Bridge Scour: Prediction, Modeling, Monitoring, and Countermeasures—Review

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Abstract: Scour is one of the main causes of bridge failures. It accounts for about 60% of bridge failures in the United States. Scour failures tend to occur suddenly without prior warning and are very difficult to monitor during flood events. This paper presents a comprehensive review of the up-to-date work on scour at bridge piers and abutments. First, a general introduction of bridge scour including the current situation of bridge scour problems and different types of bridge scour is given. Then, different approaches developed for predicting bridge scour are reviewed. Numerical and laboratory models established for bridge scour studies are also presented. Moreover, laboratory experiments and field tests conducted for bridge scour are reviewed. Different techniques and instruments developed for bridge scour monitoring are also presented with their advantages, disadvantages, and relative cost summarized in a table. Finally, various mitigation countermeasures developed for bridge scour are discussed.

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Introduction

Bridge scour is one of the main causes of bridge failures. According to a study by Shirhole and Holt (1991), in the past 30 years more than 1,000 bridges collapsed in the United States, and about 60% failures are related to the scour of bridge foundations. Bridge scour has been identified to be the most common cause of highway bridge failures in the United States (Kattell and Eriksson 1998). The extent of this potential problem is magnified by the fact that according to a study by the Transportation Research Board in 1997, there were 488,750 bridges over streams and rivers in the U.S., and the annual cost for scour-related bridge failures was estimated at $30 million (Lagasse et al. 1997).

Scour is the result of the erosive action of flowing water, which excavates and carries away materials from the bed and banks of streams, and from around the piers and abutments of bridges (Fig. 1). Bridge scour is a dynamic phenomenon that varies with many factors such as water depth, flow angle and strength, pier and abutment shape and width, material properties of the sediment, and so on. There are generally three types of scours that affect the performance and safety of bridges, namely, local scour, contraction scour, and degradational scour (Parker et al. 1997). Local scour is the removal of sediment from around bridge piers or abutments. Water flowing past a pier or abutment may scoop out holes in the sediment, which are known as scour holes (see Fig. 1). Contraction scour is the removal of sediment from the bottom and sides of the river. It is caused by an increase in the speed of the water as the water moves through a bridge opening that is narrower than the natural river channel. Degradational scour is the general removal of sediment from the river bottom by the flow of the river. This sediment removal and resulted lowering of the river bottom are a natural process, but may remove large amounts of sediment over time.

Fig. 2 (adapted from Richardson and Davis 2001) shows the schematic of the flow development in the vicinity of a circular pier situated in a scour hole. As can be seen from Fig. 2, wake vortices are formed as the flow, which is separated by the pier, converges at the downstream of the pier. Also, as the mean flow approaches the pier at the middle, a portion of the approach flow is forced to move down the front surface of the pier. When this portion of flow reaches the channel bed, a horseshoe vortex is formed at the base of the pier, which causes local scour at the pier. The mechanism of scour development can be described as the following (Richardson and Davis 2001): The action of horseshoe vortices removes bed materials from around the base of the obstruction. If the transport rate of sediment away from the base region is greater than the transport rate into the region, a scour hole develops. The strength of horseshoe vortices will be reduced as the depth of scour increases, thereby reducing the transport rate from the base region. Eventually, for live-bed local scour, equilibrium is reestablished between bed material inflow and outflow and the scouring process ceases. For clear-water scour, scouring ceases when the shear stress caused by horseshoe vortices is equal to the critical shear stress of the sediment particles at the bottom of the scour hole.

Although scour may occur at any time, scour action is especially strong during floods. Scour undermines bridges and causes bridge failures as a result of structural instability. Scour failure tends to occur suddenly without prior warning to structures. Factors affecting bridge scour include channel and bridge geometry, floodplain characteristics, flow hydraulics, bed materials, channel protection measures, channel stability, riprap placement, ice for-

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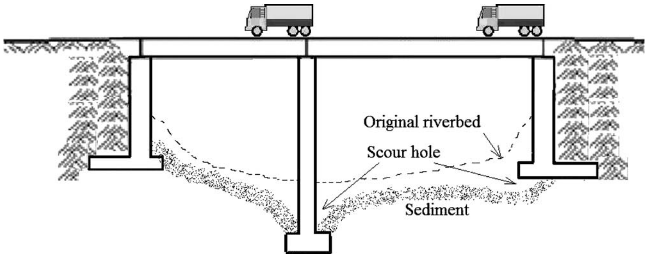

Fig. 1. Bridge scour

mations, debris, etc. This paper presents a comprehensive review of the up-to-date work on scour at bridge piers and abutments, including scour prediction, modeling, monitoring, and countermeasures.

Bridge Scour Prediction

Over the past few decades, bridge engineers and researchers have found that bridge scour is related to many factors such as the geometry of the channel, dynamic hydraulic properties of the flow, geometry of the bridge piers and abutments, etc. Predicting bridge scour using the available information of these factors prior to or during flood events is very important in preventing catastrophic failures of bridges and possible loss of life. Scour prediction practice can be generally divided into two categories: (1) predict bridge scour using empirical equations and (2) predict bridge scour using other methods, such as neural networks. It should be noted that both the final scour depth and real-time scour depth can be predicted.

