Sedimentation of Multi-Barrel Culverts

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ABSTRACT

Box culverts are generally designed to handle events with a 50 year return period and, therefore, most of the time they convey considerably lower flows. In many situations, water flow through a typical multi-barrel box culvert is relatively low throughout most of the year and usually concentrates in one barrel. A common adverse consequence for multi-barrel culverts when one barrel ends up carrying most of the flow during low-flow periods is that over several years of relatively low flow, some of the barrels may silt-in so as to become partially filled with sediment. Such sedimentation can reduce the capacity of culverts to handle the larger flow events and pose high-water problems upstream of culverts. This problem and the costs it incurs are compounded because many culverts are small enough in area, yet also rather long, that cleaning sediment from a partially filled culvert can be very difficult and costly. The problem is particularly severe for culverts draining small rural watersheds.

There is a need for methods of prevention or reduction of the in-filling of culverts, both for existing culverts and new culverts. Existing manuals, books, and guides do not provide adequate information on sediment control at box culverts, or for multi-barrel culverts generally. The present paper focuses on ways to ensure that multi-barrel culverts do not become silted in. The paper focuses especially on methods whereby culverts may self-cleanse themselves of sediment.

Key words: culverts—sedimentation—self-cleaning structures
INTRODUCTION

Culverts are the common means to convey flow through the roadway system for smaller streams. Typically, the culvert is designed to handle storm events (e.g., 50 year return period discharge). Culverts may comprise multiple culvert pipes (a multi-barrel culvert) or a single culvert pipe. In general, larger flows and road embankment heights entail the use of multi-barrel culverts. The advantage of a multi-barrel culvert is that the requirement of upstream headwater is smaller than for a single-barrel culvert. However, the adverse documented effect is sedimentation (Vassilios 1995; Andrzej el. 2001; Charbeneau 2002). Multi-barrel culverts are prone to have sedimentation problems because of the channel transition connecting dissimilar cross-sections between the stream and the culvert. In the case where the design procedure suggests that required size and geometry of culverts extend beyond the width of the natural channel, channel transitions are required to convey drainage flow to and from the culvert. Expansion is needed upstream of the culvert, and contraction is needed downstream of the culvert. The transitions disturb the natural channel regime and have undesirable consequences, such as sedimentation through the culvert.

The present paper addresses sediment deposition pattern around the culvert and self-cleaning system designed to flush sediment out by using the power of drainage flows. The issues were investigated by a brief field survey and a series of laboratory and numerical experiments.

Field Survey of Multi-Barrel Culverts

Over many years of lower flow, some of the barrels of multi-box culverts can silt-in and become partially filled with sediment. A field survey was conducted in 2006, Iowa City, Iowa, USA. Figure 1 shows a three-box culvert viewed from the road and upstream channel. The natural channel width was narrower than the culvert; the expansion was observed and sediment was allowed to deposit in this zone and barrels. This can reduce the capacity and result in decreased safety because the culvert may not perform according to design. The full field survey is reported by Muste et. al. (2009). This paper presented the site at the center line of the channel, which was approximately through the center of the culvert.

Figure 1. Culvert site at Iowa City, Iowa, USA—blue arrow indicates flow direction (a) look upstream from the culvert approximately along center line, (b) look downstream from the channel left bank
Investigate Tools

A triple set of tests was used to find a working, self-cleaning, multi-box design. A 1:20 scale three-box culvert model was used to replicate the baseline tests and screen the self-cleaning culvert configurations for their effectiveness to mitigate sedimentation problems for a range of flow conditions (Figure 2a). The tests were run using clear-water scour and continuous sediment feeding. Numerical simulations were used to refine the self-cleaning culvert geometry and test it for a range of flow conditions complementary to those tested in the laboratory experiments. Passive scalar visualizations were used to simulate the sediment transport. A 1:5 scale three-box culvert model was used to assess the performance of the designed self-cleaning culvert configuration (Figure 2b). The tests were run using live-bed scour and sediment recirculation. Extensive running times were used to achieve equilibrium for both flow and sediment transport.

![Figure 2. Overview of laboratory models—(a) a 1:20 scale three-box culvert model, (b) a 1:5 scale three-box culvert model](image)

Design Concept of Self-Cleaning System

The basic concept of a self-cleaning system for sediment control was to increase the flow velocities and concentrate the flow to the main channel. The driving criterion for designing the self-cleaning culvert geometry was to make modifications in the upstream area of the culvert that would restore the shape and functionality of the original (undisturbed) stream. For this purpose, the lateral expansion areas were filled in with sloping volumes of material to both reduce the depth and to direct the flow and sediment toward the central barrel, where the original stream was located prior to the culvert construction. The fillet-based self-cleaning design is presented in Figure 3.

