scour hole. *Laursen (1963)* investigated the relationship of clear water scour in a long contraction as a function of geometry, flow and sediment. Model is based on the assumption that the limit of clear water scour occurred when the boundary shear stress (the active attractive force) as a function of time was equal to the critical attractive force. He developed an equation for the equilibrium depth of scour for a pile or abutment.

***Dargahi B. (1990*)** conducted experiment of clear water scouring around a circular cylinder shows that the scour mechanism is coupled to the three-dimensional separation of the upstream boundary layer and the periodic vortex shedding in the wake of the cylinder. The first scour appears in the wake of the cylinder. The main scouring agent in the upstream region is a system of horseshoe vortices. The vortices have a periodical character that causes a triple-scour profile to develop in the upstream region. During scouring, the number and periods of horseshoe vortex shedding undergo no appreciable change. Despite the clear water stage, the transport phenomenon is periodical. Wake scouring is caused by the primary wake vortices and the accelerated side flow. The process is characterized by a strong periodical transport and the formation of ripples.

Gao et al. (1993) presented an equation that has been used in China for more than 20 years by highway and railway engineers. The equation was developed from Chinese data of local scour at bridge piers, including 212 live-bed data and 40 clear-water data. The equation has been tested using field data given by Froehlich (1989) and 184 filed data from U.S.S.R.

Ansari and Qadar (1994) developed envelop equations to more than 100 field measurements of pier scour depth, derived from 12 different sources and several countries including 40 measurements from India. They also presented a comparison of the field data they used with estimates of scour depth obtained by Neil (1973), Melville and Sutherland (1988).

Dey et al. (1995) derived quasi-analytical equations for the flow field (in the scour hole, adjacent to the pier above the flat bed and in the wake region) by satisfying the continuity equations and determining empirical coefficients (by curve fitting experimental data). They conducted clear water scour experiments using two sand diameters, three pier diameters, three approaching flow depths and six approach flow velocities. When equilibrium condition achieved, the flume was drained and the bed was stabilized using a synthetic resin. The authors compared their solutions and the measurements performed by *Melville (1975).* The equations showed good agreement with the measurements and maintain that the model may be useful for simulating the flow field under prototype conditions.

Landers et al. (1996) presented a detailed analysis of a subset of the local pier scour data, only one measurement being included for each bridge. Comparison of field data with trends derived from laboratory studies and those developed in New Zealand and concluded that the laboratory-based relations provide a reasonable description of the field data.

Totapally et al. (1999) examined the temporal variations of local scour under steady flow and using stepped hydrographs. It concluded that a logarithmic equation represent the variation of scour with time better than a power equation and questioned the existence of an equilibrium depth, maintaining that scour will continue with time though at a greatly reduced rate. They examined the use of superposition to calculate the scour depth under stepped hydrographs (i.e., time series developed from steady flow experiments are applied at each step of the hydrograph as if the step was a separate steady flow run). The results of the super positioning were comparable to experiments. For shorter duration steps, the superposition method tended to under predict the measured scour depth. It also found that scour holes to be geometrically similar at different times in the scour time history.

Graf et al. (2001) investigated the flow patterns in planes upstream and downstream of a cylinder and vertically in the scour hole using an Acoustic-Doppler Velocity-Profiler (ADVP). It found that the shear stress was reduced in the scour hole as compared to the approach flow but that the turbulent kinetic energy was very strong at the foot of the cylinder on the upstream side. The turbulent kinetic energy was also very strong in the wake behind the cylinder.

Sturm Terry (2006) integrated experimental results for clear-water abutment scour for different compound channel geometries by taking into account the flow redistribution that occurs between floodplain and main channel in the contracted section created by the bridge opening. In addition, sediment size, bridge backwater, abutment shape, approach velocity and depth were included in a proposed scour depth relationship. Both setback and bank line abutments were considered. Experimental evidence was presented for the characteristic non uniform lateral velocity distributions associated with compound channels in the bridge approach section as affected by backwater and for the entrainment of floodplain flow into the main channel between the approach and bridge opening cross sections. Scour depth patterns were shown as remnants of the floodplain flow acceleration and entrainment process. It was demonstrated that a common relationship for scour depth can be developed for both setback and bank line abutments provided that a consistent definition of scour depth is utilized. The experimental results were applied successfully to a field case of measured abutment scour but the need for additional high-quality, real-time field data is emphasized.

Bhuiyan. et al. (2007) advocated various structural measures for river restoration and habitat improvement schemes. The W-weir is one such structure that can be used in mobile bed alluvial rivers to diversify habitat and provide grade control. Laboratory studies have been carried out in a large-scale meandering channel with a mobile bed to investigate their effects on flow and sediment transport processes. A W-weir placed immediately downstream of a riffle section created a strongly three-dimensional flow pattern and high-turbulence zones. Two adjacent scour holes of different depths and substrate are formed under clear water and live bed conditions. The continuity of sediment transport along the channel was not interrupted by the structure and the upstream afflux is minimal. Overbank flow significantly influenced the action of the weir and the scour hole was shifted closer to the structure. In a relatively tight bend followed by a short crossover reach, the weir may affect bed load transport pathways in the downstream bend. Finally, the study provides insights to guide their design for restoration projects.

