AQUA
Water Infrastructure, Ecosystems and Society

© 2024 The Authors AQUA — Water Infrastructure, Ecosystems and Society Vol 73 No 3, 424 doi: 10.2166/aqua.2024.235

Scouring around bridge pier: A comprehensive analysis of scour depth predictive equations for clear-water and live-bed scouring conditions

Anubhav Baranwal and Bhabani Shankar Das*
Department of Civil Engineering, National Institute of Technology, Patna 800005, India
*Corresponding author. E-mail: bsd.ce@nitp.ac.in

AB, 0000-0001-8535-5369; BSD, 0000-0003-1140-0432

ABSTRACT

The failure of bridges, attributed to bridge pier scouring, poses a significant challenge in ensuring safe and cost-effective design. Numerous laboratory and field experiments have been conducted to comprehend the mechanisms and predict the maximum equilibrium scour depth around bridge piers. Over the last eight decades, various empirical methods have been developed, with different authors incorporating diverse influencing parameters that significantly impact the estimation of equilibrium scour depth around bridge piers. This paper aims to consolidate: (1) available experimental and field data sets on different types of bridge pier scouring, (2) the influence of flow and roughness parameters on both clear water scouring (CWS) and live bed scouring (LBS), and (3) existing empirical equations suitable for computing equilibrium scour depth around a bridge pier under CWS and LBS conditions. The presented research encompasses over 80 experimental/field data sets and more than 60 scour-predicting equations developed for CWS and LBS conditions in the past eight decades. Based on the performance of different empirical models in predicting scour depth ratio, suitable models are recommended for CWS and LBS conditions.

Key words: bridge pier, clear water scour, empirical equation, live bed scour, scour depth prediction

HIGHLIGHTS

- To focus on the available experimental and field data sets on different types of bridge pier scouring such as clear water scouring and live bed scouring.
- To study the effect of flow and roughness parameters on clear water and live bed scouring.
- To select the suitable existing empirical equations to compute scour depth around a bridge pier for clear water and live bed scouring.

INTRODUCTION

Bridge pier scour is characterized as lowering the riverbed elevation around a bridge pier. It occurs due to the erosive action of flowing water, which excavates and transports materials, potentially leading to bridge failure (Melville & Coleman 2000; Khalid *et al.* 2021). Local scouring around bridge piers is a common phenomenon that occurs when water flows around a bridge pier and erodes the bed material in its vicinity. The scouring can cause the bridge pier to lose support and stability, potentially leading to bridge failure. There are several factors that can contribute to the development of local scour, including the velocity and depth of the water, the type and size of the bed material, and the shape and size of the bridge pier. Local scour can be minimized through proper design and construction of the bridge pier and its foundation and ongoing maintenance and monitoring of the bridge and its surroundings. Research shows that scour caused by floods and other hydraulic conditions is responsible for over half of all bridge failures (Shirole & Holt 1991; Barbhuiya & Dey 2004). For example, Aggarwal (2001) studied scouring around a bridge over the Ambala–Kalka segment of the Jhajjar River in India, recording a depth of 3.0, 4.5, and 4.5 m below the riverbed during floods in 1976, 1982, and 1988, respectively. Basu & Gupta (2003) reported the tilting of a bridge pier occurs when scouring levels fall below the lowest bed level over the Lohit River in India. Aminoroayaie Yamini *et al.* (2018) investigated sediment scour phenomena for offshore piles due to sea waves and current interaction and suggested a numerical model to predict the shape and depth of the scour pit. Qasim *et al.* (2022) studied the impact of bed flume discordance on weir-gate structure hydraulics and found that bed flume configuration significantly alters the water surface path. Widyastuti *et al.* (2022) identified a structural solution for mitigating scouring around bridge abutments by implementing energy absorbers. Their findings indicate that the placement of these absorbers results in damping forces. Abdulkathum *et al.* (2023) verified different machine learning (ML) approaches, such as multiple nonlinear regression analysis (MNLR), gene expression programming (GEP), and artificial neural network (ANN) models to predict the local scouring around a bridge pier and found that the ANN model has better predicted the SDR (d_s/y) values than other models followed by the GEP model.

Numerous research studies on scour depth lack a common equation to predict the scour depth under clear water scouring (CWS) conditions and live bed scouring (LBS) conditions across a wide range of data points. Many researchers, as available in the literature, commonly used scour depth predictive equations without distinguishing their applicable/suitable scouring conditions and their limitation of data point range. Also, many equations very poorly predicted scour depth as they are developed only by considering one parameter (b/y) (Laursen 1958; Neill 1964; Breusers 1965) and two parameters (F_r and b/y) (Coleman 1971). So, there is a need to review different research papers and a proper classification of all available scour depth predictive equations between CWS and LBS conditions.

The novelty of the paper is as follows: (1) this paper discusses separately about CWS and LBS around the bridge pier, (2) different influencing parameters which affect the equilibrium scour depth have been summarized, (3) the laboratory data set and field data set of scour depth conducted by different researchers are presented in the Supplementary Material (4) the effect of flow parameters and roughness parameters are discussed separately for CWS and LBS. The present study focuses only on time-independent and equilibrium scour depth conditions. All the equations mentioned in the present manuscripts are equilibrium-based scour depth predictive empirical equations.

PHYSICS OF SCOURING AROUND BRIDGE PIERS

Scouring around bridge piers is a complex process that involves several mechanisms. According to Melville (1975), the primary mechanism is the downflow impinging on the bed at the pier face. When the flow approaches the pier, it slows down and comes to rest, leading to the formation of stagnation pressures that are strongest near the surface and weaken downwards. The flow creates a maximum immediately below the bed level due to the downward pressure gradient at the pier face. This maximum downflow velocity contributes to sediment scouring from the bed and is responsible for the primary scouring mechanism. Another important mechanism is the formation of a lee eddy, also known as the horseshoe vortex, around the pier. The horseshoe vortex effectively transports dislodged particles away from the pier and releases them downstream. It also pushes the maximum downflow velocity within the scour hole closer to the pier, further intensifying the scouring process. Several studies have been carried out on scouring phenomenon around the bridge pier by various researchers such as Chabert & Engeldinger (1956), Kothyari *et al.* (1992a), Arneson *et al.* (2012), Sheppard *et al.* (2014), Kaveh *et al.* (2021), Wang *et al.* (2022), and Baranwal *et al.* (2023a, 2023b). The existence and importance of the horseshoe vortex in the scouring process around bridge piers have been confirmed by Muzzammil & Gangadhariah (2003), Dey & Raikar (2007), Sheppard *et al.* (2014) and Zhao (2022). The observation of the horseshoe vortex in the vertical plane is presented in Figure 1(a) and 1(b). Briaud & Oh (2010) reported that all the layer characteristics of the soil could vary significantly with depth and with different erosion functions. Therefore, it is necessary to have an accumulation process that can handle a multi-layer system (Mylonakis *et al.* 1997; Briaud *et al.* 2005). Pokharel (2017) evaluated and attempted to understand bridge pier scour depth estimation using a multi-layer method in which the bed sediment (d_{50}) value is calculated layer by layer and compared the final scour depths with the HEC-18 equation in which the d_{50} value is taken as the average of all layers of the soil. It is reported that using only the average d_{50} value does not accurately predict the scour depth, and the d_{50} value of all layers should be considered while calculating the scour depth (Pokharel 2017). A method called the E-SRICOS method (Briaud *et al.* 1999, 2001; Kwak 2001) is proposed to predict the local scour depth versus time curve around bridge piers. This method makes it possible to handle multi-layer soil systems. Jia *et al.* (2023) conducted a study on inertial and kinematic interactions of bridge-pile groups on liquefiable multi-layer soil-induced lateral spreading and reported that a weak earthquake caused no significant seismic response under the bridge. The saturated sand displayed dilatant behavior, enhancing the acceleration peak response during the intense earthquake.

Tison (1940) laid the foundation for further research in the field of bridge pier scour and helped to better understand the factors that contribute to equilibrium scour depth around different shapes of bridge piers. Since then, numerous studies have been conducted to improve our understanding of bridge pier scour and to develop effective methods to mitigate its impacts.

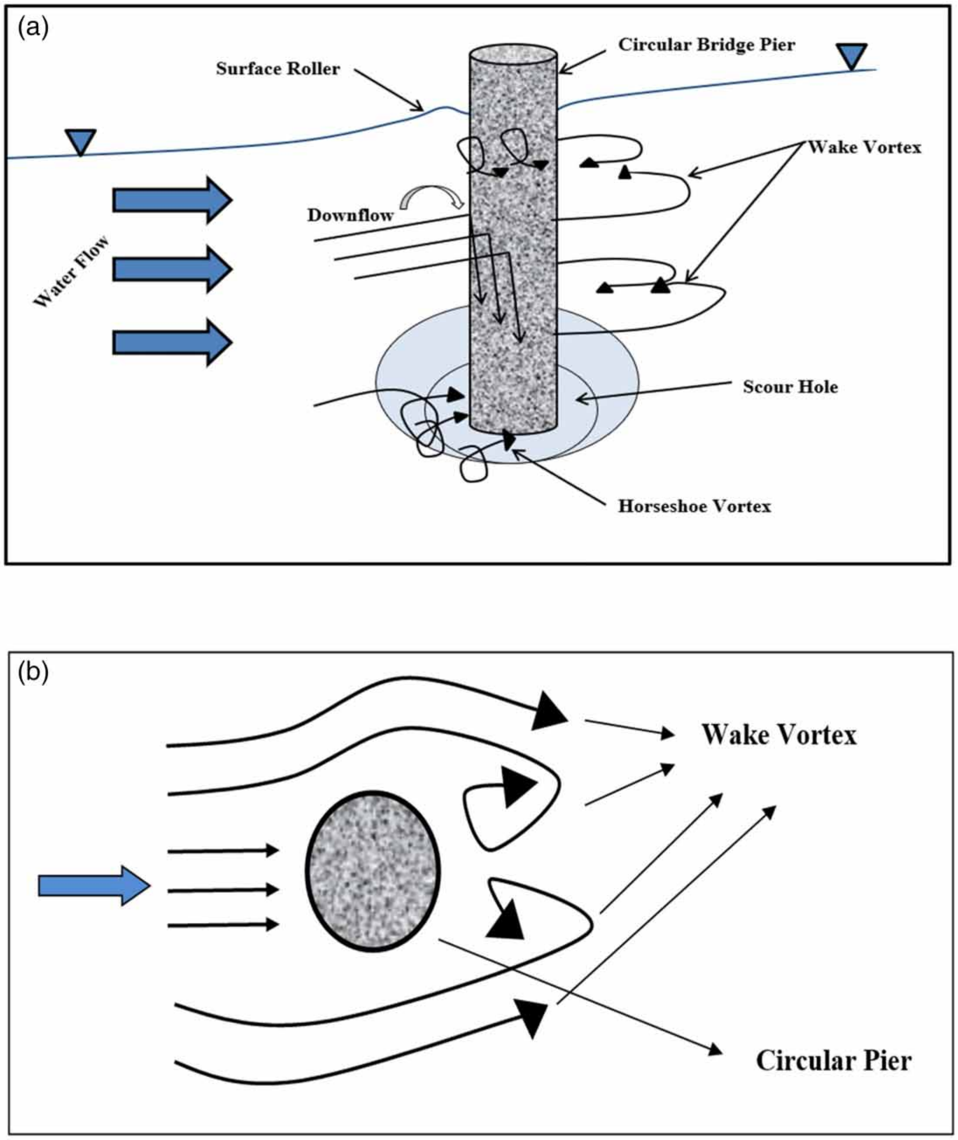

Figure 1 | (a) Scour pattern developing due to horseshoe vortices around a circular shape of the bridge pier, (b) plan view of wake vortices developing around a circular shape of the bridge pier.

For example, research has shown that the shape of the bridge pier, the size of the sediment particles, and the flow velocity are all important factors that influence scour depth (Laursen & Toch 1956; Raudkivi & Ettema 1983; Melville & Sutherland 1988; Raikar & Dey 2005; Dey & Sarkar 2006; Vijayasree *et al.* 2019). Different shapes of bridge piers, such as rectangular, round-nosed, triangular, flared, and lenticular, can have varying effects on equilibrium scour depth and must be carefully considered when designing bridges. In addition, researchers have developed various remedial measures (Chiew & Lim 2000; Garg *et al.* 2005; Clopper *et al.* 2007; Akhlaghi *et al.* 2020; Pandey *et al.* 2022) to reduce the impact of scouring on bridge piers, such as installing scour protection structures, controlling sediment transport, and designing bridge piers with shapes that are less susceptible to scouring.

DIFFERENT TYPES OF SCOURING AROUND BRIDGE PIER

It is observed that different researchers have discussed various types of scouring processes related to bridge pier scouring. So, in this section, an attempt has been made to summarize the various definitions of the scouring process (Table 1). Local scour

Table 1 | Definition and classification of different types of scouring

S. No.	Type of scouring	Definition
1	General scouring	Chiew (1984) defined the general scour as the aggradation or degradation of the bed level, either as a trend or temporal. This type of scour occurs independently of the presence of the bridge (Raudkivi & Ettema 1983; Raudkivi 1986)
2	Local scouring	Shen *et al.* (1969) defined local scour as the abrupt decrease in bed elevation near a pier due to erosion of the bed material by the local flow structure induced by the pier (Breusers *et al.* 1977; Raudkivi & Ettema 1983; Richardson & Davis 2001; Ismael *et al.* 2015; Kaveh *et al.* 2021). Local scouring is further classified as clear water, live bed, and equilibrium scour
3	Constriction scour	It occurs whenever the reduction in the cross-sectional area of the flow of water due to the presence of piers and abutments increases the flow velocity. This will increase the erosive power of the flow and hence lower the bed elevation over the area affected by the constriction (Chiew 1984; Raudkivi 1986). Constriction scour is further classified as clear water, live bed, and equilibrium scour
4	Equilibrium scour	Over a period of time, if the amount of material removed from the scour hole by the flow equals the amount of material supplied to the scour hole from upstream, it is known as the equilibrium scour stage (Raudkivi & Ettema 1983; Froehlich 1991; Brath & Montanari 2000; Richardson & Davis 2001; Lanca *et al.* 2013; Akhlaghi *et al.* 2019)
5	Clear water scour	Whenever material is removed from the scour hole but not replenished by the approach flow. This phenomenon happens when the shear stress caused by the horseshoe vortex equals the critical shear stress of the sediment particles at the bottom of the scour hole (Chabert & Engeldinger 1956; Raudkivi & Ettema 1983; Chiew 1984; Melville 1984)
6	Live bed scour	Whenever the scour hole is continually supplied with sediment by the approach flow. This type of scour occurs when the shear stress caused by the horseshoe vortex is greater than the critical shear stress of the sediment particles at the bottom of the scour hole (Chabert & Engeldinger 1956; Raudkivi & Ettema 1983; Chiew 1984; Melville 1984)

is categorized based on the amount of sediment moved into and out of the scour hole. The difference between the amount of sediment entering and exiting a scour hole determines the rate of scouring (Equation (1)):

$$q_s = q_{s2} - q_{s1} \tag{1}$$

where q_s is the volume per unit time of local scouring, q_{s1} is the volume per unit time of sediment transport into the scour hole, and q_{s2} is the volume per unit time of sediment transport out of the scour hole. Clear water scour occurs when sediment is removed from the scour hole without being replenished. The clear water scour condition occurs when the bed material upstream of the scour hole is not eroding. In this situation, the bed shear stresses away from the scour hole will be equal or less than the critical shear stress of the particles that make up the bed, i.e., $q_{s1} = 0$. There is a general movement of sediment upstream and downstream of the scour hole in live bed scour, also known as local scour with sediment transport. In this situation, the bed shear stress exceeds the critical bed shear stress, i.e., $q_{s1} > 0$ and $q_{s2} > 0$ (Chiew 1984).

From the literature, it is found that whenever mean flow velocities of the general bed sediment increase up to the critical velocity, a clear water scour condition occurs, i.e., $V/V_c <= 1$ (Figure 2(a)). When the flow velocity exceeds the critical velocity, a live bed scour condition occurs, i.e., $V/V_c > 1$ (Figure 2(b)). The maximum equilibrium scour depth occurs at $V = V_c$ (Gao *et al.* 1993; Wilson 1995; Melville 1997; Melville & Chiew 1999; Ettmer *et al.* 2015; Sharp & McAlpin 2022).

Extensive data from the scouring depth study are collected and presented separately as CWS and LBS. When the velocity of flowing water is less than or equal to critical velocity ($V \leq V_c$), then the CWS condition exists, and if vice-versa (i.e., $V > V_c$), then the LBS condition (Wilson 1995; Melville & Chiew 1999; Lee & Sturm 2009; Ettmer *et al.* 2015; Sharp & McAlpin 2022). Wherever the studies were not easily possible to distinguish between CWS and LBS then, critical velocity is calculated with the help of Equation (2) given by Neill (1968) and mentioned in HEC-18 by Richardson *et al.* (1993):

$$V_c = 6.36\, y^{1/6} d_{50}^{1/3} \tag{2}$$

where V_c is the critical velocity (m/s) that will transport bed materials, y is the depth of approach flow (m), and d_{50} is the median bed material size (m).

