Study on morpho- and hydro-dynamics of multi-box culverts

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Abstract

Culverts are used to convey a large range of flow rates and sediment load through road embankments. They customarily are designed to convey flow events having a 50-year return period. Often times, the multi-barrel culverts are preferred as they require a lesser upstream headwater elevation compared with single-barrel culverts. Most of the time, however, culverts convey flows that are of lower velocity and lesser depth than the design flows. During the transitions from high to low flows sediment deposition inherently occurs in the upstream transitioning the stream to culvert cross-section. Repetition of these flow transitions over the time results in the increase of the sediment deposits that often become "stabilized" due to the growth of vegetation, hence reducing permanently the capacity of culverts to handle large flows. The present paper investigates details of the mechanics of the formation of the sediment deposits in the upstream vicinity of the culverts and mitigation designs that ensure an efficient, hydraulic-driven cleaning effect.

1 Introduction

Culverts are commonly used to pass roads over small streams without blocking stream flow. In the past, the culvert design primarily focused on the hydraulic efficiency and the structure safety. The stream continuity, the impact on stream stability, and sedimentation problems were not considered in the traditional design process. The sediment load conveyed by streams may at times accumulate and partially block culverts, seriously reducing their capacity to convey design flows. Multi-barrel culverts (culverts with more than one conduit) are especially prone to sediment blockage because of geometric configuration (Vassillios 1995, Charbeneau *et al*. 2002, and Rigby *et al*. 2002). Sediment deposition at culverts is influenced by many factors, including the size and characteristics of material of which the channel is composed, the hydraulic characteristics generated under different hydrologic events, the culvert geometry design, the channel transition design, and the presence of vegetation around the channel. The multitude of combinations produced by this set of variables makes the investigation of practical situation a complex undertaking. Most hydraulic manuals provide design specifications only for clear water conditions, and leave the issue of sediment management unaddressed.

This study was motivated by quite widespread problems with culvert sedimentation, notably for culverts located in rural Iowa where streams typically convey substantial sediment loads. The problems indicated the need for the guidance on how culvert designs can mitigate or inhibit sediment deposition and blockage. The guidance should be applicable to new culverts and existing culverts. In regions where high rates of soil erosion occur, there is pressing need for such methods. Iowa is one such area. Its numerous multi-box culverts face chronic sediment problems. This study shows how sediment blockage may readily occur at multi-barrel culverts with field and laboratory observations, and indicates options for mitigating such blockage with laboratory and numerical experiments.

2 Field survey

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 at 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 allowed sediment to deposit in this zone and barrels. The sediment deposition can reduce the capacity and result in decreased safety because the culvert may not perform according to design. This paper presented the site which the center line of the channel approximately through the center of the culvert.

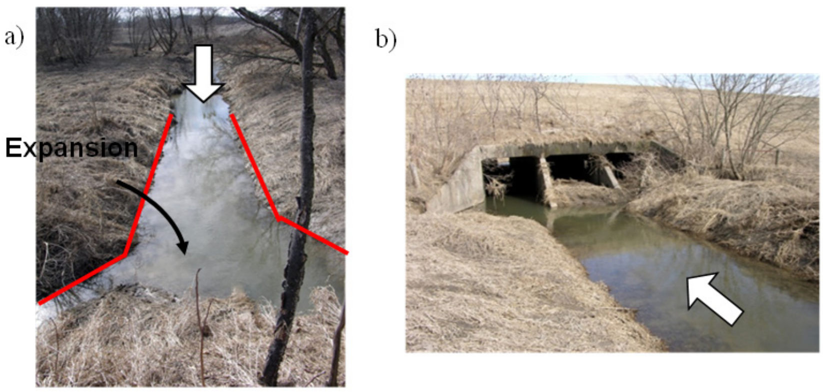

Figure 1: Silted culvert at a three-box culvert in Iowa (USA): arrow represents the flow direction: a) view of the upstream area from the culvert, and b) view of the silted culvert entrance

3 Self-cleaning culvert design

To prevent the sedimentation at the culvert sites, the self-cleaning design was proposed. The basic concept of a self-cleaning system for sediment control was to increase the flow velocities and concentrated 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 2.

