A REVIEW OF THE SCOUR MANAGEMENT FOR MITIGATING THE BRIDGE FAILURE

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ABSTRACT. Pier and abutment undermining due to scouring and riverbed erosion has been widely recognized as the main cause of bridge damage and failure. The Federal Highway Administration (FHWA) has estimated that 60% of bridge collapses in the United States are due to scour. The phenomenon of local scour has been extensively studied at bridge piers and abutments founded in non-cohesive sediments. However, only a few studies have been conducted on the scour around piers and abutments in cohesive sediments. The scour depth prediction models in both the cases have been developed based on laboratory/field data using statistical regression methods. Soft-computing techniques such as artificial neural network, multilayer perceptron, genetic algorithm, genetic programming, gene expression programming, and group method of data handling have been used in various fields of engineering and reported to give better performance over the regression model. Such soft-computing techniques are believed to give more accurate results when the physical phenomenon is very complex in nature and there is ambiguity in data. An effort has been made in this paper to determine the scour as a cause of bridge failure and to propose a suitable mitigation scheme to check the scour around bridges.

Keywords: Scour, Bridges, Pier, Abutment, Scour management.

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INTRODUCTION

Scour may be defined as a common soil-structure interaction problem which may lead to the removal of sediment in a stream due to erosive action of flowing water, as a result of this the foundation of the bridge pier get exposed, ultimately resulting in failure of bridges [1-5]. The type of scour that can occur at bridge waterway can be broadly classified as general scour and localized scour (Figure 1) [6]. The general scour occurs irrespective of the bridge existence and it can further be classified as short-term general scour and long-term general scour, whereas the localized scour is directly related to the existence of bridges. Localized scour includes contraction scour and local scour, the former occurs due to contraction in flow at pier or abutment while the latter may occur due to formation of vortices (around bridge pier and abutment) that would carry the sediment in the immediate neighbourhood of the abutments and piers and deposit the same to the other location. The total depth of scour at particular bridge foundation (for the pier or abutment) is the sum of general scour and localized scour.

