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Scour depth at inclined bridge piers along a straight path: A laboratory study

Negin Karimi [a], Mohammad Heidarnejad [b,*], Alireaza Masjedi [b]

[a] Department of Water Science Engineering, Khouzestan Science and Research Branch, Islamic Azad University, Ahvaz, Iran
[b] Department of Water Science Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran

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ABSTRACT

Scouring threatens the stability of hydraulic structures in different ways, mostly through erosion. This study aims to examine the effect of bridge pier inclination angle on the scouring process by conducting tests along a straight channel in a Plexiglas laboratory flume. To this end, cylindrical piers with four different inclination angles were placed in the flume along a straight channel and tests were conducted at four different flow rates under clear water conditions. Evenly graded sand (D_{50} = 1.46 mm) was used as flume bed material. The obtained results showed that the maximum and minimum scouring depths occurred at pier angles of 0 and 15 respectively. Similar to the scoured depth, dimensions of the scoured hole decreased with increasing pier angle (i.e., changing the pier orientation with respect to the flow direction).

1. Introduction

Bridges are structures that affect the hydrology and morphology of rivers. The existence of bridge piers and supports across a river would decrease water flow cross section, cause the flow to strike the piers, and divert stream lines towards river bed floor, thus creating horse-shoe, swirling, and rising vortices, a leading cause of local scouring at bridge piers. During the flooding season every year, many bridges are destroyed due to scouring and slippage at bridge piers, thus cutting off the very communication lifelines to the flooded areas and interrupting relief operations. For these reasons, studying bridge pier scouring is important [1].

Scouring refers to erosion of river bed floor around an obstacle cue to strong water flow [2]. In local scouring around bridge piers, pressure reduces as we move from the water surface towards the river floor, leading to creation of downward flows. Upon hitting the floor, these downward flows combine to produce horse-shoe vortices. These vortices mostly act at the front of the pier. Rising vortices can also be generated as result of separation at the pier. This type of vortex acts as a whirlwind, moving sediments from the floor towards the surface of water. In other words, this vortex system moves in an upward direction. Studies show that horse-shoe and rising vortices play a significant role in creating scour holes around bridge piers [3].

Potentially, scouring is considered a highly destructive phenomenon to the integrity of bridges and other hydraulic structures, ultimately leading to pier and foundation destruction in such structures and their consequent collapse [4]. In spite of the extensive research conducted for identifying the scouring mechanism, many aspects of this phenomenon remain unresolved and there are many contradictions in this regard. Hoffmans and Verheij [5] pointed out that scouring had to be integrated into the subgrade and pier design processes to ensure the bridge was strong enough to resist very strong flows during flooding periods. Local scouring at bridge piers is a universal problem with sad consequences in terms of loss of life. According to the estimation made in New Zealand by Melville and Coleman 2000), a 36 million dollar annual budget is required in this country to repair the destructive effects caused by scouring at bridge piers. A concise study by Cheremisinoff and Chang [6] on bridge failure in the United States showed that the Federal Bureau of Roads in America had claimed in 1987 to have spent about one million dollars annually in the period between 1964 and 1972 to repair the damages caused by regional flooding of rivers. The catastrophic collapse of a bridge across the Hatchie River in 1989 killed 8 people. The 1993 flooding of the Mississippi destroyed 23 bridges and about 15 million dollars in damages. In 1994, Hurricane Alberta in Georgia led to severe scouring at the piers of more than 500 bridges, with 73 of them requiring essential overhauls or replacement [7].

* Corresponding author.
E-mail address: mo_he3197@yahoo.com (M. Heidarnejad).
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About 86% of the 577,000 bridges registered in the National Bridge Registry (NBR) are built across channels. Of these, more than 26,000 are exposed to severe scouring [8]. Overall, 85,000 bridges across the United States are faced with the scouring problem.

Similarly, many bridges in Iran are lost to scouring. This causes considerable loss of life as well as material damages. Table 1 gives a chronological list of bridge collapse in Iran in recent decades [9]. These statistics show that, in spite of the improved technical and engineering knowledge regarding bridge construction as well as the technological advances in this regard, bridge destruction has had an increasing trend. For this reason, it is essential to study the scouring phenomenon in greater detail.

2. Laboratory studies on reducing the power of erosion

Researchers have proposed many methods to reduce the power of water erosion. The most significant methods in this regard include the rip rap method and using submerged plates, collars, and slots.

