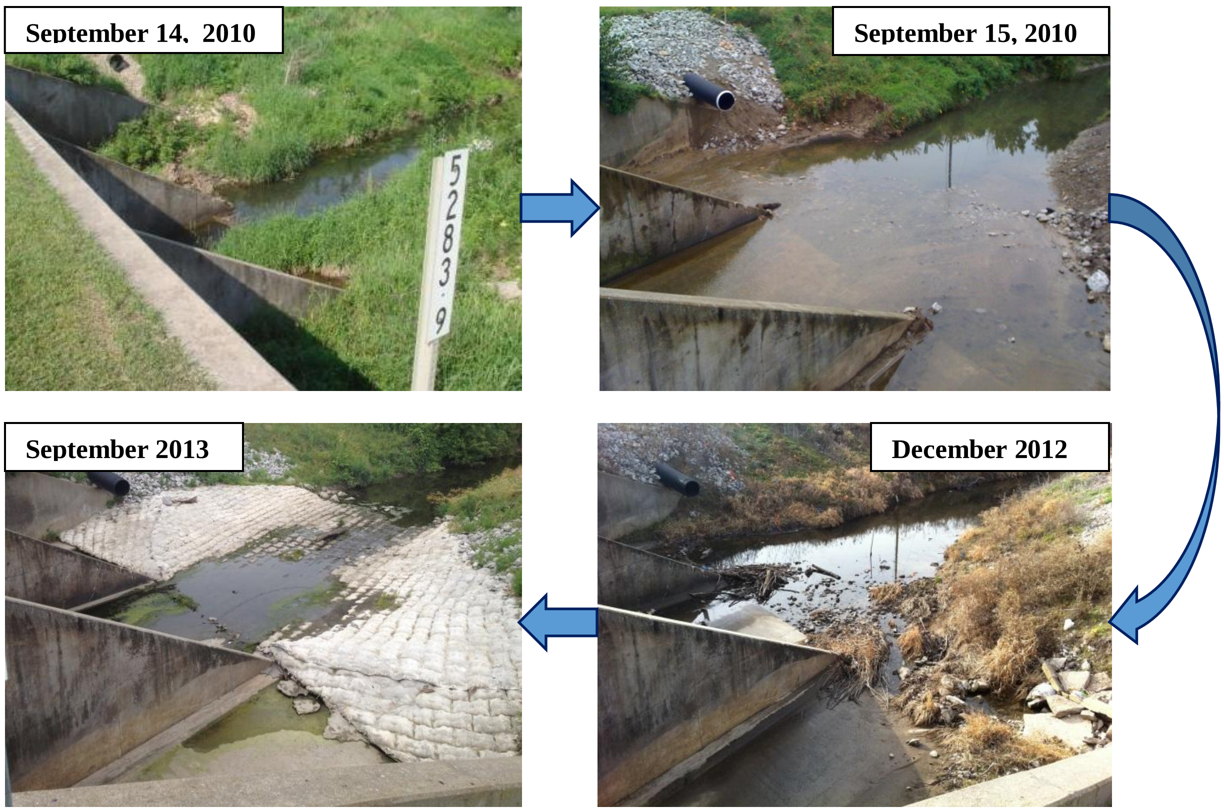
FINAL REPORT FOR IHRB TR-619

DEVELOPMENT OF SELF-CLEANING BOX CULVERT DESIGN – Phase II



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Abstract

Culverts are common means to convey flow through the roadway system for small streams. In general, larger flows and road embankment heights entail the use of multi-barrel culverts (a.k.a. multi-box) culverts. Box culverts are generally designed to handle events with a 50-year return period, and therefore convey considerably lower flows much of the time. While there are no issues with conveying high flows, many multi-box culverts in Iowa pose a significant problem related to sedimentation. The highly erosive Iowa soils can easily lead to the situation that some of the barrels can silt-in early after their construction, becoming partially filled with sediment in few years. Silting can reduce considerably the capacity of the culvert to handle larger flow events.

Phase I of this Iowa Highway Research Board project (TR-545) led to an innovative solution for preventing sedimentation. The solution was comprehensively investigated through laboratory experiments and numerical modeling aimed at screening design alternatives and testing their hydraulic and sediment conveyance performance. Following this study phase, the Technical Advisory Committee suggested to implement the recommended sediment mitigation design to a field site. The site selected for implementation was a 3-box culvert crossing Willow Creek on IA Hwy 1W in Iowa City. The culvert was constructed in 1981 and the first cleanup was needed in 2000.

Phase II of the TR 545 entailed the monitoring of the site with and without the self-cleaning sedimentation structure in place (similarly with the study conducted in laboratory). The first monitoring stage (Sept 2010 to December 2012) was aimed at providing a baseline for the operation of the as-designed culvert. In order to support Phase II research, a cleanup of the IA Hwy 1W culvert was conducted in September 2011. Subsequently, a monitoring program was initiated to document the sedimentation produced by individual and multiple storms propagating through the culvert. The first two years of monitoring showed inception of the sedimentation in the first spring following the cleanup. Sedimentation continued to increase throughout the monitoring program following the depositional patterns observed in the laboratory tests and those documented in the pre-cleaning surveys.

The second part of Phase II of the study was aimed at monitoring the constructed self-cleaning structure. Since its construction in December 2012, the culvert site was continuously monitored through systematic observations. The evidence garnered in this phase of the study demonstrates the good performance of the self-cleaning structure in mitigating the sediment deposition at culverts. Besides their beneficial role in sediment mitigation, the designed self-cleaning structures maintain a clean and clear area upstream the culvert, keep a healthy flow through the central barrel offering hydraulic and aquatic habitat similar with that in the undisturbed stream reaches upstream and downstream the culvert. It can be concluded that the proposed self-cleaning structural solution "streamlines" the area upstream the culvert in a way that secures the safety of the culvert structure at high flows while producing much less disturbance in the stream behavior compared with the current constructive approaches.

Table of content

Figures

Tables

1. Introduction

1.1 Background

Culverts are common means to convey flow through the roadway system for small streams. Various culvert types and materials are used, depending on culvert site and the characteristics of its drainage area. In general, larger flows and road embankment heights entail the use of multi-barrel culverts (a.k.a. multi-box) culverts. The advantage of multi-box culvert is that they require less headwater and are more economical than a larger single-box culvert. In many areas of Iowa, and indeed elsewhere, water flow through a typical box culvert is relatively low throughout most of the year. Box culverts are generally designed to handle events with a 50-year return period, and therefore convey considerably lower flows much of the time. However, there are problems associated with the use of multi-box culverts. The most significant problem for Iowa landscape multi-box culverts is the sedimentation. The highly erosive Iowa soil can easily lead to the situation that some of the barrels can silt-in, becoming partially filled with sediment. Silting can reduce considerably the capacity of the culvert to handle larger flow events.

During 2007, the present research team assessed the extent and severity of the sedimentation at culvert problem through a series of field visits at more than Iowa 30 culverts located in Buena Vista, Marion, and Johnson Counties. While diverse in many respects, the visited culverts showed a common feature: they were partially silted, requiring difficult and costly cleanup operations. Figure 1 illustrates a typical situation for a three-box culvert in Iowa; the sediment deposit is considerably limiting the culvert’s conveyance capacity (Ho, 2010). Field observations show that sedimentation occurs relatively rapidly, with considerable amount of sediment in the deposits only 1.5 years after complete removal of an earlier deposit (see Fig. 1). The problematic prevalence of culvert sedimentation is a major concern for road maintenance authorities in many Midwest areas. Silting situations, such as those illustrated in Figure 1, were encountered at several of the visited culverts. This problem and the costs it incurs are compounded because many culverts are small enough that cleaning sediment from a partially filled culvert can be very difficult due to the small space for cleanup vehicles.

