2.1. GENERAL

The potential losses accruable from bridge failures and the need to guard against same have prompted for better understanding of the scour process and for better scour prediction methods and equations. Under-prediction of pier scour depth can lead to bridge failure while over-prediction leads to excess expenditure of resources in terms of construction costs (Ting et al. 2001). Numerous experimental and numerical studies have been carried out by researchers in an attempt to quantify the equilibrium depth of scour in various types of soil material. Moreover, while a lot of work has been done to develop equations for predicting the depth of scour; researchers have also worked extensively to understand the mechanism of scour. Raudkivi and Ettema (1983), Ahmed and Rajaratnam (1998), Chiew and Melville (1987) and Breusers et al. (1977), among others, are some of the researchers that have worked on pier scour. Local scour around bridge piers was studied by Shen and Schneider (1969) while Breusers et al. (1977) gave a state of the art review on local scour around circular piers. Posey (1974) provided guidance on how bridge piers in erodible material can be protected from under-scour by means of an inverted filter extending out a distance of 1.5 to 2.5 pier diameters in all directions from the face of the pier. Current research areas include understanding the scour processes, temporal development of scour, predicting scour in cohesive soils, parametric studies of local scour, and prediction of scour depth at various types of hydraulic structures. For
example, Ansari et al. (2002) studied the influence of cohesion on scour around bridge piers. Ahmed and Rajaratnam (1998) investigated the flow around bridge piers in their laboratory study on flow past cylindrical piers placed on smooth, rough and mobile beds. Jia et al. (2002) reported the findings of a numerical modeling study for simulating the time-dependent scour hole development around a cylindrical pier founded on a loose bed in an open channel. Lim and Chiew (2001) presented a parametric study on riprap protection and failure around a cylindrical bridge pier with uniform bed sediments. Link and Zanke (2004) studied the time-dependent scour-hole volume evolution at a circular pier in uniform coarse sand and developed a mathematical correlation between the scour volume and the maximum scour depth for water depth to pier diameter ratios between one and two. In spite of the significant amount of research into scour processes, some aspects of scour are yet to be resolved as shown by the various contradictions reported in the literature. Raudkivi and Ettema (1983) stressed that the scientific basis for the structural design of bridges is well established whereas, in contrast, there is no unifying theory at present which would enable the designer to estimate, with confidence, the depth of scour at bridge piers. Cheremisinoff et al. (1987) and Hoffmans and Verheij (1997) supported the claims of Raudkivi and Ettema. According to the various authors, this is not only due to the extreme complexity of the problem but also due to the fact that stream characteristics, bridge constriction geometry and soil and water interaction are different for each bridge as well as for each flood. Although it has been the subject of theoretical and experimental studies for many years, Federico et al. (2003) have also indicated that a reliable assessment of the general and local erosion of pier foundation soil cannot be safely
calculated by means of the empirical correlations available in the technical literature. Hoffmans and Verheij (1997) indicated that scour analysis should form an integral part of the design of a new bridge substructure in order to ensure that the bridge can withstand the effects of high flows during flood events. The authors were of the opinion that the currently available formulas for calculating the expected depth of scour have limited usage and cannot be relied on. Therefore, it was concluded that considerable engineering judgment must be used when estimating the depth of scour in order to achieve a satisfactory and also a cost-effective design.

Literature study shows that 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.
2.2. REVIEW OF FIELD OBSERVATIONS OF LOCAL SCOUR AROUND A BRIDGE PIER

This approach might be to develop a pier scour equation from field measurements of local scour. Froehlich (1998) developed such an equation that was adapted for circular piers in uniform sediment under live-bed conditions.

It has long been recognized that field data for local scour at bridge foundations is needed to verify the laboratory-based scour depth relationships. The Federal Highway Administration (FHWA) in the United States and the U.S. Geological Survey (USGS) initiated a co-operative National Scour Study in 1987 to collect field measurements of bridge scour at bridge sites throughout the U.S. This program has generated a U.S. national bridge scour database of 470 field measurements of local scour depth at bridge piers. The data selected have been carefully checked and doubtful measurements have been omitted (Melville et al., 2002).

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) fitted 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).