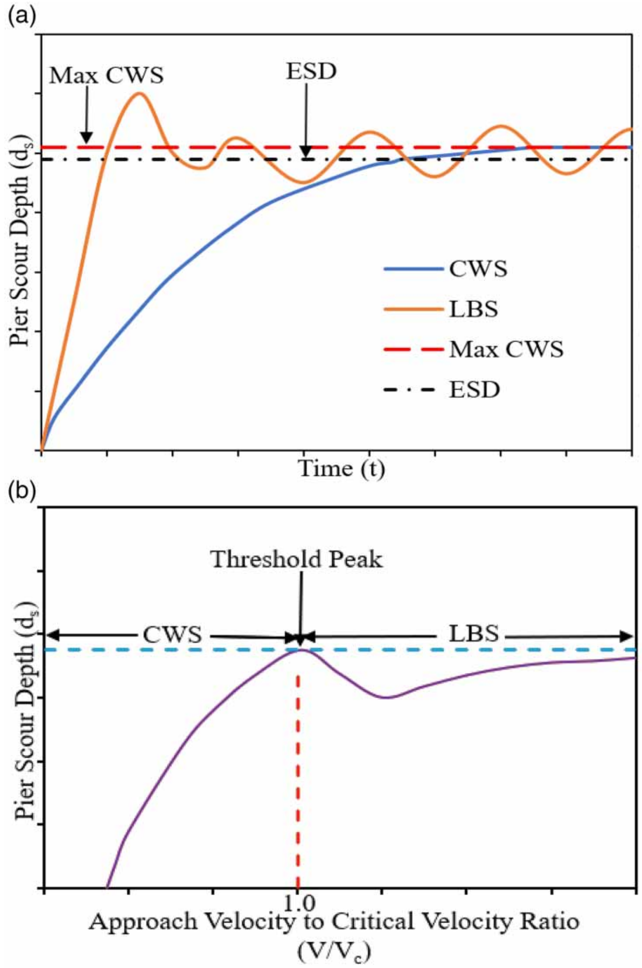

Figure 2 | (a) Variation of scour depth with time in clear water and live bed conditions (Chiew 1984; Brandimarte *et al.* 2012) and (b) variation of local scour depth with flow velocity (Sheppard & Miller 2006).

EFFECT OF BRIDGE PIER SHAPE ON SCOUR DEPTH

The design of the shape of a bridge pier is a crucial factor in determining the amount of local scour it will undergo. Chabert & Engeldinger (1956) classified the pier shape into blunt-nosed and sharp-nosed. The formation of a horseshoe vortex system around the upstream nose of the pier, where most scour occurs, defines a blunt-nosed pier. On the other hand, a sharp-nosed pier splits the flow and experiments have shown that a horseshoe vortex system does not form around its upstream face. As a result, no scour occurs at the sharp-nosed shape of the bridge pier when it is properly aligned with the flow. However, if tested at an angle to the flow, the bridge pier transforms into a blunt-nosed pier, leading to deeper scour.

Many researchers have studied different bridge pier shapes such as chamfered, cylindrical, diamond, elliptic, flared, hexagonal, joukowsky, lenticular, oblong, octagonal, sharp nose, square, rectangular, round-nosed, and triangular (Tison 1940; Inglis 1949; Chabert & Engeldinger 1956; Shen *et al.* 1966; Ettema 1980; Chiew & Melville 1987; Kumar *et al.* 1999; Ettema *et al.* 2006; Hassanzadeh *et al.* 2019; Garg *et al.* 2022; Baranwal *et al.* 2023a).

IMPORTANT PARAMETERS INFLUENCING SCOUR DEPTH AROUND A BRIDGE PIER

Different researchers performed experiments and provided empirical equations to predict equilibrium scour depth around the bridge pier (Laursen 1962; Jain & Fischer 1979; Melville & Sutherland 1988; Sheppard *et al.* 2004; Ismael *et al.* 2015; Pandey *et al.* 2018; Rathod & Manekar 2022). The existing equations on equilibrium scour depth show that the scour depth is the function of different geometry, flow, and roughness parameters. The input parameters used to model scour depth are as follows:

- Pier width (b): The width of the pier influences the scour depth, as a wider pier may cause more turbulence and a stronger scour hole ($W/b \geq 8$; Shen *et al.* 1966; Chiew 1984) where W is the width of the flume.
- Flow depth (y): The flow depth of the approaching water affects scour depth, as a deeper flow will generally create a deeper scour hole ($y/b < 3.0$; Ettema 1980).
- Flow velocity (V): The flow velocity of the approaching water also affects scour depth, as a higher velocity will cause a stronger scour hole and velocity ratio (V/V_c) (if $V/V_c \leq 1.0$, CWS and if $V/V_c > 1.0$, LBS) (Raudkivi & Ettema 1983).
- Bed sediment size (d_{50}): The size of the sediment in the riverbed affects scour depth, as the scour depth at the gravel bed ($4.10 \text{ mm} \leq d_{50} \leq 14.25 \text{ mm}$) is found to be more compared to the sand bed ($d_{50} \leq 4.0$ mm) (Raikar & Dey 2005). The size of river bed particles is a vital bed roughness parameter to model the scour depth. The critical velocity (Equation (2)) is also calculated using mean particle size, which is necessary to classify CWS and LBS conditions. Also, during the modeling using ML approaches, the parameter of bed sediment size is non-dimensionalized in terms of b/d_{50} and σ_g (Bateni *et al.* 2007; Khan *et al.* 2012; Shamshirband *et al.* 2020; Baranwal *et al.* 2023a; Kumar *et al.* 2023; Nil *et al.* 2023).
- Standard deviation of the bed material particle size (σ): The standard deviation of the bed sediment size distribution affects scour depth as a higher standard deviation indicates a more heterogeneous sediment size distribution, which can impact scour ($\sigma_g < 1.4$; Dey & Sarkar 2006).
- Froude number (F_r): The Froude number, a dimensionless quantity that describes the relative importance of inertial forces to gravitational forces in a fluid flow, affects scour depth. A higher Froude number indicates a stronger scour hole (If $F_r \leq 1$, then subcritical flow and $F_r > 1$ supercritical flow) (Ettema 1980).
- Pier correction factors (K): Various pier correction factors were used to account for the impact of specific pier geometry and flow conditions on scour depth. These correction factors can vary depending on the specific empirical equation being used (Silvia *et al.* 2021). The pier correction factor for different shapes of bridge pier is considered for cylinder and round nose shape ($K = 1.0$) Tison (1940), rectangular and square nose shape ($K = 1.1$) (Melville & Sutherland 1988), oblong ($K = 0.86$) (Laursen & Toch 1956), and sharp nose shape ($K = 0.9$) (Vijayasree *et al.* 2019).

It is important to note that the scour depth around a bridge pier is a complex and dynamic phenomenon influenced by various factors. The parameters listed earlier are just some key factors that can impact scour depth. Additionally, the specific values of these parameters can vary widely depending on the specific site and flow conditions, making it difficult to predict scour depth with certainty.

CWS AROUND BRIDGE PIER: EFFECT OF INFLUENCING PARAMETERS AND EXISTING EQUATIONS

Bridge pier scouring experimental models have been conducted for CWS conditions by many investigators in the last eight decades (Laursen 1958; Neill 1964; Jain & Fischer 1979; Melville & Sutherland 1988; Kothyari *et al.* 1992a; Mia & Nago 2003; Ebrahimi *et al.* 2018; Vaghefi *et al.* 2021; Kayadelen *et al.* 2022; Sharp & McAlpin 2022; Baranwal *et al.* 2023a, 2023b; Choudhary *et al.* 2023; Nil *et al.* 2023).

Effect of flow and roughness parameters on CWS

A list of local scour studies under CWS conditions by various researchers is presented in Supplementary Material, Table S1. The flow and roughness parameters effect on CWS are as follows:

- Ettema (1980) reported that the suspended fine silt has a major effect on scouring depths.
- Raudkivi & Ettema (1983) found that the equilibrium scour depth decreases faster as flow depth declines with smaller values of relative flow depth (y/b). The equilibrium local scour depth decreases for a b/d_{50} value less than 20–25.
- Yanmaz & Altinbilek (1991) observed an inverted cone-shaped circular scour hole around a cylindrical pier; its shape does not change over time.
- Chiew (1992) studied the influence of sediment size on scour depth around circular-shaped bridge piers for uniform sediments.
- Kothyari *et al.* (1992a) defined the effective size of non-uniform sediment for scouring purposes.
- Ahmed & Rajaratnam (1998) discovered that bed roughness caused a steeper pressure gradient and raised the amount of bed shear stress.
- Chang *et al.* (2004) developed a method for the computation of equilibrium scour depth in non-uniform sediment based on the mixing layer concept.

- Raikar & Dey (2005) reported that equilibrium scour depth increases as the size of gravel, i.e., 4.10 mm $\leq d_{50} \leq$ 14.25 mm, decreases in CWS condition for circular and square shape of bridge pier. When compared to sand beds, the effect of gravel size on scour depth is noticeably different. It is also found that generally, the scour depth at the gravel bed (4.10 mm $\leq d_{50} \leq$ 14.25 mm) is more than that of the sand bed ($d_{50} \leq$ 4.0 mm).
- Kothyari *et al.* (2007) proposed a scour depth model considering actual and entrainment densiometric particle Froude numbers and gave a criterion for the 'end scour' condition.
- Aksoy *et al.* (2017) reported that scour depth increases with pier diameter and flow velocity.
- Ebrahimi *et al.* (2018) investigated the influence of debris collection on the upstream face of a sharp nose bridge pier and found that scour depth decreases when the debris is near the bed and increases when the debris is just under the free flow surface.
- Akhlaghi *et al.* (2019) found that maximum local scour depth in uniform sediments occurs at the threshold condition.
- Pandey *et al.* (2019) reported that the maximum scour depth around the bridge pier increases with pier diameter, approach velocity and critical velocity ratio. However, it decreases with bed particle size in CWS and decreases as armor layer particle size increases.

Existing equations for estimation of CWS depth around bridge pier

A comprehensive list of scour depth predictive Equations (3)–(25) is presented in Table 2, along with the data sets used to develop each model. Yanmaz (1989) developed a semi-theoretical equation (Equation (12)) for calculating scour depth around circular and square piers under clear water conditions. This model is based on the solid sediment continuity equation and can compute the maximum scour depth under critical discharge. Lee & Sturm (2009) proposed two scour depth models using least square regression analysis (Equation (20)). Guo (2012) reported that the maximum probable scour depth is generally equal to the square root of the product of the pier diameter and approach flow depth (Equation (24)). Pandey *et al.* (2018) proposed a model (Equation (25)) to predict scour depth and two empirical equations to calculate the maximum scour length and maximum affected scour width for cohesionless bed sediment.

LBS AROUND BRIDGE PIER: EFFECT OF INFLUENCING PARAMETERS AND EXISTING EQUATIONS

Most of the bridge failures occur in live bed conditions caused by high flow intensities during flood scenarios. LBS around bridge piers has been investigated by many researchers (Chabert & Engeldinger 1956; Carstens 1966; Jain & Fischer 1979; Melville 1984; Froehlich 1988; Kothyari *et al.* 1992b; Link 2006; Zhao *et al.* 2010; Ettmer *et al.* 2015; Bordbar *et al.* 2021; Okhravi *et al.* 2022; Rathod & Manekar 2022; Choudhary *et al.* 2023; Nil *et al.* 2023).

Effect of flow and roughness parameters on LBS

The effect of flow and roughness parameters on LBS is summarized as follows:

- Chiew (1984) studied the effect of sediment size on scour depth at circular piers in live bed scour conditions.
- Scour depth decreases above the critical velocity and then increases to a maximum value at the transition to flatbed conditions.
- At higher velocities, the equilibrium scour depth decreases due to the formation of antidunes on the bed surface.
- Karim *et al.* (1986) and Chin *et al.* (1994) defined the bed armoring is a process in which the prolonged degradation of a riverbed occurs when the flow entrains finer sediment and leaves larger particles on the bed surface. This results in a gradual coarsening of the riverbed. Local scour depths are likely to be lower if bed armoring occurs. The effect of particle size depends on whether the bed sediment forms ripples or not. For ripple-developing sands, the maximum scour depth occurs at the transition to flatbed conditions, while for non-ripple-developing sediments, the maximum scour depth occurs at the threshold condition (Chiew & Melville 1987).
- Zhao *et al.* (2010) suggested that the scour depth decreases if the height of the cylindrical bridge pier is reduced, with this change occurring exponentially. The scour depth is almost independent of the pier height if the height-to-diameter ratio of the cylindrical bridge pier exceeds 2.0.
- With an increase in the V/V_c value, there is a decreasing tendency in the maximum scour depth (d_s/y) from 2.0 to 1.2 (Shen *et al.* 1966). When the value of V/V_c is 4.0, the maximum non-dimensional scour depth (d_s/y) increases to 3.1 (Jain & Fischer 1979), and when the value of V/V_c increases to 9.0, the d_s/y values vary from 2.0 to 2.5 (Zanke 1982).

Table 2 | Different existing equations used in CWS for the prediction of scour depth ratio

Reference	Equation	Citation of the equation in literature (CEL)/Data used to develop the equation (DDE)/developed equation is validated with the model of other researchers (DEV)	Eq No.
Laursen (1958)	$\frac{d_s}{b} = 1.34\left(\frac{y}{b}\right)^{0.50}$	CEL: Gülbahar (2009) and Yeleğen & Uyumaz (2016)	(3)
Neill (1964)	$\frac{d_s}{b} = 1.35\left(\frac{y}{b}\right)^{0.30}$	CEL: Abd El-Hady Rady (2020)	(4)
Breusers (1965)	$\frac{d_s}{b} = 1.4$	CEL: Abdelmonem *et al.* (2009) and Vonkeman & Basson (2019)	(5)
Shen *et al.* (1966)	$\frac{d_s}{b} = 11(F_r)^2$	CEL: Breusers *et al.* (1977) and Sheppard *et al.* (2014)	(6)
Shen *et al.* (1969)	$d_s = 0.00022R_e^{0.619}$ where $R_e = \frac{Vb}{v}$	CEL: Breusers *et al.* (1977), Ting *et al.* (2001) and Vonkeman & Basson (2019)	(7)
Hancu (1971)	$\frac{d_s}{b} = 2.42\left(2\frac{V}{V_c} - 1\right)\left(\frac{V_c^2}{gb}\right)^{1/3}$	CEL: Melville & Sutherland (1988)	(8)
Breusers *et al.* (1977)	$\frac{d_s}{b} = f\left(\frac{V}{V_c}\right)\left[2\tanh\left(\frac{y}{b}\right)\right]$ (a) if $\frac{V}{V_c} < 0.5$ then $f\left(\frac{V}{V_c}\right) = 0$, (b) if $0.5 \leq \frac{V}{V_c} < 1.0$, then $f\left(\frac{V}{V_c}\right) = \left(2\frac{V}{V_c} - 1\right)$, and (c) if $\frac{V}{V_c} \geq 1.0$, then $f\left(\frac{V}{V_c}\right) = 1.0$	CEL: Ghorbani (2008), Gülbahar (2009) and Vonkeman & Basson (2019)	(9)
Jain & Fischer (1979)	$\frac{d_s}{b} = 1.84\,F_c^{0.25}\left(\frac{y}{b}\right)^{0.3}$ for $(F_r - F_c) \leq 0$ Max $\left[\left(\frac{d_s}{b} = 2.0\,(F_r - F_c)^{0.25}\left(\frac{y}{b}\right)^{0.5}\right), \left(\frac{d_s}{b} = 1.84\,F_c^{0.25}\left(\frac{y}{b}\right)^{0.3}\right)\right]$ *for* $0 < (F_r - F_c) < 0.2$ $\frac{d_s}{b} = 2.0\,(F_r - F_c)^{0.25}\left(\frac{y}{b}\right)^{0.5}$ for $(F_r - F_c) \geq 0.2$	DDE: Own experimental data DEV: Chabert & Engeldinger (1956) and Hancu (1971)	(10)
Melville & Sutherland (1988)	$\frac{d_s}{b} = K_1K_2K_3K_4K_5K_6$	DDE: Shen *et al.* (1966), Ettema (1980), Chee (1982), and Chiew (1984) DEV: Laursen & Toch (1956), Hancu (1971), Shen (1971), and Breusers *et al.* (1977)	(11)
Yanmaz (1989)	$\frac{d_s}{b} = 0.85\left(\frac{y}{b}\right)^{0.686}$	CEL: Gülbahar (2009) and Kilinç (2019)	(12)
Kothyari *et al.* (1992a)	$\frac{d_s}{b} = 0.66\left(\frac{b}{d_{50}}\right)^{-0.25}\left(\frac{y}{d_{50}}\right)^{0.16} \times \left(\frac{\rho(V^2 - V_c^2)}{\Delta(\rho_s g)\,d_{50}}\right)^{0.4}\alpha^{*-0.3}$ where $\alpha^* = \left(\frac{B' - b}{B'}\right)$	DDE: Own experimental data DEV: Laursen & Toch (1956), Shen *et al.* (1969), Jain & Fischer (1979) and Ettema (1980)	(13)
Simplified Chinese (Gao *et al.* 1993)	$d_s = 0.78\,K_5 b^{0.6} y^{0.15} d_{50}^{-0.07}\left(\frac{V - V_{ic}}{V_c - V_{ic}}\right)$	CEL: Shin & Park (2010)	(14)
El-Saiad (1998)	$\frac{d_s}{y} = 3.4(F_r)^{0.67}\left(\frac{b}{y}\right)^{0.67}$	CEL: Shamshirband *et al.* (2020)	(15)
Ettema *et al.* (1998)	$\frac{d_s}{b} = \left(\frac{y}{b}\right)^{0.62}\left(\frac{V}{(gy)^{0.5}}\right)^{0.2}\left(\frac{b}{d_{50}}\right)^{0.08}$	DDE: Raudkivi & Ettema (1983), Melville & Sutherland (1988), and Breusers & Raudkivi (1991)	(16)
Kumar *et al.* (1999)	$\left(\frac{d_{sp} - d_{sc}}{d_{sp}}\right) = 0.057\left(\frac{W}{b}\right)^{1.612}\left(\frac{H}{y}\right)^{0.837}$	DDE: Schneible (1951), Chabert & Engeldinger (1956), Tanaka & Yano (1967), Ettema (1980), Chiew (1992), and Kumar (1996)	(17)
Melville & Chiew (1999)	$d_s = K_1K_3K_7K_8$	DDE: Chabert & Engeldinger (1956), Shen *et al.* (1966), Hancu (1971), Ettema (1980), Chee (1982), and Chiew (1984) DDV: By assuming hypothetical data	(18)