There has been a need for methods of prevention or reduction of the in- filling of culverts, both for existing and new culverts. Existing manuals, books, and guides do not typically provide adequate information on sediment control at box culverts, for single or multi-barrel culverts. An innovative solution for preventing sedimentation at 3-box culverts was developed through laboratory experiments and numerical modeling carried out through Phase I of this Iowa Highway Research Board (IHRB). The TR-545 Project developed a generic solution to ensure that box culverts do not become silted in during the annual flow cycle. The first phase of the project also investigated the sensitivity of the developed design to various changes in the culvert geometry and range of flows through the culvert. Finally, the study checked the validity for 2-box culverts (Muste et al., 2009).

Figure 1 Sediment deposits at a typical 3-box culvert sites in Iowa, showing the relatively fast accumulation and vegetation-stabilization of the sediment deposits

1.2 Study objectives

The overall objective of this project series (phase I and II) was to identify and develop methods for constructing or retro-fitting box culverts to ensure that the range of flows through a culvert would continuously provide the flow capacity needed to move the sediment transported from the drainage area through the culvert. Consequently, the culvert's entrance area and the barrels can be kept clean of sediment maintain the structure in good operating conditions with little or no maintenance. Taking into consideration the results obtained in the Phase I of this research, IHRB suggested a follow up of the theoretical study with another study aimed at implementing and monitoring the proposed design in field conditions. As a result, a new phase of the study was initiated. Phase II of the project entails the following objectives:

a. Identification of a three-box culvert prone to sedimentation and accessible for continuous, long term monitoring. Such a culvert was identified on Hwy 1 in Iowa City, on the Willow Creek)

b. Monitoring the three-box culvert selected for testing prior and after to sediment cleanup for establishing reference conditions for assessing the efficacy of the self-cleaning designs and the role of other factors involved in triggering sedimentation (e.g., the growth of riparian vegetation)
c. Prepare design specifications for implementation of the self-cleaning design
d. Conduct laboratory study to test potential modifications required by the established design
e. Monitor the self-cleaning culvert after implementation using synoptic surveys and continuous monitoring. For this purpose a real-time web-camera and a stage sensor developed by the Iowa Flood Center (iowafloodcenter.org).

The objectives associated with Phase II of TR 545 were centered on the site identified in objective a. The site is located on 1506 IA Hwy 1W and it is a triple 15’-18”-15”x12 reinforced concrete box (RCB). The culvert was built in 1981-82 replacing a previous culvert passing over Willow Creek. The culvert drains a mostly urbanized catchment developed rapidly after the culvert construction in 1981. The first cleanup after the construction of the culvert was made in 2000. At the time of inception of the present study the culvert was heavily silting throughout its more than 300-ft length as shown in Figure 2.

Upstream views

Downstream views

Figure 2 The status of the culvert selected for monitoring at the beginning of the study

The project objectives have been addressed through the sequence of tasks that are briefly described in Table 1:

Table 1 Listing and details of the project tasks

OBJECTIVE	TASK	SPECIFICATIONS/DESCRIPTION
Meeting with TAC	**T.1**	✓ The meeting purpose will be to discuss culvert construction details for implementation of the self-cleaning design ✓ Sharing the results of the pre- and post-construction monitoring results
Pre-construction monitoring	**T.2.**	✓ Monitoring is conducted for establishing the reference conditions for the assessment of the performance of the self-cleaning culvert. ✓ Periodic and after-storm site inspections for tracking the performance of the culvert prior to set the self-cleaning design. Monitoring activities include tracking of: water levels, discharges, velocity distribution, sediment deposits, vegetation growth in the second year after cleanup. Monitoring should capture the 2012 flood season (i.e., May – July).
Preparation of the self-cleaning construction drawings	**T.3**	✓ Establish and discuss with TAC the constructive details of the self-cleaning design
Post-construction monitoring	**T.4**	✓ Monitoring is conducted for establishing the performance of the constructed self-cleaning design. ✓ Periodic and after-storm site inspections for tracking the performance of the modified culvert. Monitoring activities include tracking of: water levels, discharges, velocity distribution, sediment deposits. Monitoring should capture the 2013 flood season (i.e., May – July).
Laboratory study for supporting the verification of the 3-box self-cleaning culvert design	**T.5**	✓ In case that the construction drawings depart significantly from the original design (e.g., fillet geometry, sloping angles or length of the fillets), additional testing will be conducted to test the modifications for a range of flows
Reporting	**T.6**	✓ Includes: design performance evaluation, recommendations generalization for other site conditions and culvert geometries
Presentation of the study and paper writing	**T.7**	✓ Present the final report to the Iowa Highway Research Board, and with the Board determine if adjustments are needed. ✓ Present papers giving the essential results of the project. The papers will be presented during two Iowa conferences, one being the annual meeting of the Iowa County Engineers Association, the other possibly being the biennial Mid-Continent Transportation Research Symposium series.

2. Self-cleaning culvert design specifications

In general, current knowledge on sedimentation processes at culverts is limited and the literature on this topic is scarce. To date, there is no systematic research regarding the mechanics of sediment transport through multi-box culverts or the sediment deposition impact on the flow through culverts. While is accepted that the sediment transport through culverts is strongly influenced by the nature of the local geological conditions and the soils in the drainage area adjacent to the culvert there are gaps in our knowledge about the flow and sediment transport at multi-barrel culverts. The limitations in our knowledge are due to limited focus given to this subject so far, as well as to the complexity of the flow carrying sediment through multi-barrel culverts. The complexity of the flow hampers setting precise modeling conditions for the laboratory and numerical investigations as it entails a series of aspects that require special attention, as described below. Moreover, it emphasizes the importance of the field measurements in furthering solution to this widely spread problem ant Iowa culverts. Figure 3 illustrates the complexity factors involved.

The first study complexity of the flow through culverts is related to the change in flow geometry from the undisturbed cross section of the stream (usually trapezoidal) to the geometry of the multi-barrel culvert (at least double the stream cross section area in the undisturbed region), as illustrated in Figure 3. This change in geometry is occurring twice at culvert sites. First an expansion is usually involved upstream the culvert, while a contraction to the original cross section shape occur downstream the culvert.

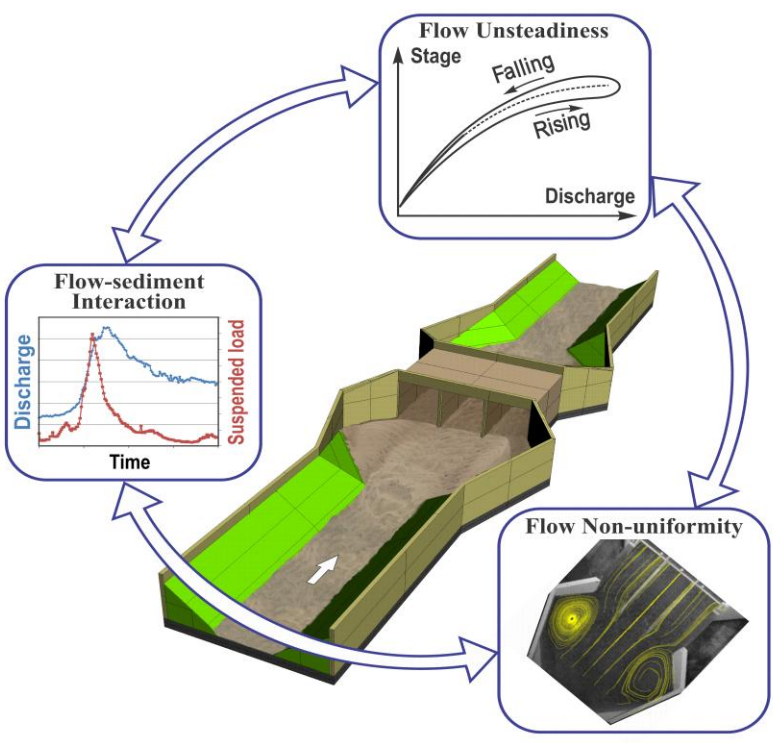


Figure 3 Complexity factors at flow through culverts

The second complexity resides in the unsteadiness of the flow during the propagation of the storm flow through the culvert. This aspect is usually neglected in laboratory studies as it is difficult to design a facility that can transitions the flow over large time scale as required by the propagation of a flood wave. Finally, consideration of the sediment phase along with the water phase during the transport of the sediment-laden flow constitutes the third complexity of the study. Currently, it is little known about how these non-uniform, unsteady sediment laden flows are developing in three-dimensional geometry. Possible knowledge comes only from field and laboratory measurements as the analytical treatment of the problem is too complex.