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. They compared the field data with trends derived from laboratory studies and those developed in New Zealand and conclude that the laboratory-based relations provide a reasonable description of the field data.

Kwak et al. (2002) presented the results using the SRICOS methods and compared the calculated scour depths with the scour depths measured at the existing bridge.

Unfortunately, most of the field results were of poor quality, often lacking in important details. The parameters that influence local scour are difficult to include explicitly in an equation based primarily on field data because of the difficulties to control flow and channel conditions in field situations.

2.3. REVIEW OF PHYSICAL MODELING OF LOCAL SCOUR AROUND A BRIDGE PIER

Experimentation and modeling are widely used techniques in fluid mechanics. Laboratory studies are needed to understand certain elements of the scour processes in a better way and to develop alternate and improved scour countermeasures. With the help of controlled experiments, the effect of the variables and parameters associated with scour can be determined, scour prediction equations can be improved and additional design
methods for countermeasures can be developed. Most papers, which are based on laboratory data, described behavioral patterns of bridge scours around cylindrical piers.

The oldest and most complete experimental study on bridge pier scour was conducted by Chabert and Engeldinger (1956). The study used a test channel of width 0.80m with four different pier diameters ranging from 0.05m to 0.15m, four uniform sediments with a grain size between 0.26mm to 3.2 mm, and three flow depths 0.10m, 0.20m, and 0.35 m. The second channel was 3.0m wide containing uniform sediment of 3mm. In addition to the 0.15m circular cylinder, six other pier shapes were tested and additional experiments were conducted aimed at finding optimum arrangements for scour protection. The total study involved around 300 tests ranging from a few hours to days. Maximum scour resulted at the transition between the clear-water and the live-bed regimes. Despite the large data set, no general scour relation was established.

Breusers et al. (1977) and Dargahi (1982) summarized the important work on local scour around piers. Hosny (1995) presented the systematic experimental study of local scour around cylinders in cohesive soils. He used remolded natural clays in his 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. He proposed an 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) conducted a detailed study of 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. His 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.

Shen et al. (1966, 1969) conducted 21 experiments using a single cylinder diameter and sediment size, but varying the hydraulic conditions (water depth and the depth averaged flow velocity) to include both clear water and live bed conditions. They allowed scour to occur around a six-inch cylinder in a flume. They stopped the experiment at some desired depth and fixed the entire flume bed with an adhesive solution. Then, they re-established the flow and measured the velocity distributions with a small pitot tube and yarn streamers to establish direction. From their experiments, they developed 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 y₀. Cunha (1975) commented that the Shen et al. model in 1969 was based on a narrow range of flow and sediment conditions and therefore is probably not very well suited to practical applications. The complete absence of sediment size as a factor in the model makes it difficult to any application of the model to conditions other than those in his experiments. It is to be noted that the model has a single time scale. Generally, experiments examining scour time histories indicate that multiple time scales exist.

Breusers (1977) carried out experiments using piles with D = 5cm and 11cm, water depths of 15cm, 25cm, and 50cm and sand particles with d = 2mm. Experiments were
carried out for fixed values of \( \frac{U_0}{U_{0c}} \) (\( U_0 \) = average flow velocity and \( U_{0c} \) = critical water velocity for the initiation of bed movement).

Yamaz et al. (1991) conducted extensive experiments using circular and square piles. Diameters of the circular piles were 6.7cm, 5.7cm and 4.7cm. Sand particles with median size of 1.07mm and 0.84mm were used. All of the experiments were carried out for clear water scour.

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 they determined that equilibrium had been reached, 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 the authors maintain that the model may be useful for simulating the flow field under prototype conditions.

Gosselin (1997) conducted a series of clear water scour experiments to measure the velocity field (at various times during the scour process). These experiments included a circular cylinder with a diameter of 0.17m, a median sand size of 0.17mm, a flow depth of 0.35m and a depth averaged velocity of 0.25 m/s. For comparison and evaluation, he also modeled the velocities in the scour hole with a commercial three-dimensional flow model. During his experiments, Gosselin stopped the flow at 1, 6 and 24-hour intervals, drained
the flume, mapped and fixed the bed. With the flow re-establishing, he measured the velocities with an acoustic Doppler velocimeter.