Lin and Dey (2008) presented an experimental investigation on the characteristics of a horseshoe vortex system near the juncture of a square cylinder and a horizontal base plate, using particle image velocimetry and flow visualization technique. Experiments were conducted for Reynolds numbers based on the free stream velocity and the width of square cylinder ranging from $2.0 \text{ X } 10^2$ to $6.0 \text{ X } 10^3$. The study mainly focused on the characteristics of steady horseshoe vortex system. The non-dimensional characteristics, including the horizontal and vertical distances from the primary vortex core to frontal face of the vertical square cylinder and bottom boundary of the base plate, respectively. The height of stagnation point at frontal face of the square cylinder and the down-flow discharge as well as circulation of the primary vortex, all increase with increase of the ratio of the height of square cylinder to undisturbed boundary layer thickness. However, they all decrease with the increase of the aspect ratio i.e., the height-to-width ratio of the square cylinder. The study provides essential properties of a steady horseshoe vortex system and gives an insight for related engineering applications. It can be served as a basis for more complicated horseshoe vortex systems occurring at high Reynolds numbers.

Deng and Cai (2010) presented a comprehensive review of the up-to-date work on scour at bridge piers and abutments. First, a general introduction of bridge scour including the current situation of bridge scour problems and different types of bridge scour is given. Then, different approaches developed for predicting bridge scour are reviewed. Numerical and laboratory models established for bridge scour studies are also presented. Moreover, laboratory experiments and field tests conducted for bridge scour are reviewed. Different techniques and instruments developed for bridge scour monitoring are also presented with their advantages, disadvantages and relative cost summarized in a table. Finally, various mitigation countermeasures developed for bridge scour are discussed.

Beheshti and Ataie-Ashtiani (2010) investigated experimentally three-dimensional turbulent flow field around a complex bridge pier placed on a rough fixed bed. The complex pier foundation consists of a column, a pile cap and a 2 X 4 pile group. All of the elements are exposed to the approaching flow. An Acoustic-Doppler Velocimeter was used to measure instantaneously the three components of the velocities at different horizontal and vertical planes. Profiles and contours of time-averaged velocity components, turbulent intensity components, turbulent kinetic energy and Reynolds stresses, as well as velocity vectors were presented and discussed at different vertical and horizontal planes. The approaching boundary layer at the upstream of the pile cap separated in two vertical directions and induced an upward flow toward the column and a contracted downward flow below the pile cap and toward the piles. The contracted upward flow on the pile cap interacts with down flow in the front of the column and deflect towards the side of the pier.

Simarro. et al. (2011) assessed data from six very long experiments on local scour at single cylindrical piers, some of the existing equilibrium criteria found in the literature. It is found that common criteria, which consider scour depth increments in 24 hours or the observation of horizontal plateaux in records of scour depth time evolution, can incur important errors on the equilibrium scour depth. Using some of the expressions for time evolution found in the literature to fit the experimental data and infer equilibrium scour depth through extrapolation to infinite time, it is found that the equilibrium scour depth cannot be specified, generally for experiments shorter than one to two weeks.

Qi et at. (2012) conducted series of experiments in a large flow-structure-soil interaction flume to analyze the scour development and pore-water pressure response around a monopile foundation under the action of combined waves and currents. They measured simultaneously, the scour depth and pore pressure response around the pile in the experiments. The experimental results indicate that the maximum equilibrium scour depth due to waves plus currents was greater than a linear sum of those caused by waves and currents respectively. This nonlinearity effect is particularly obvious when the sand-bed condition under currents or waves alone is in clear-water regime. The maximum equilibrium scour depth normalized with pile diameter is closely dependent on the Froude number with increasing the wave-induced water particle velocity meanwhile the current velocity keeping constant. The wave-induced pore pressure gradient around the monopile under the wave through weakens the buoyant unit weight of the surrounding sand and induces the sand-bed more susceptible to scouring.

Keshavarzi et at. (2014) investigated the coherent turbulent flow around a single circular bridge pier and its effects on the bed scouring pattern. In his paper, three-dimensional octant analysis was used to improve understanding of the role of bursting events in the process of particle entrainment. In this study, the three-dimensional velocity of flow was measured at 102 points near the bed of an open channel using an Acoustic Doppler Velocity meter (Micro-ADV). The pattern of bed scouring was measured during the experiment. The velocity data were analysed using Markov process to investigate the sequential occurrence of bursting events and to determine the transition probability of the bursting events. The results showed that external sweep and internal ejection events were an effective mechanism for sediment entrainment around a single circular bridge pier. The results are useful in understanding scour patterns around bridge piers.

Pu and Lim (2014) studied for the abutment bed scour to reach its equilibrium state, a long flow time is needed. Hence, implement of usual strategy of simulating such scouring event using the 3D numerical model is very time consuming and less practical. In order to develop an applicable model to consider temporally long abutment scouring process. This study modifies the common approach of 2D shallow water equations (SWEs) model to account for the sediment transport and turbulence and provides a realistic approach to simulate the long scouring process to reach the full scour equilibrium. Due to the high demand of the 2D SWEs numerical scheme performance to simulate the abutment bed scouring, a recently proposed surface gradient upwind method (SGUM) was also used to improve the simulation of the numerical source terms. The abutment scour experiments of this study were conducted using the facility of Hydraulics Laboratory at Nanyang Technological University, Singapore to compare with the presented 2D SGUM–SWEs model. Fifteen experiments were conducted with their scouring flow durations vary from 46 to 546 h. The comparison shows that the 2D SGUM–SWEs model gives good representation to the experimental results with the practical advantage.

2.3 Analytical and Numerical Approach to study fluid flow characteristics around structure

There are three methods, i.e., physical modeling, field observation and numerical simulation, in local scour research. Numerous equations have been proposed for estimation of the depth of local scour at bridge piers. Most of them are determined from laboratory studies and verified from few field observations. Laboratory research has been the primary tools in defining the relations among variables affecting the depth of pier scours in recent years. Results from these laboratory experiments must be verified by ongoing field measurements of scour. Recent development in computational fluid dynamics enables the hydraulic engineers to study the local scour around the bridge pier based on hydrodynamics.

