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Abutment Scour Countermeasures: A Review

By

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ABSTRACT

Scour of riverbeds at bridge abutments has been a problem for many years. Excessive scour can cause abutment damage and potential loss of life due to bridge collapse. Various countermeasures have been investigated and used with varying degrees of success. Countermeasures can be described in two categories: "bank and bed-hardening" and "flow-altering". Among bank- and bed-hardening countermeasures are rip-rap, cable-tied blocks, Toskanes and similar interlocking devices, and soil cement. Flow-altering countermeasures include vanes, guide banks, and spur dikes of various configurations. These countermeasures either reduce local scour at the abutment or attempt to maintain the channel alignment so that the channel does not outflank the bridge. However, several practical considerations limit the viability of most countermeasures. The considerations include washout of bank-hardening elements, winnowing of the fines between bank-hardening elements, and scour outside the lateral domain of the bank-hardening elements. Flow-altering devices can be outflanked, can be ineffective when flow direction is altered, may wash out themselves, and can snag debris or ice. A three-year research project is underway by the authors and sponsored by the National Cooperative Highway Research Program of the Transportation Research Board to define which countermeasures merit further study and to develop design guidelines for those countermeasures.

INTRODUCTION

The problem of scour around bridge abutments has been identified as one with potentially catastrophic results. Bridge failure can lead to the loss of life. In addition, the costs associated with repairs can be very expensive. Although extensive research has been performed on abutment scour, several questions remain. These substantial issues require further investigation. One issue concerns establishing effective countermeasures for

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protecting abutments against scour. The present paper was written to introduce a study aimed broadly at determining the range of effective scour countermeasures for abutments. It is hoped that presentation of the paper will stimulate useful discussion that may help the writers in conducting the study.

Unresolved Issues

There has been voluminous work done on pier and abutment scour over the years dating back at least to the 1700's. Much of the previous work on abutment scour is illuminated here, but there are several main issues remaining. The main ones are highlighted here.

Riprap is the most common countermeasure used by state bridge engineers, yet what should the size, lateral extent, and thickness of the riprap be? Is filter fabric necessary to prevent the fines under the riprap from winnowing out? Can the riprap stones at the edge of the riprap blanket be the same size as the rest of the stones or should the size gradually decrease to provide a smoother transition to the parent material? Does bedform migration across riprap cause failure? Is tying the riprap together necessary and under what conditions should this be done?

Another common method of protecting bridge abutments is to provide a foundation depth significantly deeper that the scour depth. This approach assumes that our predictions of scour depth are accurate. Should abutments be designed to act as piers, thereby allowing for the case when the river changes course and flows around both sides of an abutment?

In addition, can we use our experience on bridge piers to bear on abutment scour? Obviously piers and abutments differ in shape and location, but perhaps there are ideas and countermeasures that will work on both.

In reference to river migration, can we, or perhaps more philosophically, should we keep the river from migrating? In view of river restoration efforts, where the stream is seeking to re-establish equilibrium, is there a way we can still maintain transportation and yet allow the river to meander where it likes? Which river training structures are most appropriate and what is the most efficient design?

These are but just a few of the many queries left to wrestle with in the very rich topic of bridge abutment scour countermeasures.

Background and Problem Statement

Countermeasures for Pier Scour

The present study parallels an earlier study on countermeasures for bridge piers. The flow pattern around a pier and abutment have similar flow patterns in that both cause contraction scour, have a downward roller, side vortices, and vertical wake vortices. The countermeasures attempted for piers may also have applications for abutments. There have been studies on pier countermeasures by Lauchlan and Melville, 2001; Melville and Hadfield, 1999; Toro-Escobar et al., 1998; Melville et al., 1998; Richardson and Roberts, 1998; Shea and Ports, 1997; Burns et al., 1996; Bertoldi and Kilgore, 1993; Lewis, 1993; Richardson and Abed, 1993; Richardson and Wacker, 1991; Jones et al., 1995; Katsuya et al., 1989; and Richardson and York, 1989.

Fig. 1. Abutment scour at Muda River in Jediang, Malaysia (Photo courtesy of Shanker Kumar Sinnakaundan, River Engineering and Urban Drainage Research Center, Malaysia)

Flow around Abutments and Failure Mechanisms

In order to understand the mechanisms for abutment scour, it is first necessary to investigate the flow patterns as flow goes around an abutment. Most bridge abutments are in compound channels which are comprised of a main channel, in which flow would occur under non-flooding conditions, and a flood channel which is the over-bank area on either side of the main channel, in which flow occurs under flooding conditions.

