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DESIGN GUIDELINES AND MITIGATION STRATEGIES FOR REDUCING SEDIMENTATION OF MULTI-BARREL CULVERTS

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About
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IIHR's mission is to advance science and technology, providing innovative solutions for fluids-related problems while building upon its long tradition of excellence in laboratory, field, and simulation-based research and education.

BACKGROUND

Sedimentation at culverts is an issue frequently occurring at multi-barrel culverts located in erosion-prone watersheds. The intensification of the human activities on hillslopes, floodplains, and in streams compounded with the impacts of the climate change aggravate the chronicity of the culvert sedimentation problem raising considerable operational concerns and maintenance issues across many areas of the United States. Sediment deposits can develop quickly impairing the culvert capacity to convey design flows and potentially leading to damages to both the transportation infrastructure (e.g. road and culvert overtopping) and upstream areas (e.g. flooding).

The current culvert design protocols are based on the analyses of hydrologic, hydraulic, and geomorphological conditions at the culvert site with the focus on flood flow conveyance. Less attention is given to the assessment of the potential for sedimentation as the knowledge on the complex erosion and transport processes leading to culvert sedimentation is scarce. These knowledge gaps preclude formulation of guidelines for culvert sedimentation forecasting and mitigation that in turn require to make recourse to costly cleaning methods that often need to be repeated to keep the culverts operational.

OBJECTIVES

The overarching goal of this study, funded by the Iowa, Mississippi, Missouri, New Mexico and Utah Departments of Transportation, is to identify and evaluate the performance of mitigation solutions for reducing or eliminating sediment accumulation at three-barrel culverts. The proposed mitigation solutions are based on the Self-Cleaning-Culvert (SCC) concept that relies on the use of the stream hydraulic power for passing sediment carried by the stream through culverts.

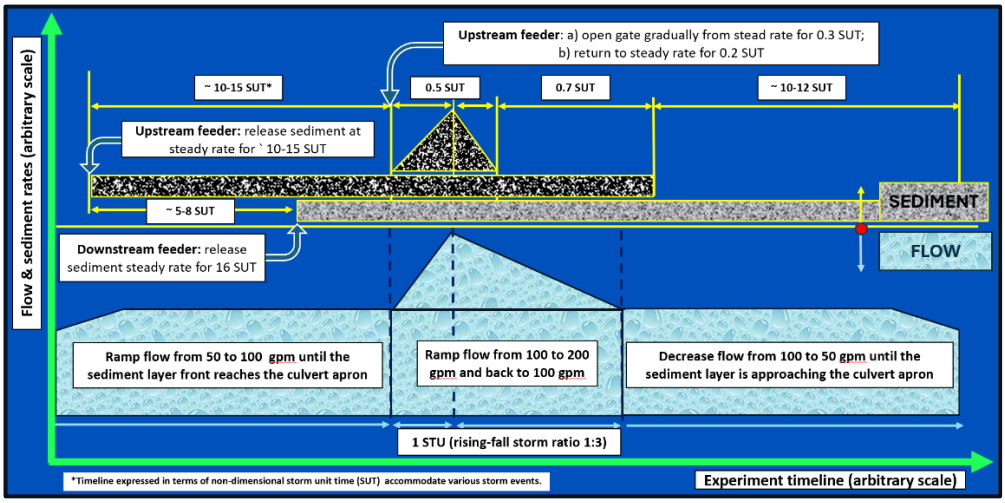
The project objectives of this multi-state effort are:

1. Assemblage of data and knowledge on sedimentation at culverts and mitigation measures
2. Synthesis of the practical knowledge in guidelines for design and operations for reducing or eliminating sedimentation at culverts
3. Develop SSC-based solutions for three-box culverts located in hydro-geomorphological conditions specific to the project partners: i.e., perennial streams in temperate climate and ephemeral streams in semi-arid regions.