This might be due to dimensional problems between the physical model and actual river. A number of text books and literature survey include these types of studies (*Chow, 1959*).

To investigate and predict the fluid flow behavior with the help of computers, different numerical techniques are used. Among them are finite difference method, finite volume method and finite element method. However major focus, now a days is on finite element method. To date a number of researchers have made use of these numerical techniques to reproduce the actual physical phenomenon observed experimentally and in the fields. These techniques have also been used for predicting and enhancing the understanding of those flow behaviors which have not been explored in detail yet. Different numerical models have been developed by various researchers to simulate open channels flows in meandering rivers. A number of authors have developed their own models.

Wang et al. (1999) examined the importance of including various flow effects on sediment transport. Numerical model is used to simulate the three dimensional flow conditions around a pile and in a scour hole. Empirical functions were used to alter the shear stress in an empirical sediment transport model to account for the effects of the main flow, down flow, vortices and turbulence intensity on sediment transport within the scour hole. Simulation of the scour hole developing around the bridge pier by using CCHE3D and examined the importance of including various flow effects on sediment transport. They used a numerical model to simulate the three dimensional flow conditions around a pile and in a scour hole. Empirical functions were used to alter the shear stress in an empirical sediment transport model to account for the effects of the main flow, down flow, vortices and turbulence intensity on sediment transport within the scour hole. After calibrating their model with experimental data, claimed their model produced reasonable results.

Chang et al. (1999) used a large-eddy simulation (LES) model to solve the flow equations around a bridge pier with a fixed bed and no scour. Then, adjusted the flatbed shear stress to account for the bed deformation without re-computing the flow equations. Applied this adjusted shear stress to *Van Rijn (1984)* bed-load formula to calculate the sediment transport and tested their results against the time series data of *Ettema (1980).* It found that results in good agreement with the data, supporting the method of applying flatbed sediment transport formula with an adjusted shear stress value to model the scour hole development with time.

Tseng et al. (2000) conducted the numerical simulation with square and circular piers by the LES. It found that the down flow is made at the front face of pier and this affects the creation of horseshoe vortex. They also compared turbulent structures; lift coefficient and drag coefficient with the experimental results. Good agreements were obtained.

Sumer et al. (2002) used a finite volume hydrodynamic model with k-ε turbulence modeling to simulate the 3-D flow around a pile. With this model, able to capture all the main features of the scour process (i.e., the horseshoe vortex, sand slides or avalanching on the sides of the scour hole, bed ripples, the shape of the scour hole) and their equilibrium scour depth agreed fairly well with measurements. Equilibrium was reached in approximately 2.5 hours, but computation time for the model was 2.5 months on an Alpha 21264 workstation. This makes model impractical for prototype size calculations where the time to equilibrium is approximately several weeks.

Pappenberger et al. (2005) conducted uncertainty analysis of the unsteady flow component (UNET) of the one-dimensional model HEC-RAS within the generalised likelihood uncertainty estimation (GLUE). For this, the model performance of runs with different sets of Manning roughness coefficients, chosen from a range between 0.001 and 0.9, are compared to inundation data and an outflow hydrograph. The influence of variation in the weighting coefficient of the numerical scheme is also investigated. The results of varying reach scale roughness shows that many parameter sets can perform equally well (problem of equifinality) even with extreme values. However, this depends on the model region and boundary conditions. The necessity to distinguish between effective parameters and real physical parameters is emphasized. The study demonstrates that this analysis can be used to produce dynamic probability maps of flooding during an event and can be linked to a stopping criterion for GLUE.

Dargahi (2006) investigated the flow field over a spillway and to simulate the flow by means of a three-dimensional numerical model. Depending on the wall curvature, the boundary layer parameters decreased or increased with increasing distance along the spillway. The growth of the boundary layer along the spillway is better described as a function of Reynolds number than the normalized stream wise length. A simplified form of the 3D momentum equation can be used to obtain a rough estimate of the skin friction. The velocity profile in the boundary layer along the spillway is described by a velocity–defect relationship. Numerical models provide a cost-effective means of simulating spillway flows. In this study, the water surface profiles and the discharge coefficients for a laboratory spillway were predicted within an accuracy range of 1.5–2.9%. The simulations were sensitive to the choice of the wall function, grid spacing and Reynolds number. A non-equilibrium wall function with grid spacing equal to the distance of 30 wall units gave good results.

Gibson et al. (2006) added sediment transport capability to the Hydrologic Engineering Center's River Analysis System (HEC-RAS). HEC-RAS can be used to perform sediment routing and mobile bed computations. Hydraulic computations are "explicitly coupled" with transport, erosion, deposition, bed mixing and cross section change computations using the set of initial value-boundary value equations used in HEC-6. Now the HEC-RAS has additional function to perform the analysis. RAS utilizes quasi-steady hydrodynamics and one of several transport equations to solve the sediment continuity equation. Sediment surpluses and deficits are modified with temporal and physical constraints and translated into bed aggradation and degradation.

Knight et al. *(2007)* used Shiono and Knight method (SKM) approach to calculating the lateral distributions of depth-averaged velocity and boundary shear stress for flows in straight prismatic channels. It accounts for bed shear, lateral shear and secondary flow effects via 3 coefficients. The values of the transverse velocities, V, have been shown to be consistent with observation. A wide range of boundary shear stress data for trapezoidal channels from different sources has been used to validate the model. The accuracy of the predictions is good, despite the simplicity of the model, although some calibration problems remain. The SKM thus offers an alternative methodology to the more traditional computational fluid dynamics (CFD) approach, giving velocities and boundary shear stress for practical problems, but at much less computational effort than CFD.