The flow in compound open channels is an area of current research, but the present understanding is that the flow in the main channel is non-uniform, with a logarithmically-varying vertical velocity profile. This means slower velocities near the bed than near the water surface. In addition, the over-bank flow tends to be slower than the main channel velocities due to the higher roughness and lower flow depths.

When an abutment is introduced into this already-complicated flow field, vortices are formed that scour around the toe of the abutment and on the backside. Abutments come in various shapes and locations in the channel. Regardless of their extent into the channel, however, a vortex forms on the upstream side that has both a downward velocity and some lateral component. This is termed the downward flow/front vortex and can be associated with significant scour. As the flow turns the corner around the toe of the abutment a toe vortex forms that creates extensive scour. This is further exacerbated by the vertical wake vortex. Flow that is not involved in any of these vortices is returned from the over-bank areas into the main channel. This can lead to a contraction of the flow and subsequent flow acceleration. This acceleration can lead to what is termed "contraction scour" in the bed of the main channel (Richardson and Richardson, 1993a; Richardson and Richardson, 1993b).

If any of these scour events extend vertically below the abutment foundation, then collapse can result (Fig. 1).

Parola et al. (1998) document many observed abutment failures from which many of the above conclusions are based. Fischer has identified excessive contraction scour at several bridges in Iowa (Fischer, 1993, 1994, 1995, 1998).

There have been several studies to predict scour at bridge abutments. Principal among them are Melville (1992, 1997), Chang and Davis (1998), Kouchakzadeh and Townsend (1997, 1998), Melville (1995), Melville and Ettema (1993), Sturm (1998), Richardson and Richardson (1998), Hagerty and Parola (1992), Shen et al. (1993), Young et al. (1993, 1998), Sturm and Janjua (1993), Kheiraldin (1995), Sturm and Sadiq (1996), Dou et al. (1996), Sturm and Chrisochoides (1997, 1998a), Kohli and Hager (1997), and Molinas et al., (1998). While each of these studies has added some light to the subject, detailed design criteria need to be developed for existing and new countermeasures.

Armoring Countermeasures

One commonly-used scour countermeasure is the enhancement of the bed's ability to resist erosion. This method is referred to as armoring, since the top layer of the sediment is hardened like a suit of armor. Methods included in this category are riprap, dolos or tetrapods, tied mats (including gabions), and soil cement.

The placement of riprap at the base and side of abutments has been used extensively in river and coastal engineering (Gales, 1938; Quazi and Peterson, 1972; Neill, 1973; Posey, 1974; Hjorth, 1975; Breusers et al., 1977, Parola and Jones, 1991; Richardson et al., 1991; Parola, 1993; Chiew, 1992, 1994; Eve and Melville, 2000). Rip rap placed exclusively for abutment scour mitigation has been studied by Atayee et al. (1993), who give some guidelines for riprap at abutments, and Smith (1984) who gives details of a case history of riprap used to protect a bridge in Canada. Sela and Oliger (1993) note the over-prediction of scour by equations based on laboratory studies and give riprap placement guidelines. Atayee (1993) gives guidelines for riprap at spill-through abutments that allow some passage of water and, thereby, relieve the return flow and contraction scour. Failure mechanisms at riprap-protected abutments include (1) shear failure of armor units, (2) winnowing of parent material, (3) seepage erosion of parent material, and (4) edge failure. Shear failure occurs when the hydrodynamic forces of flow around the abutment are able to transport the riprap material. Winnowing and seepage forces occur when seepage and turbulence remove fine particles below the riprap. With the underlying material gone, the riprap settles. The use of a filter, for example a geotextile material, can reduce winnowing. Some riprap installations function well without a filter, however. The exact use of filters in riprap is one of the goals of the present study. Edge failure occurs when the edge pieces of riprap are eroded away due to a sudden change in roughness of the bed material. With the edge pieces gone, other pieces of riprap are susceptible to erosion as well. Edge erosion occurs when the lateral extent of the riprap is insufficient and the edge pieces are, therefore, in a region of high shear stress. Each of these failure mechanisms will be extensively studied in the present work and detailed design guidelines prepared to avoid failure by these and other failure mechanisms. See Figs. 2 and 3 for laboratory applications of riprap and cable-tied blocks.

Fig. 2. Failure of riprap on an abutment in a laboratory experiment (Eve, 2000).

