Verification of ODOT Rock Channel Design Procedures

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16. Abstract

The Ohio Department of Transportation (ODOT) employs rock channel protection (RCP), also known as riprap, to manage energy dissipation and prevent scouring at culvert and storm drain outlets. The design for RCP at outlets follows guidelines outlined in Figure 1002-4 of ODOT's Location and Design Manual Volume 2, incorporating specifications from ODOT Construction and Material Specifications 601. RCP types (Type A, Type B, and Type C) are determined based on size, with specifics such as type, length, and depth guided by pipe diameter and outlet velocity as shown in Figure 1002-4. This design method, established by ODOT in July 1968, is still used to calculate RCP dimensions. However, the origins of this methodology and the basis for Figure 1002-4 are unclear, prompting a review of current procedures or adoption of a new methodology to ensure proper RCP sizing at conduit outlets due to ODOT's relatively less conservative approach. The research team conducted scaled hydraulic modeling and identified hydraulic conditions that impact RCP lengths, including factors not considered in previous studies.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Final Report

September 2024

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1 Problem Statement

The Ohio Department of Transportation (ODOT) uses rock channel protection (RCP), often referred to as riprap, for energy dissipation to protect against scour at the outlets of culverts and storm drains. Outlet RCP is designed according to Figure 1002-4 in the ODOT Location and Design (L&D) Manual Volume 2 [ODOT, 2020] with material and construction requirements per ODOT Construction and Material Specifications (C&MS) Item 601 [ODOT, 2019]. RCP is classified by size into Type A, Type B, Type C, and Type D (CMS 703.19.B) with the type, length, and depth of protection determined by the pipe diameter and the outlet velocity, as shown in Figure 1002-4 (see Figure 1, below). This guidance was implemented by ODOT in July 1968 and is still currently used to determine the length and thickness of RCP for the outlet of a culvert or storm drain.