Due to the complexity of the involved processes, the need for a systematic study of culverts and sedimentation in field conditions is becoming especially acute in Iowa, where soil erosion is high due to the geological conditions and the industrialized agriculture practiced on large surfaces. The consequence is the existence of hundreds of multi-box culverts that face chronic sediment problems. A recent survey of the Iowa County engineers and IDOT bridge specialists conducted by this research team reported several notable aspects related to flow through culverts (Muste & Ho, 2009).

These flow complexity described above required special deign for the laboratory experiments. For this purpose, a series of preliminary tests were designed and conducted in Phase I of the study to verify that the basic of the flow and sediment transport processes are adequately replicated in the experiments. The provisions for conducting the tests were described in Muste et al. (2009). The same study screened various solutions for mitigation sedimentation at culverts. Following the screening, selection of the final design and testing for its performance were carried out. The geometry of the self-cleaning solution is depicted in Figure 4 and was comprehensively documented in Muste et al (2009).

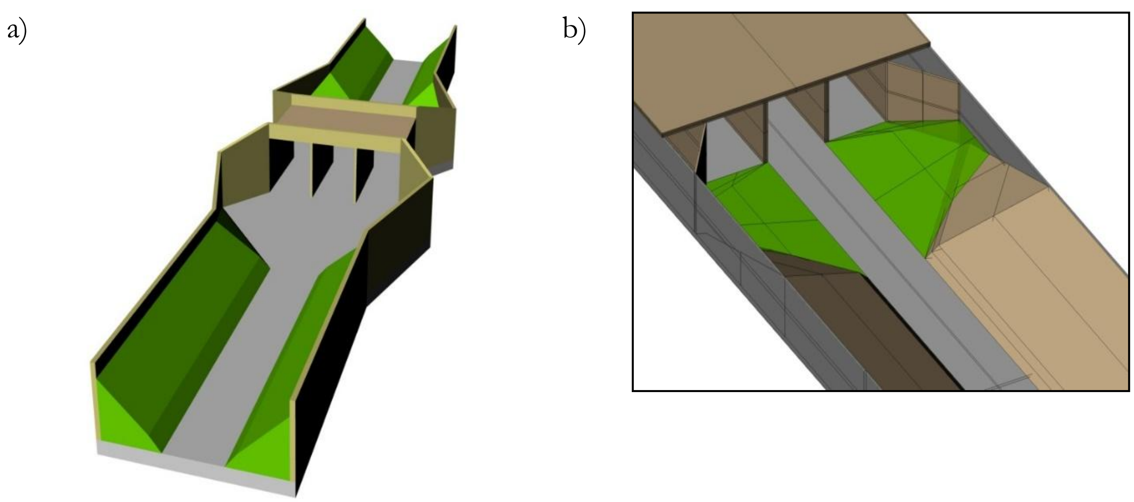


Figure 4 Schematic of the TRGB-G1-01 culvert tested in the study: a) original configuration: b) self-cleaning design established through TR 545

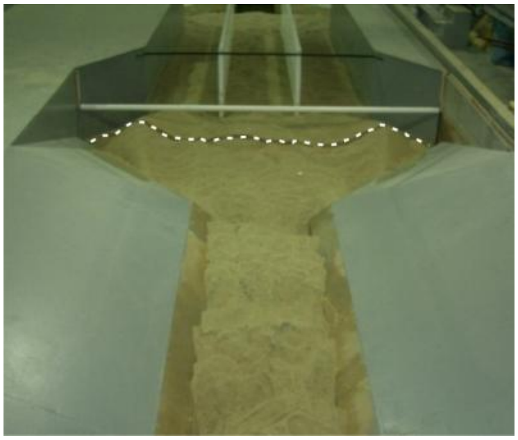
In order to obtain a realistic modeling, in Phase I of the project a Triple Reinforced Concrete Box Culvert (TRGB – G1 – 01) was adopted. The driving criterion for designing the self-cleaning culvert geometry was to make modifications in the upstream area of the culvert that would restore the shape and 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. All the initial tests for phase I of the project were conducted with a 3-box culvert and for a layout where the river approaches the culvert at an orthogonal angle. The Technical Committee requested our research team to expand the study coverage by testing the sensitivity of the design to various angle of incidence between the road and stream intersection. Those studies are described next.

3. Sensitivity analysis to stream-road angle of incidence

3.1 Large-scale three-box culvert model

In order to familiarize the reader with the experimental protocol used in the study, salient features and instrumentation used in these additional tests are briefly described first Flows with live-bed sediment transport were established for the same operating points for the original (without fillets) and the self-cleaning (with fillets) culverts. Identical experimental conditions and operating time were established in the comparison purpose. At the end of each experimental simulation the bathymetry of the upstream area of the culvert was documented using identical documentation procedures. Sediment deposition occurred in the critical area of the upstream culvert expansion where deposition occurs at the highest rates and with the most detrimental impacts (Fig. 7). Fig 7b shows that the proposed adjustment met the aforementioned main effects. The SeaTek multiple transducer arrays (MTAs) were deployed to survey the development of the bed forms in the culvert boxes. The experiment deployment was illustrated in Fig 8. Measurements were performed at 18 sections in the left and central boxes. The measured data for each section were continuously collected for 30 seconds. Assuming that the bed movement was negligible in the short time period with respect to the dominant scales of the sediment transport process, each bed profile in the box was obtained by averaging data over the 30 seconds. The sedimentation maps inside the culvert boxes for the culverts with and without the design were shown in Fig 9 and 10. The results were measured after running the test for 6 hours and for 12 hours, respectively. Fig 9a and b display the results with and without the design placed upstream of the culvert, respectively. The comparison of the sediment deposits showed that the design was able to mitigate the sediment deposition in the side boxes. The large sediment deposition present in the side boxes for the case of the standard design was mitigated when the design was installed. The design reduced the amount of deposited sediment in the side boxes by more than 70% after 12-hour operation (see Fig 10). Further study of head loss measurements in the model is ongoing to evaluate the effect of the hydro-cleaning design.

a)