(*Continued.*)

Table 2 | Continued

Reference	Equation	Citation of the equation in literature (CEL)/Data used to develop the equation (DDE)/developed equation is validated with the model of other researchers (DEV)	Eq No.
Sheppard *et al.* (2004)	$\frac{d_s}{b} = 2.5\tanh\left(\frac{b}{d_{50}}\right)^{0.4}\left\{11.175\left\{\ln\left(\frac{V}{V_c}\right)\right\}^2\right\}\left\{\frac{\left(\frac{b}{d_{50}}\right)}{0.4\left(\frac{b}{d_{50}}\right)^{1.2}+10.6\left(\frac{b}{d_{50}}\right)^{-0.13}}\right\}$	DDE: Own experimental data	(19)
Lee & Sturm (2009)	$\frac{d_s}{b} = 5.0\log\left(\frac{b}{d_{50}}\right) - 4.0$ where $6 \le \frac{b}{d_{50}} \le 25$ $\frac{d_s}{b} = \frac{1.8}{\left(\frac{0.02b}{d_{50}} - 0.2\right)^2 + 1} + 1.3$ where $25 \le \frac{b}{d_{50}} \le 1 \times 10^4$	DDE: Own experimental data,; Ettema (1980), Melville & Sutherland (1988), Ting *et al.* (2001), Sheppard (2003), Sheppard *et al.* (2004), and Sheppard & Miller (2006)	(20)
Revised Shen II (1971) equation revised by AbGhani *et al.* (2010)	$\frac{d_s}{b} = 0.716\,F_r^{0.192}$	CEL: Khan *et al.* (2012)	(21)
Revised Hancu (1971) equation revised by AbGhani *et al.* (2010)	$\frac{d_s}{b} = 0.176\left(\frac{V^2}{gb}\right)^{0.088}$	CEL: Khan *et al.* (2012)	(22)
Ettema *et al.* (2011) or modified Sheppard *et al.* (2011) equation	(a) $d_s = 2.5b^{0.6}y^{0.4}$ (b) $d_s = 2.5b$	(a) For shallow water or wide piers where $\frac{y}{b} \le 0.3$ (b) For deep water or narrow piers where $\frac{y}{b} \ge 10.0$	(23)
Guo (2012)	$d_s = \sqrt{by}\tanh\frac{H^2}{3.75\sigma_g^{1.5}}$ where $H = \frac{V}{\sqrt{gd_{50}(s-1)}}$	DDE: CSU equation-based Molinas (2004) data DEV: Laursen (1963) and Sheppard *et al.* (2011)	(24)
Pandey *et al.* (2018)	$\frac{d_s}{y} = 0.987\,(F_{d_{50}})^{-0.302}\left(\frac{y}{b}\right)^{-0.566}\left(\frac{b}{d_{50}}\right)^{0.079}$	DDE: Own experimental data; Kothyari (1989), Yanmaz & Altinbilek (1991), Dey *et al.* (1995), Sheppard *et al.* (2004), Raikar & Dey (2005), Das *et al.* (2014), Lanca *et al.* (2013), and Lodhi *et al.* (2014) DEV: Richardson & Davis (2001), Khan *et al.* (2012), and Sheppard *et al.* (2014)	(25)

DDE, data used to develop the equation; DEV, developed equation is validated with the model of other researchers; CEL, citation of the equation in literature; B', center-to-center spacing between two piers; d_{sc}, local scour depth in case of the pier with collar plate; d_{se}, local scour depth at equilibrium; d_{sp}, local scour depth in case of the pier without appurtenances; F_c, critical Froude number; F_d, Densiometric particle Froude number; F_{d50}, Particle Froude number; F_r, Froude number; H, depth of collar below the free water surface; K_1, flow intensity factor; K_2, flow depth pier size factor; K_3, sediment size factor; K_4, sediment gradation factor or bed armoring factor; K_5, pier nose shape factor; K_6, pier alignment factor; K_7, flow depth – pier width factor; K_8, time factor; N, shape number; T, dimensionless time; V, flow velocity of the upstream from the pier; V_{ic}, approach velocity corresponding to critical velocity at the pier; V_c, flow critical velocity; W, channel width; σ_g, standard deviation of grain size distribution $\left(\sqrt{\frac{d_{84}}{d_{16}}}\right)$; ϕ, dimensionless coefficient about the shape of the pier nose; α^*, opening ratio; ν, kinematic viscosity of water.

- Sheppard & Miller (2006) reported that bedforms were transported periodically from the scour hole, leading to the attainment of maximum scour depth. Additionally, it is observed that for $y/b = 2.7$ and $b/d_{50} = 563$, scour depth increased from 0.13 to 0.30 m as V/V_c increased from 0.63 to 6.0. Furthermore, for $y/b = 2.6$ and $b/d_{50} = 181$, scour depth remains nearly constant as V/V_c increases from 0.90 to 4.0.

- According to Ettmer *et al.* (2015), the scour depth under live bed conditions is generally significantly higher than under clear water conditions and further increases with flow intensity. Ettmer *et al.* (2015) proposed two conditions: (1) If $1 < V/V_c < 4$, bed load with dunes is the main transport mode; and (2) If $V/V_c \geq 4$, bedforms with entrainment into suspension without development has been dominated.
- The horseshoe primary vortex formed in front of the pier is responsible for developing the scour hole around the pier (Kothyari *et al.* 1992b).

Existing equation for estimation of LBS depth around bridge pier

A detailed list of scour depth predictive Equations (26)–(39), along with the data point used to develop the LBS model and validation of the developed model under LBS conditions, is presented in Table 3.

Johnson (1995) studied the performance of various scour depth predictive equations by collecting field data (Equation (34)). Hancu (1971) (Equation (8)) and Breusers *et al.* (1977) (Equation (9)) were found to have zero biases for the collected data when $V/V_c < 0.5$, as they assumed that no local scour takes place at low velocities. However, the Shen *et al.* (1969) (Equation (7)) and Hancu (1971) equations showed biases of less than one for the selected data, making them undesirable for safety purposes. Therefore, it is recommended not to use either of these equations to calculate scour depth around piers. In contrast, it is found that the Melville & Sutherland (1988) Equation (11) equation tends to overpredict scour depth to a greater extent than other equations, particularly if sediment gradation is considered.

The next section, titled 'Bridge Pier Scour Depth Modeling (Scour Type Not Mentioned or Undistinguishable): Available Data Sets and Existing Equations,' has been created for the following reasons.

(a) The literature shows that some researchers have not distinguished between CWS and LBS and developed the empirical equation to predict scour depth around the bridge pier.
(b) In some data sets, the range of V/V_c values varies from less than 1.0 to greater than 1.0. So, they cannot be classified either in clear water or LBS types.

BRIDGE PIER SCOUR DEPTH MODELS (SCOUR TYPE – NOT MENTIONED BY AUTHORS OR UNDISTINGUISHABLE): AVAILABLE DATA SET AND EXISTING EQUATIONS

Many researchers have conducted laboratory and field experiments on both CWS and LBS without classification of scouring types (Inglis 1949; Shen *et al.* 1969; Melville 1975; Chiew 1984; Johnson 1992; Kandasamy & Melville 1998; Sheppard & Miller 2006; Ettmer *et al.* 2015; Hassanzadeh *et al.* 2019; Sharp & McAlpin 2022). A detailed list of published research in the literature and different data sets for experimental study and field study has been compiled and presented in Supplementary Material, Table S3. Some researchers have conducted experiments in both CWS and LBS and found the range of V/V_c to be between 1 and greater than 1 (as shown in Supplementary Material, Table S3), so it is difficult to distinguish the type of scouring that occurs during the measurement of data sets. According to Hamill (2014), during an actual flood, scour may initially form in clear water, transition to live bed and/or suspended sediment conditions, and eventually return to the initial CWS condition. From Table S3, it is found that the V/V_c value is not reported by Shen *et al.* (1969), Melville (1975), Chiew (1984), and Mohamed *et al.* (2007) and additionally, the V/V_c value is reported to be in the range of 0.61–6.07 by Sheppard & Miller (2006) and 0.8–8.5 by Ettmer *et al.* (2015).

A comprehensive list of scour depth predictive Equations (40)–(63), including the data set used to develop the model and model validation, is presented in Table 4. Note that the previous authors did not mention the scour type in their literature, or it is not distinguishable in some literature.

Inglis (1949) used the flow depth (y), pier width (b), and Froude no. (F_r) to predict the scour depth and proposed Equation (40). Neil (1973) suggested Equation (49) in which a correction factor (K_s) is multiplied by the width of the pier to calculate the scour depth. The correction factor (K_s) value equals 2.0 for the rectangular shape of piers and 1.5 for circular and rounded-nosed piers, respectively. From the literature, it is noted that Johnson (1992) used all the key scour parameters (b, y, F_r, and σ)) to formulate the scour depth predictive equation, i.e., Equation (34). Equation (51) – the CSU (1975) equation is also known as Richardson *et al.* (1993) equation which is only applicable for the circular shape of the pier. Melville (1997) investigated scour depth as a function of sediment size, gradation factor, flow depth, flow intensity, channel geometry, and pier shape and proposed a common equation that contained various parameter correction variables to allow for more

Table 3 | Different existing equations used in LBS for the prediction of scour depth ratio

Reference	Equation	Citation of the equation in literature (CEL)/data used to develop the equation (DDE)/developed equation is validated with the model of other researchers (DEV)	Eq No.
Larras (1963)	$d_s = 1.05b^{0.75}$	CEL: Gülbahar (2009)	(26)
Laursen (1963)	$\frac{d_s}{b} = 1.11\left(\frac{y}{b}\right)^{0.50}$	CEL: Gülbahar (2009)	(27)
Carstens (1966)	$\frac{d_s}{b} = 0.546\left(\frac{N_S^2 - 1.64}{N_S^2 - 5.02}\right)^{\frac{5}{6}}$	CEL: Gülbahar (2009)	(28)
Veiga (1970)	$\frac{d_s}{b} = 1.35\left(\frac{y}{b}\right)^{0.3}$	CEL: Ghorbani (2008)	(29)
Hancu (1971)	$\frac{d_s}{b} = 2.42\left(\frac{V_c^2}{gb}\right)^{1/3}$	CEL: Melville & Sutherland (1988)	(30)
Froehlich (1988)	$\frac{d_s}{b} = 0.32\,\phi\,F_r^{0.2}\left(\frac{b_e}{b}\right)^{0.62}\left(\frac{y}{b}\right)^{0.46}\left(\frac{b}{d_{50}}\right)^{0.08}$ or $d_s = 0.32K_5 g^{-0.1}V^{0.2}y^{0.36}b^{0.62}d_{50}^{-0.08}$	CEL: Pal *et al.* (2013)	(31)
Kothyari *et al.* (1992b)	$\frac{d_s}{d_{50}} = 0.99\left(\frac{b}{d_{50}}\right)^{0.67}\left(\frac{y}{d_{50}}\right)^{0.4}(\alpha*)^{-0.3}$ where $\alpha* = \left(\frac{B' - b}{B'}\right)$	DDE: Own experimental data DEV: Chabert & Engeldinger (1956), Laursen & Toch (1956), Liu *et al.* (1961), Chitale (1962), Shen *et al.* (1969), Hancu (1971), Neil (1973), Melville (1975), Jain & Fischer (1979), Chee (1982), and R.D.S.O. (1987)	(32)
Simplified Chinese (Gao *et al.* 1993)	$d_s = 0.65\,K_5 b^{0.6}y^{0.15}d_{50}^{-0.07}\left(\frac{V - V_{ic}}{V_c - V_{ic}}\right)^c$ where $\left(c = \frac{V_c}{V}\right)^{9.35+2.23\log(d_{50})}$	CEL: Mueller (1996) and Shin & Park (2010)	(33)
Johnson (1995)	$\frac{d_s}{b} = 2.02\left(\frac{y}{b}\right)^{0.02}F_r^{0.21}\sigma_g^{-0.24}$	DDE: Zhuravlyov (1978), Jain & Modi (1986), Froehlich (1988), and Dongguang *et al.* (1993) DEV: Laursen & Toch (1956), Larras (1963), Shen *et al.* (1969), Hancu (1971), Breusers *et al.* (1977), Melville & Sutherland (1988), and Hydraulic engineering circular (HEC-I8) (1993)	(34)

Fischenich & Landers (1999) or Modified Froelich formula	$\frac{d_s}{y} = 2\left(\frac{\theta}{90}\right)^{0.13}(F_r)^{\,0.61}\left(\frac{b}{y}\right)^{0.43}+1$	CEL: Abd El-Hady Rady (2020) and Kayadelen *et al.* (2022)	(35)
Lim & Chiew (2001)	$\frac{d_s}{b} = 2\left\{K\left(\frac{y}{b}\right)\right\}\;\left\{K\left(\frac{b}{d_{50}}\right)\right\}+0.06\;\pi y$ where $\left\{K\left(\frac{y}{b}\right)\right\}\sim$ Sediment size factor, and $\left\{K\left(\frac{b}{d_{50}}\right)\right\}\sim$ Flow depth adjustment factor	DDE: Own experimental data	(36)
Yanmaz (2001)	$\frac{d_s}{b} = 1.564\left(\frac{y}{b}\right)^{0.405}F_r^{0.413}$	DDE: Froehlich (1988) DEV: Chabert & Engeldinger (1956), Laursen & Toch (1956), Tarapore (1962), Laursen (1963), Shen *et al.* (1966, 1969), Hancu (1971), Basak *et al.* (1975, 1977), Jain & Fischer (1979), and Melville (1984)	(37)
Sheppard & Miller (2006)	(a) $\frac{d_s}{b^*} = \tanh\left[\left(\frac{y}{b^*}\right)^{0.4}\right]\left[2.2\left(\frac{\frac{V}{V_C}-1}{\frac{V_{lp}}{V_c}-1}\right)+2.5\left(\frac{\frac{b^*}{d_{50}}}{0.4\left(\frac{b^*}{d_{50}}\right)^{1.2}+10.6\left(\frac{b^*}{d_{50}}\right)^{-0.13}}\right)\left(\frac{\frac{V_{lp}}{V_c}-\frac{V}{V_c}}{\frac{V_{lp}}{V_c}-1}\right)\right]$ (b) $\frac{d_s}{b^*} = 2.2\tanh\left[\left(\frac{y}{b^*}\right)^{0.4}\right]$	(a) When live bed scour ranges up to live bed peak i. e., $1.0 < \frac{V}{V_c} \leq \frac{V_{lp}}{V_c}$ (b) when the live bed scour ranges above the live bed peak $\left(\frac{V}{V_c} > \frac{V_{lp}}{V_c}\right)$ where $b^* = K_5 b$ and V_{lp} is the live bed peak scour velocity or velocity where the bed planes out	(38)
Ismael *et al.* (2015)	$\frac{d_s}{y} = \left\{1680.6\left(\frac{d_{50}}{y}\right)\mathrm{Fr} - 0.121\ln K_5 \log\left(\frac{d_{50}}{y}\right) - 0.0393K_5^2 e^{\mathrm{Fr}} - 1.73\right\}$	DDE: Own experimental data	(39)

b_e, the width of the bridge pier projected normal to the approach flow; $b*$, effective structure width (or diameter); d, size of uniform sediment; N_s, grain number; ϕ, dimensionless coefficient based on the shape of the pier nose; θ, angle of attack; EP, expression programming.