Predicting Bridge Scour Using Empirical Equations

Numerous studies have been conducted with the purpose of predicting scour, and various equations have been developed (Laursen and Toch 1956; Liu et al. 1961; Shen et al. 1969; Breusers et al. 1977; Jain and Fischer 1979; Melville and Sutherland 1988; Froehlich 1989; Melville 1992; Abed and Gasser 1993; Richardson and Richardson 1994; Lim 1997; Heza et al. 2007). Most of these empirical equations were based on laboratory results and field data and they differ from each other with respect to the factors considered in constructing the scour model, parameters used in the equation, laboratory or site conditions, etc. Among these equations, one of the most commonly used pier scour equations in the United States is the Colorado State University equation recommended in the U.S. Department of Transportation's Hydraulic Engineering Circular No. 18 (HEC-18) (Federal Highway Administration 1993), which is expressed as follows:

$$d_s = 2.0yK_1K_2K_3(b/y)^{0.65}F^{0.43} \tag{1}$$

where d_s=scour depth; y=flow depth at the upstream of the pier; K_1, K_2, and K_3=correction factors for the pier nose shape, angle of attack flow, and bed condition, respectively; b=pier width; and F=Froude number. It is recommended in the HEC-18 that the limiting value of d_s/y is 2.4 for $F \leqslant 0.8$ and 3.0 for $F > 0.8$. Eq. (1) was developed from laboratory data and was recommended for both live-bed and clear-water conditions.

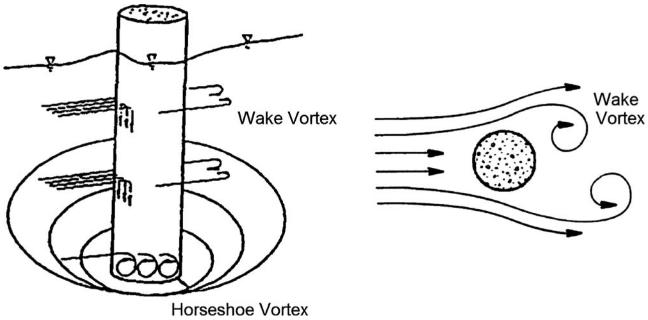

Fig. 2. Flow around a circular pier in a scour hole [adapted from Richardson and Davis (2001)]

A few other commonly used equations are also listed in the following. For the purpose of simplification, repeated terms in the following equations will not be explained again.

Equation presented by Neil (1964), which was developed from the design curves by Laursen and Toch (1956)

$$d_s = 1.35b^{0.7}y^{0.3} \tag{2}$$

Shen equation (Shen et al. 1969)

$$d_s = 0.000\,22\left(\frac{Vb}{v}\right)^{0.3} \tag{3}$$

where V=average velocity of approach flow and $v = 1 \times 10^{-6}\ \text{m}^2/\text{s}$.

Jain and Fischer equation (Jain and Fischer 1979)

$$\begin{cases} d_s = 2.0b(F - F_c)^{0.25}\left(\dfrac{y}{b}\right)^{0.5} & (F - F_c) > 0.2 \\ d_s = 1.85b(F_c)^{0.25}\left(\dfrac{y}{b}\right)^{0.5} & 0 < (F - F_c) \end{cases} \tag{4}$$

where F_c=critical Froude number. For $0 < (F - F_c) < 0.2$, the larger of the two scour depths computed using the two equations is used.

Froehlich equation (Froehlich 1989)

$$d_s = 0.32b\phi F^{0.2}\left(\frac{b_e}{b}\right)^{0.62}\left(\frac{y}{b}\right)^{0.46}\left(\frac{b}{D_{50}}\right)^{0.082} \tag{5}$$

where ϕ=coefficient based on the shape of the pier nose; b_e=width of the bridge pier projected normal to the approach flow; and D_{50}=median grain size of bed material.

Melville and Sutherland equation (Melville and Sutherland 1988):

$$d_s = K_lK_dK_yK_aK_sb \tag{6}$$

where K_l=flow intensity factor; K_d=sediment size factor; K_y =flow depth factor; K_a=pier alignment factor; and K_s=pier shape factor.

Though all these proposed equations have been demonstrated to be applicable and have good accuracy for a certain set of data, there has been considerable uncertainty when selecting these equations to predict scour in field practice. To test the accuracy of the developed bridge scour equations, comparative studies have been conducted by many researchers. Jones (1984) compared the available bridge scour equations using laboratory data and limited field data. In his study, he classified all equations into three categories, namely, those of the University of Iowa, those of the Colorado State University, and those based on foreign literature. He found that the Colorado State University equation enveloped the data, but that the scour depths were less than other equations.

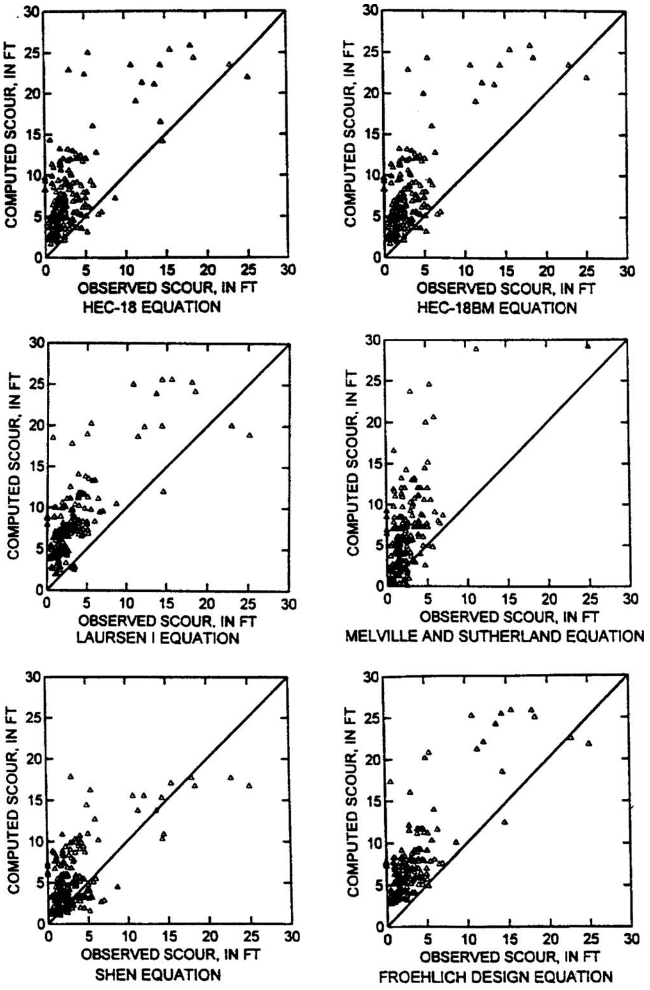

Fig. 3. Comparison of scour equations with field scour measurements [Reprinted from Mueller (1996), with permission]