Kirkil et al. (2008) investigated Large-eddy simulation (LES) and laboratory-flume visualizations to coherent structures in the flow field around a circular cylinder located in a scour hole. The bathymetry corresponds to equilibrium scour conditions and is fixed in LES.

The flow parameters in the simulation correspond to the experimental conditions in which the approach flow is fully turbulent. Detailed consideration is given to the interaction of the horseshoe vortex (HV) system within the scour hole with the detached shear layers formed from the cylinder, and the near bed turbulence. It is found that the overall structure of the HV system varies considerably in space and time, though a large, relatively stable, primary necklace vortex is present at practically all times inside the scour hole. The simulation captures the presence of bimodal chaotic oscillations inside the HV system, as well as the sharp increase in the resolved turbulent kinetic energy levels and pressure fluctuations reported in prior experimental investigations. High levels of the mean bed shear stress are observed beneath the primary necklace vortex, especially over the region where the bimodal oscillations are strong, as well as beneath the small junction vortex at the base of the cylinder. It is also found that the detachment and advection of patches of vorticity from the downstream part of the legs of the necklace vortices can induce large instantaneous bed shear stress values. When the critical bed shear stress value for sediment entrainment on a flat surface is adjusted for bed slope effects, the LES simulation correctly predicts that the distribution of the mean bed shear stress is consistent with equilibrium scour conditions.

Zeng et al. (2010) focused on two test cases corresponding to laboratory experiments performed in an S-shaped channel in which the suspended sediment load is comparable to the bed load. The flow, sediment transport and bathymetry at equilibrium conditions in loose-bed open channels are predicted using a fully three-dimensional (3D) Reynolds-Averaged Navier-Stokes model that was validated for cases in which the bed-load transport is dominant. A modified version of the original model that accounts for gravitational force effects due to the total sediment load is proposed. It is shown that the way bed-slope effects are accounted for plays a major role in improving the predictive capabilities of the model for a case in which the equilibrium bathymetry is characterized by relatively large values and sharp variations of the transverse slope. The model is then used to qualitatively and quantitatively analyze the distributions of several flow variables that are difficult to measure in the laboratory. They included the distributions of the bed-shear stress and of a Chezy-type friction coefficient assumed to be constant by most lower-order models.

Fang et al. (2010) used a three-dimensional model of river flow and sediment transport to examine the effect of the vertical resolution and the choice a non-equilibrium adaptation length L_s in predicting flow and sediment transport around groins in China's Yongding River. The results show that a fine vertical grid and non-equilibrium sediment transport model provide good predictions, especially on the river bed profile with an obvious main channel and flood plain.

Jeong and Girimaji (2010) proposed closure model is validated in the flow past a square cylinder. The Partially Averaged Navier–Stokes (PANS) approach is a bridging closure model intended for any level of resolution between the Reynolds Averaged Navier–Stokes (RANS) method and direct numerical simulations. The desired ratio of the modeled-to-resolved scales in the PANS closure is achieved by appropriately specifying two bridging parameters. PANS calculations of different bridging parameter values are performed and the results are compared with experimental data and large-eddy simulations. The Strouhal number (St), mean/root-mean-square (RMS), drag coefficient C_D, RMS lift coefficient (C_L), mean velocity profiles and various turbulent stresses are investigated. The results gradually improve from the RANS level of accuracy to a close agreement with the experimental results with decreasing value of the bridging parameter fk. Overall, the results indicate that the PANS method clearly satisfies the basic tenets of a bridging model: (i) provides a meaningful turbulence closure at any modeled-to-resolved scale ratio and (ii) yields improved accuracy with increasing resolution.

Timbadiya et al. (2011**)** studied the effect of Channel roughness parameter in development of hydraulic model for flood forecasting and flood inundation mapping. The requirement of multiple channel roughness coefficient Manning's 'n' values along the river created through simulation of floods, using HEC-RAS for years 1998 and 2003, supported with the photographs of river reaches. The calibrated model, in terms of channel roughness has been used to simulate the flood for year 2006 in the river. The performance of the calibrated HEC-RAS based model has been accessed by capturing the flood peaks of observed and simulated floods; and computation of root mean squared error (RMSE) for the intermediate gauging stations on the lower Tapi River. It is found that different Manning's roughness coefficients are required for upper and lower reaches of the lower Tapi River for simulation of flood. Close agreement have been arrived between simulated and observed stages for Kak-rapar gauging station. However, the performance is reasonably good for Mandavi and Ghala gauging stations.

Kazemi et al. (2011) conducted a study at two reach of Taleghan and Jajroud rivers to determine this ratio and stream flow was simulated by HEC-RAS software in both reaches. Bed load was calculated by Meyer-Peter-Muller, Casey, Schoklitch and VanRijn equations, Einstein, Chang-Simons-Richardsin, Begnold and Toffalati equations were used to estimate suspended load. Results showed that in both rivers, Schoklitch equation provides the best estimation for bed load. Also for suspended load, Einstein and Begnold equations provide the best estimation for Jajroud and Taleghan rivers respectively. The bed load to suspended load ratio was estimated 376% and 14% in Jajroud and Taleghan rivers respectively.

Foti and Sabia (2011) reported a case history of assessment and monitoring with dynamic tests for a bridge affected by scouring and subjected to retrofitting. Foundation scour is a major issue affecting the structural safety of existing bridges, hence its monitoring is of paramount importance. Two different approaches measuring traffic-induced vibrations are applied as potential tools for monitoring foundation scour. The modal identification of bridge spans is one approach and the observation of the dynamic response of pier foundations is the other approach. A finite-element model is used to choose the parameters for scour monitoring. Both approaches are applied to the experimental data collected about the structure prior to and after retrofitting to show their effectiveness.