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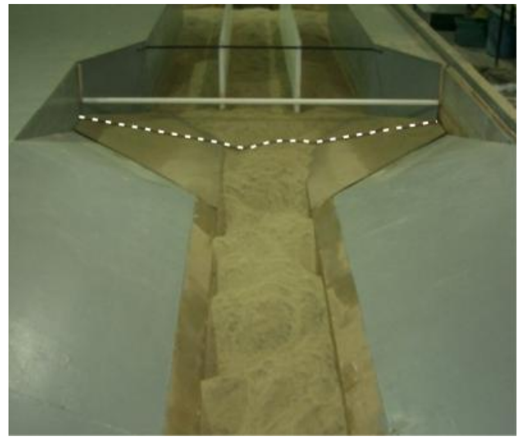
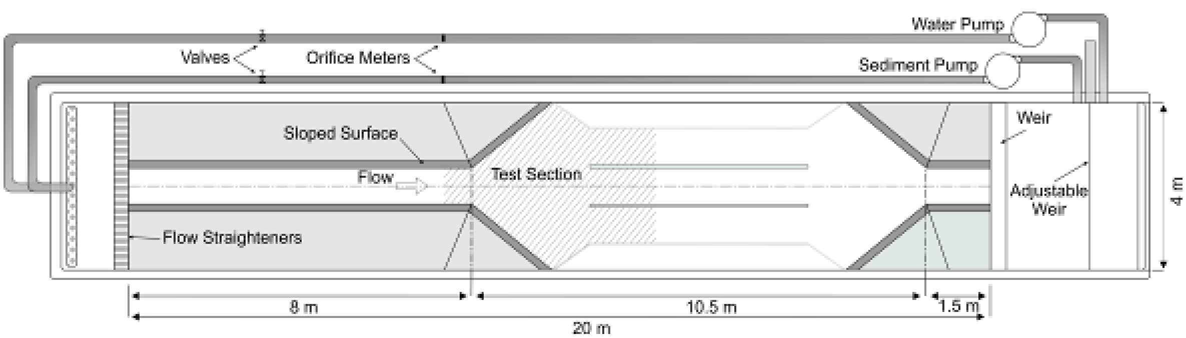


Figure 5 Sediment deposition patterns without and with fillet-based self-cleaning system: a) no hydro-cleaning design, b) hydro-cleaning design constructed

a)



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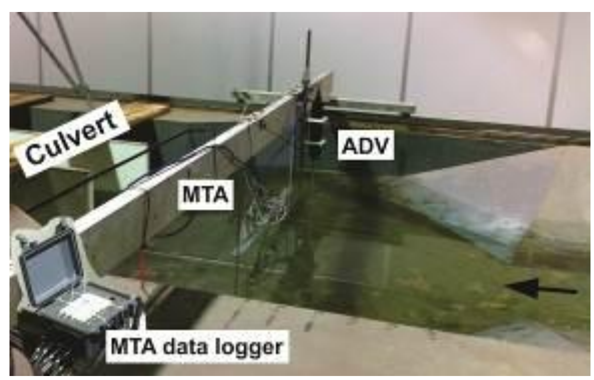


Figure 6 Arrangement of the acoustic sensors for the measurement of sediment deposition in the 1:5 scale culvert model

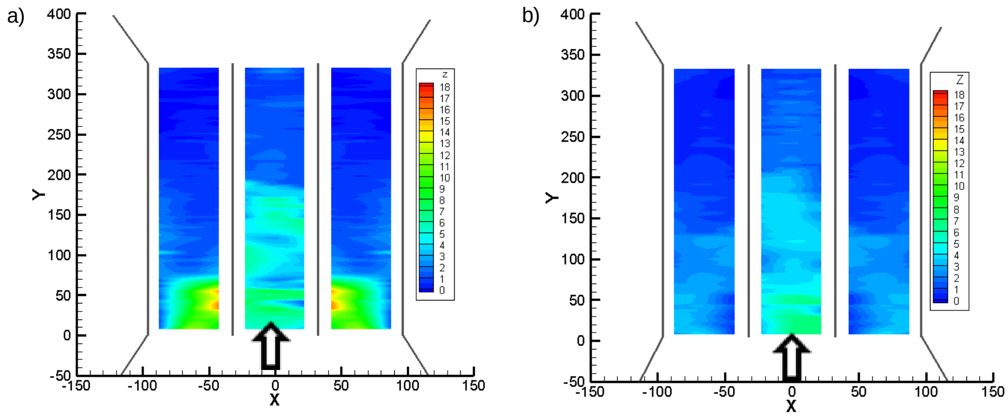


Figure 7 Mapping of the sediment deposits formed in three culvert boxes after 6-hours: a) without the design placed in expansion; b) with design placed in expansion

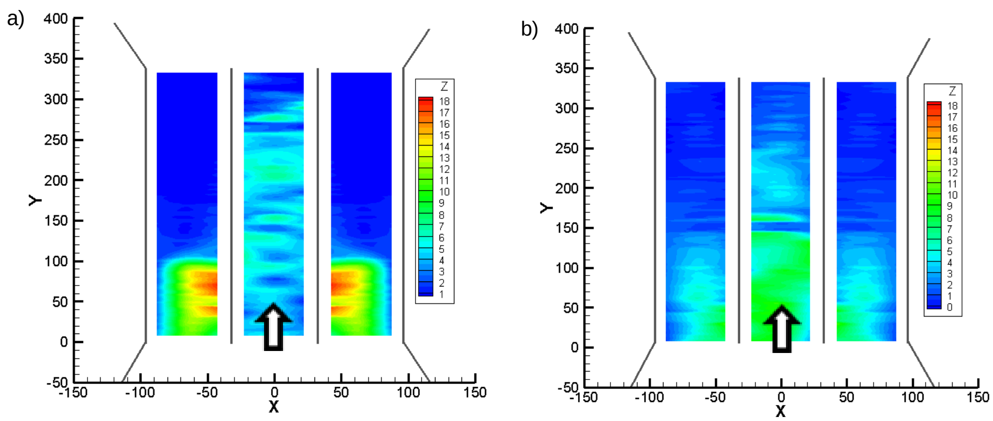


Figure 8 Mapping of the sediment deposits formed in three culvert boxes after 12-hours: a) without the design placed in expansion; b) with the design placed in expansion

Large-Scale Particle Image Velocimetry (LSPIV) was used to measure free surface velocity distribution for the reference culvert model and the hydro-cleaning design culvert in the expansion. The iso-velocity contours plotted in Fig 11 illustrated 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 demonstrated that water and sediment were forced to the central culvert box when the hydro-cleaning design was placed in the expansion. The above performance tests conducted to evaluate the hydro-cleaning design provide the following conclusions: 1) instead of creating or increasing the size of recirculation areas, the design removes them, 2) the design strengthens the convection of sediment into the central box, and 3) the design amplifies the turbulence at the entrance into the side boxes and mitigates the sediment deposition inside them.

a) b)

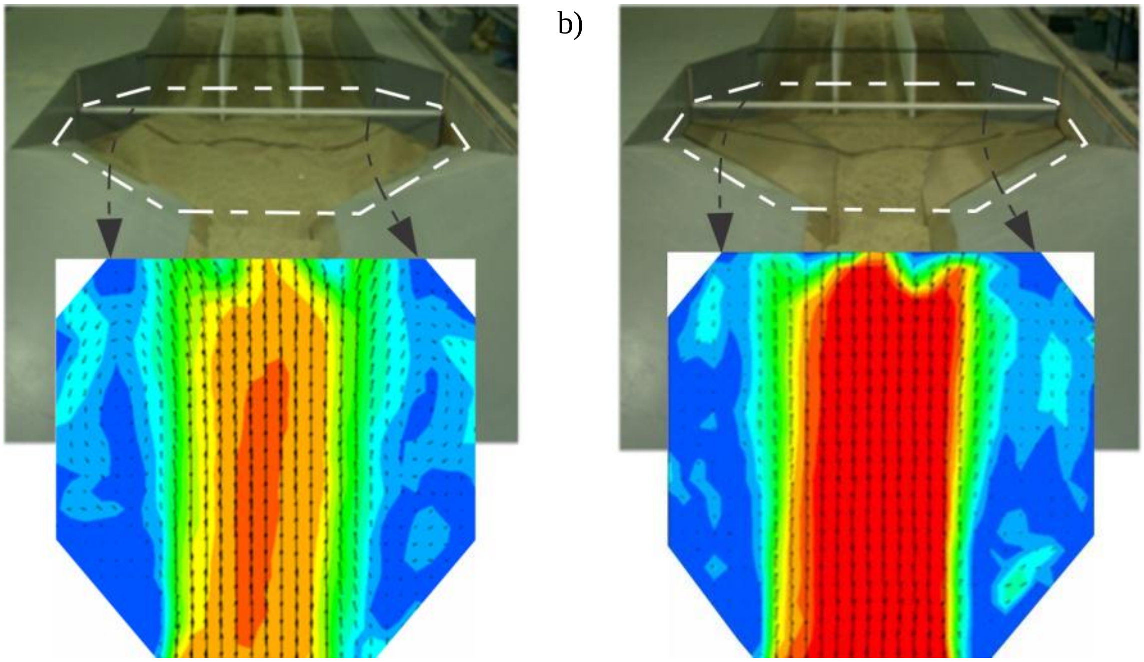


Figure 9 Velocity distributions upstream the 1:5 culvert model: a) original configuration, b) hydro-cleaning design implemented