Johnson (1995) compared seven of the most commonly used and cited scour equations and models using a large set of field data from both live-bed and clear-water scour. Differences between these equations and their limitations were explained in his study. Landers and Mueller (1996) evaluated selected pier scour equations using 139 measurements of local scour in live-bed and clear-water conditions. Comparisons of computed and observed scour depths in their study indicate that none of the selected equations accurately estimate the depth of scour for all of the measured conditions.

Mueller (1996) compared 22 scour equations using a large amount of field data collected by the USGS (Landers et al. 1999). In his study, he concluded that the HEC-18 equation was good for design because it rarely underpredicted the measured scour depth. However, it frequently overpredicted the observed scour. Fig. 3 shows the data containing 384 field measurements of scour at 56 bridges from his study.

Though conclusions from comparative studies by different researchers more or less differ from each other, it is generally believed, based on the conducted laboratory experiments and field tests, that most existing equations may overestimate the scour depth and are generally conservative (Johnson and Ayyub 1996; Melville 1997; Ataie-Ashtiani and Beheshti 2006; Benedict et al. 2007; Lu et al. 2008).

Most work on scour prediction discussed previously is focused on the equilibrium scour depth. Time development of scouring has also attracted the attention of many researchers (Ettema 1980; Yanmaz and Altinbilek 1991; Kothyari et al. 1992; Cardoso and Bettess 1999; Melville and Chiew 1999; Oliveto and Hager 2002; Chang et al. 2004).

Yanmaz and Altinbilek (1991) studied the time-dependent local scour around bridge piers under clear-water conditions with single cylindrical and square piers. In their study, the time variation of the scour depth around bridge piers can be determined by solving a differential equation. They concluded that the shape of the scour hole around bridge piers remains almost unchanged with respect to time. However, the rate of scour development decelerates with time.

Melville and Chiew (1999) studied the temporal development of clear-water local scour depth at cylindrical bridge piers in uniform sand beds. The temporal development of the scour depth as a function of t was described using the equation below

$$\frac{d_s}{d_{se}} = \exp\left\{-0.03\left|\frac{V_c}{V}In\left(\frac{t}{t_e}\right)\right|^{1.6}\right\} \tag{7}$$

where d_{se}=equilibrium scour depth; V_c=critical mean approach flow velocity for entrainment of bed sediment; and d_{se}=time for equilibrium depth of scour to develop.

Predicting Bridge Scour Using Neural Networks

The mechanism of flow around a pier structure is so complicated that it is difficult to establish a general empirical model to provide accurate estimation for scour, as has been demonstrated in the previous section where comparative studies of different equations were reviewed. Besides the complexity of the scour process, there are also two other reasons why existing methods do not always produce reasonable results for scour predictions. First, site conditions are usually much more complicated than laboratory conditions. Second, the traditional analytical tools of statistical regression have limitation regarding selecting the parameters used in the formulas and determining the exact types of relationships between the responses and the parameters.

Recently, artificial neural networks (ANNs) have been successfully used in predicting bridge scour (Choi and Cheong 2006; Bateni et al. 2007; Lee et al. 2007; Zounemat-Kermani et al. 2009). A significant advantage of using ANNs in predicting the bridge scour is that there is no need to have well-defined physical relationships between the bridge scour (the output) and various factors that affect bridge scour (the inputs). Because the ANNs have more freedom in defining the relationships between the bridge scour and the factors, they have the potential to predict more accurate scour information than the traditional regression based methods (Zounemat-Kermani et al. 2009).

Fig. 4 shows the configuration of a typical three-layer neural network, which consists of an input layer, a hidden layer, and an output layer. The basic idea of the neural network can be described as the following: First, a set of data $(X_1, X_2, \ldots, X_n)$ as raw information is fed into the network at the input layer; then, the neural network will be trained and the complex relationships between inputs and output (y) will be determined during the training process using specified mathematical functions and weights on the connections between the units in the hidden layer and the units in the input layer as well as the output layer; finally, the output can be determined from the weights on the connections between the units in the hidden layer and the output.