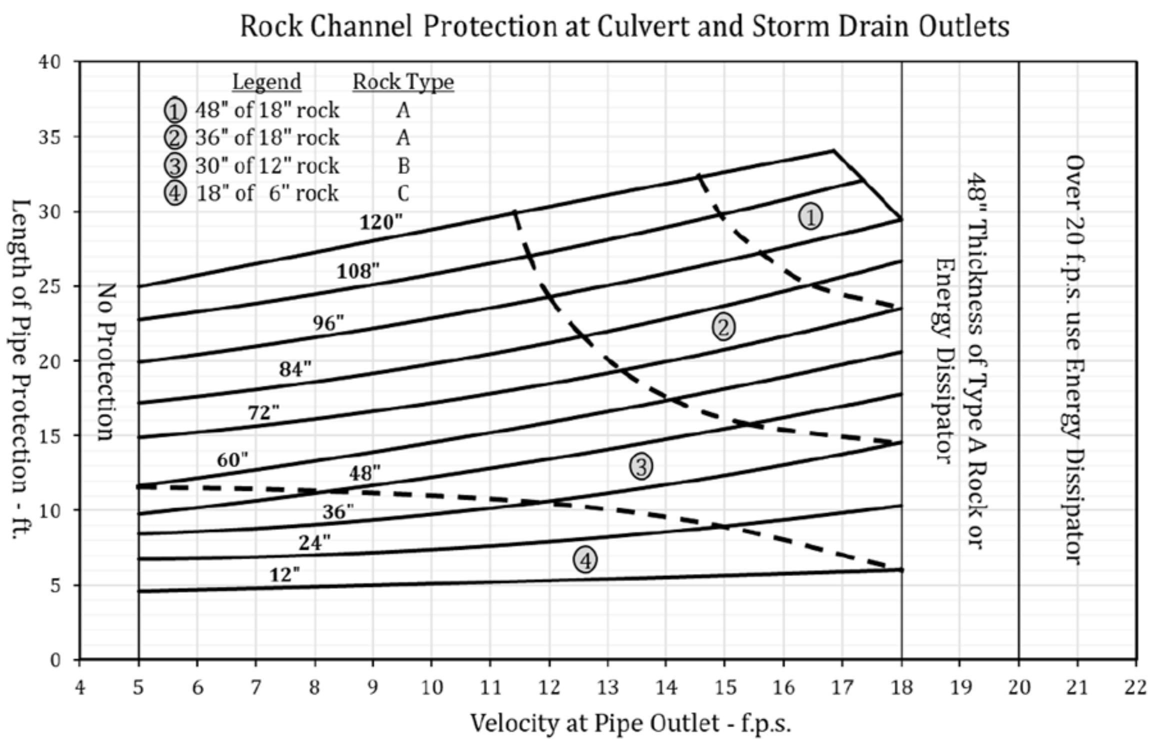


Figure 1. Current ODOT RCP Design Graph, as presented in ODOT L&D Manual (2020, Figure 1002-4). 1 ft = 0.30 m, 1" = 1 in = 25.4 mm, 1 f.p.s. (ft/s) = 0.3 m/s.

The origin of the ODOT RCP design procedure and the basis for Figure 1002-4 are unknown. The current method was previously thought to have been developed from research performed by Laushey (1966). Additional research was conducted by Sarikelle and Simon [1980], who concluded that "although the lengths of rock channel protection schemes used in Ohio are shorter than the lengths designed by other accepted procedures for a given design flow, it was determined that the actual number of sites which had scour problems at the end of the rock was small, therefore, the Ohio design lengths have proved adequate." This conclusion supports those from Laushey [1966]. However, a research-on-call study completed by E.L. Robinson Engineering of Ohio and Stantec [White et al., 2021] concluded that the true origin of Figure 1002-4 in the ODOT L&D Manual is unknown. In this study, ODOT's method of design was compared to those of other DOTs as well as the guidance from the Federal Highway Administration (FHWA) Hydraulic Engineering Circular HEC-14 [Thompson and Kilgore, 2006]; the results indicated that the HEC-14 method is typically more conservative as the pipe size increases and the required length for the RCP becomes longer. Furthermore, most DOTs use the HEC-14 method or a modified version of HEC-14 that is more conservative than ODOT's method, thus requiring a longer length of RCP protection. The research-on-call study highlighted that HEC-14 includes a design method for riprap aprons based on research by Fletcher and Grace [1972], which can be used to develop a design graph similar to Figure 1002-4 and include ODOT rock gradations. Due to the unknown origin of the ODOT RCP design procedures and the less conservative approach employed by ODOT compared to other agencies, verification of the current procedures or a replacement methodology is needed to ensure adequate sizing of RCP at conduit outlets.

The goal of this research is to determine the appropriate RCP design based on a variety of factors by building scaled models and conducting hydraulic flume testing. The results are documented in this report and can be used to support or replace ODOT L&D Figure 1002-4, which is the current guidance ODOT uses for RCP design.

2 Research Background

2.1 Goals and Objectives

The specific objectives of this project are:

1. Perform a review of related research, including studies by other DOTs. The information will be used to draft a proposed modeling plan of RCP performance and improvement. The modeling plan will include scaled physical hydraulic modeling at Ohio University (OHIO) and the University of Michigan (Michigan).
2. Conduct scaled physical modeling and gather data. Procedures and data are presented in this report.
3. Verify and/or develop equations that represent different size ranges for RCP placed at culvert and storm drain outlets. These equations can be used as a tool for designers.
4. Verify and improve Figure 1002-4 in the ODOT L&D Manual [ODOT, 2020] for use of RCP at culvert outlets. The improved figures are based on the updated RCP design equations.
5. Detail all supporting tests and evidence to verify ODOT RCP sizing in a final report. This report also makes recommendations for the service life of RCP.

The research team proposed to conduct scaled physical modeling at OHIO and Michigan. Both teams conducted scaled model testing for five different pipes (corresponding to full-size pipe diameters of 1' (0.3m), 4' (1.2 m), 6' (1.8 m), 8' (2.4 m), and 10' (3.0 m) , at three different target velocities (5 ft/s (1.5 m/s), 12 ft/s (3.7 m/s), and 20 ft/s (6.1 m/s)) each by using their own flume. Both modeling flumes were performed at horizontal bed slope (0%). The University of Akron (Akron) assisted OHIO in processing LiDAR data collected by Ohio University, and E.L. Robinson Engineering offered expert insights into the design and implementation of the models. ~~application of RCPs.~~ The two-team modeling approach provided quality assurance when comparing the results and identifying any sensitivities in the scaled hydraulics modeling. To sum up, this research evaluated the current ODOT L&D Manual Figure 1002-4 by determining size, depth, and length of RCP required for adequate scour protection and rock stability for a given culvert size and velocity.