3.2 Small-scale three-box skewed culvert model

The stream location and the planned roadway centerline do not always establish a 90-degree discussed above. To minimize the environmental stress the culvert is often skewed with respect to the roadway centerline. The design skew angle can vary from 0-degrees to the maximum of about 45-degrees (Normann et. al, 1985). To assess the performance of the proposed fillet design (Figure 4), a 15-degrees skewed three-box culvert was conducted in the 1:20 scale model to simulate the storm events. The configuration of the fillet design in the skew model is similar to the aforementioned one which utilizes the hydro-cleaning concept. After one hour operation, the sediment particles started to accumulate in the central and right barrels because of the skewed angle (Fig 12a). The self-cleaning design was then placed upstream the culvert and repeated the same operation. The accumulation of sediment particles was mitigated shown in Fig 12b. The sediment particles were force to the center and were delivered to the downstream. The hydro-cleaning design shows the ability and efficiency to mitigate the sedimentation issue not only for the general three-box culvert but also for the skewed three-box culvert.

a) b)

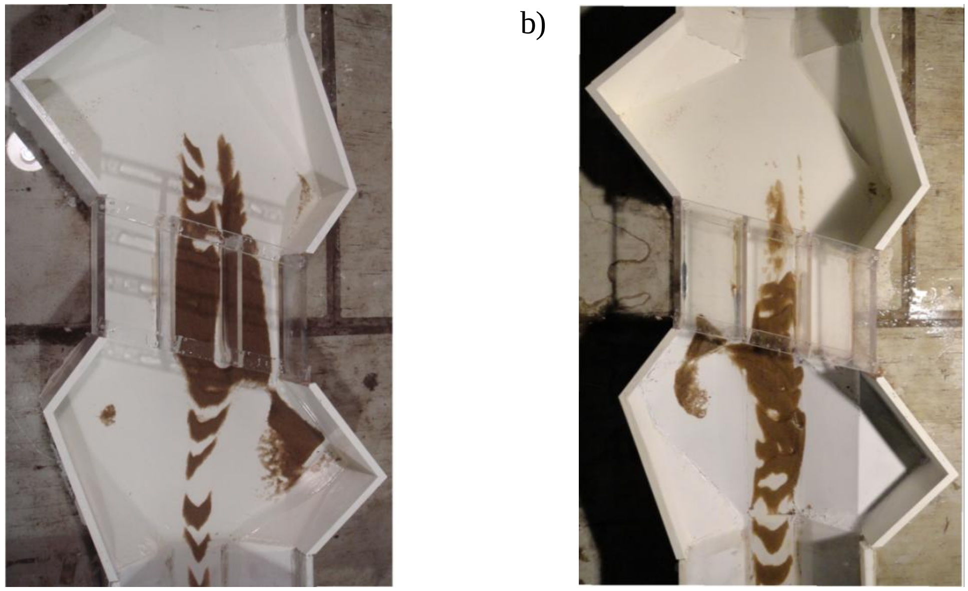


Figure 10 Sediment deposition pattern at 15 degree skewed culvert model after one-hour operation: a) no design in the expansion, and b) fillet-based design in the expansion

a) b)

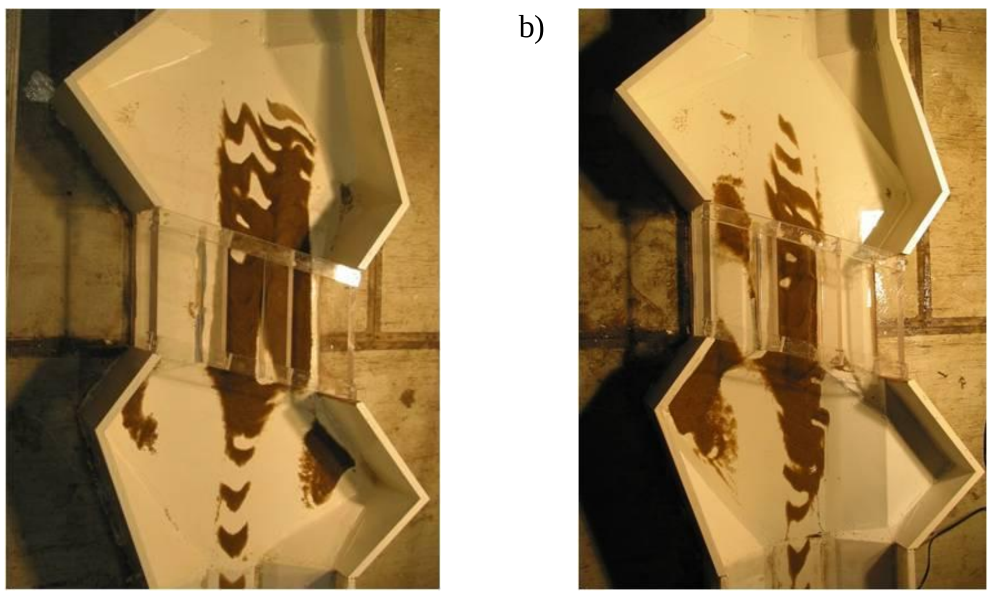


Figure 11 Sediment deposition pattern at 15 degree skewed culvert model after three-hour operation: a) no design in the expansion, and b) fillet-based design in the expansion

4. Site characteristics of the monitored culvert

In parallel with conducting the sensitivity analysis tests, during Phase II of TR 545 the research team and TAC identified a culvert site for implementation o the self-cleaning sediment mitigation configuration developed through Phase I of the study. The best candidate, out of a dozen of sites identified for implementation, was found to be the 3-box culvert located on 1506 IA Hwy 1W in Iowa City. The culvert is a triple 15’-18”-15”x12 reinforced concrete box (RCB), as shown in Figure 12. The culvert was built in 1981-82 replacing a previous culvert passing over Willow Creek. The culvert drains a rapidly growing urbanized catchment that experience considerable residential and commercial developed after its construction in 1981.

The first culvert cleanup after its construction in 1981 was made in 2000. The second cleanup was conducted on September 15, 2011 for supporting the goals of the present research. The cleaned culvert monitoring was needed to provide a reference for the operation of a culvert designed with conventional design specifications, i.e., without special provisions for mitigation of sediment transport through the culvert. By cleaning the culvert to its original conditions, the culvert was brought back to the stage of the stream-structure configuration in place after the finalization of its construction in 1981. Figure 13 shows the status of the culvert before and after the cleanup conducted on September 15, 2010.

a) b)