Table 4 | Different scour depth predictive equations where scour type is not mentioned by authors/undistinguishable

Reference	Equation	Citation of the equation in literature (CEL)/data used to develop the equation (DDE)/developed equation is validated with the model of other researchers (DEV)	Eq No.
Inglis (1949)	$\frac{d_s}{b} = 4.2\left(\frac{y}{b}\right)^{0.78} F_r^{0.52}$	CEL: Abdelmonem *et al.* (2009) and Ghorbani (2008)	(40)
Inglis (1949) or Inglis – Poona I	$\frac{d_s}{y} = \frac{(1.7\, b^{0.22}\, V^{0.52}\, y^{0.52})}{y} - 1$	CEL: Mueller (1996) and Abdelmonem *et al.* (2009)	(41)
Inglis (1949) or Inglis – Poona II	$\frac{d_s}{y} = \frac{(1.73\, b^{0.22}\, V^{0.78})}{y} - 1$	CEL: Mueller (1996) and Abdelmonem *et al.* (2009)	(42)
Laursen & Toch (1956)	$d_s = 1.35\, b^{0.7} y^{0.3}$	CEL: Vonkeman & Basson (2019) and Shamshirband *et al.* (2020)	(43)
Blench (1960) or Blench – Inglis I	$\frac{d_s}{y} = \frac{(1.53\, b^{0.5}\, y^{0.5}\, V^{0.5}\, d_{50}^{-0.125})}{y} - 1$	CEL: Mueller (1996) and Boehmler & Olimpio (2000)	(44)
Blench (1960) or Blench – Inglis II	$\frac{d_s}{y} = \frac{(1.8\, b^{0.5}\, y^{0.75})}{y} - 1$	CEL: Mueller (1996) and Boehmler & Olimpio (2000)	(45)
Chitale (1962)	$\frac{d_s}{y} = (-5.49\, F_r^2 + 6.65\, F_r - 0.51)$	CEL: Mueller (1996), Lee *et al.* (2019), and Vonkeman & Basson (2019)	(46)
Laursen (1962)	$\frac{d_s}{b} = \frac{\left[\left(\frac{d_s}{11.5y} + 1\right)^{1.7} - 1\right]^{-1}}{5.5}$	CEL: Shin & Park (2010)	(47)
Coleman (1971)	$\frac{d_s}{y} = 1.39\, F_r^{0.2}\left(\frac{b}{y}\right)^{0.9}$	CEL: Lee *et al.* (2019)	(48)
Neil (1973)	$\frac{d_s}{b} = K_5$	CEL: Vonkeman & Basson (2019)	(49)
Basak *et al.* (1975)	$d_s = 0.558\, (b)^{0.586}$	CEL: Breusers *et al.* (1977)	(50)
CSU Equation (1975)	$\frac{d_s}{b} = 2.2\, F_r^{0.43}\left(\frac{y}{b}\right)^{0.35}$	CEL: Abd El-Hady Rady (2020), Kayadelen *et al.* (2022)	(51)
Chitale (1988)	$\frac{d_s}{b} = 2.5$	CEL: Abdelmonem *et al.* (2009)	(52)
Breusers & Raudkivi (1991)	$\frac{d_s}{b} = 2.3 K_2 K_3 K_4 K_5 K_6$	CEL: Zanke *et al.* (2011) and Hoffmans & Verheij (2021)	(53)
HEC-18 (Richardson *et al.* 1993)/ (Arneson *et al.* 2012)	$\frac{d_s}{b} = 2.0\, K_5 K_{10} K_{11}\left(\frac{y}{b}\right)^{0.35}(F_r)^{0.43}$	CEL: Wilson (1995)	(54)
CSU formula (Richardson & Davis 1995)	$\frac{d_s}{b} = 2.0\, K_3 K_5 K_{10} K_{11}\left(\frac{y}{b}\right)^{0.35}(F_r)^{0.43}$	CEL: Choi & Chong (2006) DDE: Jones (1984)	(55)
Wilson (1995)	$\frac{d_s}{b} = 0.9\left(\frac{y}{b}\right)^{0.4}$	DDE: Data collected from bridge sites in the Mississippi river DEV: HEC-18 (Richardson *et al.* 1993)	(56)
HEC-18/Mueller (1996)	$d_s = 2.0 K_4 K_5 K_{10} K_{11} g^{-0.215} V^{0.43} y^{0.135} b^{0.65}$ (a) $K_4 = 1.0$ for ($d_{50} \leq 2.0$ mm or $d_{95} \leq 20$ mm) (b) $K_4 = \left(\frac{V - V_{a\,d_{50}}}{V_{c\,d_{50}} - V_{a\,d_{95}}}\right)^{0.15}$ ($d_{50} > 2.0$ mm or $d_{95} > 20$ mm)	CEL: Nadal (2007) where $V_{a\,d_{50}}$ and $V_{a\,d_{95}}$ are the approach velocity required to initiate scour for grain sizes d_{50} and $d_{95,}$ respectively, and $V_{c\,d_{50}}$ is the critical velocity for the incipient motion for grain size d_{50}	(57)
Melville (1997)	$d_s = K_1 K_3 K_5 K_6 K_7 K_9$	DDE: Chabert & Engeldinger (1956), Shen *et al.* (1966), Hancu (1971),	(58)

(*Continued.*)

Table 4 | Continued

Reference	Equation	Citation of the equation in literature (CEL)/data used to develop the equation (DDE)/developed equation is validated with the model of other researchers (DEV)	Eq No.
		Ettema (1980), Chee (1982), and Chiew (1984) DEV: By assuming hypothetical data	
Kandasamy & Melville (1998)	$d_s = K_5 K\, y^n b^{1-n}$ where $\frac{y}{b} \leq 0.04$ for $(K = 5, n = 1)$, $0.04 < \frac{y}{b} < 1$ for $(K = 1, n = 0.5)$, and $\frac{y}{b} \geq 1$ for $(K = 1, n = 0)$	DDE: Own experimental data; Mueller (1996)	(59)
Melville & Coleman (2000)	$d_s = K_1 K_2 K_5 K_6 K_7 K_8$	CEL: Vonkeman & Basson (2019)	(60)
Ali & Karim (2002)	$d_s = \frac{K D_*^{1.2} y}{R_e}\left[1 - \mathrm{Exp}\left\{-0.000532\,\frac{V}{y}\right\}\right]$ for steady flow case, where $K = 0.1\sqrt{g(s-1)}\; d_{50}^{3/2} b^{-0.3}$ and $D_* = [(s-1)\, g^{-2}]^{1/3}$	DDE: Yanmaz & Altinbilek (1991) DEV: Laursen & Toch (1956), Neill (1964), Breusers (1971) and Melville (1975)	(61)
CSU formula Mohamed *et al.* (2005)	$\frac{d_s}{b} = 2.1\left(\frac{y}{b}\right)^{0.35}(F_r)^{0.43}$	CEL: Azamathulla *et al.* (2010) DDE: Own experimental data DEV: Laursen & Toch (1956), Jain & Fischer (1979), Melville & Sutherland (1988), HEC-18 (Richardson *et al.* 1993)	(62)
Sharafi *et al.* (2016)	$\frac{d_s}{y} = 0.28^{(0.13)}(F_r^{0.47})\left(\frac{d_{50}}{y}\right)^{-0.1}\left(\frac{b}{y}\right)^{0.44}\left(\frac{l}{y}\right)^{0.23}$	CEL: Shamshirband *et al.* (2020)	(63)

K, coefficient; n_e, exponent; K_9, channel geometry factor; K_{10}, angle of attack of flow factor; K_{11}, bed condition factor; s, specific gravity of the bed material.

accurate scour prediction for all types of piers which is given in Equation (58). Richardson & Davis (2001) proposed an empirical equation (Equation (55)) to calculate the scour depth which is also known as modifying Colorado State University (CSU) eq or HEC-18 equation. Inglis-Poona II (1949) (Equation (42)) and Blench-Inglis I (1962) (Equation (44)) provide a fair approximation of scour depth value in the case of round and sharp nose shape piers with a large width. Sheppard *et al.* (2014) reviewed different scour depth predictive equations and suggested that all the predictive equations are better in experimental data sets but overpredict scour depth for field data sets. It is found that the value of the densiometric Froude number (F_{rd}) has a substantial effect on the maximum equilibrium scour depth.

As shown in Tables 2–4, scour depth predictive equations were developed by using only the width (b) of the bridge pier as the input parameter. Larras (1963) developed a scour depth predictive equation, as shown in Equation (26), Breusers (1965) developed Equation (5), Neil (1973) developed Equation (49), Basak *et al.* (1975) developed Equation (50), and Chitale (1988) developed Equation (52). Many researchers, such as Johnson (1995), Mohamed *et al.* (2005), Choi & Chong (2006), Briaud (2015), Abd El-Hady Rady (2020), Kayadelen *et al.* (2022), and Baranwal *et al.* (2023b) generally used CSU equation (Equation (51)) for predicting the local scour depth in both clear water scour (CWS) and live bed scour (LBS) conditions.

RESULTS AND DISCUSSIONS

Comparison of existing CWS equation for predicting SDR

In CWS, a total of 864 data points are used from different researchers such as Yanmaz & Altinbilek (1991), Melville & Chiew (1999), Dey & Raikar (2005), Mueller & Wagner (2005), Lee & Sturm (2009), Lanca *et al.* (2013), Khan *et al.* (2017), Pandey *et al.* (2018), Yang *et al.* (2020), and Garg *et al.* (2022) which contain 33, 84, 33, 360, 38, 38, 168, 27, 64, and 19 data points, respectively, have been used to compare the CWS empirical equations. The ranges of minimum to maximum values of the observed scour depth ratio (SDR) of 10 different researchers are shown in Table 5. A sub-set of the reviewed scour depth predictive equations, such as Neill (1964), Shen *et al.* (1966), CSU (1975), Jain & Fischer (1979), Yanmaz (1989), Ettema *et al.* (1998), Lee & Sturm (2009), and Pandey *et al.* (2018), are applied on all the collected CWS data and the predicted value of SDR is depicted in Figure 3.

Table 5 | Different scour depth ratio (SDR) (d_s/y) range for clear water scouring

S. No.	Reference	No. of data points used	SDR (d_s/y) range Minimum	Maximum
1	Yanmaz & Altinbilek (1991)	33	0.56	2.25
2	Melville & Chiew (1999)	84	0.10	2.23
3	Dey & Raikar (2005)	33	0.06	1.23
4	Mueller & Wagner (2005)	360	0.04	8.74
5	Lee & Sturm (2009)	38	0.83	3.38
6	Lanca *et al.* (2013)	38	0.28	2.05
7	Khan *et al.* (2017)	168	0.37	2.56
8	Pandey *et al.* (2018)	27	0.29	2.60
9	Yang *et al.* (2020)	64	0.28	3.37
10	Garg *et al.* (2022)	19	0.26	2.01
	Total no. of data points	864	0.04 (minimum for the present study)	8.74 (maximum for the present study)

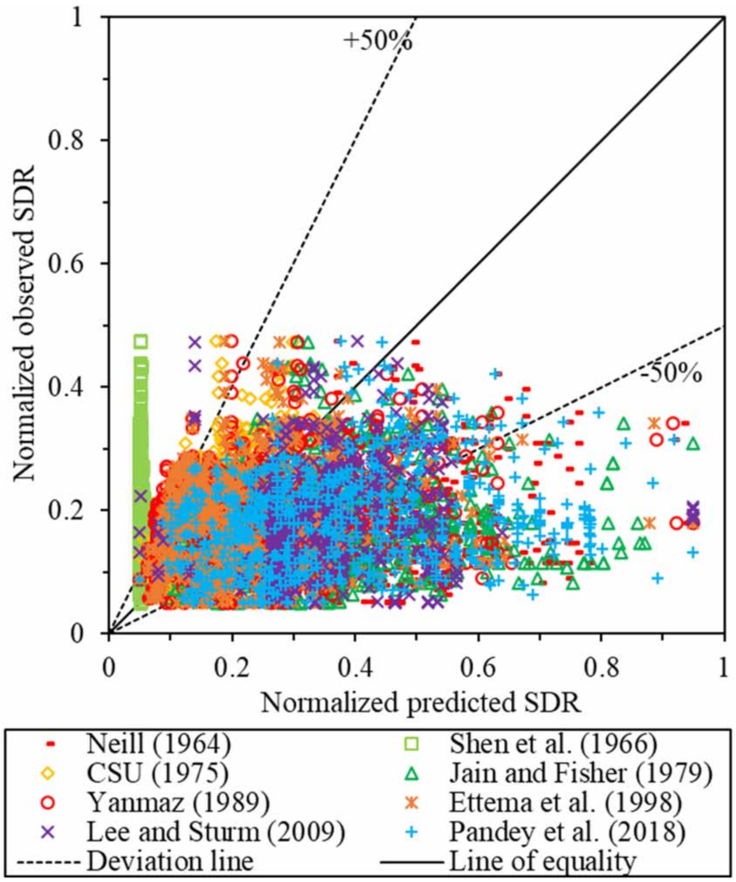

Figure 3 | Comparison of normalized observed vs predicted scour depth ratio (SDR) for different scour depth models under CWS condition.

The error analyses (MAE, MAPE, RMSE, and R^2) are performed on all 864 CWS data points to assess the effectiveness of these eight-scour depth predictive equations, as indicated in Table 6. Based on high R^2, low MAPE, and low RMSE values and from Figure 3 scatter plot, the top five scour depth predictive equations obtained for the present study are Neill (1964), CSU (1975), Yanmaz (1989), Ettema *et al.* (1998), and Pandey *et al.* (2018). Further, these selected five scour depth predictive equations are implemented on individual author data points and presented in Figure 4.

In Table 6, all the selected models predict poor results based on statical indices, yet among all, the CSU (1975) equation provides MAE, RMSE, and R^2 values of 1.04, 1.47, and 0.04, respectively, whereas Shen *et al.* (1966) equation predicted high value of MAE and RMSE and very low R^2 value. The Pandey *et al.* (2018) model utilizes the particle Froude number parameter to predict the scour depth, which provides an error in terms of MAE = 2.31, RMSE = 25.55, and $R^2 = 0.02$. These predictive models are providing poor results, and this may be due to the input parameter range used in the present research being in a wider range of data sets, as mentioned in Table 5 for the CWS condition and Table 7 for the LBS condition. The various author models are derived for a limited range of data sets. In the present study, the critical velocity of flow is calculated by the Neill (1968) formula. Still, it may differ when V_c is calculated from other models, so it may also be a possible cause of poor prediction of the model. A scour depth model is needed to handle a wide range of data for both CWS and LBS conditions.

In Figure 4(a), almost all the predictive equations give good results, but the Neill (1964) data point is overestimated. In Figure 4(b), Neill (1964) and CSU (1975) data are overestimated and some data from Yanmaz (1989) between 0.5 and 0.7 underestimate the SDR. In Figure 4(c), only Yanmaz (1989) gives a good result, and others poorly estimated the result for this data set. Figure 4(d) shows that all the Mueller & Wagner (2005) data come in the 0.05–0.3 range after the normalization, and Pandey *et al.* (2018) provide good results, and other models are overestimating. In Figure 4(e), Yanmaz (1989) and Ettema *et al.* (1998) overestimate the scour depth from 0.05 to 0.6 and Pandey *et al.* (2018) underestimate the scour depth in the range of 0.4–0.8. In Figure 4(f), Yanmaz (1989) data underestimate the scour depth, Neill (1964) data overestimate in the range of 0.15–0.5, and Pandey *et al.* (2018) are good at predicting the scour depth among all. In Figure 4(g), it is found that Pandey *et al.* (2018) overestimate the scour depth in the range of 0.2–0.24 and underestimate the scour depth in the range of 0.3–0.6, Yanmaz (1989) underpredicts the scour depth 0.3–0.6 and Neill (1964) estimates the good scour depth in the range of 0.3–0.5. In Figure 4(h) , CSU (1975) poorly overestimates the scour depth, Neill (1964), Yanmaz (1989), and Ettema *et al.* (1998) overestimate the scour depth, and Pandey *et al.* (2018) predict the good scour depth in the range of 0.3–0.6. In Figure 4(i) and 4(j), all the models are over predicting scour depth. The reason may be the estimation of the selected five equations in the condition in which the existing developed models do not fall in the category of the data set obtained by Yang *et al.* (2020) and Garg *et al.* (2022), respectively. A spurious effect is introduced to the regression parameters when regressing predicted vs observed (PO) values and comparing them against the 1:1 line and reported to opt for observed (on the *y*-axis) versus predicted (on the *x*-axis) (OP) regressions instead (Pineiro *et al.* 2008) so in the present study, observed (on the *y*-axis) versus predicted (on the *x*-axis) (OP) axis is used.