Totapally et al. (1999) examined the temporal variations of local scour under steady flow and using stepped hydrographs. They concluded that a logarithmic equation represented 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 were a separate steady flow run). They found that for steps with duration on the order of 2.5 hours, the results of the superposition were comparable to experiments. For shorter duration steps, the superposition method tended to under predict the measured scour depth. Totapally et al. (1999) also found the 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). They 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.
The scale effect becomes evident when one considers the similitude requirements for hydraulic modeling of pier scour. The requirements are difficult to meet, because these equations do not include key parameters needed for pier-scour similitude.

2.4 REVIEW OF NUMERICAL SIMULATION OF LOCAL SCOUR AROUND BRIDGE PIER

In recent years, with the ever-increasing capabilities of computer hardware and software, computational fluid dynamics (CFD) has been widely used to determine fluid flow behavior in industrial and environmental applications. Some progression of using numerical simulation to study the flow around a pier and scouring process has been made in recent years.

Most models for predicting sediment transport are based on a single-phase flow approach. Bakker (1974) developed a numerical model to calculate suspended sediment concentration. Hagatun et al. (1986) presented a turbulence model to simulate the instantaneous sediment concentration and the turbulent boundary layer in the sheet flow regime over a flat bed. Ahilan et al. (1987) investigated the motion of sediment in oscillatory flow over a flatbed both theoretically and experimentally. Nadaoka et al. (1990) developed a mobile bed model considering the mass and momentum transport of a single-phase flow. Olsen et al. (1993) predicted local scour developing processes using a three-dimensional flow and sediment transport model. They solved the Reynolds equations with the $k-\varepsilon$ model for turbulence closure. Considering both suspended load and bed load, they
solved the bed sediment conservation equation by iterating the procedure until the scour hole at an equilibrium state is obtained. Ribberink et al. (1995) conducted time-dependent measurements of flow velocities and sediment concentrations in a large oscillating water tunnel.

The fluid-particle and particle-particle interactions are not accounted for in these models. Thus, the single-phase flow models have their limitation in solving sediment motions with the relatively high sediment concentration that usually happens under sheet flow conditions. Recently, several two-phase flow-modeling techniques have been developed. Asano (1990) proposed a partial two-phase flow model in which the vertical velocity of particles was approximated by an empirical expression rather than being solved in the governing equations. Li et al. (1995) followed Asano’s work by formulating a complete set of two-phase flow equations. Gotoh et al. (1997) presented a numerical simulation of the sediment transport and flow kinematics with a closure for particle-particle interactions in the sheet flow regime. Dong et al. (1999) proposed a complete two-phase flow model that simulates the fluid and sediment motions in the sheet flow regime under oscillatory flow conditions. All major forcing terms, such as, the fluid-particle and particle-particle interactions and the turbulent stresses are included in the model.

Richardson et al. (1998) simulated the flow structures around a bridge pier with and without the scour hole. They used FLOW3D with the RNG k-ε model. Comparing the simulated with the experimental results, they found that the three dimensional (3D) hydrodynamic model well simulates the complex flow patterns around the bridge pier.
Wang et al. (1999) 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, Wang et al. (1999) claim their model produced reasonable results. Wang et al. (1999) simulated an evolution of the scour hole developing around the bridge pier by using CCHE3D. They examined the importance of including various flow effects on sediment transport. After calibrating their model with experimental data, they claim 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, they adjusted the flatbed shear stress to account for the bed deformation without re-computing the flow equations. They 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). They found their 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 the square and the circular piers by the LES. They found that the down flow is made at the front face of the pier and this affects the creation of the 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. They were 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. Conditions for the simulation were: $D=10\text{cm}$, $d_{50}=0.26\text{mm}$, depth of flow=$20\text{cm}$, $U/U_c=1.6$. Equilibrium was reached in approximately 2.5 hours, but computation time for the model was 2.5 months on an Alpha 21264 workstation (equivalent to a 1.5 GHz Pentium 4 PC). This makes the Sumer model impractical for prototype size calculations where the time to equilibrium is approximately several weeks.