2.2 Summary of Literature Search

In the past, ODOT sponsored two research projects on the design of culvert outlet protection. The first was a study conducted in 1966 by the University of Cincinnati [Laushey, 1966]. The project consisted of scale model testing of pipe culverts utilizing uniform, mostly spherical gravel as the outlet protection material. The study investigated the parameters related to scour hole formation as well as the time-dependent growth of the formed scour hole, the final size of the scour hole at equilibrium, and the material size necessary to resist incipient bed erosion. The report also indicates the use of a level bed in their experimental setup, suggesting the absence of a streamwise bed slope, with flow being solely driven by the free surface slope. Additionally, the experimental model bed consisted entirely of the armor stones under investigation for stability, indicating that the required dimensions of the armor stone apron were calculated based on the scour hole created within the armor material itself, without consideration for the potential depth or length of the scour hole in the absence of the armor stones.

The University of Akron performed a follow-up study in 1980 that was focused on validating the field performance of rock channel protection designed in accordance with ODOT L&D Manual Figure 1002-4 [Sarikelle and Simon, 1980]. The report also compared the length of RCP designed using the ODOT method versus the other methods used at the time. A key conclusion from the study is that “although the lengths of rock channel protection schemes used in Ohio are shorter than the lengths designed by other accepted procedures for a given design flow, it was determined that the actual number of sites which had scour problems at the end of the rock was small, therefore, the Ohio design lengths have proved adequate.” However, the authors also noted that the culverts had generally not yet experienced a significant flood event. Over the last half century, average annual precipitation in most of the Midwest has increased by 5 to 10 percent, but rainfall during the four wettest days of the year has increased by about 35 percent, and the volumetric flow rate in most streams during the worst flood of the year has increased by more than 20 percent [EPA 430-F-16-037, 2016 Report; State Climate Summaries 150-OH, 2022]. Therefore, the changing climate is likely to increase the frequency of floods in Ohio, thus increasing the failure probability of RCPs.

2.2.1 ODOT’s Current Methodology:

It has long been assumed that the research report by Laushey [1966] was the basis for ODOT’s guidance on rock channel protection. ODOT L&D Manual Figure 1002-4 [ODOT, 2020], reproduced in Figure 1, shows the relationship between RCP length of pipe protection needed and velocity at outlet (> 5 fps (1.5 m/s)) is a continuous function for each pipe diameter. For the curves to be continuous, the dependent variable (length of protection) can only contain velocity and pipe diameter as independent variables. However, this is not the case for the Laushey equations, as the length calculation also includes the size of rock as a dependent variable [White et al., 2021]. The true origin of the ODOT RCP design procedure is unknown.

2.2.2 Other DOTs’ Methodologies:

Many state or local agencies have adopted the HEC-14 method published by FHWA, which includes a design approach for a *riprap apron*, which is a “commonly used device for outlet protection for culverts 60 in. (1.5 m) or smaller” [Thompson and Kilgore, 2006]. DOTs in Arizona, Indiana, Kentucky, Minnesota, Nevada, North Dakota, and South Dakota have adapted this method with their own local considerations [White et al., 2021]. Several other states indicate that the design of energy dissipation at a pipe outlet is in accordance with either in-house procedures or HEC-14, with no preference given to either method. These states include Kansas, Maryland, Missouri, Montana, and Washington.

In their report on *Evaluation of Rock Channel Protection Design Procedures*, Kevin White, Eric Adkins, and Joseph Sullivan [2021] state:

Of the remaining 42 states (ones for which energy dissipation design information could be located), 23 make direct reference to HEC-14 without modification, 12 use HEC-14 with limitations or modifications, 4 utilize in-house equations or nomographs, one state, Texas, uses structural modifications within the pipe network, or HEC-15 (Kilgore, et al., 2005), and one state requires energy dissipation design to be reviewed on a case-by-case basis (Idaho).

FHWA publication HEC-14 includes a design method for "Riprap Aprons" which is a "commonly used device for outlet protection for culverts 60 in (1.5 m) or smaller" [Thompson et al., 2006]. The method for determining the required size of rock is based on the work of Fletcher and Grace [1972].