Table 6 | Error analysis of existing scour depth predictive equation under CWS condition

		Statical indices			
S. No.	**Reference**	**MAE**	**MAPE**	**RMSE**	R^2
1	Neill (1964)	2.35	633.59	25.24	0.14
2	Shen *et al.* (1966)	8.0	1,433.46	50.79	0.01
3	CSU (1975)	1.04	692.20	1.471	0.04
4	Jain & Fischer (1979)	3.49	1,215.21	25.01	0.08
5	Yanmaz (1989)	2.15	481.95	24.21	0.12
6	Ettema *et al.* (1998)	2.44	717.06	24.64	0.13
7	Lee & Sturm (2009)	2.63	833.62	25.54	0.01
8	Pandey *et al.* (2018)	2.31	355.54	25.55	0.02

MAE, mean absolute error; MAPE, mean absolute percentage error; RMSE, root-mean-square error; R^2, coefficient of determination.

Comparison of existing LBS equation for predicting SDR

In LBS, a total of 213 data points from different researchers such as Chiew (1984), Chiew & Lim (2003), Bozkus & Yildiz (2004), Sheppard & Miller (2006), Zhao *et al.* (2010), Ettmer *et al.* (2015) and Ismael *et al.* (2015) which contain 108, 28,

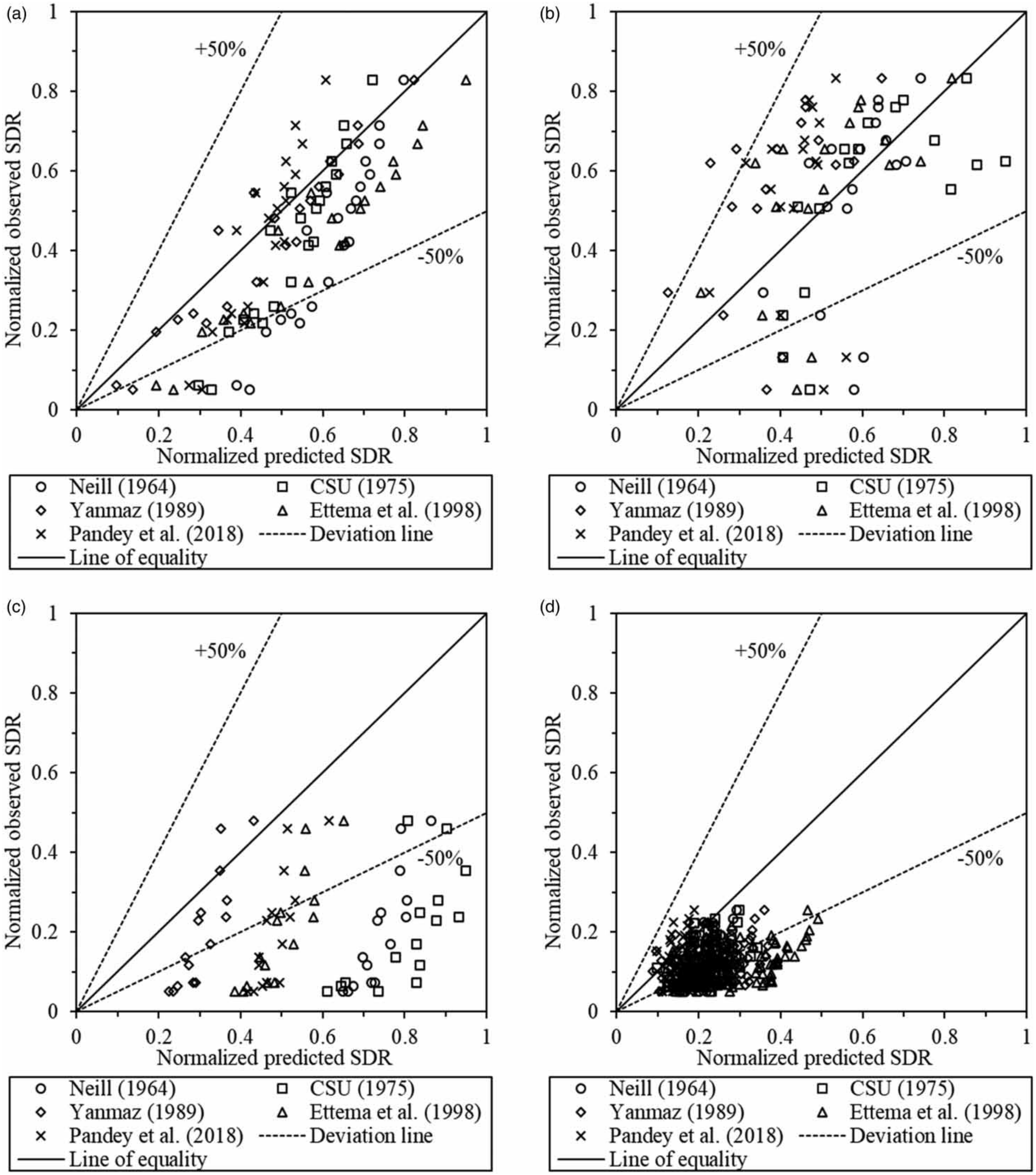

Figure 4 | Normalized observed vs predicted scour depth ratio variation (d_s/b) in CWS condition of various researchers such as (a) Yanmaz & Altinbilek (1991); (b) Melville & Chiew (1999); (c) Dey & Raikar (2005); (d) Mueller & Wagner (2005); (e) Lee & Sturm (2009); (f) Lanca *et al.* (2013); (g) Khan *et al.* (2017); (h) Pandey *et al.* (2018); (i) Yang *et al.* (2020), and (j) Garg *et al.* (2022). (*continued*.).

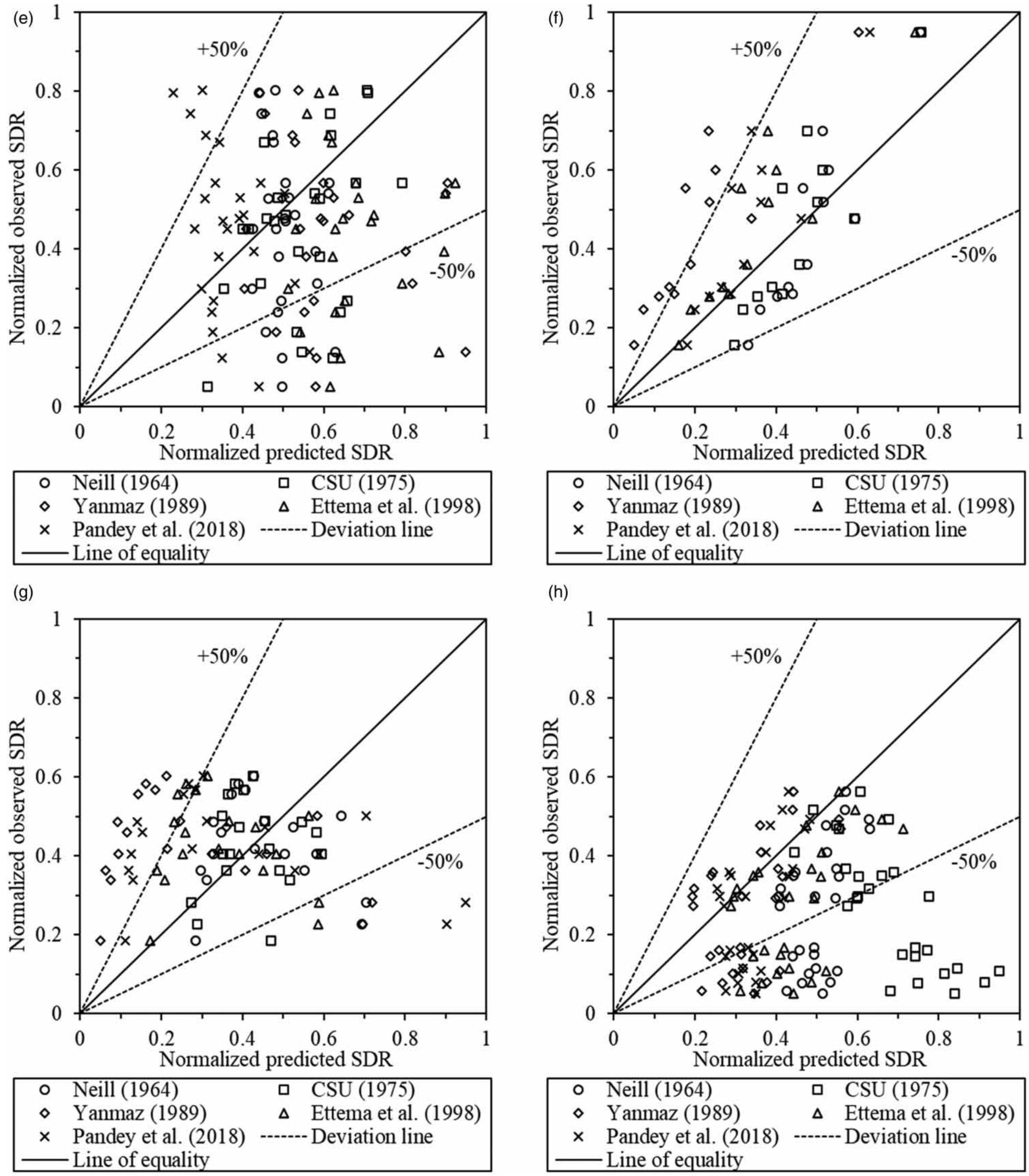

Figure 4 | Continued.

10, 20, 14, 15, and 18 data points, respectively, have been used to validate the LBS empirical equation. The ranges of minimum to maximum values of the observed SDR of seven different researchers are shown in Table 7. A sub-set of the seven reviewed equations namely Laursen (1963), Veiga (1970), Hancu (1971), CSU (1975), Kothyari *et al.* (1992b), Johnson (1995), and Yanmaz (2001) are employed in all LBS data points to predict the SDR and presented in Figure 5. The error

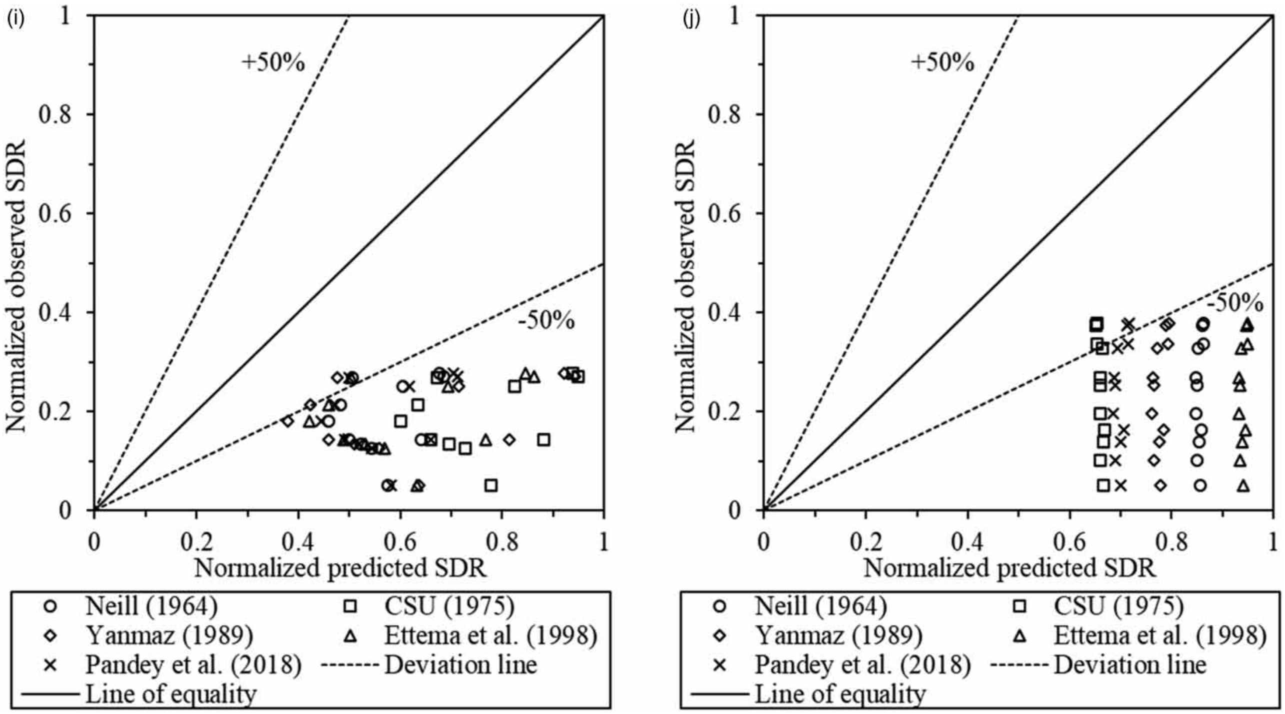

Figure 4 | Continued.

Table 7 | Different scour depth ratio (d_s/y) range for live bed scouring

S. No.	Reference	No. of data points used	SDR (d_s/y) range	
			Minimum	**Maximum**
1	Chiew (1984)	108	1.32	5.01
2	Chiew & Lim (2003)	28	1.66	3.64
3	Bozkus & Yildiz (2004)	10	0.68	2.34
4	Sheppard & Miller (2006)	20	1.18	3.08
5	Zhao *et al.* (2010)	14	0.58	3.28
6	Ettmer *et al.* (2015)	15	0.81	3.33
7	Ismael *et al.* (2015)	18	0.42	1.62
	Total no. of data points	213	0.42 (minimum for the present study)	5.01 (maximum for the present study)

analyses (MAE, MAPE, RMSE, and R^2) are performed on all 213 LBS data points to assess the effectiveness of these seven-scour depth predictive equations, as indicated in Table 8. Based on high R^2, low MAPE, and low RMSE values and from Figure 5, the top five scour depth predictive equations obtained for the present study are Veiga (1970), CSU (1975), Kothyari *et al.* (1992b), Johnson (1995), and Yanmaz (2001) equations. Further, these selected five scour depth predictive equations are implemented on individual author data points and presented in Figure 6.

In Table 8, all the models predict poor results based on statical indices, yet among all, Yanmaz (2001) equation provides MAE, RMSE, and R^2 values of 0.36, 0.53, and $R^2 = 0.54$, respectively, whereas Hancu (1971) equation predicted high value of MAE and RMSE and very low R^2 value. CSU (1975) model also predicts the scour depth, which provides an error in terms of MAE = 0.77, RMSE = 0.91, and $R^2 = 0.55$.

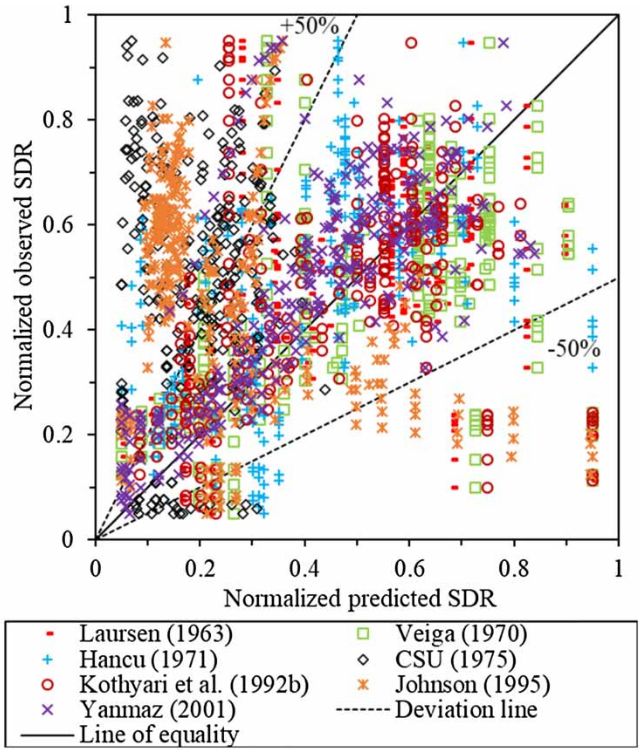

Figure 5 | Comparison of normalized observed vs predicted scour depth ratio (SDR) for different scour depth models under LBS condition.

In Figure 6(a), the CSU (1975) model poorly overestimated the scour depth, and Kothyari *et al.* (1992b) overestimated the scour depth in the range of 0.1–0.4. Figure 6(b) depicts that Veiga (1970), Kothyari *et al.* (1992b), Johnson (1995), and Yanmaz (2001) models over-predicted the SDR, whereas only the CSU (1975) model underpredicted the SDR in the range of 0.4–1.0. In Figure 6(c), CSU (1975) overestimates the scour depth, and Veiga (1970) underestimates the scour depth in the range of 0.38–0.6. In Figure 6(d), all the models poorly overestimate the scour depth, in which Johnson (1995) overestimated the scour depth maximum among all. In Figure 6(e), CSU (1975) data poorly overestimated the scour depth, and Veiga (1970) data underpredicted the scour depth in the range of 0.35–0.6. In Figure 6(f), all the models poorly predicted the scour depth, so it can be found that for different author data points, the empirical scour depth predictive equation behaves differently.