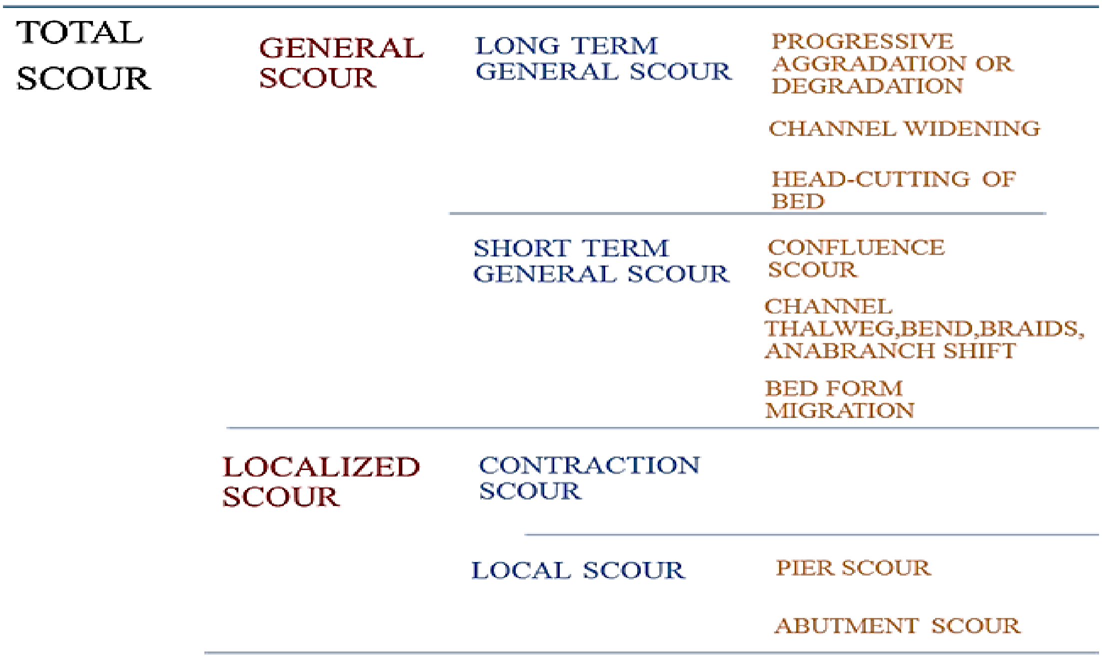

Figure 1 Classification of scour

Scour around bridge piers

When the flow approaches a bridge pier (Figure 2), there is a stagnation point of intersection of the flow with the pier, thus in an ideal case a vertical line of stagnation is obtained. Due to the velocity distribution of the approaching flow which is zero at the bed and approaches a maximum at or near the surface, a pressure gradient from top to bottom is created. Thus, a vertical stagnation flow is divided into an up-flow and down-flow jet on the leading face of the pier. This would ultimately results in a complex three dimensional flow system as a combination of down flow at the nose of the pier and a horseshoe vortex in front of the pier and extending past it. The down flow component is directed to the bed while the up flow component moves toward the level of the approach flow water surface, thus creating a bore wave that increases the water surface elevation at the face of the pier. The plan view of this set of vortices is in the form of a horseshoe and as such this vortex structure is known as horseshoe vortex [6-19]. In addition to these vortices, there exist wake vortices in the separation zone in the downstream region of the pier. These vortices are formed by separation of flow in two parts resulted by the partial blockage of the flow. The vortices caused by this separation are also called cast-off vortices or Karman vortices [20-26]. One vortex develops on one side of the pier simultaneously followed by another vortex from the other side, these vortices then meets at the downstream and dissipates energy as they move away from the pier. In the wake region of the pier sediment transport condition occurs while scouring occurs at upstream nose of pier and its sides [2, 25, 27-28].