The RCP design methods used by various states are summarized below; more details, such as figures and tables from state manuals and specifications, can be found in White, Adkins, and Sullivan [2021].

2.2.2.1 Kansas DOT:

The Kansas DOT allows natural scour hole formation in the outlet of pipe culvert, which then acts as an energy dissipation structure. If the scour hole can reach the culvert or road, then RCP or concrete aprons are recommended. For cases of severe erosion, following HEC-14 is recommended.

2.2.2.2 Maryland SHA:

Maryland State Highway Administration (MSHA) uses nomographs originally developed by the United States Department of Agriculture Soil Conservation Service for Froude Numbers less than 2.5. HEC-14 is utilized for Froude Numbers above 2.5.

2.2.2.3 Missouri DOT:

The Missouri DOT (MODOT) utilizes a design chart for determining the required rock size. A standard detail sheet, reproduced in White, Adkins, and Sullivan [2021, Figure 6, p. 14], provides a table which specifies the required depth, length, and width of the RCP apron. The dimensions of the apron are based solely on the diameter of the pipe.

2.2.2.4 Montana DOT:

The Montana DOT utilizes the equations set forth in an out-of-date FHWA publication [Schilling, 1975]. However, the procedure is given as a guide, and the manual indicates that engineering judgement along with field observations of the actual scour hole should be used in determining the required size of RCP.

2.2.2.5 Washington DOT:

Washington DOT utilizes a design chart for determining the required rock size which is based solely on pipe outlet velocity. Like MODOT, the horizontal dimensions of the apron are based solely on the diameter of the pipe. However, the depth of RCP is 3D50.

There are four state DOTs which utilize procedures wholly independent from HEC-14. These include Arkansas, North Carolina, New Jersey, and Wyoming. These specific requirements are described below.

2.2.2.6 Arkansas DOT:

The Arkansas DOT (ARDOT) requires rock channel protection immediately downstream of a culvert outlet for a distance not less than 20 ft (6 m), or to the right-of-way, whichever is less. ARDOT also has a nomograph, based on Manning's Equation, for determining the necessary size of RCP for given channel parameters.

2.2.2.7 North Carolina DOT:

North Carolina offers a set of nomographs to evaluate the stability of various standard rock classes, considering critical factors such as flow velocity, discharge rates, flow depth, and stream slope. However, the NCDOT's RCP design approach does not provide guidelines on determining the RCP length for a given design velocity.

2.2.2.8 New Jersey DOT:

NJDOT utilizes a series of equations for the design of RCP size and apron length. The section lists the work of Fletcher, et. al. [1972] as a reference document.

2.2.2.9 Wyoming DOT:

WYDOT is the only DOT which utilizes a shear stress-based approach. WYDOT uses an in-house computer program Culvert Design System to determine the outlet shear stress and scour hole, as well as the RCP size and length of need. For small culverts, the software results are then used in a flow chart to determine appropriate erosion protection.

From the review of the 1966 ODOT report [Laushey, 1966], a research paper by J. P Bohan [1970], HEC-14 [Thompson and Kilgore, 2006], State DOT reports, and the report by Fletcher and Grace [1972], the findings can be summarized as:

The FHWA method in HEC-14 [Thompson and Kilgore, 2006] were based on USACE experiments that used natural bedding material (sand with $d_{50} \approx 0.2$ mm (8 mil)) under the armor stone, while the ODOT method is based on only the armor stone itself. The USACE experiments determined the size of armor stone necessary to resist motion, as well as the length of stone protection needed to stop the sand itself from being mobilized, while ODOT [Laushey, 1966] didn't have any sand bedding. Their RCP was modeled entirely of gravel with $d_{50} \approx 6$ mm (1/4 in) to represent the armor stone. Laushey [1966] looked at scour holes in the gravel to determine if the armor stone wasn't large enough; there was no consideration of the natural material under the armor stone.

3 Research Approach

3.1 Hydraulic Similitude

Hydraulic similitude is paramount in scaled modeling for RCP as it ensures the accurate replication of hydraulic conditions encountered in real-world scenarios. By maintaining similarity between the scaled model and the prototype, modeling results can be used to predict the performance of RCP structures under scaled-up flow conditions. A hydraulic similitude makes the two fluid systems similar in terms of geometry, kinematics, and dynamics.