Different researchers have performed laboratory experiments in CWS and LBS conditions and developed the scour depth predictive model in which different non-dimensional input parameters, such as b/y, V/V_c, F_r, b/d_{50}, and σ_g, have been considered. These non-dimensional parameters have different input data ranges. The model may be used only when the input

Table 8 | Error analysis of existing scour depth predictive equation under LBS condition

		Statical indices			
S. No.	**Reference**	**MAE**	**MAPE**	**RMSE**	R^2
1	Laursen (1963)	0.61	78.37	0.86	0.05
2	Veiga (1970)	0.49	31.38	0.60	0.21
3	Hancu (1971)	1.39	80.15	1.55	0.01
4	CSU (1975)	0.77	43.09	0.91	0.55
5	Kothyari *et al.* (1992b)	0.50	38.43	0.71	0.17
6	Johnson (1995)	0.54	65.92	0.70	0.03
7	Yanmaz (2001)	0.36	19.71	0.53	0.54

parameters for the prediction of d_s/y for field conditions are available; otherwise, the predictive results may produce a large error in estimation. Precaution must be taken before applying any empirical models to estimate d_s/y in CWS and LBS to avoid scale effect. The reader may refer to Link *et al.* (2019) for more details on the scale effect of different scour depth predictive models for CWS and LBS conditions.

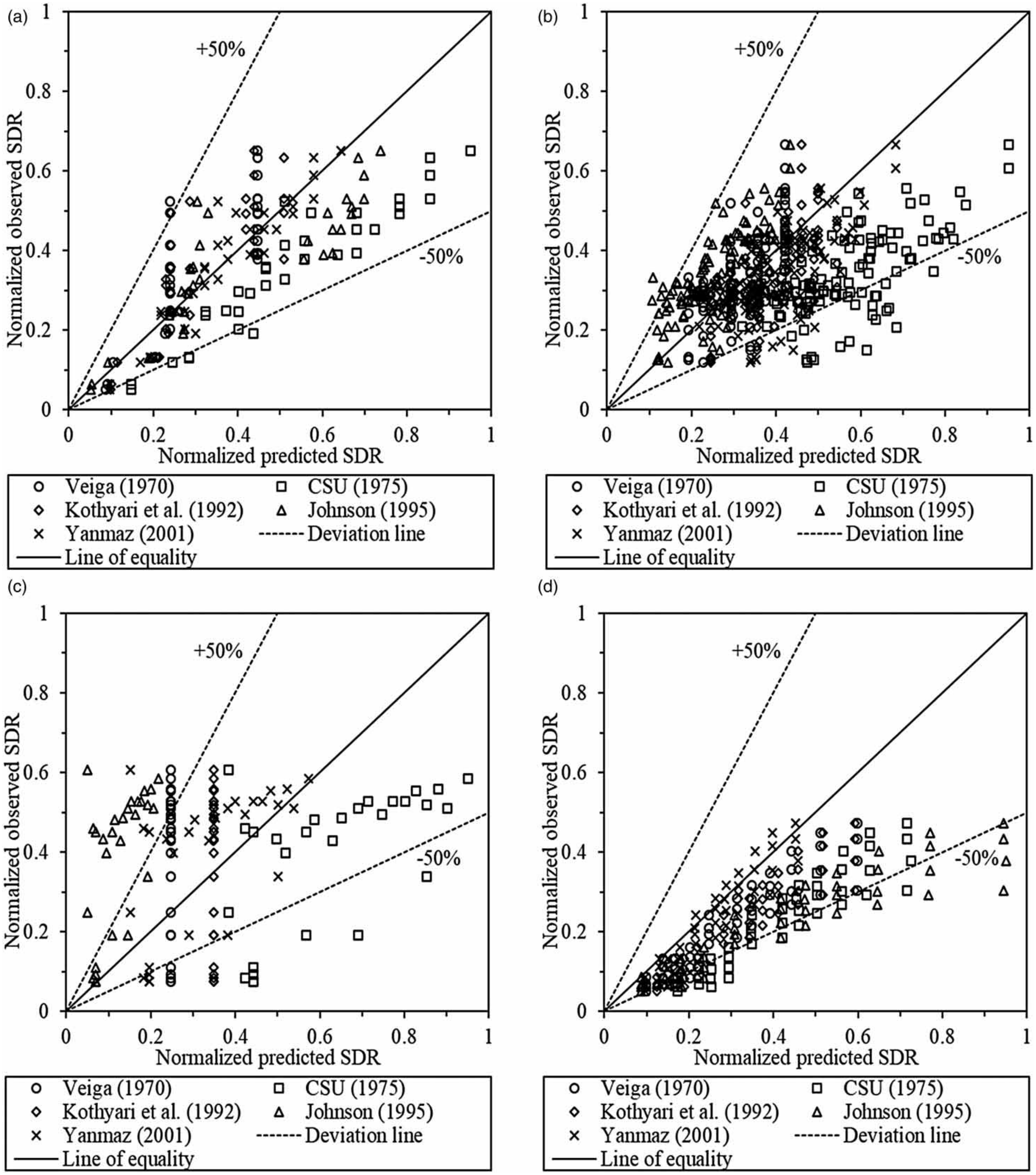

Figure 6 | Normalized observed vs predicted scour depth ratio variation (d_s/b) in LBS condition of various researchers such as (a) Jain & Fischer (1979); (b) Chiew (1984); (c) Chiew & Lim (2003); (d) Bozkus & Yildiz (2004); (e) Sheppard & Miller (2006); (f) Zhao *et al.* (2010); (g) Ettmer *et al.* (2015); and (h) Ismael *et al.* (2015). (*continued*.).

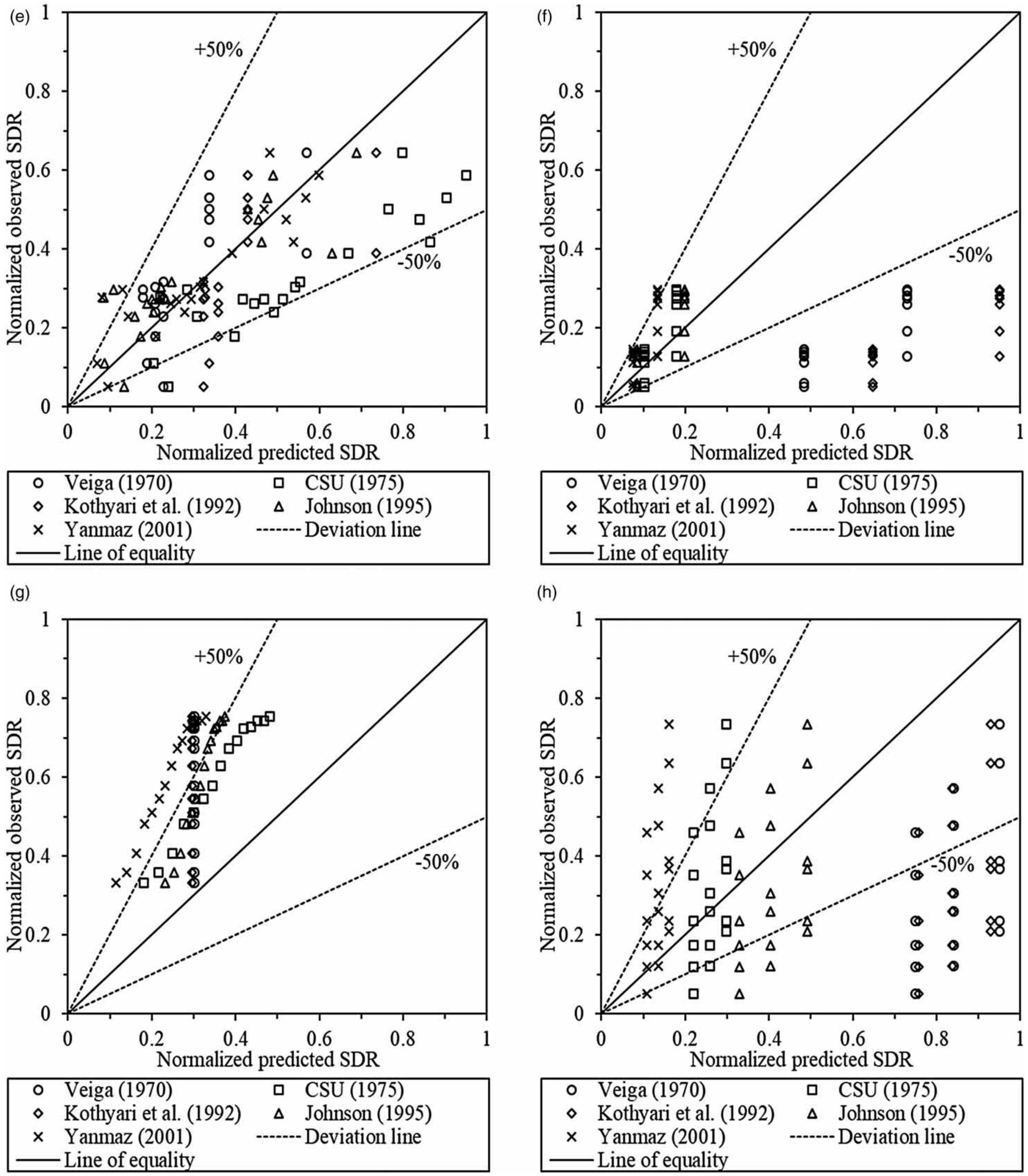

Figure 6 | Continued.

CONCLUSIONS

The paper presents more than 80 experimental/field data sets and more than 60 scour depth predictive equations developed over the past seven decades for CWS and LBS conditions. Each equation has limitations, including the type of scouring, the number of data used, the combination of input parameters, and the range of input data used in their development. From the present review of different scour depth predictive models and the application of each to different data points, the following conclusions and recommendations are made:

- The factors affecting scour depth under CWS and LBS are found to be pier width, flow depth, velocity of flow, bed sediment size, standard deviation of bed material, Froude number, and pier correction factors.
- In the case of the CWS condition, it is found that the equilibrium scour depth decreases at a faster rate as flow depth declines with smaller values of relative flow depth (y/b). The bed roughness caused a steeper pressure gradient and raised the amount of bed shear stress. The maximum scour depth around the bridge pier increases with pier diameter, approach velocity, and critical velocity ratio and decreases with bed particle size in CWS. It also decreases as armor layer particle size increases.
- From the LBS condition, it is found that scour depth decreases above the critical velocity and then increases to a maximum value at the transition to flatbed conditions. At higher velocities, the equilibrium scour depth decreases due to the formation of antidunes on the bed surface. It is also found that the scour depth under live bed conditions is generally significantly higher than under clear water conditions and further increases with flow intensity.
- For CWS, Neill (1964), CSU (1975), Yanmaz (1989), Ettema *et al.* (1998), and Pandey *et al.* (2018) and in the case of LBS around bridge pier, Veiga (1970), CSU (1975), Kothyari *et al.* (1992b), and Yanmaz (2001) are recommended to use for predicting scour depth. While utilizing these equations, the input data set range of influencing parameters must be considered while selecting the aforementioned scour depth predictive equations.

Application of all available scour depth predictive models to estimate scouring around the bridge pier is inappropriate for field scenarios. If clear water scour or live bed scour conditions are present around the bridge pier, it is recommended to prefer the clear water scour equation or live bed scour equation, respectively.

The primary reason for global bridge collapses is recognized as the scour of bridge piers. Climate change associated with global warming has the capacity to worsen bridge scour, primarily due to increased river flooding. Bridge engineers need to understand evolving climate risks for effective long-term strategies. Insufficient data and omissions in scour risk assessments create uncertainties. Therefore, more research is recommended by considering different flow, roughness, and non-circular shapes, i.e., square, rectangular, elliptical, and chamfered under temporal scouring conditions. Additionally, exploring the impact of climate change linked to global warming is essential for advancing studies on river flooding conditions.

AUTHORS CONTRIBUTION

A.B. rendered support in collecting experimental data, analyzing the data, using different scour depth predictive empirical equations and writing the first draft of the manuscript; and B.S.D. rendered support in article supervising, data analysis and discussion, concluding remarks, and manuscript proofreading.

FUNDING

The authors declare that the research described in this work is not supported financially.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abd El-Hady Rady, R. 2020 Prediction of local scour around bridge piers: Artificial-intelligence-based modeling versus conventional regression methods. *Applied Water Science* **10** (2), 57.

Abdelmonem, Y., Mostafa, Y. E. & Atta, D. M. 2009 Validation of bridge pier and abutment scour equations. In: *Sixth International Conference on Environmental Hydrology with the 1st Symposium on Coastal & Port Engineering*. ASCEESC, Cairo.

Abdulkathum, S., Al-Shaikhli, H. I., Al-Abody, A. A. & Hashim, T. M. 2023 Statistical analysis approaches in scour depth of bridge piers. *Civil Engineering Journal* **9** (1), 143–153.

AbGhani, A., Azamathulla, H., Yahaya, A. S. & Zakaria, N. A. 2010 Revised equations for bridge pier scour prediction. In: *Hydro-2010 National Conference on Hydraulics, Water Resources, Coastal and Environmental Engineering at M.M. Engg College, Mullana, Ambala*, India.

Aggarwal, M. K. 2001 Case history of failure of bridge due to natural calamity. *Indian Highways* **29** (3), 11–14.

Ahmed, F. & Rajaratnam, N. 1998 Flow around bridge piers. *Journal of Hydraulic Engineering* **124** (3), 288–300. https://doi.org/10.1061/(ASCE)0733-9429(1998)124:3(288).

Akhlaghi, E., Babarsad, M. S., Derikvand, E. & Abedini, M. 2019 Assessment of the effects of different parameters on scour around single piers and pile groups: A review. *Archives of Computational Methods in Engineering.* **27** (1), 183–197. https://doi.org/10.1007/s11831-018-09304-w.

Akhlaghi, E., Babarsad, M. S., Derikvand, E. & Abedini, M. 2020 Assessment the effects of different parameters to rate scour around single piers and pile groups: A review. *Archives of Computational Methods in Engineering* **27** (1), 183–197. https://doi.org/10.1007/s11831-018-09304-w.

Aksoy, A. O., Bombar, G., Arkis, T. & Guney, M. S. 2017 Study of the time-dependent clear water scour around circular bridge piers. *Journal of Hydrology and Hydromechanics* **65** (1), 26. https://doi.org/10.1515/johh-2016-0048].

Ali, K. H. & Karim, O. 2002 Simulation of flow around piers. *Journal of Hydraulic Research* **40** (2), 161–174.

Aminoroayaie Yamini, O., Mousavi, S. H., Kavianpour, M. R. & Movahedi, A. 2018 Numerical modeling of sediment scouring phenomenon around the offshore wind turbine pile in marine environment. *Environmental Earth Sciences* **77**, 1–15.

Arneson, L. A., Zevenbergen, L. W., Lagasse, P. F. & Clopper, P. E. 2012 Evaluating scour at bridges. *Hydraulic Engineering Circular No. 18*, 5th edition, 1–340.

Azamathulla, H. M., Ghani, A. A., Zakaria, N. A. & Guven, A. 2010 Genetic programming to predict bridge pier scour. *Journal of Hydraulic Engineering* **136** (3), 165–169.

Baranwal, A., Das, B. S. & Setia, B. 2023a A comparative study of scour around various shaped bridge piers. *Engineering Research Express* **5** (1), 015052.

Baranwal, A., Das, B. S. & Choudhary, A. 2023b Bridge pier scour depth prediction model – a review. Fluid mechanics and hydraulics. In: *Proceedings of 26th International Conference on Hydraulics, Water Resources and Coastal Engineering (HYDRO-2021)*, Springer Nature. doi: 10.1007/978-981-19-9151-6_7.

Barbhuiya, A. K. & Dey, S. 2004 Local scour at abutments: A review. *Sadhana* **29** (5), 449–476.

Basak, V., Basamisli, Y. & Ergun, O. 1975 Maximum equilibrium scour depth around linear-axis square cross-section pier groups. *Devlet su Isteri Genel Mudurlugu*, Ankara, Turkey.

Basak, V., Baslamisli, Y. & Ergun, O. 1977 Local scour depths around circular pier groups aligned with the flow. *Report No. 641, State Hydraulic Works*, Ankara, Turkey. (In Turkish.)

Basu, B. K. & Gupta, A. K. 2003 Scour consideration for bridge foundation in Bouldery river bed – case study. *Indian Highways* **31** (1), 43–57.

Bateni, S. M., Borghei, S. M. & Jeng, D. S. 2007 Neural network and neuro-fuzzy assessments for scour depth around bridge piers. *Engineering Applications of Artificial Intelligence* **20** (3), 401–414.