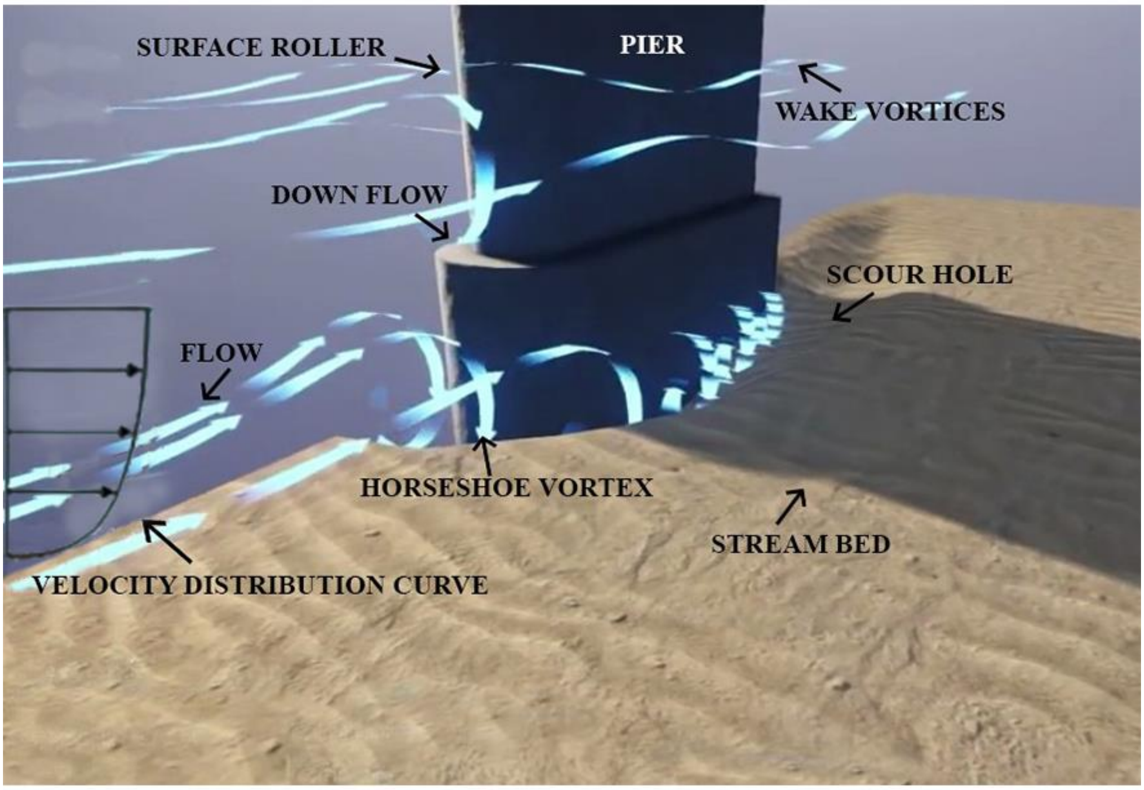

Figure 2 Mechanics of Scour around bridge pier

Scour around bridge pier is inevitable, and if the scouring process is not considered adequately in bridge pier design, then it would lead to several modes of bridge pier failure. Moreover, an initially stable bridge pier either settles vertical or collapse completely after prolonged scouring. Many a time due to scour the stream wise longitudinal support of a pier gets reduced, further causing the tilting of the pier [6]. It is also very common for the bridge to lose support in the stream wise direction. Depending on the hydrodynamic loading against the pier, as well as the sideways strength of the connection between the pier and the bridge deck, flow pressure may push the pier backwards or it may push the support piles backwards. It has been estimated that 1062 number of bridges collapsed in the United States from 1980 to 2012, 19 percent of these bridges were collapsed due to scour [29]. Besides causing huge damage to life and property and disruption in the development of a country, flood is also the most common cause of scouring that would ultimately leads to the bridge failure (Figure 3) [30-31]. It is evident from the above discussion that the evaluation of scour depth in bridge design is of utmost importance.