Bateni et al. (2007) used ANNs and an adaptive neurofuzzy inference system (ANFIS) to estimate both the equilibrium and

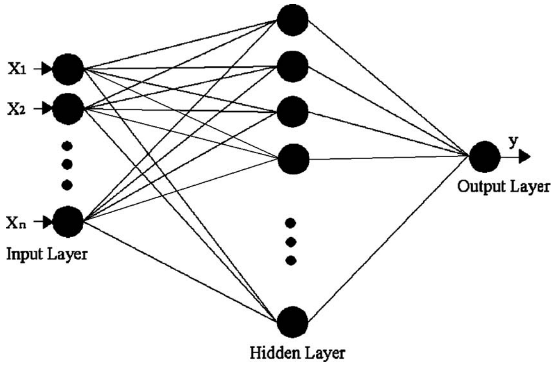

Fig. 4. Configuration of a typical feed forward neural network [adapted from Hornik et al. (1989)]

time-dependent scour depth with a large amount of laboratory data. In their study, two ANN models, a multilayer perception using back-propagation (MLP/BP) algorithm and radial basis function using orthogonal least-squares (RBF/OLS) algorithm, were used. The equilibrium scour depth was modeled as a function of five variables, namely, flow depth, mean velocity, critical flow velocity, mean grain diameter, and pier diameter. The time variation of scour depth was also modeled in terms of the equilibrium scour depth, equilibrium scour time, scour time, mean flow velocity, and critical flow velocity. Numerical test results in their study indicated that the MLP/BP model provides a better prediction of scour depth than the RBF/OLS and ANFIS models as well as the previous empirical approaches. Lee et al. (2007) used the Back-Propagation Neural Network to predict the scour depth around bridge piers and their study showed the scour depth can be efficiently predicted using the back-propagation neural network. Zounemat-Kermani et al. (2009) also used two ANN models, the feed forward back-propagation model and the RBF model, to predict the depth of the scour hole around a pile group. Their numerical test results indicated that the ANN predictions are generally more satisfactory than those obtained using empirical methods because of their low errors and high correlation coefficients. Through a sensitivity analysis they also found that the pile diameter and the ratio of pile spacing to pile diameter are the two most significant parameters that affect the scour depth.

Bridge Scour Modeling

As discussed earlier, bridge scour is a very complicated process which involves the interaction between the flow around a bridge pier or abutment and the erodible bed surrounding it. To study the complicated bridge scour process, different numerical models as well as laboratory models have been developed in the past few decades.

Numerical Models

In order to verify the accuracy of the developed numerical models, most numerical models were developed along with laboratory models and their results were compared with each other. Fukuoka et al. (1994) developed a three-dimensional (3D) numerical simulation model for the local scour around a bridge pier. Their study showed that the developed numerical model can obtain, with adequate accuracy, solutions that are in good agreement with the experimental results of the local scour from the large-scale hydraulic model. Richardson and Panchang (1998) used a fully 3D hydrodynamic model to simulate the flow occurring at the base of a cylindrical bridge pier within a scour hole. The results of the numerical simulation were also compared with laboratory observations by Melville and Raudkivi (1977). Quite good agreements were achieved between the studies, both quantitatively and qualitatively. They concluded that the discrepancies between the results of the two studies may be attributed to the parameters chosen in the numerical model.

Numerical results for bridge scour were also compared to empirical equations. Young et al. (1998) developed a numerical model for clear-water abutment scour depth along with an independent 3D finite element model. In their study, the predicted scour depths were in agreement with the predicted results from the finite element model. They also concluded, from a comparative study, that the HEC-18 (Federal Highway Administration 1993) prediction overestimates measurement by 22%. Kassem et al. (2003), at the University of South Carolina, developed a computational fluid dynamics mode, FLURNT, to simulate the field data. Their numerical model was verified against measurements obtained in the laboratory and satisfactory agreements were obtained between the numerical results and measurements. Using the developed model, they demonstrated that the HEC-18 (Federal Highway Administration 1993) significantly overestimates the scour depth in their case study.

Laboratory Models

The advantage of laboratory studies of bridge scour is that they cannot only help better understand the effect of different variables and parameters associated with scour and therefore improve the scour prediction equations, but can also help develop alternative or improved scour countermeasures. In the past two decades, a significant amount of research effort has been spent on laboratory investigation of bridge scours. Different laboratory models for bridge scour have been established and tests have been conducted for different purposes.

To study the deep scour hole downstream of a large circular pier at the Imbaba Bridge, one of the major bridges across the Nile River, an undistorted mobile bed model, with a scale 1:60, was constructed at the Hydraulics and Sediment Research Institute, Cairo (Abed and Gasser 1993). A series of clear-water scour tests were performed to investigate the causes of the local scour downstream the circular pier. It was found that the large scour hole downstream the circular pier was produced by the conflicting velocity fields at the intersection of the wake vortex streams from adjacent piers, and increased by the confluence flow. Based upon the results of this investigation, an empirical formula was developed to predict the wake and confluence maximum local scour depth downstream of a circular pier for a clear-water condition.

Umbrell et al. (1998) investigated clear-water bridge contraction scour caused by pressure flow beneath a bridge without the localized effect of piers or abutments. A tilting fume that measured 21.3 m long, 1.8 m wide, and 0.6 m deep was used in their study. A model bridge deck was tested under a variety of laboratory-controlled pressure-flow conditions. Different factors such as approach velocity, pressure-flow velocity under the bridge deck, and sediment size were studied.

Sheppard and William (2006) studied the local clear-water and live-bed scour using laboratory tests for a range of water depths and flow velocities with two different uniform cohesionless sediment diameters (0.27 and 0.84 mm) and a circular pile with a diameter of 0.15 m. The tests were performed in a tilting flume

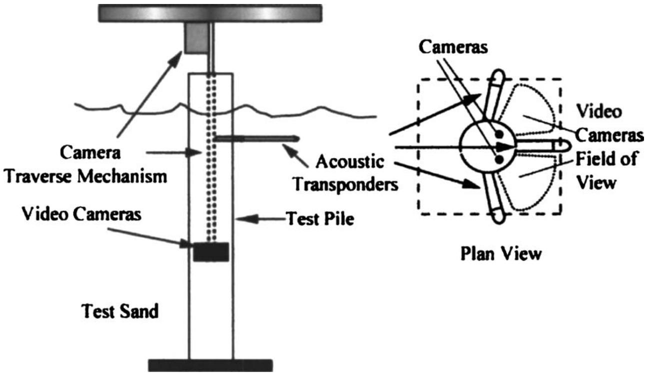

Fig. 5. Local scour depth measuring instruments [Reprinted from Sheppard and William (2006), with permission]