Chiew [10] proposed a formula for designing the rip rap rocks. Others have suggested different ways for determining the flow velocity in designing the diameter of rip rap rocks. Neil [11] proposed a design flow velocity of 1.5 times the actual river flow for designing the rocks diameter in the rip rap.

Using plates arranges as collars in parallel to the river floor and perpendicular to the pier can hinder the upward flow created at the upstream nose of the pier, thus preventing scouring. Dargahi [12] used collars to reduce the effects of local scouring. Chiew [10] conducted experiments to study the effect of collars in scouring reduction. Kumar [13] studied reduced scouring under clear water conditions. Chiew [10] proposed – for the first time-to use slots as method for preventing and controlling local scouring. He pointed out that the slot at the pier serves two different functions, as explained below: The slot near the river bed would create a horizontal water jet to divert the downward flow – the main cause of horse-shoe and an important contributor to pier erosion – thus reducing the effective flow depth as well as scour depth. On the other hand, the slot near the surface would reduce the effective flow depth as well as pressure gradient, causing the strength of the downward flow to decrease, as a result of which the scour depth would also decrease. Heidarnejad [14] showed that slot width, slot height, and slot position were important parameters in reducing scour. Maximum scour depth reduction by the slots (having a depth of ¼ and a height of twice that of the pier) near the bed and near the water surface were found to be 20% and 5% respectively.

Technological advances in design and construction of structures have led to the design of modern bridges including bridges with inclined piers for the purpose of reducing scouring.

Bahmani and Haydarpour [15] studied the effect of the angle at which the flow impacted a cylindrical pier under clear water conditions. To this end, they used twosome and threesome groups of cylindrical piers, placed along a 0.03 m wide strip at a spacing of 3 times the pier diameter. The group of piers was then tested at impact angles of 0, 56, 10, and 15 degrees. All the tests were conducted within a 12 m (length) × 0.4 m (width) × 0.6 m (height) laboratory channel. The obtained test results were subsequently compared with those obtained for the single-pier test group. It was observed theta, at angles greater than 15 degrees, the effects of strengthening and shielding at the piers would decrease and that each pier would act as a single pier. Chreties et al. [16] studied a new method for finding the equivalent scour at bridge piers. Assuming that the scour hole shape depended on scouring depth and sedimental properties, they concluded that their proposed method could considerably reduce the required time for conducting tests as well as to remove any doubts that might arise as a result of using the equivalent scour. Buzkus and Cesme [17] conducted experiments in the laboratory to study the effect of reducing scour depth by using inclined piers. They conducted their tests on two piers, 5 and 7 cm in diameter, and applied different flow depths, flow rates, and angles (15, 10, 5, and 0 degrees) under clear water conditions. The mean diameter of the sediments was 1.44 mm with a standard deviation of 3. By comparing their respective measurements in different tests, they concluded that increasing the pier angle would considerably reduce scours due to erosion.

Technological advancements have made possible the construction of bridges with inclined piers in different parts of the world including in Ahvaz, Iran (The Eight Bridge shown in Fig. 1). Since no other study than that by Buzkus and Cesme [17] has so far been conducted on scouring around inclined piers, the authors decided to study this phenomenon in the laboratory.

3. Dimensional analysis

Scour depth around bridge piers depends on several factors including the geometrical parameters of the bridge foundation, hydraulic conditions of the flow, fluid characteristics, and type of sediments on the river bed.

$$f_1(D, V, g, \mu, \rho, V_c, \beta, d_o, d_{50}, d_s) = 0 \quad (1)$$

where d_s is scour depth, D is pier diameter, d_{50} is effective particle diameter, d_o is the flow depth, α is the pier inclination angle measured with respect to a plane parallel to that of the flow, V_c is the threshold velocity, V is the mean velocity, g is the acceleration of gravity, μ is dynamic viscosity, and ρ is water density.

According to Buckingham's Theory, Eq. (1) can be rewritten in the nondimensional form as:

Table 1
Bridges Destroyed in Iran between 1952 and 2011 [9].

Period (year)	Number of Collapsed Bridges
1952–1961	78
1962–1971	648
1972–1981	97
1982–1991	5724
1992–2001	9392
2002–2011	12452

Fig. 1. The Eight Bridge with inclined piers, built in Ahvaz, Iran [18].

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