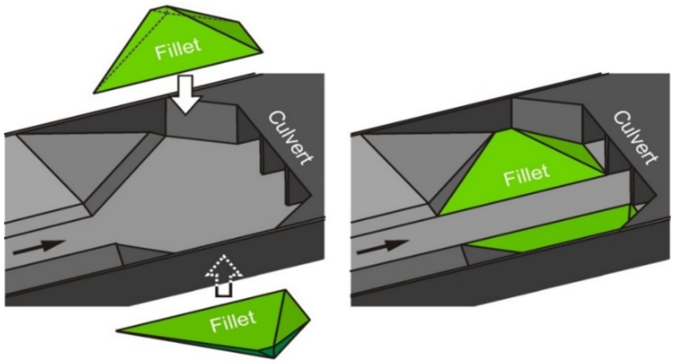

Figure 2: The fillet-based self-cleaning design geometry

4 Performance of self-cleaning design

The fillet-based self-cleaning design developed through this study proved their reliability and efficiency through a variety of tests. Figure 3a 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 3b 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:

(i) Direct the sediment through the central barrel of the multi-box culvert

(ii) 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)

(iii) Maintain the overall sediment transport rates within the boxes of the conditioned culverts at levels comparable with those in the original culverts

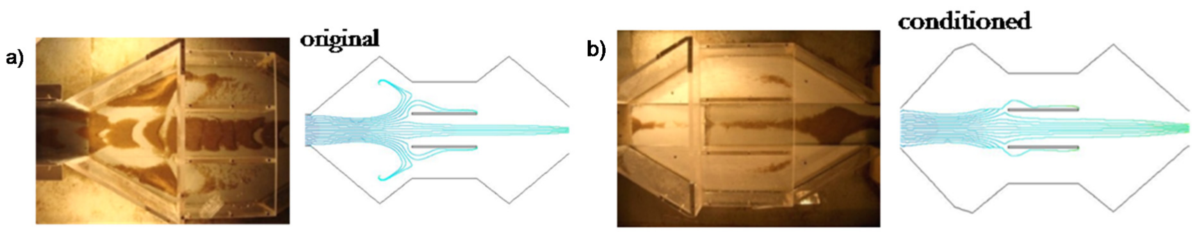

Figure 3: Comparison between the culvert with and without self-cleaning system (experiments-left column; numerical simulations-right column): a) without fillets, b) with fillets installed

The efficiency of self-cleaning system was also conducted in the 1:5 model. Photographs (see Figure 4) 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 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 4b shows that the self-cleaning fillets set in the expansion have the aforementioned effects. The SeaTek multiple transducer arrays (MTAs) were deployed to survey the development of the bed forms in the culvert boxes. Measurements were performed at 18 sections in the left and central boxes. Measurements in each section were continuously collected for 30 seconds. Assuming that the bed movement over 30 seconds is negligible with respect to the dominant scales of the sediment transport process, each bed profile in the box was obtained by averaging 30 sets of data. The sedimentation maps inside the culvert boxes are shown in Figure 5. The results were measured after running the test for 6 hours and for 12 hours, respectively. Figure 5 shows the results with and without the self-cleaning system placed upstream of the culvert, respectively. The comparison of the sediment deposits shows that the self-cleaning system was able to mitigate the sediment deposition in the left box. The large sediment deposition present in the left box for the case of the standard design was avoided when the self-cleaning system was installed in the culvert. Figure 5 shows that the self-cleaning system was able to reduce the amount of deposited sediment in the left box by more than 70%. The further study of head loss measurements in the model is ongoing to evaluate the effect of the filled-based self-cleaning system.

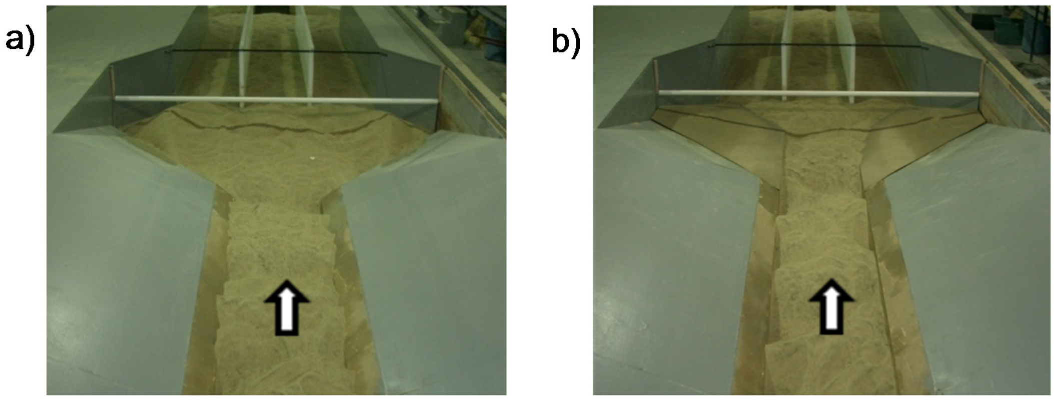

Figure 4: Sediment deposition patterns without and with fillet-based self-cleaning system: a) no self-cleaning system, b) self-cleaning system constructed