(1.5 m wide, 1.2 m deep, and 45 m long) located in the Hydraulics Laboratory at the University of Auckland in Auckland, New Zealand. Fig. 5 (Sheppard and William 2006) shows the measuring instruments for local scour depth used in their study. As shown in Fig. 5, the scour depth as a function of time is measured with acoustic transponders and video cameras. Bed forms and bed elevation at the flume walls during the live-bed tests can be monitored with video cameras. Flow velocity, water depth, and temperature can also be measured during the tests. In their experiments, large bed forms were observed to migrate through the scour hole during a number of the live-bed scour tests and they concluded that Sheppard's equations (Sheppard 2003) appeared to perform well for the range of conditions covered by the experiments.

Field Scour Measurement and Monitoring Instrumentation

Though laboratory studies provide a good way to verify bridge scour theories and a better understanding of the complicated scour process, laboratory results may vary with respect to different laboratory conditions. Also, many times results from laboratory studies cannot be directly used to guide design practice because of the simplifications and assumptions made in laboratory study, which may make the results not applicable to field applications. Therefore, field data are still very important and desirable since they provide critical information of the bridge condition with which engineers can directly use to make important decisions. Field data are also very important with regard to evaluating and verifying existing laboratory scour models and empirical equations.

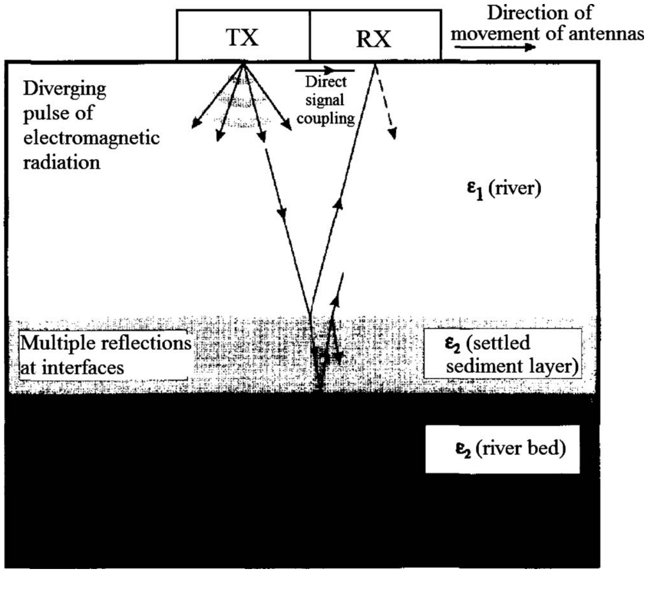

Fig. 6. Transmission and deflection of signal in detecting scour using radar [Reprinted from Millard et al. (1998), with permission]

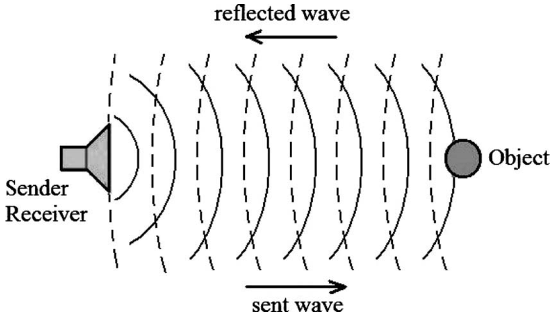

Fig. 7. Working principle of sonar

Over the past half century, the USGS along with the Federal Highway Administration (FHWA) and state departments of transportation (DOTs) in the United States have put a significant amount effort into the study of bridge scour in field. In 1987, the FHWA funded the USGS to initiate the National Bridge Scour Program. After many years of effort, in 1996, the USGS published a national bridge scour report (Landers and Mueller 1996), which aimed to guide the practice of engineers. In addition to research effort and the reports released by the USGS, many journal articles and conference proceedings have also been published in the past several decades.

Over the past few decades, measurement and monitoring instrumentation has also been developed for bridge scour. In the early days, radar (Gorin and Haeni 1989; Horne 1993; Millard et al. 1998; Park et al. 2004) and sonar (Mason and Shepard 1994; Hayes and Drummond 1995; De Falco and Mele 2002; Hunt 2005) were employed successfully to identify the scour depth.

Radar is a system that uses electromagnetic waves to identify the range, altitude, direction, or speed of both moving and fixed objects such as aircraft, ships, motor vehicles, weather formations, and terrain. Fig. 6 (Millard et al. 1998) illustrates how radar can be used to detect bridge scour. In Fig. 6, electromagnetic waves are sent out through the transmitting antenna (TX). The majority of the signal sent out will be propagating downward until an interface is reached where the underlying material has different electrical properties to the current layer in which the signal is propagating. At this interface (the interface between the river and sediment layer in Fig. 6), part of the radar signal will be reflected back toward the upper surface and may be detected by the receiving antenna (RX). The other part of the signal is, however, refracted at the interface and propagates through the underlying material (the sediment) until it reach another interface (between the sediment layer and river bed) and will be reflected again. The received radar signal at the receiving antenna will then be used to detect the surface conditions of the interfaces. During the detection process, both the transmitting antenna and receiving antenna move at a constant rate across the surface of interest.