Benedict, S. T. & Caldwell, A. W. 2014 A pier-scour database – 2,427 field and laboratory measurements of pier scour. *U. S. Geological Survey Data Series* **845**, 1–22.

Blench, T. 1960 Discussion of scour at bridge crossings. *Journal of the Hydraulics Division* **86** (5), 193–194.

Boehmler, E. M. & Olimpio, J. R. 2000 *Evaluation of pier-scour measurement methods and pier-scour predictions with observed scour measurements at selected bridge sites in New Hampshire, 1995-98 (No. FHWA-NH-RD-12323E)*. Department of Transportation, New Hampshire, USA.

Bordbar, A., Sharifi, S. & Hemida, H. 2021 Investigation of the flow behavior and local scour around single square-shaped cylinders at different positions in live-bed. *Ocean Engineering* **238**, 109772. https://doi.org/10.1016/j.oceaneng.2021.109772.

Bozkus, Z. & Yildiz, O. 2004 Effects of inclination of bridge piers on scouring depth. *Journal of Hydraulic Engineering* **130** (8), 827–832.

Brandimarte, L., Paron, P. & Di Baldassarre, G. 2012 Bridge pier scour: A review of processes, measurements and estimates. *Environmental Engineering and Management Journal* **11** (5), 975–989.

Brath, A. & Montanari, A. 2000 The effects of the spatial variability of soil infiltration capacity in distributed flood modeling. *Hydrological Processes* **14** (15), 2779–2794.

Breusers, H. N. C. 1965 Scour around drilling platforms. *Bulletin Hydraulic Research, International Assoc. for Hydraulic Research* **19**, 276.

Breusers, H. N. C. 1971 Local scour near offshore structures. In: *Proc. Symp. on Offshore Hydrodynamics*, Wageningen.

Breusers, H. N. C. & Raudkivi, A. J. 1991 *Scouring. IAHR Hydraulic Structures Design Manual 2*. AA Balkema, Rotterdam, The Netherlands.

Breusers, H. N. C., Nicollet, G. & Shen, H. W. 1977 Local scour around cylindrical piers. *Journal of Hydraulic Research* **15** (3), 211–252. doi:10.1080/00221687709499645.

Briaud, J. L. 2015 Scour depth at bridges: Method including soil properties. I: Maximum scour depth prediction. *Journal of Geotechnical and Geoenvironmental Engineering* **141** (2), 04014104.

Briaud, J. L. & Oh, S. J. 2010 Bridge foundation scour. *Geotechnical Engineering Journal of the SEAGS & AGSSEA* **41** (2), 1–16.

Briaud, J. L., Ting, F. C., Chen, H. C., Gudavalli, R., Perugu, S. & Wei, G. 1999 SRICOS: Prediction of scour rate in cohesive soils at bridge piers. *Journal of Geotechnical and Environmental Engineering* **125** (4), 237–246.

Briaud, J. L., Ting, F., Chen, H., Cao, Y., Han, S. & Kwak, K. 2001 Erosion function apparatus for scour rate predictions. *Journal of Geotechnical and Geo Environmental Engineering* **127** (2), 105–113.

Briaud, J. L., Chen, H. C., Li, Y., Nurtjahyo, P. & Wang, J. 2005 SRICOS-EFA method for contraction scour in fine-grained soils. *Journal of Geotechnical and Geoenvironmental Engineering* **131** (10), 1283–1294.

Carstens, M. R. 1966 Similarity laws for localized scour. *Journal of the Hydraulics Division* **92** (3), 13–36.

Chabert, J. & Engeldinger, P. 1956 'Etude des affouillements autour des piles de points' Bureau Central d.Etudes les Equipment d.Outre-Mer, Laboratoire National d.Hydraulique, France.

Chang, W. Y., Lai, J. S. & Yen, C. L. 2004 Evolution of scour depth at circular bridge piers. *Journal of Hydraulic Engineering* **130** (9), 905–913. doi: 10.1061/(ASCE)0733-9429(2004)130:9(905).

Chee, R. K. W. 1982 Live-bed scour at bridge piers. *Rep. No. 290, School of Engg.*, University of Auckland, Auckland, New Zealand.

Chiew, Y. M. 1984 *Local Scour at Bridge Piers*. *PhD Thesis*, Department of Civil Engineering, Auckland University, Auckland, New Zealand.

Chiew, Y. M. 1992 Scour protection at bridge pier. *Journal of Hydraulic Engineering* **118** (9), 1260–1269.

Chiew, Y. M. & Lim, F. H. 2000 Failure behavior of riprap layer at bridge piers under live-bed conditions. *Journal of Hydraulic Engineering* **126** (1), 43–55.

Chiew, Y. & Lim, S. 2003 Protection of bridge piers using a sacrificial sill. *Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering* **156** (1), 53–62.

Chiew, Y. M. & Melville, B. W. 1987 Local scour around bridge piers. *Journal of Hydraulic Research* **25** (1), 15–26. https://doi.org/10.1080/00221688709499285.

Chin, C. O., Melville, B. W. & Raudkivi, A. J. 1994 Streambed armoring. *Journal of Hydraulic Engineering* **120** (8), 899–918.

Chitale, S. V. 1962 Scour at bridge crossings. *Transactions of the American Society of Civil Engineers* **127** (1), 191–196.

Chitale, W. S. 1988 Estimation of scour at bridge piers. *Journal of Irrigation and Power, India* **45** (1), 57–68.

Choi, S. U. & Cheong, S. 2006 Prediction of local scour around bridge piers using artificial neural networks 1. *JAWRA Journal of the American Water Resources Association* **42** (2), 487–494.

Choudhary, A., Das, B. S., Devi, K. & Khuntia, J. R. 2023 ANFIS and GEP based model for prediction of scour depth around bridge pier in clear-water scouring and live-bed scouring conditions. *Journal of Hydroinformatics* **25** (3), 1004–1028.

Clopper, P. E., Lagasse, P. F. & Zevenbergen, L. W. 2007 Bridge Pier Scour Countermeasures. presented at World Environmental and Water Resources Congress 2007: Restoring Our Natural Habitat, Tampa, FL, USA, 1–13. https://doi.org/10.1061/40927(243)380.

Coleman, N. L. 1971 Analyzing laboratory measurements of scour at cylindrical piers in sand beds. In: *Proc. 14th Congress IAHR, International Association of Hydraulic Research*. International Association for Hydraulic Research, Madrid, Spain, pp. 307–313.

Colorado State University (CSU) 1975 Highways in the river environment, hydraulic and environmental design considerations. In: *The Federal Highway Administration, U.S. Department of Transportation*, Washington, DC, USA.

Das, S., Ghosh, R., Das, R. & Mazumdar, A. 2014 Clear water scour geometry around circular piers. *Ecology Environment and Conservation* **20** (2), 479–492.

Dey, S. & Raikar, R. V. 2005 Scour in long contractions. *Journal of Hydraulic Engineering* **131** (12), 1036–1049. doi: 10.1061/(ASCE)0733-9429(2005)131:12(1036).

Dey, S. & Sarkar, A. 2006 Scour downstream of an apron due to submerged horizontal jets. *Journal of Hydraulic Engineering* **132** (3), 246–257.

Dey, S. & Raikar, R. 2007 Characteristics of horseshoe vortex in developing scour holes. *Journal of Hydraulics Engineering* **133**, 399–413.

Dey, S., Bose, S. K. & Sastry, G. L. 1995 Clear water scour at circular piers: A mode. *Journal of Hydraulic Engineering* **121** (12), 869–876.

Dongguang, G., Pasada, L. & Nordin, C. F. 1993 *Pier Scour Equations Used in the People's Republic of China: Review and Summary, Report No. FHWA-SA-93-076*.

Ebrahimi, M., Kripakaran, P., Prodanović, D. M., Kahraman, R., Riella, M., Tabor, G. & Djordjević, S. 2018 Experimental study on scour at a sharp-nose bridge pier with debris blockage. *Journal of Hydraulic Engineering* **144** (12), 04018071. doi: 10.1061/(ASCE)HY.1943-7900.0001516.

El-Saiad, A. A. 1998 Local scour around bridge piers. *Engineering Research Journal* **57**, 129–137.

Ettema, R. 1980 *Scour at Bridge Piers. Rep. No. 216*. School of Eng. University of Auckland, Auckland, New Zealand.

Ettema, R., Mostafa, E. A., Melville, B. W. & Yassin, A. A. 1998 Local scour at skewed piers. *Journal of Hydraulic Engineering* **124** (7), 756–759. https://doi.org/10.1061/(ASCE)0733-9429(1998)124:7(756).

Ettema, R., Nakato, T. & Muste, M. V. I. 2006 An illustrated guide for monitoring and protecting bridge waterways against scour. *IIHR-Hydroscience and Engineering*, University of Iowa. Project No. TR-515.

Ettema, R., Melville, B. W. & Constantinescu, G. 2011 *Evaluation of Bridge Scour Research: Pier Scour Processes and Predictions*. Transportation Research Board of the National Academies, Washington, DC, USA.

Ettmer, B., Orth, F. & Link, O. 2015 Live-bed scour at bridge piers in a lightweight polystyrene bed. *Journal of Hydraulic Engineering* **141** (9), 04015017. doi: 10.1061/(ASCE)HY.1943-7900.0001025.

Fischenich, C. & Landers, M. 1999 Computing scour: EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-05), U.S. Army Engineer Research and Development Center, Vicksburg, MS, USA.

Froehlich, D. C. 1988 Abutment scour prediction. In: *68th TRB Annual Meeting*, Washington, DC.

Froehlich, D. C. 1991 Upper confidence limit of local pier-scour predictions. *Transportation Research Record* **1290**, 224–235.

Gao, D., Posada, G. & Nordin, C. F. 1993 Pier scour equations used in the People's Republic of China-Review and summary. FHWA-SA-93076. US Dept. of Transportation, Federal Highway Administration, Washington, DC, USA, pp. 1031–1036.
Garg, V., Setia, B. & Verma, D. V. S. 2005 Reduction of scour around a bridge pier by multiple collar plates. *ISH Journal of Hydraulic Engineering* **11** (3), 66–80. https://doi.org/10.1080/09715010.2005.10514802.
Garg, V., Setia, B., Singh, V. & Kumar, A. 2022 Scour protection around bridge pier and two-piers-in-tandem arrangement. *ISH Journal of Hydraulic Engineering* **28** (3), 251–263.
Ghorbani, B. 2008 A field study of scour at bridge piers in flood plain rivers. *Turkish Journal of Engineering and Environmental Sciences* **32** (4), 189–199.
Gülbahar, N. 2009 Case study: Comparing performance of pier scour equations using field data for the Gediz Bridge, Manisa, Turkey. *Canadian Journal of Civil Engineering* **36** (5), 801–812. doi:10.1139/L09-021.
Guo, J. 2012 Pier scour in clear water for sediment mixtures. *Journal of Hydraulic Research* **50** (1), 18–27. http://dx.doi.org/10.1080/00221686.2011.644418.
Hamill, L. 2014 *Bridge Hydraulics*. CRC Press, Boca Raton, FL, USA.
Hancu, S. 1971 Sur le calcul des affouillements locaux dams la zone des piles des ponts. In: *Proceedings of the 14th IAHR Congress*, Paris, France 3 (1), 299–313.
Hassanzadeh, Y., Jafari-Bavil-Olyaei, A., Aalami, M. T. & Kardan, N. 2019 Experimental and numerical investigation of bridge pier scour estimation using ANFIS and teaching–learning-based optimization methods. *Engineering with Computers* **35**, 1103–1120.
Hoffmans, G. J. C. M. & Verheij, H. J. 2021 *Scour Manual, Current-Related Erosion*. CRC Press, Taylor & Francis Group, London, UK.
Inglis, S. C. 1949 Maximum depth of scour flatheads of guide bands and groynes, pier noses, and downstream bridges-the behavior and control of rivers and canals. *Indian Waterways Experimental Station*, Poona, India, 327–348.
Ismael, A., Gunal, M. & Hussein, H. 2015 Effect of bridge pier position on scour reduction according to flow direction. *Arabian Journal for Science and Engineering* **40** (6), 1579–1590. doi:10.1007/s13369-015-1625-x.
Jain, S. C. & Fischer, E. E. 1979 *Scour Around Circular Bridge Piers at High Froude Numbers FHWA-RD*. Final Rpt. No. 79–104.
Jain, B. P. & Modi, P. N. 1986 Comparative study of various formulae on scour around bridge piers. *Journal of the Institution of Engineers* **67**, 149–159.
Jia, K., Xu, C., El, N., Dou, M. H., Pan, P. R. & Song, J. 2023 Inertial and kinematic interactions of bridge-pile group subjected to liquefaction induced lateral spreading: Large-scale shaking table experiments. *Earthquake Engineering & Structural Dynamics* **52** (4), 1267–1290.
Johnson, P. A. 1992 Reliability-based pier scour engineering. *Journal of Hydraulic Engineering* **118** (10), 1344–1358. https://doi.org/10.1061/(ASCE)0733-9429(1992)118:10(1344).
Johnson, P. A. 1995 Comparison of pier-scour equations using field data. *Journal of Hydraulic Engineering* **121** (8), 626–629. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:8(626).
Jones, J. S. 1984 Comparison of prediction equations for bridge pier and abutment scour. In: *Tramp. Res. Record 950: 2nd Bridge Eng. Conf.*, Volume 2. Transportation Research Board, Washington, DC USA.
Kandasamy, J. K. & Melville, B. W. 1998 Maximum local scour depth at bridge piers and abutments. *Journal of Hydraulic Research* **36** (2), 183–198.
Karim, M. F. & Holly Jr., F. M. 1986 Armoring and sorting simulation in alluvial rivers. *Journal of Hydraulic Engineering* **112** (8), 705–715.
Kaveh, K., Mai, D. N., Pham, Q. B. & Anh, D. T. 2021 A hybrid feed-forward neural network with grasshopper optimization for observing pattern of scour depth around bridge piers. *Arabian Journal of Geosciences* **14**, 1–11.
Kayadelen, C., Altay, G., Önal, S. & Önal, Y. 2022 Sequential minimal optimization for local scour around bridge piers. *Marine Georesources & Geotechnology* **40** (4), 462–472.
Khalid, M., Muzzammil, M. & Alam, J. 2021 A reliability-based assessment of live bed scour at bridge piers. *ISH Journal of Hydraulic Engineering* **27** (1), 105–112.
Khan, M., Azamathulla, H. M. & Tufail, M. 2012 Gene-expression programming to predict pier scour depth using laboratory data. *Journal of Hydro Informatics* **14** (3), 628–645.
Khan, M., Tufail, M., Ajmal, M., Haq, Z. U. & Kim, T. W. 2017 Experimental analysis of the scour pattern modeling of scour depth around bridge piers. *Arabian Journal for Science and Engineering* **42**, 4111–4130.
Kilinç, B. B. 2019 *Experimental Investigation of Local Scouring Around Bridge Piers Under Clear-Water Conditions*.
Kothyari, U. C. 1989 *Scour Around Bridge Piers*. *Doctoral Thesis*, University of Roorkee, India.
Kothyari, U. C., Garde, R. C. J. & Ranga Raju, K. G. 1992a Temporal variation of scour around circular bridge piers. *Journal of Hydraulic Engineering* **118** (8), 1091–1106. https://doi.org/10.1061/(ASCE)0733-9429(1992)118:8(1091).
Kothyari, U. C., Garde, R. C. J. & Ranga Raju, K. G. 1992b Live-bed scour around cylindrical bridge piers. *Journal of Hydraulic Research* **30** (5), 701–715. https://doi.org/10.1080/00221689209498889.
Kothyari, U. C., Hager, W. H. & Oliveto, G. 2007 Generalized approach for clear-water scour at bridge foundation elements. *Journal of Hydraulic Engineering* **133** (11), 1229–1240. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:11(1229).
Kumar, V. 1996 *Reduction of Scour Around Bridge Pier Using Protective Devices*. *PhD Thesis*, University of Roorkee, Roorkee, India.
Kumar, V., Raju, K. G. R. & Vittal, N. 1999 Reduction of local scour around bridge piers using slots and collars. *Journal of Hydraulic Engineering* **125** (12), 1302–1305.

Kumar, A., Baranwal, A. & Das, B. S. 2023 Modelling of clear water scour depth around bridge piers using M5 tree and ANN-PSO. *AQUA – Water Infrastructure, Ecosystems and Society* **72** (8), 1386–1403.

Kwak, K. 2001 Prediction of scour depth versus time for bridge piers in the case of multi-flood and multi-layer soil system. *KSCE Journal of Civil Engineering* **5**, 67–74.

Lanca, R. M., Fael, C. S., Maia, R. J., Pêgo, J. P. & Cardoso, A. H. 2013 Clear-water scour at comparatively large cylindrical piers. *Journal of Hydraulic Engineering* **139** (11), 1117–1125. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000788.

Larras, J. 1963 Profondeurs maximales d'èrosion des fonds mobiles autour des piles en rivière. *Ann. Ponts et Chaussèes* **133** (4), 411–424.