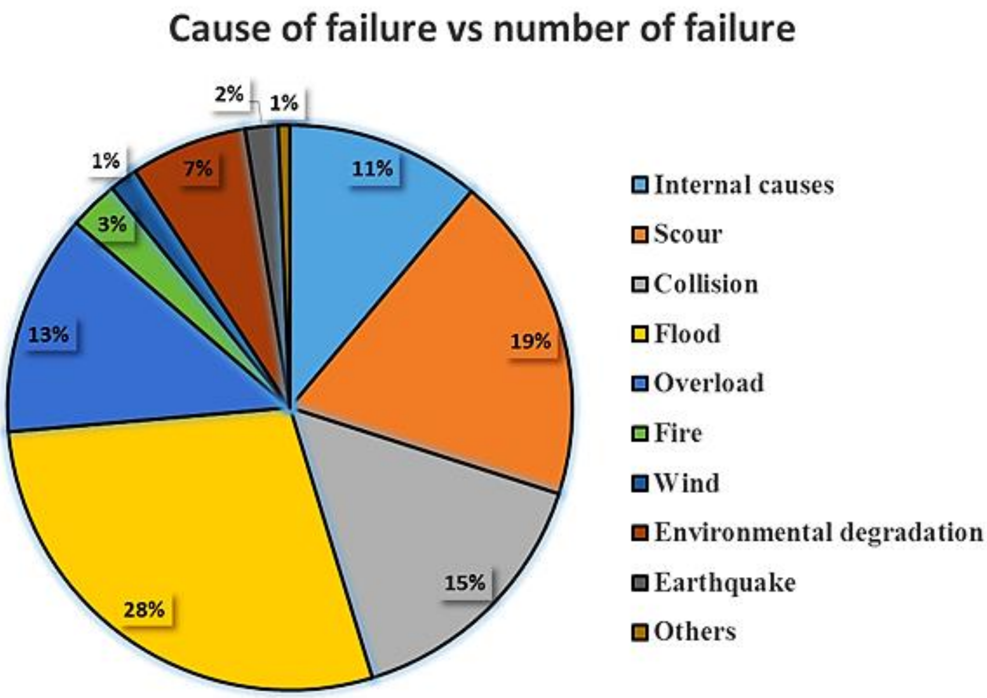

Figure 3 Causes of bridge failure from 1980-2012

Extensive research has been conducted in the recent years for the prediction of scour depth. Many researches have proposed several empirical equations, numerical models and most recently, models based on artificial intelligence. These researches were based on various laboratory experiments and also several field experiments [32]. Mallick and Tawil [33] conducted a case study on reinforced concrete bridge built across Nadi-el-Magah watercourse in Libya. Two of the three bridges have been collapsed due to heavy flood. These heavy floods caused severe damage due to scour, erosion and undermining of the soil below foundations of intermediate piers and the abutments. Another victim of scour was Malahide Viaduct in Dublin Ireland, which was collapsed in 2009 [2]. Prendergast and Gavin [2] gave prime importance to monitoring scour for safety and also indicated that most monitoring regimes are based on under water instrumentation that can also subjected to damage during flood when scour risk is at its peak. In light of current changes in climate, increasing frequency of flooding, coupled with the increasing magnitude of these flood events, will lead to a higher risk of bridge failure. Brian [34] performed case study on railway bridges in United Kingdom and Ireland. He illustrated different ways in which scour has caused structure to collapse or required protection. He had also evaluated the ways to avoid the failures due to scour by applying good bridge management system. Garde and Kothyari [35] proposed methods for the prediction of scour around bridge piers. They described various techniques used for scour control and protection and made brief comment on scour around bridge piers in clay bed and gravel bed of rivers. Most of the available scour equations for bridge piers do not consider uncertainties of various scouring parameters adequately to achieve desirable level of safety of pier foundation [36]. In order to incorporate the complexity of scour and also to get accurate prediction of scour depth soft-computing techniques viz. artificial neural network, multilayer perceptron, genetic algorithm, genetic programming, gene expression programming, and group method of data handling and support vector machine etc. were used by various researchers. [32, 37-38].

CONVENTIONAL METHODS FOR THE ESTIMATION OF SCOUR DEPTH

The following section explains the current conventional practice adopted in India and U.S. for the estimation of scour.

Indian practice for the estimation of scour

Lacey [39] developed a method for the estimation of regime depth of flow in loose bed alluvial rivers and Inglis [40] developed simultaneously a method based on observations made on canals in India and Pakistan. Indian road congress and Indian railways [41-43] recommended Lacey-Inglis method for the estimation of scour depth around bridge piers with slight variation as given below.

$$D_{Lq} = 1.34(\frac{q^2}{f})^{\frac{1}{3}}$$

$$f = 1.76\sqrt{d_{mm}}$$

where, D_{Lq} is the normal scour depth in m below the design flood level, q is the discharge intensity in cumec /m, f is lacey's silt factor, d_{mm} is the median size of bed material in mm.
The existing provisions in Indian codes not only produce large values of scour but also there is no consideration for different types of bed materials. It has been found that the scour depth varies with the variation in soil properties. Therefore the existing code of practice for determination of design scour require immediate review [44]

U.S. practice for the estimation of scour

HEC-18 equation has been adopted in the United States for the determination of scour depth [45]

$$\frac{y_s}{y_1} = 2.0k_1k_2k_3\left(\frac{a}{y_1}\right)^{0.65} + fr_1^{0.43}$$

where, y_s = scour depth, y_1 = flow depth directly upstream of the pier, k_1 = correction factor for pier nose shape, k_2 = correction factor for angle of attack of flow, k_3 = correction factor for bed condition, a = pier width, in m, L = length of pier, in m, Fr_1 **=** Froude number directly upstream of the pier.

PROTECTION OF BRIDGE FOUNDATION AGAINST LOCAL SCOUR

The best techniques which have been employed till now for the protection of local scour around foundation of bridge pier and abutments during the early stages are discussed here [16].

- Posy et al. [27] conducted several investigations on the use of flexible mats and monitored the reduction of scour around bridge piers. The link chain tight jointed block mats amongst other types are found to be most effective in reducing the scour.

- Levi and Luna [46] conducted laboratory investigation to devices means for reducing the scour at the nose of a pier. These methods consist of inserting and isolated piles in the channel bed upstream of the pier. The material secured around the pile is deposited in the scour hole of the pier subsequently reducing the scour depth at pier. Based on experimental investigations they determined the dimensions and location of piles for achieving maximum efficiency.

- Ettema [6] has studied about the placement of their circular collar at different elevation above the bed and its effect in reducing scour. His studies concluded that a collar of twice the diameter of pier placed at a level of one pier diameter above the bed is quite effective in reducing the scour by suppressing the foundation of horse shoe work.

The most commonly used method for the protection of stream bed which is susceptible to scour is providing loose apron of rock around the pier.

BRIDGE SCOUR MONITORING USING DEVICES

The commonly used devices for monitoring scour around bridge pier are sonar, magnetic sliding collar, fibre Bragg grating, electrical conductivity devices, ground penetrating radar and float out devices. These devices are commonly used and prove to be more efficient and effective.