FLUENT is widely used for industrial flow application with complex three-dimensional geometry. Ali et al. (2002) used FLUENT to predict the three-dimensional flow field around a circular cylinder for rigid beds. There was satisfactory agreement between the bed shear stresses predicted by FLUENT and those calculated from the experimental velocities near the bed.

However, due to the complexities of both the flow field and the scour mechanism, numerical modeling of the scour process around bridge piers remains a difficult research topic. There have been few attempts to model numerically, the flow field within a scour hole, much less couple such a hydrodynamic model with a sediment transport model to reproduce the growth of a scour hole.
2.5. DIFFERENT APPROACHES FOR SCOUR DEPTH PREDICTION

The phenomenon of scour around hydraulic structures has been studied for a few decades. These early studies led to the development of a large database of information relating to the experimental, theoretical and numerical methods used in the area for a range of different hydraulic structures. Despite the large data set, no general scour relation was established.

Ettema (1980) developed a model that modeled only the upstream half of the scour hole. He found that the width of the erosion area at the bottom of the scour hole varied according to D/d, where D is the pier diameter and d the water depth. Ettema (1980) derived an equation for the time rate of scour as

$$\frac{\partial(d_{s}/D)}{\partial t} = \frac{k_3 d}{k_2 k_4 D^2} \cdot \sqrt{\frac{1+\cot^2 \phi}{\cot \phi}} I_p$$

(2.1)

where $k_1$ is a volume constant, $k_2$ and $k_4$ are area constants and $\phi$ is the sediment submerged angle of repose. Ettema (1980) did not attempt to solve for the scour depth as a function of time and so he did not attempt to evaluate $I_p$, the integral of the probability function for the entrainment of particles within the scour hole. He noted that $I_p$ can be considered independent of particle size for similar values of $d_s/D$, flow intensity based on shear velocities ($U/U_c$) and normalized sediment size (D/d).

Melville (1997) presented an integrated approach to estimate local scour depth at bridge piers similar to Ettema (1980) and Chiew (1984). The proposed method is based on empirical relations, termed K-factors that account for the effects of flow depth, foundation size, flow intensity, sediment characteristics, foundation type, shape and alignment and
approach channel geometry on scour depth. Melville developed the following equation to determine equilibrium scour depth

\[ d_s = K_{w}K_{d}K_{o}K_{G} \]  

(2.2)

Where the K-factors are defined by envelope curves developed from valid laboratory data. The method proposed by Melville is incapable of predicting the lesser scour depths, if the design flood duration is shorter than that required to develop the equilibrium scour depth. The expressions envelop the available laboratory data making them fundamentally conservative.

Yanmaz and Altinbilek (1991) conducted clear-water bridge pier experiments for almost uniform sediments with grain sizes of 0.84mm and 1.07mm in a 0.67m wide rectangular flume. Circular and square shaped piers between 47mm and 67mm were tested under zero angle of attack. A differential equation for the progress of scour hole depth was established and solved numerically. Yanmaz and Altinbilek (1991) discussed the shortcomings of their model. The model only applies in the range of experimental values on which the coefficients were based.

Oliveto and Hager (2002) used a rectangular channel of one meter wide and eleven meters long to conduct clear water pier scour experiments for 3 uniform sediments of grain size 0.55mm, 3.3mm and 4.8mm and 3 non-uniform sediments. Piers between 1-60% of channel width were tested with flow depths ranging from 1-40% of channel width. A general scour equation was developed based on similarity analysis and detailed hydraulic experimentation. This equation is useful in predicting scour depth providing that the experimental criteria are met.
Sheppard et al. (2004) conducted 14 large diameter pier scour experiments in a 6.1m wide, 6.4m deep and 38.4m long flume. Clear water scour tests were performed with three different diameter circular piers (0.114m, 0.305m and 0.914m), three different uniform cohesion less sediment diameters (0.22mm, 0.80mm and 2.90mm) and a range of water depths and flow velocities. Two different mathematical functions were found to fit local scour time history in the clear water range:

\[
d_s(t) = a\left[1 - \frac{1}{1 + abt}\right] + c\left[1 - \frac{1}{1 + cdt}\right] \tag{2.3}
\]

\[
d_s(t) = a[1 -\exp(-bt)] + c[1 -\exp(-dt)] \tag{2.4}
\]