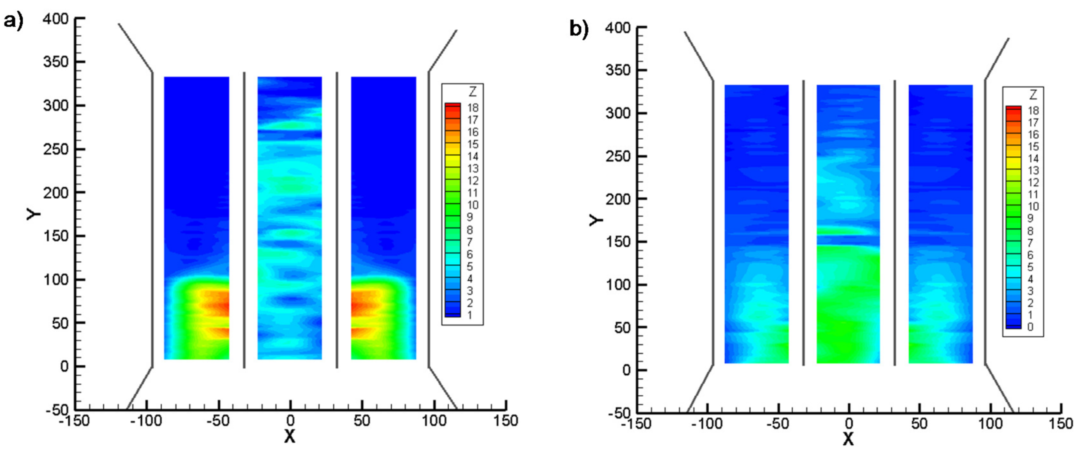

Figure 5: Mapping of the sediment deposits formed in the culvert boxes after 12-hours: a) without self-cleaning fillets; b) with self-cleaning fillets placed upstream the culvert boxes

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 iso-velocity 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.

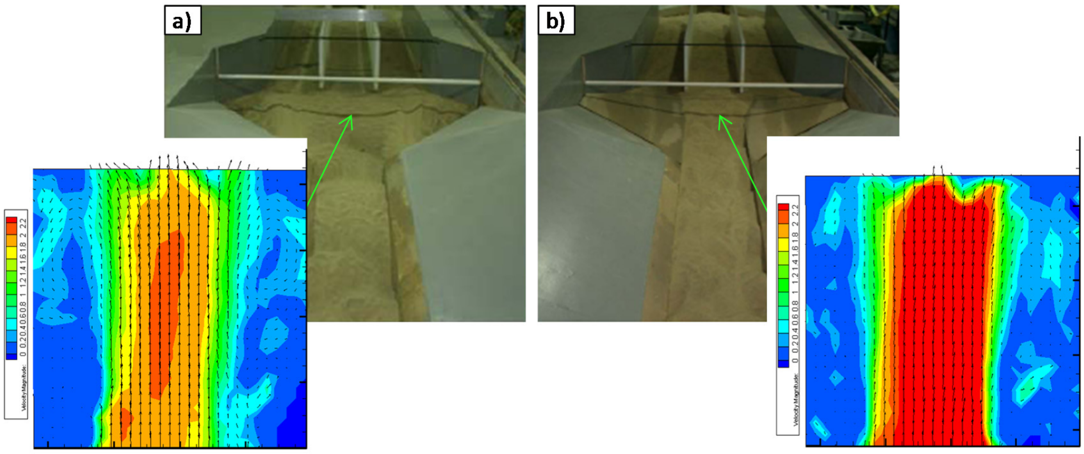

Figure 6: Velocity distributions upstream the 1:5 culvert model: a) no self-cleaning system, b) self-cleaning system constructed

The above performance tests conducted to evaluate the self-cleaning system provide the following conclusions:

(i) Instead of creating or increasing the size of recirculation areas, the self-cleaning system removes them

(ii) The self-cleaning system strengthens the convection of sediment into the central box

(iii)The self-cleaning system amplifies the turbulence at the entrance into the side boxes and mitigates the sediment deposition inside them

5 Conclusions

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 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-rap"- ed and, possibly, grouted to roughen their surface for enhanced resistance to flow action. The grouting is also recommended for creating a vegetation barrier.

References

Andrzej J. K., and Stanley R. D., (2001) "Consideration of Stream Morphology in Culvert and Bridge Design" J. of Transportation Research Board, Vol. 1743, pp 57-59

Charbeneau, R. J., Henderson A. D., Murdock R. C., and Sherman L. C., (2002) "Hydraulics of Channel Expansion Leading to Low-Head Culverts", Report FHWA/TX-03-2109-1, Texas Center for Transportation Research, Austin, Tex.

Rigby E. H., Boyd M. J., Roso S., Silveri P., and Davis A. (2002) "Causes and Effects of Culvert Blockage during Large Storms" ASCE Conf. Proc. Vol 112, 298

Vassilios (1995) "Effects of sediment on Drainage Culvert Serviceability" J. Performance of Constructed Facility, 9(3).

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