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A review of bridge scour monitoring techniques

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ABSTRACT

The high profile failure of the Malahide Viaduct in Dublin, Ireland, which is a part of the EU TEN-T network of critical transport links, was caused by foundation scour. Scour is a common soil-structure interaction problem. 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. Monitoring scour is of paramount importance to ensure the continued safe operation of the aging bridge asset network. Most monitoring regimes are based on expensive underwater instrumentation that can often be subjected to damage during times of flooding, when scour risk is at its highest. This paper presents a critical review of existing scour monitoring equipments and methodologies with a particular focus on those using the dynamic response of the structure to indicate the existence and severity of the scour phenomenon affecting the structure. A sensitivity study on a recently developed monitoring method is also undertaken.

1. Introduction

Scour of foundations is the number one cause of bridge collapse in the United States (Melville and Coleman, 2000; Briaud et al., 2001, 2005). During the last 30 years, 600 bridges have failed due to scour problems (Shirole and Holt, 1991; Briaud et al., 1999), causing major operating disruption and financial losses (De Falco and Mele, 2002). In one study of five hundred bridge failures that occurred in the United States between 1989 and 2000, flooding and scour were the cause of 53% of the recorded failures (Wardhana and Hadipriono, 2003). In the United States, the average cost for flood damage repair of highways is estimated at $50 million per year (Lagasse et al., 1995). During a single flood event in the upstream Mississippi and downstream Missouri river basins which occurred in 1993, at least 22 of the 28 bridges failed due to scour. The associated repair costs were more than $8,000,000 (Kamojjala et al., 1994).

Scour can be defined as the excavation and removal of material from the bed and banks of streams as a result of the erosive action of flowing water (Hamill, 1999). Scour occurs in three main forms, namely, general scour, contraction scour and local scour. General scour occurs naturally in river channels and includes the aggradation and degradation of the river bed that may occur as a result of changes in the hydraulic parameters governing the channel form such as changes in the flow rate or changes in the quantity of sediment in the channel (Forde et al., 1999). It relates to the evolution of the waterway and is associated with the progression of scour and filling, in the absence of obstacles (Federico et al., 2003). Contraction scour occurs as a result of the reduction in the channel's cross-sectional area that arises due to the construction of structures such as bridge piers and abutments. It manifests itself as an increase in flow velocity and resulting bed shear stresses, caused by a reduction in the channel's cross-sectional area at the location of a bridge. The increasing shear stresses can overcome the channel bed's threshold shear stress and mobilize the sediments (Briaud et al., 1999). Local scour occurs around individual bridge piers and abutments. Downward flow is induced at the upstream end of bridge piers, leading to very localized erosion in the direct vicinity of the structure (Hamill, 1999) (see Fig. 1). Horseshoe vortices develop due to the separation of the flow at the edge of the scour hole upstream of the pier and result in pushing the down-flow inside the scour hole closer to the pier. Horseshoe vortices are a result of initial scouring and not the primary cause of scour. Furthermore, separation of the flow at the sides of the pier results in wake vortices (Heidarpour et al., 2010). Local scour depends on

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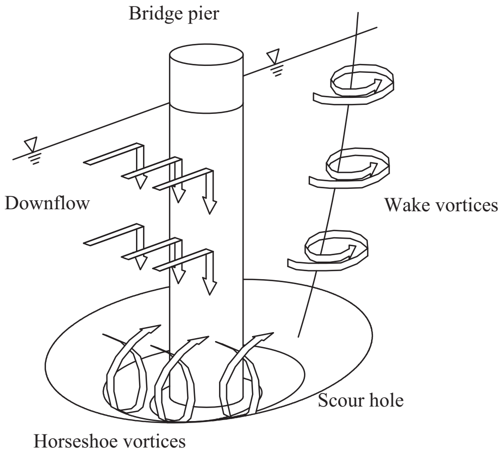

Fig. 1. Schematic of the scour process.

the balance between streambed erosion and sediment deposition. Clear-water scour is the term given to describe the situation when no sediments are delivered by the river whereas live-bed scour describes the situation where an interaction exists between sediment transport and the scour process (Brandimarte et al., 2006). The presence of live-bed conditions leads to smaller ultimate scour depths than in clear-water conditions.

Scour poses obvious problems to the stability of bridge structures. Current practice dictates that the depth of scour is determined by the addition of the individual scour depths caused by the aforementioned mechanisms (general, contraction and local scour) (Briaud et al., 2005). This is the most critical design case. The scour hole generated has the effect of reducing the stiffness of foundation systems and can cause bridge piers to fail without warning. Notable bridge failures due to scour in Europe include the failure of the Sava bridge in Zagreb and the collapse of the Malahide viaduct (Maddison, 2012) in Dublin (Fig. 2).

Scour can be combatted in a number of ways. At the bridge design stage, it is possible to allow for scour mitigation by providing both hydraulic and structural countermeasures (NCHRP, 2009). Hydraulic countermeasures involve the prevention of rapid flow expansion or contraction caused by suddenly induced changes in flow direction that would occur due to blunt pier faces obstructing the flow. These sudden flow changes can lead to the creation of the vortices responsible for the occurrence of scour. They can be prevented by maintaining larger bridge openings at the design stage and also by streamlining pier geometries (May et al., 2002). It is imperative to maintain clear openings by removing debris such as fallen trees and other objects that can often become lodged in bridge openings, obstructing the flow. However, it is noteworthy that maintaining large bridge openings and streamlined pier faces can often be a futile exercise as natural changes in channel deposition and erosion upstream of a bridge can often change the angle of flow relative to the alignment of a bridge and cause these hydraulic problems. Structural countermeasures can be implemented at the design stage by ensuring spread footings that are located below the maximum design scour depths, or as remediation by adding rock-armor and rip-rap to the base of piers and abutments. This countermeasure is limited by uncertainties in predicted design scour depth obtained using formulas such as the Colorado State University (CSU) formula (Bolduc et al., 2008) formulated in the Hydraulic Engineering Circular (HEC-18) design code (Arneson et al., 2012). It can also only be implemented on new structures, since many existing structures have unknown foundation depths. More information on the uncertainties in bridge scour depth estimation is available in Johnson and Dock (1998).

(a)

(b)

Fig. 2. Failure of bridges due to scour. (a) Sava bridge, Zagreb and (b) Malahide viaduct, Dublin. Both bridges failed in 2009.

A more effective and economically viable method of combatting scour is to monitor its evolution over time and to implement remediation works required (Briaud et al., 2011). The most widespread monitoring scheme in place as part of any national bridge asset management framework is to undertake visual inspections. These types of inspections are commonplace in engineering and are used to detect structural anomalies such as cracking and other damages (Sohn et al., 2004). With regard to scour, visual inspections involve the use of divers to inspect the condition of foundation elements and to measure the depth of scour using basic instrumentation (Avent and Alawady, 2005). Two particular disadvantages associated with this inspection method include the fact that inspections cannot be carried out during times of flooding, when the risk of scour is the highest, and the maximum depth of scour may not be recorded as scour holes tend to be filled in as flood water subsides (Lin et al., 2010; Foti and Sabia, 2011). The fact that scour holes tend to be refilled can be dangerous and misleading as the true extent of the scour problem may be missed in the inspection. A more effective alternative is to use fixed or discrete scour depth recording instrumentation. A number of instruments have been developed that can monitor the depth of scour around bridge piers and abutments. Some of these sensing instruments are discussed in Section 2.

2. Scour monitoring using depth-measuring instrumentation

Given the importance of the scour problem, a range of instrumentation has been developed to monitor scour hole development.