Sonar, originally an acronym for sound navigation and ranging, is a technique that uses sound propagation (usually underwa-

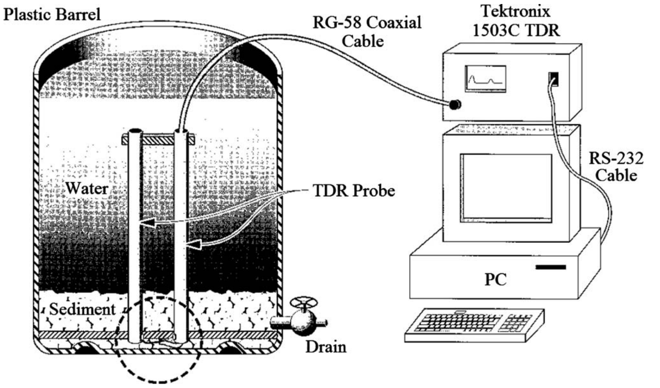

Fig. 8. Experimental setup for the TDR system [Reprinted from Yankielun and Zabilansky (1999), with permission]

ter) to navigate, communicate with, or detect other vessels. The working principle of using sonar to detect scour is similar to that of using radar (Fig. 7). To measure the distance to an object, a pulse of sound is sent out and will be reflected back when it reaches an object. The time from transmission of a pulse to reception is measured and can then be converted into a range by knowing the speed of sound. Sonar has been developed and used to characterize the sea bottom information, for example, mud, sand, and gravel, by converting echo parameters into sediment type. Different algorithms exist in different sonar types, but they are all based on changes in the energy or shape of the reflected sounder pings. Sonar can also be used to derive maps of the topography of an area by moving the sonar across it just above the bottom. These properties make the sonar an excellent tool to detect bridge scour.

Though both radar and sonar were successfully used to detect the profile of the bridge scour, they have limited applications in monitoring scour development and are usually only used to determine the final status of the sedimentation surrounding a pier. It is difficult to employ these techniques to continuously monitor the scour process during flood events. Therefore, techniques for continuous monitoring scour process are desirable because real-time scour information can provide warning prior to bridge failures and help bridge engineers make important decisions during floods.

In recent years, techniques using time-domain reflectometry (TDR) (Yankielun and Zabilansky 1999; Yu and Zabilansky 2006; Yu and Yu 2007) and fiber Bragg grating (FBG) sensors (Lin et al. 2004, 2005) have been developed and used for real-time monitoring of bridge scour. Fig. 8 shows the experimental setup for the TDR system used for scour monitoring by Yankielun and Zabilansky (1999). The TDR operates by sending an electromagnetic pulse through the transmission line with a fixed velocity. The pulse propagates down the transmission line until the end of the line or some intermediate discontinuity (air/water interface and water/sediment interface) is reached, where part of the pulse is reflected back to the source. By measuring the returning time of the sent pulse, the physical distance between the line end or the discontinuity and the TDR source can be calculated.

Fiber optic sensors have many advantages over traditional sensors such as their long-term stability and reliability, resistance to environmental corrosion, and multiplexity along one single fiber (Deng and Cai 2007). Lin et al. (2005) developed two types of local scour monitoring systems to monitor real-time scour (Fig. 9). In Model I, three FBG sensors are mounted on the surface of a cantilevered beam and arranged in series along one single fiber. In Model II, several FBG sensors are arranged along one single optical fiber, but are mounted on cantilevered plates installed at different levels of a hollow chamber of a steel pile fixed to the pier or abutment. In both models, when the running water flows toward the cantilevered beam or plates, deformations will be generated on the beam or plates by bending moment and strains will be detected by the FBG sensors. However, only the FBG sensors that are exposed to the water flow will pick up the strain information; for those buried under the river bed surface, no or very small strains will be generated because that part of the cantilevered beam or plates is not bended. The scour depth can then be detected by knowing the exposure conditions of the FBG sensors. It should be noted that the resolution of this two scour monitoring systems depends on and can be adjusted by the number of FBG sensors used in the systems.

Lu et al. (2008) also used a sliding magnetic collar (SMC) and a steel rod to monitor the total bridge scour during floods. The

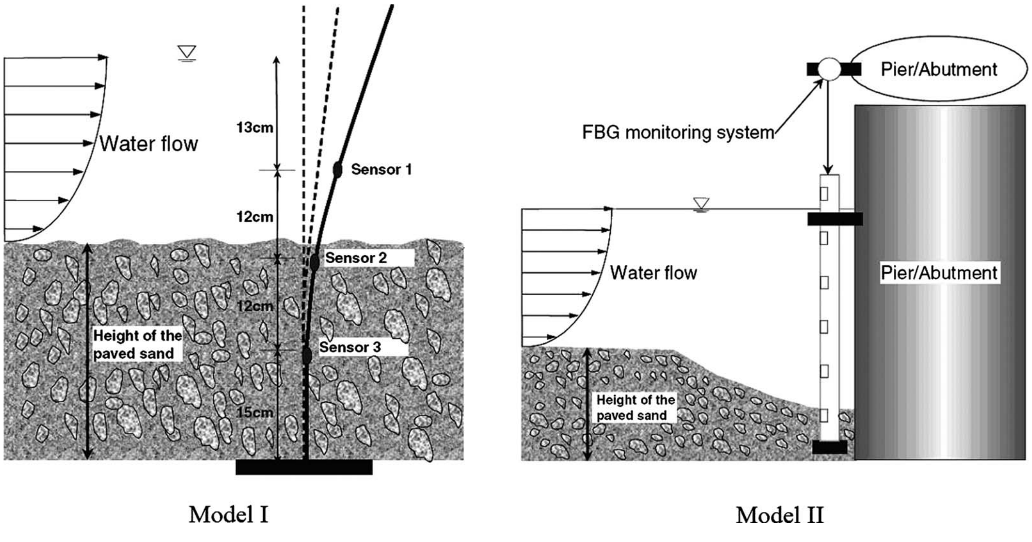

Fig. 9. FBG scour monitoring system [Reprinted from Lin et al. (2005), with permission]