![Figure 3. The fillet-based self-cleaning design geometry (a) fillets constructed upstream from the three-box culvert, (b) close-view of the fillet](image)
Self-Cleaning System Outcomes

The fillet-based self-cleaning design developed through this study proved its reliability and efficiency through a variety of tests. Figure 4a shows baseline tests in the 1:20 model and the numerical model. A strong non-uniform velocity distribution was observed in the experiments. Sediment was prone to deposit and accumulate in the side of the expansion upstream the culvert. Figure 4b shows screening tests in the 1:20 model and the numerical model. The conditioned culverts (with fillets set in) displayed favorable flow behavior compared with the original ones. Among the fillets’ main effects are the following:

1. Direct the sediment through the central barrel of the multi-box culvert
2. Maintain the effectiveness over a range of flows (even for the highest flows where small deposits are created, they do not obstruct the active area of the lateral culvert boxes)
3. Maintain the overall sediment transport rates within the boxes of the conditioned culverts at levels comparable with those in the original culverts

![Figure 4. Comparison between the three-box culvert with and without self-cleaning system (a) no self-cleaning system in physical and numerical models, (b) self-cleaning system constructed in physical and numerical models](image)

The efficiency of self-cleaning system was also conducted in the 1:5 model. Photographs (see Figure 5) of sediment deposition were taken from the same distance at an oblique angle using a reference in the images (the horizontal pole). The images allow us to observe that the sedimentation that occurs in the critical area of the upstream culvert expansion where deposition occurs at the highest rates and with the most detrimental impacts. Visual inspection of the images in Figure 5b shows that the self-cleaning fillets set in the expansion have the aforementioned effects.
Figure 5. Sediment deposition patterns without and within fillet-based self-cleaning system (a) no self-cleaning system, (b) self-cleaning system constructed

Large-Scale Particle Image Velocimetry (LSPIV) was used to measure velocity distribution for the reference culvert model and the fillet-based self-cleaning culvert design. The isovelocity contours plotted in Figure 6 illustrate that the velocity magnitude was considerably increased throughout the center area of the expansion leading to an increased flow power that enhances the transport of sediment incoming toward the culvert. The LSPIV measurements undoubtedly demonstrate that water and sediment are forced to the central culvert box when the self-cleaning fillets are set in the expansion.

Figure 6. Velocity distribution upstream from the 1:5 culvert model (a) no self-cleaning system, (b) self-cleaning system constructed

CONCLUSION

Site visits of multi-barrel culverts in Iowa showed a common feature: sediment deposits developed in the upstream vicinity of the culvert. Severe sedimentation situations were encountered at several culverts. The deposits were partially blocking the culvert active area and usually were covered by vegetation. Cleanup operations are costly and for some of the visited culverts, were needed just two years after a previous cleanup. The main objective of this research is to understand and conceptualize the mechanics of sedimentation process at multi-box culverts and develop self-cleaning systems that flush out sediment deposits using the power of drainage flows.
Observations in the laboratory conducted in a 1:20 scale three-box culvert model, guided by companion numerical simulations, enabled the researchers to understand the mechanics of the sedimentation processes developing in three-box culverts, a typical culvert design for Iowa small streams. The first finding of the study was that the culvert design assumption of flow uniformity in expansion leading to the culvert is not correct. A strong non-uniform flow distribution was documented in the experiments through the culvert vicinity.

The fillet-based self-cleaning culvert design developed through the present study proved its reliability and efficiency through a triple set of tests (hydraulic model runs in the 1:20 and 1:5 scale models, and numerical simulations). The design is simple to implement in any stage of the culvert lifetime, i.e., at the time of construction or later on by retrofitting the area in the vicinity of the structure at the time of a cleanup. In the latter situation, the fillets can be mostly constructed with local material, i.e., the sediment deposited at the culvert is relocated in the area of fillets during the cleaning. The retrofitting using the actual sediment deposits are obviously the most efficient from cost perspective. The fillets such obtained can be “rip-rapped” and, possibly, grouted to roughen their surface for enhanced resistance to flow action. The grouting is also recommended for creating a vegetation barrier.

Due to the number and complexity of the factors involved in the sedimentation process and the limited amount of resources available for the study, only one culvert’s geometry was investigated. The modeled geometry replicates the triple reinforced box culvert (TRRCBG1-01), which is typical for Iowa small streams. The flow approaching the structure was assumed to be perpendicular, despite the fact that many culvert situations depart from this layout. Finally, complex flow aspects related to modeling of sediment transport could have not been captured in the study, both because of existing knowledge gaps (e.g., triggering events, sedimentation-prone flow regimes) and modeling complexity (e.g., simultaneous suspended and bed load transport). An ongoing study will address many of these aspects and consequently further the results of the present investigation.
ACKNOWLEDGEMENTS

The work presented in this paper was conducted with support from the Iowa Department of Transportation Project TR-545. The support is greatly appreciated.

REFERENCES