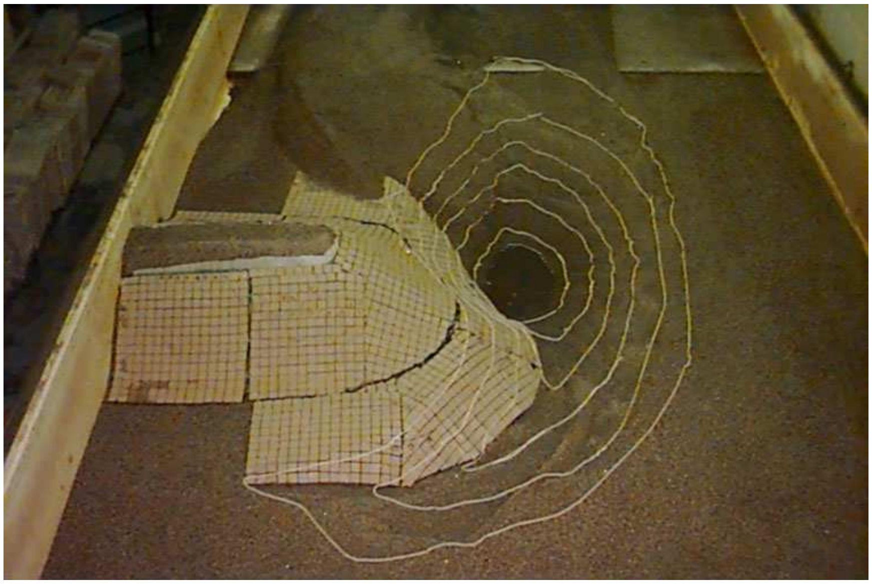

Figure 3: Laboratory test of spill-through abutment protection using cable-tied blocks, Hoe (2001)

Other methods that have been attempted for abutment scour mitigation are Toskanes, Tetrapods, reinforced soil, and tied mats. Burns et al. (1996) developed Toskanes as an alternative scour countermeasure where riprap is not feasible. Results of model studies and design guidelines are presented. Ruff et al. (1995) used Toskanes to protect bridge piers. Reinforced soil was used by Adams et al. (1999) for bridge abutments but they conclude that reinforced soil is not suitable for permanent bridges in scour zones.

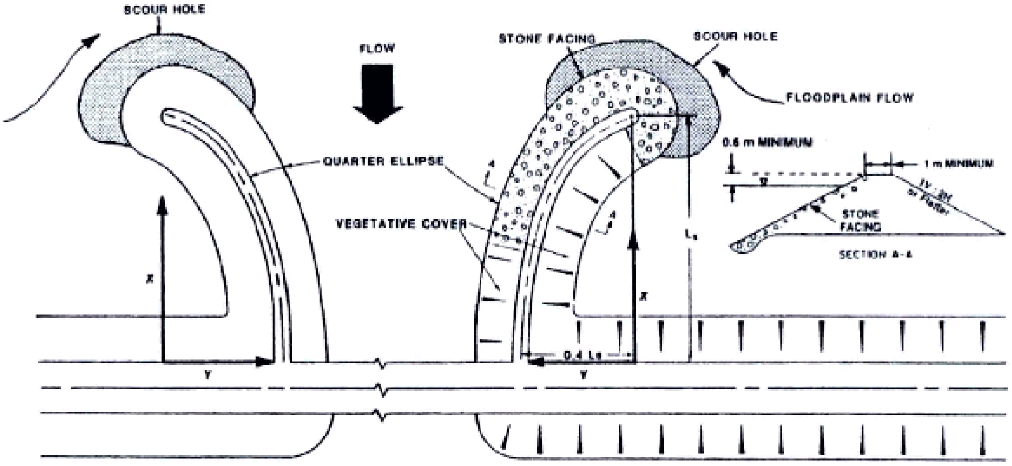

Fig. 4. Example of typical guide banks (from Lagasse et al., 2001).