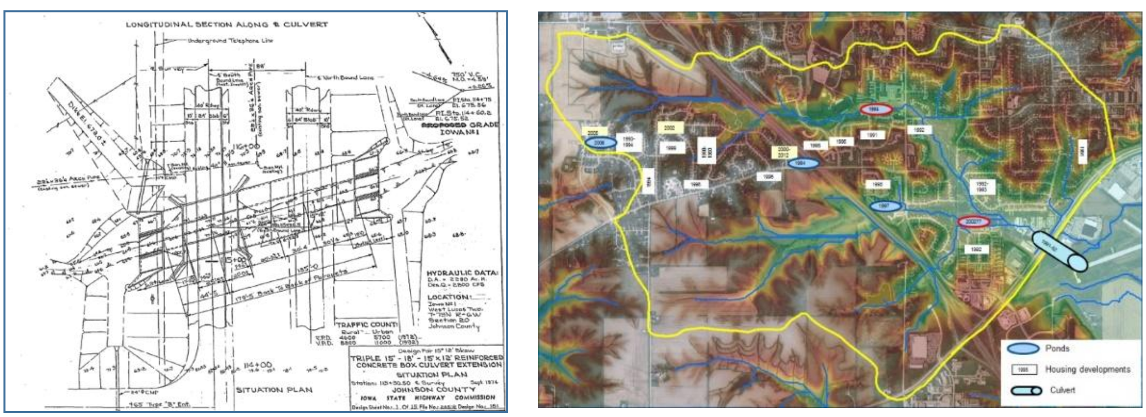


Figure 12 a) Construction drawings for the culvert for monitoring; b) drainage area for the culvert

A monitoring program was designed and implemented for the culvert starting in September 2010 and ending in December 2012. The goal of this monitoring phase was to document individual and cumulative effects of storms propagating through the culvert with special attention given to sedimentation. For this purpose, a thorough set of quantitative and qualitative observations have been made and subsequently corroborated with stage and precipitation measurements after each storm. The latter hydrological characteristics were needed to assess the relationship between sediment deposition and the characteristics driving the flow and sedimentation processes at the culvert site.

A snapshot of the culvert after the first year of monitoring is provided in Figure 13c. This culvert photo-document demonstrates that following one year of operation, the culverts started to initiate deposition patterns that replicate the 10-year sediment deposit geometry as can be inferred comparing Figures 13 a and 13c. Moreover, it can be noticed that after just one year of operation, the vegetation grew on the sides of the culvert upstream areas (see Figure 13c). The vegetation growth is an accelerating factor for sediment deposition by lowering the flow velocity during storms and providing a favorable environment for sediment settling.

Figure 13 The culvert site under monitoring on Hwy 1, Iowa City: a) before cleanup (September 15, 2010); b) the culvert right after the September 15, 2010 cleanup; c) the status of the culvert after two years of operation (August 29, 2012)

5. Self-cleaning culvert construction

The details of the culvert construction details for the self-cleaning design were discussed by IDOT, Iowa City water, and IIHR research team prior to implementation. A particular aspect of these discussions was to adjust the laboratory established geometry to the site conditions. The original design has to be modified to not interfere with the city water pipe line located at the upstream end of the proposed self-cleaning structure. The rough geometry of the fillets shaping the self-cleaning structure was created using local soil topped with a base layer of rip-rap. The superficial layer of the finished geometry was attained with geomat, a newer and flexible bed protective solution (see appendix).

The specific geomat used for the construction of the self-cleaning structure at our site is articulating block mats (ABM) produced by Texicon (http://www.texicon.com). ABM provides a cable-reinforced, articulating concrete block mattress for use over soft subgrades or where a revetment is exposed to attack by waves. When filled with a fine aggregate concrete, they form a system of staggered, interconnected, cable-reinforced, concrete blocks. The permeable interwoven perimeter of each block serves as a drain, filter, and hinge. The hinge permits articulation of the filled compartments (blocks). Factory installed high-strength cables and optional transverse cables are threaded between the two layers of fabric and through the fabric form's grout ducts to link the concrete blocks. The cables are self-positioning within the fabric formed concrete blocks and are embedded at approximately the vertical center of the concrete blocks.

A generic view of the BMA used at our site is provided in Figure 14.a. The construction drawings for setting the self-cleaning structure are provided in Figure 14.b. The construction work was accomplished by DeLong Construction, Inc, Washington (IA) during two winter weeks (December-Jan, 2012-13) with an approx. cost of $37,000. A photo documentary of the construction is provided in Appendix A.

a)

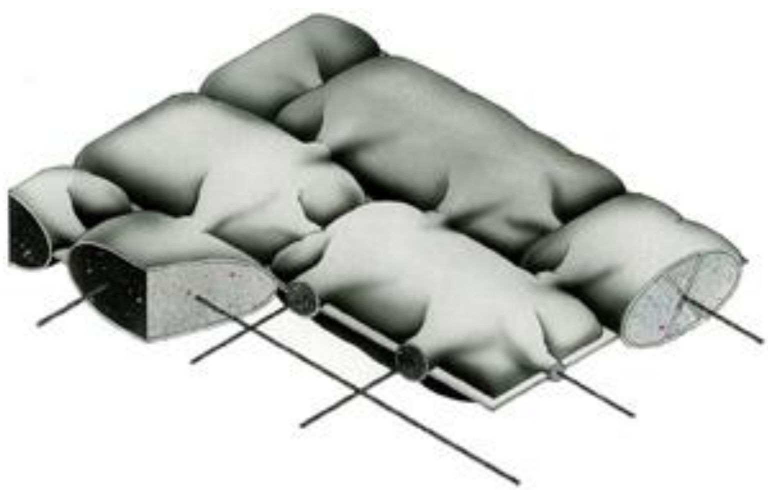
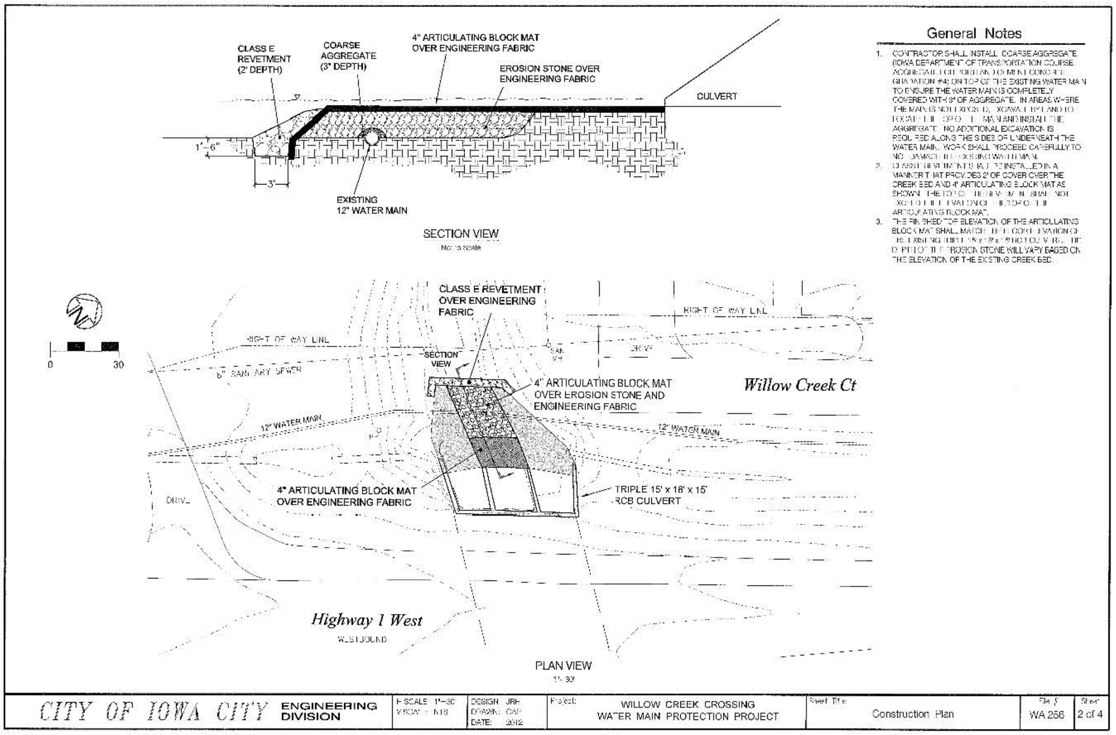