Zhi-wen (2012) studied in order to predict the local scour hole and its evaluation around a cylindrical bridge pier, the computational fluid dynamics (CFD) and theories of sediment movement and transport were employed to carry out numerical simulations. In the numerical method, the time-averaged Reynolds Navier-Stokes equations and the standard k-ε model were first used to simulate the three-dimensional flow field around a bridge pier fixed on river bed. The transient shear stress on river bed was treated as a crucial hydrodynamic mechanism when handling sediment incipience and transport. Then river-bed volumetric sediment transport was calculated, followed by the modification of the river bed altitude and configuration. Boundary adaptive mesh technique was employed to modify the grid system with changed river-bed boundary. The evolution of local scour around a cylindrical bridge pier was presented. The numerical results represent the flow pattern and mechanism during the pier scouring, with a good prediction of the maximum scour hole depth compared with test results.

Mousavi and Daneshfaraz (2013) studied on HEC-RAS software and found that HES-RAS software uses CSU and Froehlich (1991) equations to calculate local scour. In this study, software output and manual calculation output of CSU and Froehlich equations were compared. Results of empirical equations and HEC-RAS in the scattering length of Haraz River were compared with each other to create equal hydrological and hydraulic conditions. Reviewing the Froude number, its measurement and the effective coefficients of common empirical equations and software has significant effect on changes of these parameters in the results. The study also indicate that equations used in HEC-RAS will have acceptable results if their coefficients are examined with sufficient engineering, accurate perspective and controlling use or non-use of coefficients in ranges closer to the defined boundary.

2.4 Energy loss in channel

A channel transition is defined as a change in the direction of channel, the slope of bed level or cross-sectional area. Channel expansions are worth investigating because they disturb the approaching flow and more importantly because they can cause significant energy losses. On one hand, the disturbances emerge locally in the expansion but persist much further downstream. On the other hand, the energy losses in expansions cannot be recovered. The issue of energy losses in expansion must be addressed if conservation of flow energy is required, as is the case under many circumstances. The issue of flow energy losses in channel is relevant and important in many other hydraulics engineering applications.

Open-channel flows are classified as supercritical flow, critical flow and subcritical flow depending on the Froude number. Most of the time, it is subcritical flows that are generally observed in open channels, including channel expansions and contraction. Although the physical process of flow separation has attracted extensive research attention with impressive applications in many different fields, no satisfactory theory has been developed to determine the energy losses for a given channel expansion. The energy loss coefficient is almost always given assumed values, which are very likely to be subject to errors. There is a difficulty in using the energy principle because of an unknown amount of energy loss.

IMolinas and Ted fVang (1985) developed a computer model based on both the energy and momentum equations. This generalized model can be used for the computation of water surface profiles through hydraulic jumps. It also allows computation of water surface profiles regardless of whether the bed slope is steep, mild, horizontal and adverse or a combination of these. The control section can be a lake, weir, gate or a natural river section. The Manning, Chezy or Darcy-Weisbach equations can be used for head loss computation. A detailed description of methods used and a step-by-step computation procedure is given. Examples are used to demonstrate the applications of this generalized model for water surface profile computations.

Patra and Khatua (2005) suggested values for Manning's *n* are found tabulated in Chow (1959), Henderson (1966) and Streeter (1971). Roughness characteristics of natural channels are given by Barnes (1967). During uniform flow in open channels the resistance to the flow is dependent on a number of flow and channel parameters. The usual practice in one dimensional analysis is to select a value of *n* depending on the channel surface roughness and take it as uniform for the entire surface for all depths of flow. The influences of all the parameters are assumed to be lumped into a single value of *n*. Patra (1999), Patra and Kar (2000) and Pang (1998) have shown that Manning’s coefficient *n* not only denotes the roughness characteristics of a channel but also the energy loss in the flow. The larger the value of *n*, the higher is the loss of energy within the flow. Although much research has been done on Manning's *n*, for straight channels, very little has been done concerning the roughness values for simple meandering channels and also for meandering channels with floodplains. An investigation concerning to the loss of energy of flows with depths ranging from in bank to the over bank flow, spreading water to floodplains for meandering and straight compound channels are presented. The loss of energy in terms of Manning's *n*, Chezy's *C* and Darcy-Weisbatch coefficient *f* are evaluated.

Xun et al. (2005) investigated experiment in a low speed annular wind tunnel. The energy loss evolution from upstream to downstream in the blade cascade channel with aft-loaded profiles was measured in detail. The results of the present study showed that energy loss was generated mainly in places near the leading and the trailing edges. Therefore, measurements were taken to improve the cascade performance by choosing the appropriate leading edge diameter, to provide a good match between the affecting length and the magnitude of adverse pressure gradient on suction surface and to improve the static pressure distribution along the span height.

Valiani and Caleffi (2008) analytically explained on the depth–specific energy relationship and the depth–total force relationship in open channel flows of wide rectangular cross-section. The non-dimensional expressions of the specific energy and of the total force, as functions of the non-dimensional water depth are considered. The inversion of such functions consists of finding the roots of third degree algebraic equations, simple analytical solutions are obtained. More specifically, for a given specific discharge and for each meaningful value of the specific energy, a subcritical and a supercritical depth are found analytically. Similarly, for a given specific discharge and for each meaningful value of the total force, a subcritical and a supercritical depth are found analytically. For both functions, it is also shown that the third root corresponds to a negative depth which can be discarded on the basis of physics.