Flow-altering Countermeasures

In contrast to countermeasures that armor the sediment surface, flow-altering countermeasures reduce the ability of the flow to scour sediment. Flow-altering countermeasures include guidebanks (Fig. 4), dikes or spurs (Fig. 5), to train the upstream river and in-channel devices such as vanes and bendway weirs. Although there have been many studies on spur dikes for river training (Kuhnle et al.,1997, 1998, and 1999; Farsirotou et al., 1998; Molinas et al., 1998; Zhang and Du, 1997; Soliman et al., 1997; Tominaga et al., 1997; Wu and Lin, 1993; Khan and Chaudry, 1992; Shields et al., 1991, 1995, and 1998; Molis et al., 1995; Mayerle et al., 1995; Muneta and Shimizu, 1994), the use of spur dikes specifically for use upstream of abutments was studied by Herbich (1967) using fixed-bed and movable-bed laboratory models and Richardson and Simons (1984) give design recommendations based on the literature. Lagasse et al., (1995) and Richardson et al. (1990) give design guidelines for impermeable and permeable spurs, guide banks, and riprap stability factor design. Richardson and Davis (1995) give guidelines for sizing rock riprap at abutments. Vanes have been used for erosion reduction on river bends (Ettema, 1990 and 1992; Odgaard and Kennedy, 1982; Odgaard and Kennedy, 1983; Odgaard and Lee, 1984; Odgaard and Mosconi, 1987; Odgaard and Spoljaric, 1986; Odgaard, Spoljaric, and Mosconi, 1988; Odgaard and Wang, 1990; Odgaard and Wang, 1990; Odgaard and Wang, 1991) and for reducing sediment ingestion in intakes (Barkdoll, Ettema, and Odgaard, 1999). They are small foils placed in the riverbed at an angle of attack to the flow, which creates a vortex downstream that can be used to manage sediment and alter flow.

Fig. 5. Spur dike on Goodwin Creek Experimental Watershed, Mississippi. Flow direction is from right to left.

Scale Effects

There is a widely held concern that laboratory studies on scour find greater scour depths than occur in full-scale situations. Sturm and Chrisochoides (1997) investigated scale effects for bridge abutments, but they used only two different scales. Ettema, Melville, and Barkdoll (1996), who focused on pier scour, also noted scale effects. They concluded that scale effects are significant and can be difficult to predict due to scale-related differences in strength of large-scale turbulence at piers and abutments. A set of experiments, entailing experiments over a wide range of scales, is needed to confirm the suspected scale effects.

Debris and Ice

Potential problems with debris and ice can plague hydraulic structures in general and may have implications for selection and design of abutment scour countermeasures in forested and/or cold regions.

Debris can collect on bridge piers and abutments and, if not cleared, can alter the flow characteristics considerably. Debris can also cause a type of contraction scour in which the flow area is constricted and, therefore, raises the flow velocity and correspondingly increases the scour of the bed. Studies addressing debris flow include Mueller and Parola, 1998; Parola et al., 1998; and Hagarty, Parola, and Fenske, 1995.

Ice runs and jams are the principal ice concern for bridges. Bridge abutments often serve as flow constrictions leading to ice jams. In this regard, ice and debris likely have similar effects on scour at bridge crossings. Ice may also freeze to and modify the performance of scour-protection systems, such as vanes, riprap (e.g., by plucking riprap stones), and fender structures. These actions of ice need careful consideration when designing abutments for ice-prone rivers. In overall terms, little work has been done to determine on ice effects on scour at bridge abutments. The few prior studies concerning ice and local scour (e.g., Yankielun and Zabilansky (2000), Zabilansky 2000) have focused essentially on developing field instrumentation and on obtaining field measurements from a single bridge site. There is scope for considerable fundamental investigation into ice effects on scour at abutments.

The principle studies in the area of ice interaction with hydraulic structures are: Ettema, 1999; Ettema et al., 1999;Tan, Sinha, and Ettema, 1999; Streitz and Ettema, 1998; Ettema et al., 1998;Ettema et al., 1997a and b; Smith and Ettema, 1997a and b; Braileanu, Ettema, and Muste, 1997; Urroz and Ettema, 1994a, b, c, and d; Urroz, Schaefer, and Ettema, 1994; Teal, Ettema, and Walker, 1994a and b; Yoon and Ettema, 1993; Nixon, Ettema, Matsuishi, and Johnson, 1993; Braileanu, Ettema, and Wuebben, 1996; Chung, Howard, and Ettema, 1992; Yoon, Patel, and Ettema, 1992 and 1996; Tsai and Ettema et al., 1990; Ettema et al., 1991; Crissman, Ettema et. al., 1995; Ettema and Urroz-Aguirre, 1991; Jain and Ettema, 1989; Ettema et al., 1989; Schaefer, Ettema, and Nixon, 1989; Stern, Ettema, and Lazaro, 1989; Nixon and Ettema et al., 1989; Teal and Ettema, 1994; Ettema et al., 2000.

ABUTMENT SCOUR COUNTERMEASURE STUDY

This review of existing countermeasures is part of an ongoing study funded by the National Cooperative Highway Research Program of the Transportation Research Board. At the writing of this paper, Project NCHRP 24-18 is finishing Phase I in which all existing information was gathered, each state Department of Transportation was surveyed as to their abutment scour countermeasure experiences, and countermeasures worthy of further laboratory study were identified. Phase II will include laboratory experiments to guide in the formation of design guidelines for selected abutment scour countermeasures.

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