Figure 14 Construction drawings for setting the self-cleaning structure for the culvert: a) conceptual sketch for the articulating black mat: b) construction drawings (Continues on the next page)

b)



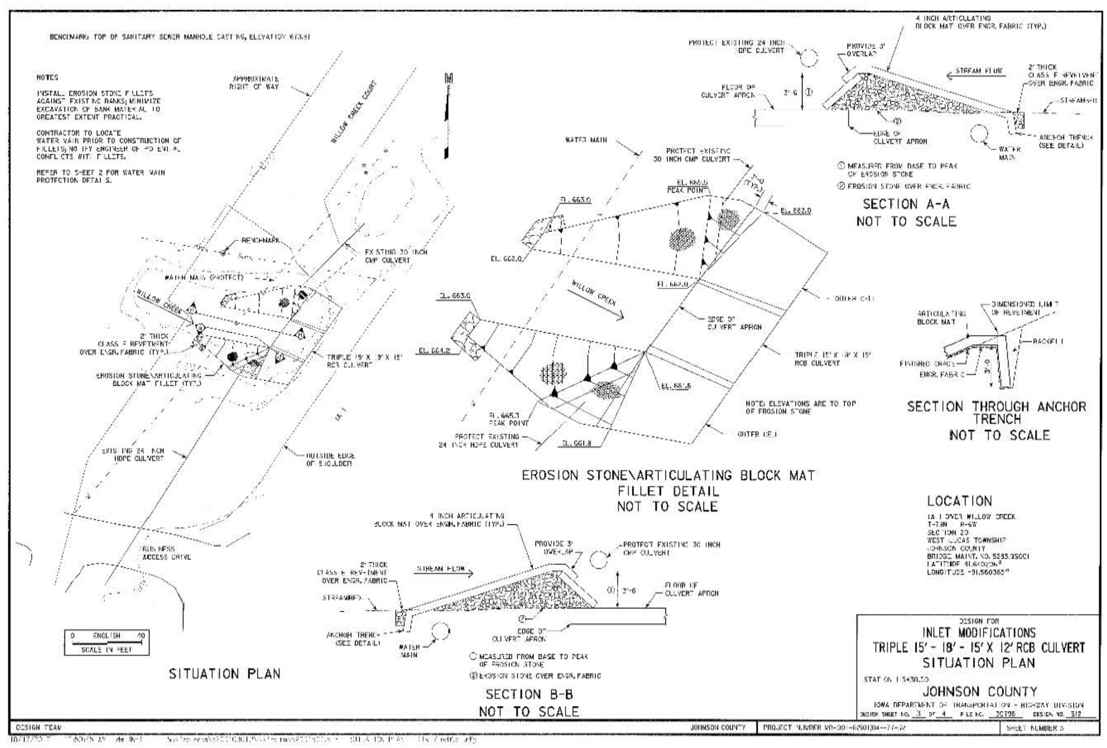


Figure 14 Construction drawings for setting the self-cleaning structure for the culvert: a) conceptual sketch for the articulating black mat: b) construction drawings

6. Culvert monitoring protocols results

6.1 Monitoring system

During the monitoring activities conducted in 2011, the research team temporarily deployed at the culvert site a real-time camera with continuous recording and communication via cell phone network (see Figure 15). The system is powered by solar panels and a backup battery during nights and overcast sky. Recording settings and other operation controls can be executed remotely via the Internet. The continuous real-time monitoring enables to track the stage at the site and the flow patterns developing at the culver entrance as the storm unfolds.

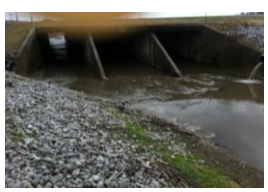
Figure 15 Real-time webcam deployed at the culvert site under monitoring

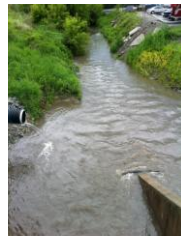
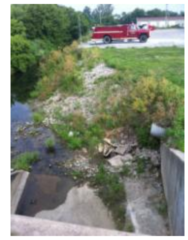
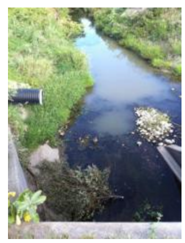
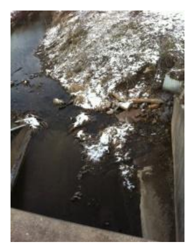
6.2 Before fillets installation (September 15, 2010 – December 15, 2012)

Following the culvert cleanup, the culvert brought to its original status was monitored for observing flow and sedimentation during high flow events for more than two years. As can be observed from the sequence of photos assembled in Table 2, the results indicated that the sedimentation areas prone to sediment retention were the upstream area of the left and right barrels. The sedimentation increased during storm events. Specifically, the high flow events that passed through the culvert on May 21, 2011, May 29, 2011, and April 14, 2012 have brought most of the deposited material during the pre-construction monitoring phase.

The photos taken on July 16, 2011 and May 21, 2012 showed that sediment deposits established on the left and right barrels led to vegetation growth at short time after the sediment pockets were formed. The vegetation growth is an additional factor in sediment retention by reducing the flow velocity through the vegetated area and developing a sheltered area for sediment settling as the velocity of the vegetated bed further reduce the velocity of the flow. This reduction impedes development of high shear stresses that can mobilize the sand when the area is exposed to high flow events. In turn, the fresh soil layer brings soils reach in nutrient that further accelerates the vegetation worth. The two-year photographic documentary of the culvert site before the self-cleaning structure implementation clearly showed the initiation of the sediment deposits following the pattern that was observed before the 2010 cleaning. This observations lead to the conclusion that the processes was on its way and have had resulted in clogging of the side barrels as observed before the cleanup.

Table 2 Photographic tracking of the culvert site before fillets installation

Overview 1	Overview 2	Left barrel	Right barrel
M1: Nov 4, 2010			
			
M2: Mar 19, 2011			
			
M3: May 21, 2011			
			
M4: May 29, 2011 (Largest event in 2011)			

			
M5: July 16, 2011			
			
M6: Aug 21, 2011			
			
M7: March 3, 2012			
			
M8: April 14, 2012			
			

M9: May 21, 2012			
			
M10: July 20, 2012			
			
M11: Dec 8, 2012			
			

6.3 After fillets installation

The fillets as the self-cleaning culvert designed were installed during two weeks starting on December 9th, 2012. Table 3 assembles the photographic records gathered during the December 2012 – September 2013 time interval (the time covered by the project funding. The associated time series data of precipitation and water depth data are shown in Figure 18. The photographic and field observations showed no signs of sediment deposition inception in the upstream area of the culverts during, after or in the long term. Practically, at the end of the project funding there were no signs of any deposition in the areas previously covered by sediment and vegetation. Moreover, the articulating block mat layer provided a good protection against vegetation growth such that the area is up to now vegetation free as can be observed from the photo documentary. Sporadic observations were made until December 2013 to further observe changes during the fall storm events. The status of the culvert is practically the same since December 2012.

Another beneficial effect of the construction of the fillets is the fact that they keep the geometry of the flow very close to the original stream bed by maintaining the flow in the main barrel for different storm event intensities, as can be observed for M13, M14 and M16 storm events (see Table 4). During the highest flow event on April 20, 2013 (see Figure M16 in Table 4) the dominant discharge is as expected flowing through the main barrels with less discharge and more turbulent flows in the side barrels. The sequence of photographs M16 and M17 show that even the largest storm of the year has not left sediment deposited in the side barrels. The photo evidence in Table 5 shows that the vegetation growth was practically none, excepting some growth of algae ins some area of the culvert entrance. The culvert is absolutely clean at the time of writing this report. These set of visual evidence clearly demonstrates that the proposed solution works efficiently both in terms of hydraulics and transport processes.