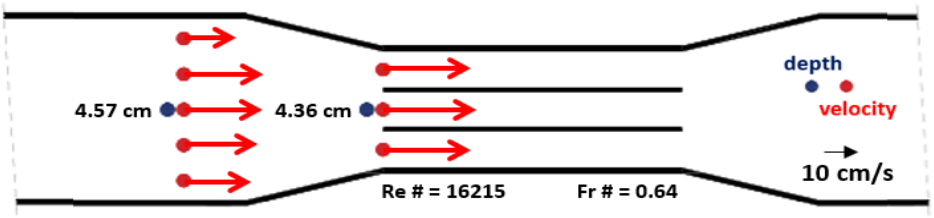
RESEARCH APPROACH & EXPERIMENTAL PROTOCOLS

Given the complexity of the sedimentation processes at culverts and the lack of previous reliable information from field and numerical simulations studies, the emphasis of the present research is placed on laboratory experiments that enable execution of controlled and repeatable tests. The laboratory study entails 180 stand-alone tests conducted in two flume arrangements, i.e., Iowa-Mississippi-Missouri (IMM) and New Mexico-Utah (NMU). The geometry of the culverts subjected to investigations is a typical IDOT design for three-box culvert for IMM tests and a slightly modified configuration for the NMU tests. A single invert slope was tested for IMM conditions and three slopes for NMU conditions. The "as-is" culverts (original design) and SCC-designs were exposed to runoff events realistically replicated in the model with precisely controlled experimental protocols. The runoff events were modeled based on observations collected in the field. The tests were documented with qualitative and quantitative experimental methods that collectively lead to abundant data and information about the sedimentation process development and the sediment accumulation in the culvert vicinity. Samples of methods used to conduct the experiments and acquire the data are illustrated below.

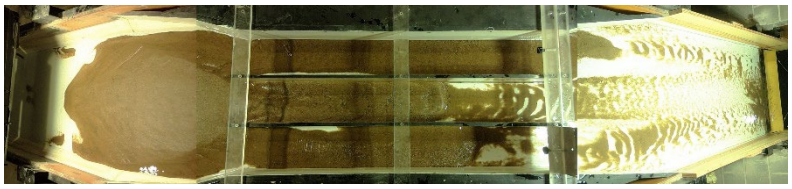
Water and sediment hydrographs for storms modelled in the IMM flume (adjustments made for the storm hydrographs modelled for the NMU conditions).



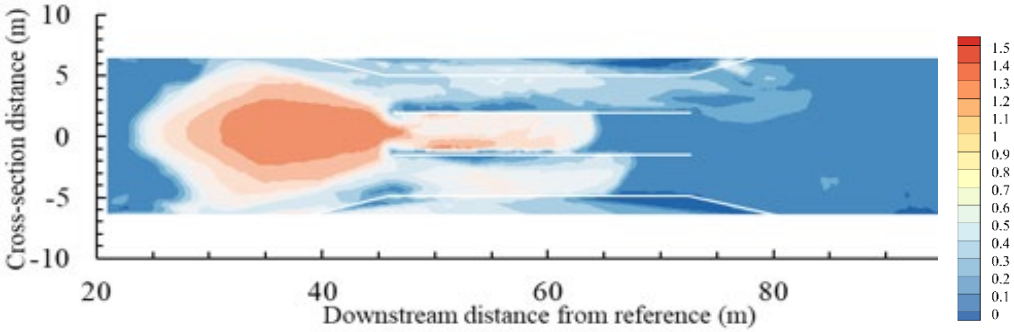
Velocity and depth distribution for "As-is" NMU culvert set at 0.3 degree slope in a medium flow (model dimensions)



Sediment accumulation at an "As-is" NMU culvert set at 0.3 degree slope exposed to a realistic hydrograph (distorted image)