Where \(a\), \(b\) and \(c\) are curve fitting coefficients and \(t\) is the time elapsed. The duration of the test must be at least that used in the experiments in order to produce accurate estimates of equilibrium scour depths. The discovery of the sensitivity of clear-water equilibrium scour depth and scour rate on suspended sediment concentration is also significant. This might help in explaining some of the scatter in published data and the differences in data obtained by different researchers. It might also help to explain why laboratory data results often over predict clear-water scour values observed in the field. This equation had been found to fit experimental time series reasonably (Gosselin, 1997). Bertoldi and Jones (1998) developed the same equation and determined the coefficients of the equation by fitting a long-term experiment with sediment of the same size as that of the data set.

Melville and Chiew (1999) conducted experiments in four different flumes to consider the temporal development of clear-water local scour depth at cylindrical bridge
piers in uniform sands. To provide a broader range of data, Ettema’s (1980) and Graf’s (1995) results of local scour depth were included. Melville and Chiew (1999) drew the following conclusions from the study-

- Equilibrium scour depth is approached asymptotically under clear-water conditions
- After 10% of the time to equilibrium, scour depths vary between about 50% and 80% of equilibrium depth depending on flow intensity
- Equilibrium time scale for development of the scour hole is a function of flow intensity ($U/U_c$), flow shallowness ($y/D$) and sediment coarseness ($D/d_{50}$).
- The equations developed allow estimation of local scour depth.

2.5.1 Scour Depth by FHWA (HEC-18)

The Federal Highway Administration (FHWA) by its Hydraulic Engineering Circular-18 (HEC-18) has recommended the following equation for local scour.

$$\frac{d_s}{y} = 2.0K_1K_2K_3K_4 \left(\frac{b}{y}\right)^{0.65} \left(R_f\right)^{0.43}$$

(2.5)

Where;

- $d_s$ = scour depth
- $K_1$ = shape factor (1.1 for square nose, 1.0 for round nose, 0.9 for sharp nose)
- $K_2$ = angle of attack factor
- $K_3$ = dune factor (varies from 1.0 to 1.3)
- $K_4$ = coefficient based on armoring by larger particles in the bed material equals to 1 (ignoring armouring action)
\( b = \text{effective pier width} \)

\( F_i = \text{Froud's number} = \frac{U}{\sqrt{gy}} \)

\( y = \text{depth of flow} \)

### 2.5.2 Laursen-Toch Equation

The equation proposed by Laursen and Toch for prediction of scour depth \( d_{sc} \) is (Garde and Kothyari, 1998)

\[
\frac{d_{sc}}{y} = 1.35(D/y)^{0.70} \tag{2.6}
\]

Where:
- \( d_{sc} = \text{clear water scour below bed level} \)
- \( y = \text{average depth of flow} \)
- \( D = \text{pier width or pier diameter} \)

### 2.5.3 Melville and Sutherland's Equation

Melville and Sutherland's method for estimating the scour at bridge piers is completely based on the analysis of the laboratory data. They assumed that the largest possible scour depth around the bridge pier is given by (Garde and Kothyari, 1998)

\[
d_{sc} = 2.4 \, D \tag{2.7}
\]

This scour depth below the general bed level is reduced by multiplying factors depending on type of scour, depth of scour and sediment gradation. The multiplying factors are determined from the analysis of experimental data covering a wide range of pertinent variables.
2.5.4 Chitale's Method

The method proposed by Chitale for estimating the probable maximum scour depth $d_{scm}$ at bridge pier as (Garde and Kothyari, 1998)

$$d_{scm} = 2.5 D \quad (2.8)$$

If the bridge is located at a constriction caused by guide bunds, the average depth $d_2$ in the contracted section is related to that in the uncontracted section $d_1$ by

$$d_2/d_1 = (B_1/B_2)^{0.69 \text{ to } 0.79}$$

Where $B_1$ and $B_2$ are the unobstructed and obstructed widths of the river channel. This average depth $d_2$ in the contracted section may not uniform across the width because of non-uniform flow distribution and curved entry. Analysis from eight bridges in Indo-Gangetic plain indicated that ratios of maximum depth to the average depth $d_2$ varied from 1.2 to 1.67. Hence Chitale recommends a ratio of 1.7.