Table 1. Comparison of Existing Instruments for Measuring Bridge Scour (Lu et al. 2008)

Instrument	Advantages	Disadvantages or limitations	Relative cost
Bridge mounted sonar	Continuous and accurate record of riverbed	Mild slope river/estuary	Medium
Acoustic Doppler current profiler	Portable; measuring both velocity profile and water depth	Not applicable to high sediment concentration conditions	High
Ground penetrating radar	Continuous record of riverbed	Time consuming in operation; specialized training required	High
FBG sensor	Continuous monitoring of riverbed	Limited successful field tests, tests for extreme environment needed	High
Numbered bricks	Commercially available; applicable to highly turbulent or rapid flows	Excavation of riverbed required; suitable for ephemeral rivers	Low
SMC	Easy to operate	Excavation of riverbed required; high maintenance/repairing cost	Low
Steel rod	Easy to operate	Excavation of riverbed required; high maintenance/repairing cost	Low

lower tip of the steel rod, with a diameter of 100 mm, was initially placed slightly below the riverbed in the main channel. When scour occurs, the steel road will drop as the surface of the riverbed drops. The scour depth is determined based on the total lowering distance of the steel rod with respect to its initial position. One of the major disadvantages of this instrumentation is that it cannot detect the refilling process of the scour. They also compared the advantages, disadvantages or limitations, and relative costs of existing instruments for measuring bridge scours, which are summarized in Table 1 (Lu et al. 2008).

Scour Countermeasures

Scour mitigation at bridge sites has received much attention in the past. There are many techniques, measures, and practices available for countering scour at existing bridge piers and abutments. Scour countermeasures can be generally categorized into two groups: armoring countermeasures and flow altering countermeasures. The basic idea of armoring countermeasures is the addition of another layer, which can act as a resistant layer to the hydraulic shear stress and therefore provides protection to the more erodible materials underneath. Armoring countermeasures do not necessarily alter the hydraulics of approach flows. In contrast, flow altering countermeasures, as their name indicates, aim at changing the hydraulic properties of flows by using spur dikes, guidebanks, parallel walls, collars, etc., and therefore reducing the scour effect at bridge piers and abutments. A comprehensive review of different scour countermeasures for bridge piers and abutments can be found in Lagasse et al. (2007) and Barkdoll et al. (2007), respectively. A comparison between the working principle, advantages, and problems of the two different types of scour countermeasures is summarized in Table 2.

The most commonly used armoring countermeasure is riprap (Lauchlan and Melville 2001). Other types of armor include tetrapods, cable-tied blocks, grout filled bags, mattresses, concrete aprons, etc. An extensive review of experiments, model studies, and laboratory tests conducted on the use of riprap as a scour countermeasure around bridge piers was provided by Parker et al. (1998). Fig. 10 shows the typical pier riprap configurations in Lagasse et al. (2007), with (a), (b), (c) representing placing the riprap layer at the surface of the channel bed, in a preexisting scour hole or in a hole excavated around the pier, and at the depth below the average bed level, respectively. Placing the riprap layer at depth below the average bed level was recommended in their study. Lauchlan and Melville (2001) experimentally studied the effects of failure mechanisms, stability, and placement level for riprap at bridge piers. Their study also showed that deeper placement level of the riprap layer provides better protection against local scour.

Different flow altering countermeasures have also been proposed, using submerged vanes (Odgaard and Wang 1987), sacrificial sill (Chiew and Lim 2003), collars and slots (Kumar et al. 1999; Zarrati et al. 2006), parallel wall (Li et al. 2006), etc. Fig. 11 shows the use of a collar in preventing scour by Zarrati et al. (2006).

As can be seen from Fig. 11, the collar (with a round shape) divides the approach flow into two regions above and below the collar. The collar acts as an obstacle against the down flow and therefore reduces its strength. The strength of the down flow at the region below the collar is also reduced, so is the strength of the horseshoe vortex. The efficiency of a collar depends on its size and relative location on the pier with respect to the bed.

Most countermeasures mitigate scour effect by using devices on the upstream side of bridge piers or by changing the geometry of bridge piers facing the approach flow. Grimaldi et al. (2009)

Table 2. Comparison between Armoring and Flow-Altering Sour Countermeasures

	Armoring countermeasures	Flow-altering countermeasures
Principle	Protect the bed materials underneath the armoring layer from being scoured away	Alter the flow alignment or break up vortices and therefore reduce the scour effect
Advantages	Most commonly used type; easy to use; works well in most situations	Different designs can be selected for different site conditions to achieve satisfactory results
Problems	Winnowing of sands through the armor; difficult to keep the armor in place; constrict the channel and cause additional contraction scour	Special design may be needed for particular site conditions; significant cost and construction of new structures may be needed