Sonar

Scour instruments is also known as scour transducer are sound waves to ping the bottom of the waterway. The corresponding echo will indicate depth the rivers bed. When the transducer is angled to an area of potential scour the sensor will measure the level of erosion occurring. The data logger controls the scour device and data collection. It is programmed to take measurement at prescribed intervals. This instrument can trace both scour and refill process [47]. Most of the scour instruments are mounted directly to a pier or substructure of bridge. This indirect measurement method limits interference from debris in the water and makes the instrument easier to maintain. Sonar can continuously measure and return the data as well as easily connected to the elementary station for real time data transmission this is why it is popular monitoring system. It does not require to be buried in the river bed so they are easy to implement. It does not easily get affected by external agencies except some surface debris.

Magnetic sliding collar

Sliding collar solution comprised of a rod and a ring driven into the river bed. Due to erosion of bed material, the collar slides down the rod. Magnetic loggers in the rods will determine the collar depth based on its position on the rod. This type of device proved to be economical during low flow events, but it is easily affected by debris on the water. On the other hand automatic magnetic sliding collars are more expensive but also it is more robust then their manual counterparts [48]. This device provides relatively a straightforward method to minimize progressive scour depth, although it has number of disadvantages like in manual reading system. This system requires metallic cover to provide safeguard against impact caused by debris mainly in heavy flood flow. Another drawback is that scour depth can be detected in the direct vicinity of the device so for evaluating effectiveness of scour prediction, more number of devices may be required after each flood event [2, 49].

Fibre Bragg grating

Fibres Bragg grating devices are highly attractive owing to their inherent wavelength response and their multiplexing capacity for the distributive serving network. Fibres Bragg grating sensors are a form of piezoelectric device. These types of sensors are based on the concept of measuring strain along embedded cantilever rods to generate electric signals which can indicate the progression of scour along the road. It has been found that the shift of the Bragg wavelength has a linear relationship with the applied strain in the axial direction. The rod which is subjected to hydrodynamic forces due to the flowing water and as a result bending is induced in the exposed rod. This bending allows the strain sensors to detect. This device is relatively cheap and performs really well to monitor the changes in scour depth [2, 50].

Electrical conductivity devices

These devices are based on the difference in the electrical conductivity of various media to determine the location of water sediment interface. They work on the principle of measuring an electrical current between two probes. If the material between probes changes, the ability offers a current to be drawn will also change. This phenomenon can also be used to indicate the presence and depth of scour. Electrical conductivity probe device use this technology [2].

Ground penetrating radar

Ground penetrating radar proves to be very effective in low water level for measuring scour and after a flood. It can be easily taken from a portable, inflammable boat as an employment platform in any area around bridge. Ground penetrating radar is also known as effective tool for measuring scour around the entire perimeter of pier and along the upstream and downstream faces. It works on the principle of transmitting pulses into the ground or other medium, by measuring the signals we can easily identify the internal structure and its properties, which are reflected from the internal faces between different geological materials. Ground penetrating radar was used to provide continuous profiles of the streambed surface and it was found to be very effective tool for detecting scour holes, unfilled scour holes, and previous scour surface at bridge sites. The equipment is relatively expensive and data may be contained by noise [2, 51].

Float out devices

Buried at strategic points near the bridge, float out are activated when scour occurs directly above the scour. The sensor floats to the stream surface and on board transmitter is activated and transmits the float out devices digital identification number to a data logger [49-50]. These devices are installed vertically into the bed, the internal radio transmitter triggers a signal when the device is in horizontal position, and it simply works on principle that the device floats out when the depth of scour reaches the installation depth. They are not susceptible to damage from debris as they are installed under the bed as well they can be easily installed in dry beds and riprap. These devices give adequate results for local scour at the vicinity of the pier where it is installed.

COMMON COUNTERMEASURES

Federal highway administration provided guidelines for countering bridge scour and stream bed instability. Hydrologic engineering circular no. 23 [52] provides guideline for countermeasure applicability design installation and maintenance.

Riprap

Riprap is one of the most prominent techniques for the remedial measure to resist the local scour around bridge pier and abutments. Its simple handling and low cost make it widely useable but it needs proper design and placement for proper sizing. HEC-18 & HEC-23 [52] provide proper guidelines for the designing of rip rap. This will facilitate in reducing contraction scour problem because improperly placed rip rap will reduce the hydraulic opening significantly. Mainly it works for abutment and the use of riprap to protect intermediate piers is now considered only a temporary measure. Moreover improperly designed rip rap can increase local scour.