Valiani and Caleffi (2009) presented analytical results concerning open channel flows, assuming that the cross-section is defined by a power law relationship between the channel width and the channel depth. Explicit equations to compute the normal flow depth are derived by considering the liquid discharge, the channel roughness height and the cross-section geometry (based on knowledge of the power law exponent, the reference width and the reference depth) as known quantities. Such equations are deduced by writing the physical quantities as a power expansion in the power law exponent and expressing the wetted perimeter using a Gauss hyper geometric function. With the designed procedure, accurate estimations of the integrals required to invert the uniform flow formula are obtained, at least for cross-sections characterized by aspect ratios of technical interest. Two relationships are proposed between the normal depth and the flow discharge. The first relationship is shown to work well for any discharge, provided that the width to depth ratio is sufficiently large. If this is not the case, the second procedure must be used for non-dimensional discharge larger than a given threshold, while the former procedure remains valid under the threshold.

Tokyay and Sakarya (2011) determined energy losses occur when there is a transition in open channel flow. Even though local losses in subcritical open channel flow due to changes in channel width have been studied, till date no studies have been reported for losses due to changes in bed elevations. Steps are commonly used in engineering applications to stabilize the flow in open channels. Hence, it is important to estimate local losses for design purposes. The aim of the study was to formulate the local energy losses at positive and negative steps in subcritical open channel flows. Flow rates and water depths before and after the steps were measured for varying step heights of abrupt and 45^{o} inclined steps. Empirical equations relating the local losses to the Froude number on the step and the relative step heights are proposed for positive and negative steps. In addition, practical values of local loss coefficients are determined.

Vatankhah & Valiani (2011) explained analytically specific energy–depth relationship in open channels with parabolic cross-sections. Two non-dimensional expressions of the specific energy are considered, depending on the prescribed quantity (specific energy or alternate depth). The inversion of such functions consists of finding the roots of cubic and quartic equations. By solving a quartic equation for a given discharge and for each value of the specific energy, a subcritical depth and a supercritical depth are found analytically. In this case, two acceptable roots are recognized and two other roots are discarded on the basis of their physical meaning. Moreover, by solving a cubic equation for a given discharge and for each value of the depth, the other corresponding alternate depth is found analytically. Then, one acceptable root is recognized and two other complex conjugate roots are discarded. Finally, different examples are presented to show the efficiency of the proposed solutions. Such analytical solutions can be easily used in natural rivers and parabolic channels.

2.5 Preventive measurement of scouring

The purpose of this section of the literature review is to briefly focus on the various methods available for preventing local scour at a bridge pier. Countermeasures as measures incorporated into a highway-stream crossing system to monitor, control, inhibit, change, delay or minimise stream instability and bridge scour problems. They further stated that an action plan for monitoring structures during or after flood events can also be considered a countermeasure. Mitigation measures for local scour at bridge piers can be grouped into *armouring techniques* and *flow alteration devices.*

Armouring techniques are relevant where piers are protected to withstand shear stresses during high flow events while the flow altering device aims to disrupt the flow field around the pier and thereby decrease the erosive strength of the down-flow and horseshoe vortex systems by way of breaking up vortices and reducing the velocity in the vicinity of the piers. Armoring techniques for piers and abutments include riprap, precast concrete units, grout-filled bags, foundation extensions, concrete aprons and gabions. Armoring devices protect the river bed within the vicinity of the pier against erosive forces. When it is installed to prevent local scour around a pier, riprap prevents the down-flow and horseshoe vortex systems created by the presence of the pier from removing sediment from the pier face. The use of riprap to deal with pier scour problems is very common in civil engineering practice (Lauchlan 1999). Flow altering devices at piers include the use of sheet piles and sacrificial piles placed upstream of the pier or circular shields or collars constructed around the piers. Basically two types of flow altering devices identified. The first category is used to break-up vortices and reduce the high flow velocities, particularly upstream of a pier. Sacrificial piles, such as sill, sheet or cylindrical piles are common examples of the first category. The second category realigns the flow to prevent local and contraction scour together with bank widening and lateral migration. The common examples of the second category of flow altering devices include vanes and guide banks.

Ettema (1980) conducted a series of experiments to ascertain the possibility of using a thin collar to mitigate against local scour at a circular bridge pier. Collars were installed on a circular pier at various elevations on, above and below the channel bed. A 0.4 mm thick, circular, brass collar of width two times the pier diameter was installed on the circular pier at four different locations, viz. yc/D = 0.5, 0, -0.5 and -0.1. The minus sign denotes that the collar was positioned below the channel bed. It was observed that, when a collar of width twice the size of the pier diameter was installed at an elevation of half the diameter (yc/D = 0.5) above the channel bed, the collar was not effective at reducing the scour depth. However, the effectiveness of a collar at reducing scour became noticeable when the collar was installed at the channel bed. No scour developed below the collar when the collar was installed at yc/D = -0.1. He compared the result with the results obtained by Tanaka and Yano (1967) and Thomas (1967). The general conclusion was that the influence of the width of the collar on scour increased as the elevation of the collar is decreased.

Dargahi (1990) carried out research on the mechanisms of local scour and how a collar may influence the horseshoe vortex system and ultimately reduce the amount of scour. The experiments were conducted using a uniformly-graded fine sand and a circular pier of diameter 0.15 m for each test. In order to study the effect of collar shape on performance, two separate collar shapes were tested: One shape was a thin circular collar of diameter 0.28 m (with W/D = 1.86) and the other was a collar with a Joukowski profile. It has a rounded leading edge and a trailing edge that ends in a cusp. A cusp as used here is a point at which two branches of a curve meet such that the tangents of each branch are equal. The Joukowski collar was attached to the circular pier such that its blunt nose faced upstream. The collar was positioned at elevations yc/yo = 0.25, 0.05, -0.015, and -0.05 relative to the initial channel bed. The total test duration for each experiment was 12 hours. At the end of the test, the scour profiles were measured along the line of symmetry for each collar position.