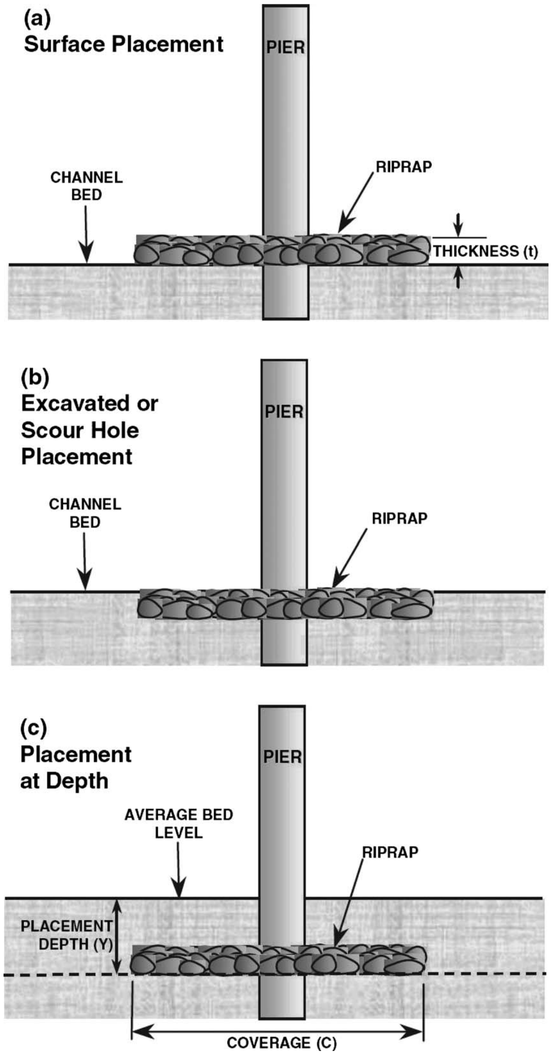

Fig. 10. Scour protection by riprap [Reprinted from Lagasse et al. (2007), with permission]

presented a scour control method at bridge piers by a downstream bed-sill (Fig. 12). The reason of setting the bed-sill downstream instead of upstream is to avoid the risk of decreasing the bed elevation due to the general and local scouring downstream of the bed-sill. As can be seen in Fig. 12, the final bed with the use of the downstream bed-sill is better protected than the case without bed-sill.

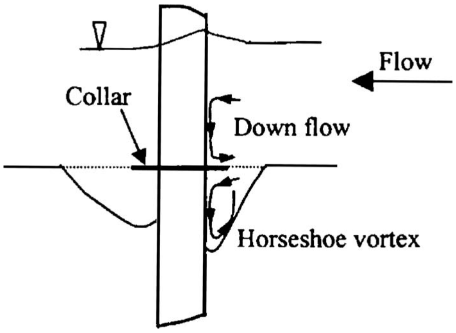

Fig. 11. Scour protection by using a collar [Reprinted from Zarrati et al. (2006), with permission]

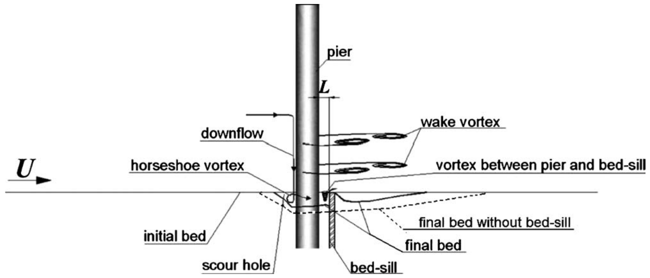

Fig. 12. Scour countermeasure using a downstream bed-sill [adapted from Grimaldi et al. (2009)]

The selection of various countermeasures is dependent on the application and the nature of the problem: a local scour at the pier or abutment, contraction scour across the bed at the bridge opening, reach-wide channel degradation, or lateral channel movement or widening (Johnson and Niezgoda 2004). The relative effectiveness, cost, maintenance, and ability to detect failures are also important factors to be considered when selecting a scour countermeasure. Sometimes, different countermeasures need to work together to optimize the scour mitigation effect. Lagasse et al. (2001) compared different countermeasures with regard to the type of scour, hydraulic condition, maintenance, and so on, and provided the design guidelines for different countermeasures.

Since the use of countermeasures often introduces uncertainty due to a lack of systematic testing and unknown potential for failures, Johnson and Niezgoda (2004) introduced a risk-based method for ranking, comparing, and choosing the most appropriate scour countermeasures using failure modes and effect analysis and risk priority numbers. In their study, the uncertainty was incorporated in the failure modes and effect analysis in the selection process by considering risk in terms of the likelihood of a component failure, the consequence of failure, and the level of difficulty required to detect failures. Risk priority numbers were then used to provide justification for selecting a specific countermeasure and the appropriate compensating actions to be taken to prevent failure of the countermeasure.

In addition to the effort spent on developing appropriate scour countermeasures for existing bridge piers, a significant amount of effort has also been spent on investigating the factors that affect bridge scour, which includes type of soil in the sediment and river bed (Molinas and Abdeldayem 1998; Molinas et al. 1999), geometry and configuration of bridge piers and abutments (Bertoldi and Kilgore 1993; Melville and Raudkivi 1996; El-Razek et al. 2003), foundation geometry (Melville and Raudkivi 1996; Parola et al. 1996), incline of bridge piers (Bozkus and Yildiz 2004), and so on. Results from these studies can also be used as references in designing bridge piers and abutments for scour and selecting appropriate scour countermeasures.

Concluding Summary

A comprehensive review of the up-to-date work on bridge scour is presented in this paper. Different types of bridge scour and the scour development process are introduced. Different approaches developed for predicting and monitoring bridge scour are reviewed. Laboratory work and field tests conducted for bridge scour are collected. Various scour countermeasures developed in practice are also summarized.

Bridge scour is a very complicated 3D interaction problem between the flow and sediment and riverbed. Though most empirical equations for predicting bridge scour depth have been demonstrated to be good for a certain data set under certain laboratory or field condition, they may not be suitable any more where laboratory or field conditions are changed. All existing scour monitoring instruments and countermeasures have their own advantages and disadvantages. The selection of bridge scour monitoring instrument or countermeasure should be based on a consideration of many factors such as the nature of the problem, the site condition, the relative effectiveness and cost, etc.

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