Laursen, E. M. 1958 Scour at bridge crossings. *Bulletin No. 8 Iowa Highway Research Board*, Ames, IA, USA.

Laursen, E. M. 1962 Scour at bridge crossings. *Transactions of the American Society of Civil Engineers* **127** (1), 166–209.

Laursen, E. M. 1963 An analysis of relief bridge scour. *Journal of the Hydraulics Division* **89** (HY3), 93–118. Hydro 2010 India.

Laursen, E. M. & Toch, A. 1956 Scour around bridge piers and abutments. Bulletin No. 4, Iowa Highway Research Board, Ames, IA.

Lee, S. O. & Sturm, T. W. 2009 Effect of sediment size scaling on physical modeling of bridge pier scour. *Journal of Hydraulic Engineering* **135** (10), 793–802. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000091.

Lee, H. J., Chang, H. J. & Heo, T. Y. 2019 Statistical characteristics of pier-scour equations for scour depth calculation. *Journal of Korean Society of Disaster and Security* **12** (3), 51–57.

Lim, F. H. & Chiew, Y. M. 2001 Parametric study of riprap failure around bridge piers. *Journal of Hydraulic Research* **39** (1), 61–72.

Link, O. 2006 Time scale of scour around a cylindrical pier in sand and gravel. Third Chinese-German Jt. Symp. Coast. *Ocean Eng*. Natl. Cheng K. Univ. Tainan.

Link, O., Henríquez, S. & Ettmer, B. 2019 Physical scale modelling of scour around bridge piers. *Journal of Hydraulic Research* **57** (2), 227–237. https://doi.org/10.1080/00221686.2018.1475428.

Liu, H. K., Chang, F. M. & Skinner, M. M. 1961 Effect of bridge constriction on scour and backwater, *Eng. Res. Ctr*., Colorado State Univ., Fort Collins, Col.

Lodhi, A. S., Jain, R. K., Sharma, P. K. & Karna, N. 2014 Time evolution of clear water bridge pier scour. In: *Proceedings of International Civil Engineering Symposium*. VIT University Vellore, India, pp. 252–260.

Melville, B. W. 1975 *Local Scour at Bridge Sites*. *PhD Thesis*, School of Engineering University of Auckland, Auckland, New Zealand.

Melville, B. W. 1984 Live-bed scour at bridge sites. *Journal of Hydraulic Engineering* **110** (9), 1234–1247.

Melville, B. W. 1997 Pier and abutment scour-an integrated approach. *Journal of Hydraulic Engineering* **123** (2), 125–136. https://doi.org/10.1061/(ASCE)0733-9429(1997)123:2(125).

Melville, B. W. & Chiew, Y. M. 1999 Time scale for local scour at bridge piers. *Journal of Hydraulic Engineering* **125** (1), 59–65. https://doi.org/10.1061/(ASCE)0733-9429(1999)125:1(59).

Melville, B. W. & Coleman, S. E. 2000 *Bridge Scour*. Water Resources Publication, Highlands Ranch, CO, USA.

Melville, B. W. & Sutherland, A. J. 1988 Design method for local scour at bridge piers. *Journal of Hydraulic Engineering* **114** (10), 1210–1226. https://doi.org/10.1061/(ASCE)0733-9429(1988)114:10(1210).

Mia, M. F. & Nago, H. 2003 Design method of time-dependent local scour at circular bridge pier. *Journal of Hydraulic Engineering* **129** (6), 420–427. https://doi.org/10.1061/(ASCE)0733-9429(2003)129:6(420).

Mohamed, T. A., Noor, M. J., Halim, A. G., Yusuf, B. & Saed, K. 2007 Physical modelling of local scouring around bridge piers in erodible bed. *Journal of King Saud University* **19** (2), 195–207. https://doi.org/10.1016/S1018-3639(18)30947-4.

Mohamed, T. H., Noor, M. J. M. M., Ghazali, A. H. & Huat, B. B. K. 2005 Validation of some bridge pier scour formulae using field and laboratory data. *American Journal of Environmental Science* **1** (2), 119–125.

Molinas, A. 2004 *Bridge Scour in Non-Uniform Sediment Mixtures and in Cohesive Materials. Report FHWA–RD-03-083*. US Department of Transportation, Federal Highway Administration, Washington, DC.

Mueller, D. S. 1996 *Local Scour at Bridge Piers in non-Uniform Sediment Under Dynamic Conditions*. PhD Thesis, Colorado State Univ., Fort Collins, Colo.

Mueller, D. S. & Wagner, C. R. 2005 *Field Observations and Evaluations of Streambed Scour at Bridges no. FHWA-RD-03-052*. Federal Highway Administration. Office of Research, Development, and Technology. United States.

Muzzammil, M. & Gangadhariah, T. 2003 The mean characteristics of horseshoe vortex at a cylindrical pier. *Journal of Hydraulic Research* **41**, 285–297.

Mylonakis, G., Nikolaou, A. & Gazetas, G. 1997 Soil-pile-bridge seismic interaction: Kinematic and inertial effects. Part I: Soft soil. *Earthquake Engineering and Structural Dynamics* **26**, 337–359.

Nadal, N. C. 2007 Expected flood damage to buildings in riverine and coastal zones. *Dissertation Abstracts International* 68 (12).

Neil, C. R. 1973 *Guide to Bridge Hydraulics*. Roads and Transportation Assoc. of Canada, University of Toronto Press, Toronto, Canada, p. 191.

Neill, C. R. 1964 *River Bed Scour: A Review*. Res. Council of Alberta, Bridge Engineers, Contract No. 281, Calgary, Alberta, Canada.

Neill, C. R. 1968 Note on abutment and pier scour in coarse bed material. *Journal of Hydraulic Research* **6**, 173–176.

Nil, Baranwal, A. & Das, B. S. 2023 Clear-water and live-bed scour depth modelling around bridge pier using support vector machine. *Canadian Journal of Civil Engineering* **50** (6), 445–463.

Okhravi, S., Gohari, S., Alemi, M. & Maia, R. 2022 Effects of bed-material gradation on clear water scour at single and group of piles. *Journal of Hydrology and Hydromechanics* **70** (1), 114–127.

Pal, M., Singh, N. K. & Tiwari, N. K. 2013 Pier scour modelling using random forest regression. *ISH Journal of Hydraulic Engineering* **19** (2), 69–75. https://doi.org/10.1080/09715010.2013.772763.

Pandey, M., Sharma, P. K., Ahmad, Z. & Karna, N. 2018 Maximum scour depth around bridge pie in gravel bed streams. *Natural Hazards* **91**, 819–836. https://doi.org/10.1007/s11069-017-3157-z.

Pandey, M., Chen, S., Sharma, P. K., Ojha, C. S. P. & Kumar, V. 2019 Local scour of armor layer processes around the circular pier in non-uniform gravel bed. *Water* **11** (7), 1421. doi:10.3390/w11071421.

Pandey, M., Pu, J. H., Pourshahbaz, H. & Khan, M. A. 2022 Reduction of scour around circular piers using collars. *Journal of Flood Risk Management*. https://doi.org/10.1111/jfr3.12812.

Pineiro, G., Perelman, S., Guerschman, J. P. & Paruelo, J. M. 2008 How to evaluate models: Observed vs. predicted or predicted vs. observed? *Ecological Modelling* **216** (3–4), 316–322. https://doi.org/10.1016/j.ecolmodel.2008.05.006.

Pokharel, S. 2017 *Evaluating and Understanding of Bridge Scour Calculation*. *MSc Thesis*, Auburn University, Alabama, USA.

Qasim, R. M., Mohammed, A. A. & Abdulhussein, I. A. 2022 An investigating of the impact of bed flume discordance on the weir-gate hydraulic structure. *HighTech and Innovation Journal* **3** (3), 341–355.

Raikar, R. V. & Dey, S. 2005 Clear-water scour at bridge piers in fine and medium gravel beds. *Canadian Journal of Civil Engineering* **32** (4), 775–781. https://doi.org/10.1139/l05-022.

Rathod, P. & Manekar, V. L. 2022 Gene expression programming to predict local scour using laboratory and field data. *ISH Journal of Hydraulic Engineering* **41** (3), 1–9. https://doi.org/10.1080/09715010.2020.1846144.

Raudkivi, A. J. 1986 Functional trends of scour at bridge piers. *Journal of Hydraulic Engineering* **112** (1), 1–13.

Raudkivi, A. J. & Ettema, R. 1983 Clear water scour at cylindrical piers. *Journal of Hydraulic Engineering* **109** (3), 338–350. https://doi.org/10.1061/(ASCE)0733-9429(1983)109:3(338).

Research and Design Standard Organization (RDSO) 1987 *Scour Around Bridge Piers on Alluvial Rivers, Report No. 1/87, Ministry of Railways*. Govt. of India, India.

Richardson, E. V. & Davis, S. R. 1995 *Evaluating Scour at Bridges*. Report No. FHWA-IP-90-017, Hydraulic Engineering Circular No.18 (HEC-18) (Third Edition), Office of Technology Applications, HTA-22, Federal Highway Administration, US Department of Transportation, Washington DC, USA.

Richardson, E. V. & Davis, S. R. 2001 *Evaluating Scour at Bridge – Fourth Edition*. Hydraulic Engineering Circular No. 18, Publication No. FHWA NHI 01-001, U.S. Department of Transportation, USA.

Richardson, E. V., Harrison, L. J. & Richardson, J. R. 1993 Evaluating Scour at Bridges: Federal Highway Administration *Hydraulic Engineering Circular (HEC*), 1993 revision. FHWA-IP-90-017, Washington, DC.

Schneible, D. E. 1951 *An Investigation of the Effect of Bridge Pier Shape on the Relative Depth of Scour*. MSc Thesis, Graduate College of the State, University of Iowa, Iowa City, Iowa.

Shamshirband, S., Mosavi, A. & Rabczuk, T. 2020 Particle swarm optimization model to predict scour depth around a bridge pier. *Frontiers of Structural and Civil Engineering* **14**, 855–866.

Sharafi, H., Ebtehaj, I., Bonakdari, H. & Zaji, A. H. 2016 Design of a support vector machine with different kernel functions to predict scour depth around bridge piers. *Natural Hazards* **84**, 2145–2162.

Sharp, J. A. & McAlpin, T. O. 2022 Case study: Experimental investigation into the feasibility of pier nose extensions to reduce local scour around bridge piers. *Journal of Hydraulic Engineering* **148** (1), 05021010.

Shen, H. W. 1971 *Scour Near Piers*, *River Mechanics II*, Chap.23, Ft. Collins, Colo.

Shen, H. W., Schneider, V. R. & Karaki, S. 1966 *Mechanics of Local Scour*. Report, Dept. of Commerce, National Bureau of Standards, Inst. For Appl. Technol., Washington, DC, USA.

Shen, H. W., Schneider, V. R. & Karaki, S. 1969 Local scour around bridge piers. *Journal of the Hydraulics Division* **14** (3), 120–153.

Sheppard, D. M. 2003 Large scale and live bed local pier scour experiments. *Live Bed Experiments/Phase 2 Final Rep*., Florida Dept. of Transportation.

Sheppard, D. M. & Miller, M. J. 2006 Live-bed local pier scour experiments. *Journal of Hydraulic Engineering* **132**, 635–642.

Sheppard, D. M., Odeh, M. & Glasser, T. 2004 Large scale clear-water local pier scour experiments. *Journal of Hydraulic Engineering* **130** (10), 957–963. https://doi.org/10.1061/(ASCE)0733-9429(2004)130:10(957).

Sheppard, D. M., Demir, H. & Melville, B. W. 2011 Scour at wide piers and long skewed piers. *NCHRP Report 682, Transportation Res. Board of National Academies*, Washington, DC.

Sheppard, D. M., Melville, B. & Demir, H. 2014 Evaluation of existing equations for local scour at bridge piers. *Journal of Hydraulic Engineering* **140** (1), 14–23. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000800.

Shin, J. H. & Park, H. I. 2010 Neural network formula for local scour at piers using field data. *Marine Georesources and Geotechnology* **28** (1), 37–48.

Shirole, A. M. & Holt, R. C. 1991 *Planning for a Comprehensive Bridge Safety Assurance Program*. Transport Research Board, Washington, DC, pp. 137–142.

Silvia, C. S., Ikhsan, M. & Wirayuda, A. 2021 Analysis of scour depth around bridge piers with round nose shape by HEC-RAS 5.0. 7 Software. *In Journal of Physics: Conference Series* 1764(1):012151 IOP Publishing.

Tanaka, S. & Yano, M. 1967 Local scour around circular cylinder. *Proc. 12th IAHR Congress*, Fort Collins, CO 3:125–134.

Tarapore, Z. S. 1962 *A Theoretical and Experimental Determination of the Erosion Patterns Caused by Obstructions in an Alluvial Channel with Particular Reference to A Vertical Cylindrical Pier*. PhD Thesis, University of Minnesota, MN, USA.

Ting, F. C., Briaud, J. L., Chen, H. C., Gudavalli, R., Perugu, S. & Wei, G. 2001 Flume tests for scour in clay at circular piers. *Journal of Hydraulic Engineering* **127** (11), 969–978.

Tison, L. J. 1940 Erosion autour de piles de pont en rivière. *Annales des Travaux Publics de Belgique* **41** (6), 813–871.

Vaghefi, M., Solati, S. & Abdi Chooplou, C. 2021 The effect of upstream T-shaped spur dike on reducing the amount of scouring around downstream bridge pier located at a 180 sharp bend. *International Journal of River Basin Management* **19** (3), 307–318.

Veiga, L. 1970 Discussion to Shen *et al.* (1969); *Proc. ASCE,* 96 (8):1742–1747.

Vijayasree, B. A., Eldho, T. I., Mazumder, B. S. & Ahmad, N. 2019 Influence of bridge pier shape on flow field and scour geometry. *International Journal of River Basin Management* **17** (1), 109–129.

Vonkeman, J. K. & Basson, G. R. 2019 Evaluation of empirical equations to predict bridge pier scour in a non-cohesive bed under clear-water conditions. *Journal of the South African Institution of Civil Engineering* **61** (2), 2–20. http://dx.doi.org/10.17159/2309-8775/2019/v61n2a1.

Wang, C., Yuan, Y., Liang, F. & Tao, J. 2022 Experimental investigation of local scour around cylindrical pile foundations in a double-layered sediment under current flow. *Ocean Engineering* **251**, 111084.

Widyastuti, I., Thaha, M. A., Lopa, R. T. & Hatta, M. P. 2022 Dam-break energy of porous structure for scour countermeasure at bridge abutment. *Civil Engineering Journal* **8** (12), 3939–3951.

Wilson Jr., K. V. 1995 *Scour at Selected Bridge Sites in Mississippi, Reports No. 94-4241)*. US Geological Survey; Earth Science Information Centre, USA.

Yang, Y., Qi, M., Wang, X. & Li, J. 2020 Experimental study of scour around pile groups in steady flows. *Ocean Engineering* **195**, 106651.

Yanmaz, M. A. 1989 *Time Dependant Analysis of Clear Water Scour Around Bridge Piers*. *Doctorate Thesis*, METU, Ankora, Turkey.

Yanmaz, M. A. 2001 Uncertainty of local scour parameters around bridge piers. *Journal Engineering and Environmental Science* **25** (4), 127–137.

Yanmaz, A. M. & Altinbilek, H. D. 1991 Study of time-dependent local scour around bridge piers. *Journal of Hydraulic Engineering* **117** (10), 1247–1268. https://doi.org/10.1061/(ASCE)0733-9429(1991)117:10(1247).

Yeleğen, M. Ö. & Uyumaz, A. 2016 *Flow Velocity Effect on Clear Water Bridge Pier Scour*.

Zanke, U. 1982 Scours at piles in steady flow and under the influence of waves ("Kolke am Pfeiler in richtungskonstanter Stroemung und unterWelleneinfluss," in German). Mitteilungendes Franzius-Instituts, University of Hannover, Hannover, Germany.

Zanke, U. C., Hsu, T. W., Roland, A., Link, O. & Diab, R. 2011 Equilibrium scour depths around piles in non-cohesive sediments under currents and waves. *Coastal Engineering.* **58** (10), 986–991. https://doi.org/10.1016/j.coastaleng.2011.05.011.

Zhao, M. 2022 A review on recent development of numerical modelling of local scour around hydraulic and marine structures. *Journal of Marine Science and Engineering* **10**, 1139.

Zhao, M., Cheng, L. & Zang, Z. 2010 Experimental and numerical investigation of local scour around a submerged vertical circular cylinder in steady currents. *Coastal Engineering* **57** (8), 709–721.

Zhuravlyov, M. M. 1978 New method for estimation of local scour due to bridge piers and its substantiation. *Trans Ministry of Transport Constr*., State All Union Scientific Res. Ins. on Roads. Moscow, Russia, 4–51.

First received 20 September 2023; accepted in revised form 12 February 2024. Available online 24 February 2024