It was observed that the collar was not effective at hindering the horseshoe vortex formation. It was reported that, irrespective of the collar position and shape, the scour mechanism was similar to the case of a circular pier unprotected with a collar. The maximum reduction in scour depth as a result of the collar occurred at a collar position of yc/yo = -0.015 and yc/yo = -0.015, it was found that the maximum reduction of scour depth was 50% and 75% at the upstream and downstream region of the pier, respectively. The collar position yc/yo = 0.25 did not significantly influence the amount of scour. Similar results were obtained for the two collar shapes tested. It was also reported that, when the ratio of the collar thickness to the pier diameter becomes large, an increase in the effective diameter of the pier resulted, which subsequently caused an increase in the scour depth. However, cautioned that further research is needed before a practical application of a collar is recommended.

Chiew (1992) experimentally studied the effect of a collar, a slot and a combination of the two in reducing the local scour in the vicinity of a pier. A slot is a hole through the pier to allow the passage of flowing water. The objective of the study was to review existing mitigation approaches and to propose alternative or new devices for mitigating scour in the vicinity of bridge piers. The experiment was conducted using a 32 mm diameter pier and a median particle size of 0.33 mm. The flow intensity, (i.e., u*/u*c) was maintained at 0.9 and the depth of flow was 180 mm. The collar consisted of 1 mm thick stainless steel plate. Experiments with 2D and 3D wide collars were tested alone and in combination with a pier slot while the positions of the collars were systematically varied. Equilibrium scour depth was defined as the depth attained when there was less than 1 mm change in scour depth in 8 hours. Using this criterion, the tests were run for approximately 72 hrs. The collar alone was found to reduce the scour depth by as much as 20% while no scour occurred when a D/4 slot was used in conjunction with a collar. Similar results were obtained for the two collar diameters tested. It concluded that a combination of collar and slot can be a suitable substitute for the use of riprap as a countermeasure for local scour at bridge piers. These results compared favourably with the results of Ettema (1980) and Tanaka and Yano (1967).

Vittal et al. (1994) studied and compared the scour reduction efficacies of a circular collar on a pier group that was made up of three individual smaller piers. Similar experiment was also performed on a single solid pier. In the study, a collar fitted to a group of three cylindrical piers angularly spaced at 120º was studied as a scour reduction device. The particular arrangement of the cylinders is such that any one of them can just pass through the gap between the others two. The sediments used in their experiment were cohesion less. In the experiment, the diameter of the solid pier and that of the circumscribing circle of the pier group was 112.5 mm, while the width of the collar was 2.0D. The collar was positioned at a height of 15 mm above the channel bed. The duration of each test was six hours. The scour due to the pier group was compared with that of a solid circular pier. Regarding scour reduction, the full pier group alone without the collar was found to be more effective than a solid cylinder having a full slot of width equal to half the cylinder diameter and as effective as a solid cylinder fitted with a collar of width 3.5 times its diameter. They observed that a collar of 2.0D on a full pier group is equivalent to a collar of more than 6.0D on solid pier. He concluded that a collar fitted to a pier group is much more effective than the one fitted on a solid pier as far as scour mitigation is concerned.

Fotherby and Jones (1993) studied how effective collars are at reducing scour. The authors recognised the potential usage of both a collar and a footing at reducing scour. Footings are seldom considered as countermeasures but provide the same type of protection as a collar by interrupting down flow at the face of the pier. Data from earlier studies by Chiew (1992), Schneibe (1951), Tanaka and Yano (1967) and Thomas (1967) were combined and the possible relationships between them were identified. The relationships established were in agreement with the work of other researchers. According to authors, the parameters influencing the scour mechanism for footings and collars are their height above the channel bed, width and thickness. It was concluded that the larger the collar the more its effectiveness at reducing scour and that collar effectiveness reduces when the collar is placed at a greater elevation above the channel bed. Also pointed out that a collar has been recognised as a conceptual scour countermeasure technique but has not been used in practice.

Kumar et al. (1999) worked on the use of collars around a cylindrical pier to reduce the scour depth. For the experiment on collar efficacy, five different collar sizes of thickness 3 mm were used (i.e., W = 1.5D, 2.0D, 2.5D, 3.0D and 4.0D). It was observed that the width of the collars as well as the relative position of the collars to the bed affected both the depth and location of the maximum scour location. It was also observed that small collars resulted in large scour holes at the upstream pier face, while scour depth was greatest in the wake regions for the larger collars. They concluded that a large collar placed at a low elevation relative to the bed was most effective at reducing scour. They also worked on the possible combination of collars and slot and found the combination to be very effective at reducing scour. They cautioned, however, that a slot is practically ineffective if the approach flow has a high angle of attack with respect to the slot.

Singh et al. (2001) worked on a collar as a scour protection device around a circular pier. The authors believed that the growth of a vortex can be arrested by retaining the vortex on a rigid surface such as a collar plate. It was observed that the efficacy of a collar in preventing scour is a function of its width and its vertical location with respect to the channel bed. It was observed that, as the size of a collar plate increases, the scour decreases. Collar plates of sizes W = 1.5D, 2.0D and 2.5D placed on the channel bed resulted in a reduction of scour by 50%, 68% and 100%, respectively, of an unprotected pier. Collar plates of size W = 2.0D when placed at 0.1D below the bed gave a maximum reduction in scour depth of 91%. However, when the same collar plate was located at 0.5D above the bed, a 25% reduction in scour depth resulted.