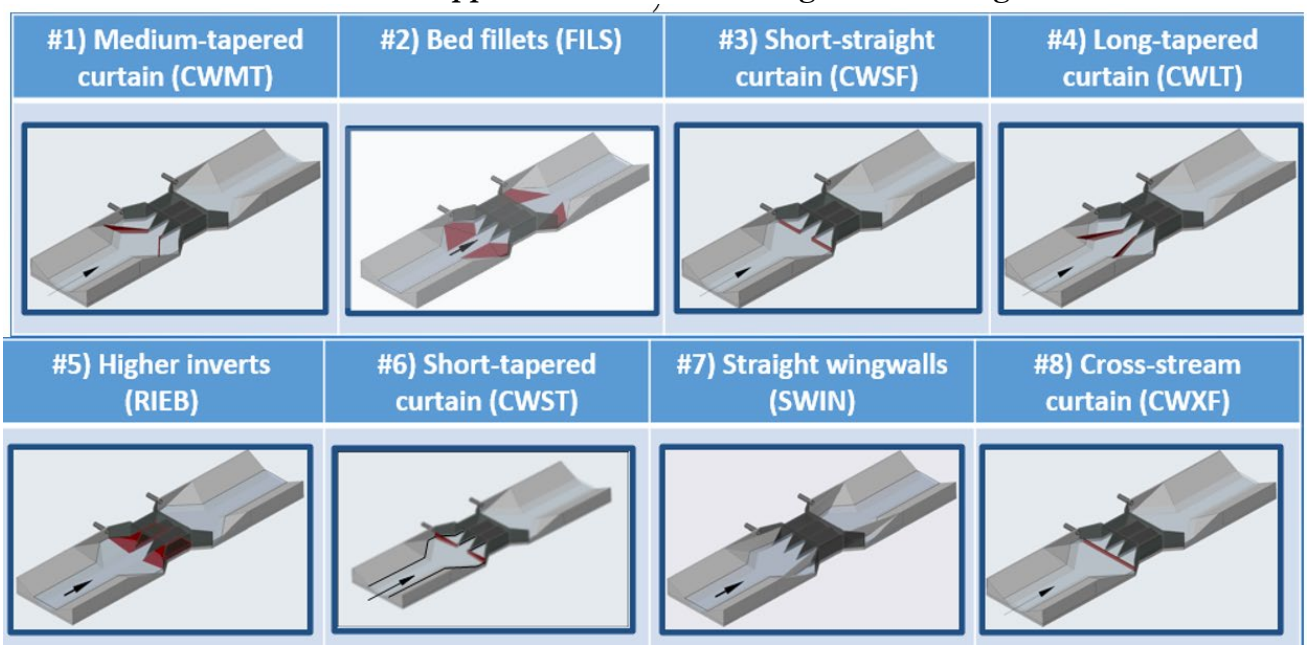
Lidar scanning of the sediment accumulation for an "As-is" NMU culvert set at 0.3 degree slope exposed to a realistic hydrograph (undistorted map, prototype dimensions)



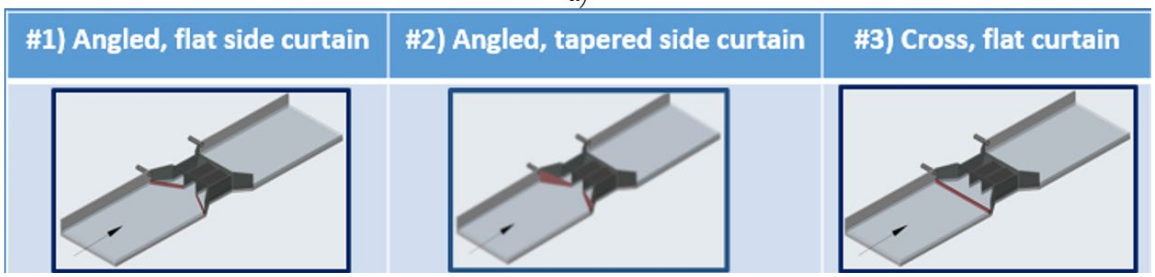
SELF-CLEANING CULVERT DESIGNS

The sedimentation patterns and areal distributions obtained for the as-is IMM and NMU culverts consistently display different sedimentation patterns across the tested hydro-morphological conditions. Specifically, the IMM culverts favor sedimentation in the outer areas of the culvert entrance and culvert body while the NMU culverts display a much more uniform sediment distribution at culvert entrance and throughout the culvert. Based on these preliminary inferences, we designed and tested 8 IMM and 6 NMU SCCs by changing the geometry of the transition areas leading to the culvert inlet with streamlined shapes that directed the flow through the central barrel. The ranking of the SCC performance for the IMM and NMU culverts is illustrated below.

Iowa-Mississippi-Missouri Self-Cleaning Culvert Designs



New Mexico – Utah Self-Cleaning Culvert Designs



KEY FINDINGS & CONTRIBUTIONS

The tested SSC demonstrated satisfactory sediment conveyance efficiency for the IMM culverts, with more than half of the tested SCC designs increasing sediment conveyance capacity by 50 to 72%. However, the addition of the SCC at the NMU culvert entrance resulted in reduced conveyance (less than 25%) due to geometric changes that further hampered structure's ability to handle the heavier sediment load typical of NMU flash floods, compared to the extreme precipitation events in the IMM landscape. Nevertheless, the NMU SCCs exhibited beneficial impacts by locally elevating the stream bed layer, which in turn enhances stream power during subsequent storms, and by retaining large volumes of sediment upstream of the culvert, making it easier to remove in case of culvert operation failure. The qualitative and quantitative data and information accumulated through the experimental research enabled a clear distinction of SCC designs, allowing for confident ranking of the structures based on various criteria, such as hydraulic and sediment transport efficiency, upfront and operational costs, and secondary effects on stream aesthetic appearance and ecological aspects.