Table 3 The fillet covered with the articulating black mats following their construction

<table>
<tr><td colspan="2">Upstream view</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Right barrel</td><td>Left barrel</td></tr>
<tr><td></td><td></td></tr>
</table>

Table 4 Photographic tracking of the culvert site after fillets installation

Overview 1	Overview 2
M12: Feb 8, 2013	
	
M13:Feb 10, 2013	
	
M14: Mar 10, 2013	
	
M15: Mar 30, 2013	


M16:April 20, 2013


M17: April 20, 2013


M19: July 13, 2013


Table 5 Documentation of the culvert performance following the highest storm event

July 13, 2013		
Right barrel	Central barrel	Left barrel
		
		

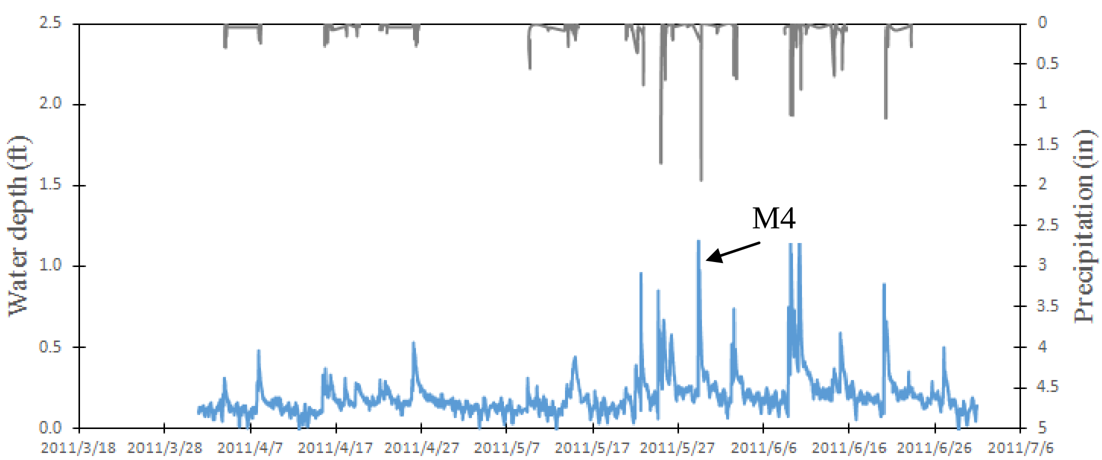


Figure 16 Stage and precipitation records at the culvert site (2011/04/01 ~ 2011/ 06/30)

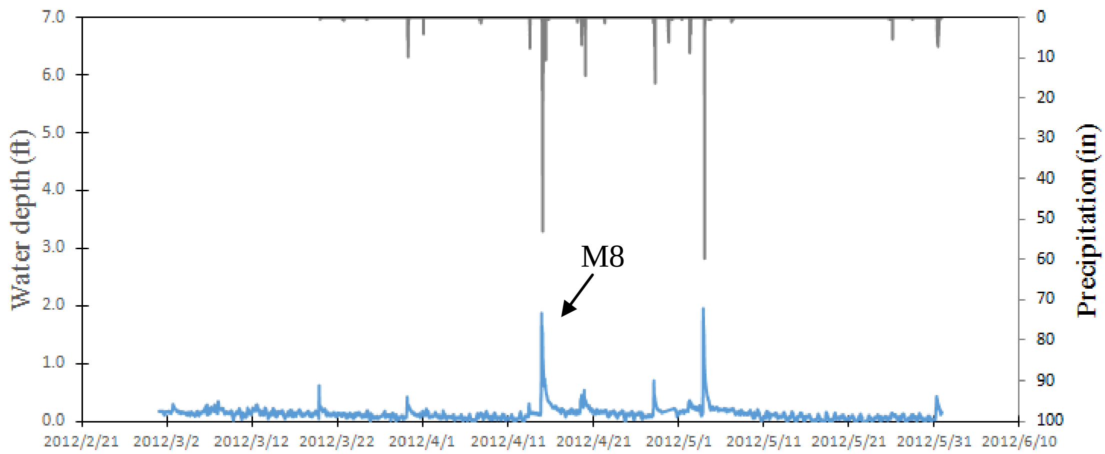


Figure 17 Stage and precipitation records at the culvert site (2012/03/01 ~ 2012/05/31)

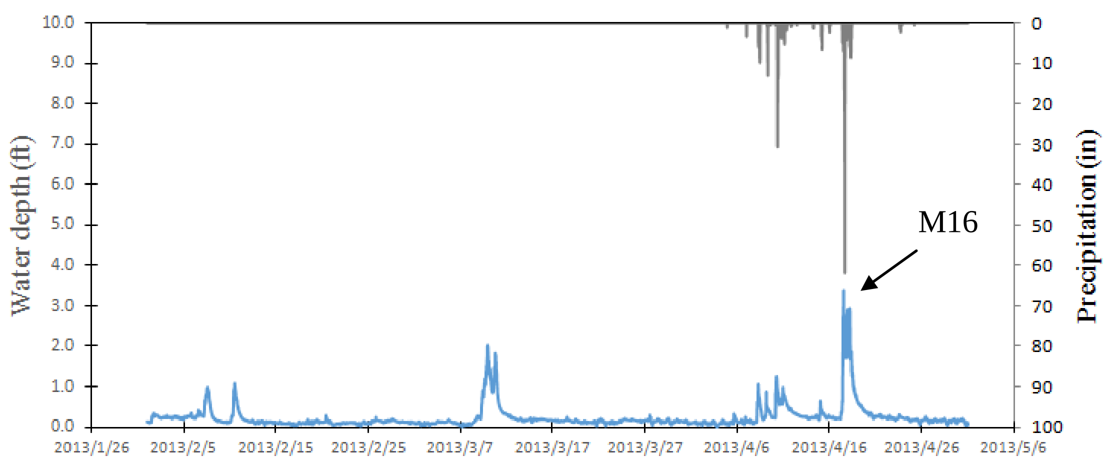


Figure 18 Stage and precipitation records at the culvert site (2013/02/01 ~ 2013/4/30)

7. Conclusions

The experimental and analytical evidence garnered in Phase II of the study demonstrates the efficiency of the self-cleaning structure for mitigating sediment deposition at culverts. Besides their primary role in sediment mitigation, the designed self-cleaning structure maintains a clean and clear area upstream the culvert, keeps a healthy flow through the central barrel offering hydraulic and aquatic habitat similar with that in the undisturbed stream reaches upstream and downstream the culvert. It can be concluded that the proposed self-cleaning structural solution "streamlines" the area adjacent to the culvert in a way that secures the safety of the culvert structure at high flows while disturbing the stream behavior less compared with the traditional constructive approaches. The present end-to-end study (from laboratory experiments to field implementation) suggests that if these types of sediment mitigation solutions are implemented at the culvert construction time they might result in savings in maintenance costs over the lifetime of the construction. This project also demonstrates the need and value of blending experiments, numerical simulation and analyses (as done in Phase I of the project) for building sound evidence prior to establish practical solutions to costly IDOT maintenance problems such as the sedimentation at culverts.

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Appendix A

Construction of the self-cleaning structure

(December 18, 2012 - Jan 7, 2013)

December 16, 2012: Culver status before the construction

Upstream culvert area

Left barell – upstream view

Right barell – upstream view

Culvert site during construction

Finalized construction (January 7, 2013).

Construction viewed from the culvert (upstream orientation)

Construction viewed from upstream

Construction viewed from upstream

Upstream view (right bank)

Upstream view (centerline)

Upstream view(left bank)

Right barrel (upstream view)

Central barrel (upstream view)

Left barrel (upstream view)

Upstream view (right side)

Divider foot

(view from right barrel)

Divider foot

(view from left barrel)

Upstream view (left side)