Spur, Dikes, Barbs, Groins and Vanes

These all considered river training structures to alter the water flowing system and train it towards suitable direction to mitigate erosion action of water. They are commonly used on unstable stream channel to train stream flaws to a more desirable location through the bridge.

Structural Strengthening:

Structural strengthening involves modification in the bridge structure to prevent failure due to scour. These modifications are made after scouring to enhance the stability of the structure.

- Foundation Strengthening: This involves adding adequate strength to the foundation with reinforcement and to extend the foundations of the bridge. These counter measures are adopted when the stream bed is levelled to the designed depth of scour or to restore structural integrity after scour has occurred. Retrofitting a simply span bridge with continuous spans could also serve as countermeasure after scours has occurred or when a bridge assessed has scour critical.

- Pier Geometry Modification: These modifications are used primarily to minimize local scour. Modifications are made either to reduce local scour at bridge piers or to transfer the scour to another location.

Biotechnical Counter Measure

In the past few decades, vegetation has been used increasingly to control the erosion or as a bank stabilizer. Primary its serves for the purpose of restoration rehabilitation project and can be applied independently orient combination with structural counter measures. These are several forms that describe vegetative scrambled stabilizations and countermeasures. The use of soft revetment (consist solely of living plant materials) is often referred to as bioengineering. Biotechnical engineering and biotechnical slope protection are the techniques that combine the use of vegetation with structural (hard) elements. The biotechnical engineered countermeasures include vegetated geo-synthetic products, fascines /woody mats, vegetated riprap, root woods and line staking. Drawback of this technique is that the failure of countermeasure could lead up to failure of a bridge.

CONCLUSION

Scouring is a process of undermining of the bridge foundation due the erosive action of flowing water. During a course of time scouring causes severe damages to the bridge and ultimately causing serious threat to life and property. It is a common saying that, the one who overlooks water under bridge will find the bridge under water. This is very true if during the design of bridge, the scour depth is not incorporated or if the correct prediction of scour depth has not been made, then the chances of bridge failure would be very high. Therefore, extensive researches have been conducted in the past for developing a suitable numerical model or empirical relations for the prediction of scour depth. Moreover the prediction of scour depth does not only limit to conventional regression models but also it has gone to another level of machine learning tools. Since the scour is a very complex phenomenon, it is wise to consider all the possible parameters before proposing a scour depth prediction method. A blend of regression techniques with advanced machine learning tools and artificial intelligence techniques proves to be beneficial that will incorporate the complexity of the scouring process and thus such techniques should be encouraged in developing scour prediction equations. The Indian road congress and Indian railways recommends the use of Lacey-Inglis equation for the scour depth calculation in bridge design which was developed about seventy years ago and has been since used in India. These equations were based on observations made on canals in India and Pakistan. The Lacey-Inglis method is meant for non-cohesive sandy material with mean sediment size of about 0.15 mm to 0·43 mm. In this size range the geometric standard deviation of the bed material would vary between 1·4 and 1·8. The method is not valid outside this range. It has been observed that the method adopted by Indian road congress for the calculation of scour depth has several limitations. Moreover, this formula does not consider the scour in cohesive soil, and if applied, it would overestimate the values of scour depth. Therefore for an economical design there is an immediate need to modify Indian Road Congress (IRC) codes in order to incorporate better equation(s) that can accurately calculate scour in cohesive soils. Since the scour is inevitable and it is bound to occur during the lifetime of the structure, hence robust mechanism should be develop to monitor the depth of scour during the whole lifespan of the bridges. The commonly used devices for monitoring scour around bridge pier are sonar, magnetic sliding collar, fibre Bragg grating, electrical conductivity devices, ground penetrating radar and float out devices. For controlling bank or channel erosion biotechnical engineering can be useful and cost efficient tool, beside this it will also enhance the aesthetic and habitat diversity of the site. But traditional scour monitoring instrumentation often requires expensive installation and maintenance and can also be susceptible to debris damage during flooding. Often, the interpretation of data from these instruments can also be time-consuming and difficult. It is an immediate need to adopt and implement a proper scour monitoring program in India. It is also required to sanction funds and research programs for developing a state of the art mechanism to check scour in general and to mitigate the bridge failure in particular.

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