Therefore maximum local scour depth = 1.70 $d_2$

Hence

$$D_{scm} = 2.5 D + 1.70 d_2$$

Where $D_{scm}$ is the maximum anticipated scour depth below water surface.

2.5.5 Kothyari-Garde-RangaRaju's Method

Based on extensive laboratory results using uniform and nonuniform sediments, stratification and steady flow, Kothyari et al. (1998) have proposed equations for determining clear water scour depth $d_{sc}$ for steady flows. The analysis was done using the mathematical model based on the assumption of formation of horse-shoe vortex on the
upstream side of the pier. Such a vortex increases the shear stress on the bed and causes scour. Their equations for scour depth are- (Garde and Kothyari, 1998)

Clear water scour:

\[
\frac{d_{sc}}{b} = 0.66 \left( \frac{b}{d} \right)^{0.75} \left( \frac{D}{d} \right)^{0.16} \left( \frac{U^2 - U_{c}^2}{\Delta \gamma d / \rho_f} \right)^{0.40} \alpha^{-0.30}
\]  

(2.8)

Where the average critical velocity \(U_c\) is given by

\[
\left( \frac{U_c^2}{\Delta \gamma d / \rho_f} \right) = 1.20 (b/d)^{-0.11} (D/d)^{0.16}
\]

Scour under Sediment Transporting flow:

\[
d_{sc}/b = 0.88 (b/d)^{0.67} (D/d)^{0.40} \alpha^{0.30}
\]  

(2.9)

Where: 
\(d_{sc}\) = clear water scour below bed level

\(b\) = pier width or pier diameter

\(B\) = channel width

\(d\) = sediment size

\(U\) = average velocity of flow

\(U_c\) = critical velocity for sediment

\(\alpha\) = opening ratio = \(\frac{B-b}{B}\)

\(\Delta \gamma\) = difference in specific weight of sediment and water

\(\rho_f\) = the mass density of water
2.5.6 Indian Practice on Estimation of Design Scour Depth

The Lacey’s method of estimating regime depth of flow in loose bed alluvial rivers was developed by Lacey (1929) and Inglis (1944) mainly based on observations made in canals in India and Pakistan. This method is commonly used in India for estimation of scour depth also around bridge piers placed in alluvial rivers, and is recommended for design by the Indian Road Congress and Indian Railways.

Lacey–Inglis method

During the early 20th century Lacey analyzed data from stable irrigation channels flowing through loose sandy material in the Indo-Gangetic plain. These channels used to carry relatively less bed load since in the upstream reach of the channel, a sediment excluder or ejector was provided. The analysis of field data gave the following two relations for depth (or hydraulic radius) \( D_{LQ} \) and perimeter (or width) \( P \) of the channel:

\[
D_{LQ} = 0.47(Q/f)^{1/3} \quad (2.10)
\]

and

\[
P = 4.75\sqrt{Q} \quad (2.11)
\]

Here \( D_{LQ} \) is the normal scour depth in meter below the design flood level, \( Q \) the design flood discharge in \( m^3/s \) and ‘\( f \)’ the Lacey’s silt factor related to the median size of bed material \( d \) by the equation:

\[ f = 1.76 \sqrt{d_{50}} \quad ; \quad d_{50} \text{ being in mm}. \]
Inglis (1944) collected data from 17 bridges on alluvial rivers in India and found that maximum scour depth below the highest flood level (HFL), $D_{sc}$, when expressed in terms of computed depth of flow in the river $D_{LQ}$ using (2.10) gave

$$D_{sc} = KD_{LQ}$$

(2.12)

Where $K$ varied from 1.76 to 2.59 with a mean value of 2.09. Hence, according to Inglis

$$D_{sc} = 2.0D_{LQ}$$

(2.13)

According to the Indian Road Congress (IRC 1998 & 2000) for natural channels flowing in alluvium the mean depth of scour below flood level can be calculated using the Lacey-Inglis formula

$$D_{Lq} = 1.34(q^{2/3})^{1/3}$$

(2.14)

Wherein $D_{Lq}$ is the mean scour depth (m) below design flood level, $q$ is the design flood discharge intensity in m$^3$/s/m allowing for concentration of flow.