Zarrati et al. (2004) worked on the application of a collar to control the scouring around rectangular bridge piers having a rounded nose. It was found that collar effectiveness improves as the collar becomes wider and as the level at which it is positioned on the pier becomes lower. They also found that the effectiveness of a collar is reduced as the pier skewness with respect to the flow is increased. On the time of development of the maximum scour depth, Mashahir and Zarrati (2002) and Zarrati et al. (2004) concluded that the time to reach an equilibrium condition is different depending on whether or not the pier is protected with a collar. According to them, it took 20 hrs to reach an equilibrium condition when the pier was unprotected with a collar as compared to 50 hours that was required to reach an equilibrium condition for the pier protected with a collar.

Mashahir et al. (2004) studied the temporal development of scour depth at a bridge pier. In their experiment, a collar size of three times the pier diameter was used. The sediment material had a median size of 0.95 mm and a geometric standard deviation which was less than 1.2 (i.e., very uniform). While the diameter of the circular pier used in the study was 400 mm, the ratio of the shear velocity to the critical shear velocity was calculated to be 0.92 based on the Shields criterion. Using a definition of time to equilibrium scour depth for which the change in scour depth was less than 2% of the pier diameter in eight hours, the duration of each experiment was limited to 44 hours. As concluded in the study by Mashahir et al. (2004), placing the collar below the channel bed level did not lead to an appreciable increase in the efficacy of the collar. This was so because the depth of the sand sediments above the collar will itself become part of the scour hole as this is swept away very fast by the erosive action of the flow. Comparison of the results for rectangular piers aligned with the flow and the previous experiments on circular piers by showed that a collar of W/D = 3 is more effective at reducing the depth of the scour hole for rectangular piers than for circular piers. For a possible application of two collars at the same time, it was reported that installation of a second collar at an elevation above the channel bed increases the effectiveness of collars. Also compared their results with that of Ettema (1980) and concluded that a collar placed on the channel bed and with a width three times the pier diameter or width is more effective than a collar with a size of two times the pier diameter.

Kayaturk et al. (2004) studied the effect of a collar on the temporal development of scour around bridge abutments. The experiments were conducted in a 1.5 m wide flume having a bottom slope of 0.0001. With a flow intensity of 0.90, all of the tests were run under clear-water scour conditions. Operating at a flow depth of 100 mm and a discharge of 0.05 m^3/s, each experiment was limited to duration of six hours. The soil material had a d50 = 1.48 mm and geometric standard deviation, σg = 1.28. In this study, the time development of the local scour around the abutment fitted with and without collar plates was studied. The effects of various sizes of collars fitted at different elevations on the temporal development of scour depth at the abutment were also studied. Four different collar widths, W = 0.025 m, 0.050 m, 0.075 m and 0.10 m were tested. Depth of the scour hole reduced because of the collar irrespective of the collar size and vertical position. The experimental results signified that not only the presence of a collar reduce the scour depth, the rate of temporal development of the scour hole was also reduced.

Zarrati et al. (2006) studied the use of independent and continuous pier collars in combination with riprap for reducing local scour around bridge pier groups. Their results showed that with two piers in line, a combination of continuous collars and riprap led to a scour reduction of about 50% and 60% for the front and rear piers, respectively. The general agreement is that a collar can be used to reduce scour depth as well as to reduce the scouring rate.

Masjedi et al. (2010) studied the use of oblong collars for reducing the effects of local scour at a bridge pier is presented together with the time aspect of the scour development. The study was conducted using in a 180 degree laboratory flume bend. Tests were conducted using one oblong pier in positions of 60 degree under one flow conditions. In this study, the time development of the local scour around the oblong pier fitted with and without collar plates was studied. The effects of various sizes of collars fitted on the temporal development of scour depth at the oblong pier were also studied. The time development of the scour hole around the model pier with and without a collar installed was compared with similar studies on bridge piers. The results of the model study indicated that the maximum depth of scour is highly dependent on the experimental duration. It was observed that, as the size of a collar plate increases, the scour decreases. So minimum depth of scour is dependent on the 3D collar. On the basis of model studies, collars are not only very effective at reducing scour but are also much more economical when compared to countermeasure techniques like rip rap. It has been concluded that the larger the collar the greater the scour reduction level and for maximum performance the collar should be placed at or below the channel bed level. All previous studies on the use of a collar as a countermeasure for local scour at a bridge pier are based on experiments carried out using a physical hydraulic model and as such the practicality of using a collar on the field through a prototype study has not yet been done.

2.6 Critical Observation

1. Local scour around hydraulic structure in erodible bed section is important. Accurate prediction of local scour such as the maximum depth of scour hole around structure is complex phenomenon and critical to estimate.

2. The slender structures such as bridge piers in river or open channel flow causes the disruption the flow conditions in the channel section.

3. The channel morphology changes on construction of structures in the flow path and the geometry of channel depends on the discharge, characteristics of bed materials and the sediment capacity of the channels.

4. No single approach is available to calculate channel geometry applicable to all types of channel with all types of barrier.

5. There are empirical and semi empirical formula is available for different channel section but these formulas have its own limitations.

6. A structure made in the flow path reduces the waterways and increases the discharge, velocity and scour.

7. The flow pattern around the structure changes due to vortex motion and fluid-structure interaction effect.

Literature shows that there is more research required to predict the flow pattern around structure of different shape in different flow conditions and its consequent effect on channel morphology.

2.7 Scope of the present investigation

Based on the critical observations on the review of literature and keeping the objective in mind, the scope of the present investigation is limited to the following:

1. Experimental study of scouring and flow behavior around slender pier in erodible channel bed.
2. Effect of shape and size of laboratory pier model on scouring.
3. Effect of concentric collar as scour countermeasure.
4. Visualization of flow field and vortex motion around pier model embedded in sand bed in flume.
5. Efficient channel section with multiple obstructions in flow path.
6. Numerical study on flow field around slender structure in flow path.
7. Study on Ganga River morphology near Varanasi.