Initially Lacey’s equations (2.10) and (2.11) were meant for constant discharge flowing through channels in loose non-cohesive material having the bed material size in the range 0.13 to 0.43mm. Later, an analysis of data from some rivers in India flowing through Indo-Gangetic plain, it was stated that these equations also apply to meandering rivers at the bankful stage. The bankful discharge was defined by Inglis (1947) as 2/3 to 3/4 of the flood discharge, and it was basically the maximum discharge that the main river channel (excluding flood plain) carried. The bankful discharge has a return period of about 1.6 to 2 years. In the context of bridge scour, the designer applies these equations for a
flood discharge of 50 to 100 year return period which is much greater than the bankful discharge (Garde and Kothyari, 1998).

2.5.7 Artificial Neural Network (ANN)

It has been highlighted that various design methods and formulae for the estimation of local scour depth around bridge piers have been proposed. The main problem with these formulae is that the existing equations are based on laboratory data. They do not accurately consider environmental conditions and thus, tend to give conservative estimates.

An alternative method to overcome the variations involved with experimental and theoretical estimates is Artificial Neural Network (ANN). ANN’s act as universal function approximators, this making them useful in modeling problems in which the relationship between dependent and independent variables is poorly understood.

Recently, ANN has been widely applied in various areas of hydrology and water resource engineering. Among these, Grubert (1995) used ANN to predict the flow conditions when interfacial mixing in stratified estuaries commences. The neural network results were compared to the semi-theoretical solution based on a combination of results from in viscid flow theory, turbulent flow theory and interfacial friction experiments. Although neither of the two solutions was perfect in every respect, they were sufficiently close to one another. Engineers can now compute the critical velocity at which interfacial mixing commences at a particular location in a stratified channel.
Kambekar and Deo (2003) carried out scour data analysis using neural networks. Different networks were developed to predict the scour depth based on the input parameters of wave height, wave period, water depth, pile diameter, Reynold’s number, maximum wave particle velocity, maximum shear velocity, Shield’s parameter and Keulegan-Carpenter number. The neural network was able to provide a better alternative to the statistical curve fitting with a weight matrix developed to predict non-dimensional scour depth from the input of wave height, wave period, water depth and pile diameter.

Birikundavyi et al. (2002) investigated the performance of neural networks as potential models capable of forecasting daily stream flows. An appropriate model was identified and a comparison approach was used to evaluate it against a conceptual model presently in use. It was found that the neural networks outperform the deterministic model for up to 5-day-ahead forecasts. It was also found that the results obtained with the neural network were far superior to the ones obtained with the classic model.

Nagy et al. (2002) used an ANN model to estimate the natural sediment discharge in rivers in terms of sediment concentration. Several trials were done to design a suitable architecture of the network. The model was trained with measured field data of variables selected on the basis of fluid and sediment dynamics. Model verification was done with a large number of data from several rivers. The results indicated that a neural network approach estimates sediment concentration well compared to conventional methods.

Coppola et al. (2003) demonstrate the feasibility of training an ANN for accurately predicting transient water levels in a complex multilayered ground-water system under variable state, pumping, and climate conditions. The ANN was trained to predict transient
water levels in response to changing pumping and climate conditions. The trained ANN was validated with ten sequential seven-day periods and the results compared against both measured and numerically simulated ground-water levels. The results indicate that the ANN technology has the potential to serve as a powerful prediction and management tool for many types of ground-water problems.

ANN models are attractive in the area of estimation of local scour around bridge piers in this study. This is because of their adaptive nature where learning by example replaces programming or making functions in solving problems. This feature renders computational models very appealing in domains, where one has little or incomplete understanding of the problem to be solved but where training data examples are available. In the reviewed papers it was concluded that ANN provided a higher level of accuracy in solving a particular problem when compared to experimental and theoretical results. ANN may therefore be a viable alternative in the estimation of local scour depth around bridge piers, provided a reliable database is available.