3.1.1 Geometric Similarity

The liner dimensions ratios (length ratio, depth ratio, width ratio,) of two systems are equal. These relationships only show the similarity of form and shapes of two systems.

$$\lambda = \frac{L_p}{L_m} = \frac{D_p}{D_m} = \frac{B_p}{B_m}$$

λ is the ratio, L is the horizontal length of prototype, D is the depth of water and B is the width of flow for prototype model. The subscript p denotes the prototype and m represents the scaled model.

3.1.2 Kinematic Similarity

This is the similarity of motion in two systems. The ratios of velocities and accelerations are equal in homologous point of two systems with equal geometric ratio. The paths of homologous particles will also be geometrically equal.

$$V_r = \frac{V_p}{V_m} = \frac{u_p}{u_m} = \frac{v_p}{v_m} = \frac{w_p}{w_m}$$

V_r is the velocity ratio, V is the mean velocity and u, v, and w are the velocity components along the x, y, and z directions.

3.1.3 Dynamic Similarity

Dynamic similarity between two geometrically and kinematically similar systems require that ratios of all homologous forces in the two systems be the same. In the case of flow of real fluids, the forces acting on an element of the fluid are: F_p due to pressure variation, F_f due to viscosity, and F_g due to gravity. These sum to the total force ma.

$$F_p + F_g + F_f = ma$$

The OHIO and Michigan flumes are scaled down based on dynamic similarity.

To obtain dynamic similarity between two flow pictures, all independent force ratios that can be written must be the same in both the model and the prototype. Thus, dynamic similarity between two flow pictures is expressed in the equations below.

$$\left[\frac{F_I}{F_G}\right]_p = \left[\frac{F_I}{F_G}\right]_m = \left[\frac{V^2}{lg}\right]_p = \left[\frac{V^2}{lg}\right]_m = [Fr]_p = [Fr]_m$$

where the subscripts *p* and *m* stand for prototype and model respectively, and

F_I = inertia force, F_G = gravity force, *Fr* = Froude number, *l* = characteristic length, *V* = velocity, and *g* = acceleration of gravity.

The OHIO and Michigan models are scaled by Froude similarity and lambda which is the length scale ratio, $L_r = \frac{L_p}{L_m} = \lambda$. By assuming the gravity acceleration between prototype and model is same, we can derive the different ratios below:

1) Velocity Scale ratio (V_r):

$$\left(\frac{V_p}{L_p^{0.5}}\right) = \left(\frac{V_m}{L_m^{0.5}}\right) \rightarrow V_r = \frac{V_p}{V_m} = \left(\frac{L_p^{0.5}}{L_m^{0.5}}\right) = \lambda^{0.5}$$

2) Time Scale ratio (T_r):

$$T_r = \frac{T_p}{T_m} = \left(\frac{\frac{L_p}{V_p}}{\frac{L_m}{V_m}}\right) = \left(\frac{\frac{L_p}{L_m}}{\frac{V_p}{V_m}}\right) = \left(\frac{\lambda}{\lambda^{0.5}}\right) = \lambda^{0.5}$$

3) Discharge Scale ratio (Q_r):

$$Q_r = \frac{Q_p}{Q_m} = \left(\frac{\frac{L_p^3}{T_p}}{\frac{L_m^3}{T_m}}\right) = \left(\frac{\frac{L_p^3}{L_m^3}}{\frac{T_p}{T_m}}\right) = \left(\frac{\lambda^3}{\lambda^{0.5}}\right) = \lambda^{2.5}$$

3.2 Experimental Plan

To understand the empirical relationship between different variables of the RCP design process, fifteen (15) experiments were conducted for five different pipes representing unscaled diameters of 1' (0.3 m), 4' (1.2 m), 6' (1.8 m), 8' (2.4 m), 10' (3.0 m), at three reference velocities of 5ft/s (1.5 m/s), 12ft/s (3.7 m/s), and 20ft/s (6.1 m/s) with zero bed slope. Three different scaling factors (λ = 12, 24, 30) were applied to reduce the RCP size of Type A, Type B and Type C. The proposed experiments are represented by red dots as shown in Figure 2, superimposed on ODOT Figure 1002-4. These experiments were conducted on physically scaled RCP setups in hydraulic flumes at OHIO and Michigan.

For each of the red dots, the research team planned to obtain three velocity values. First, the velocity which triggers the initial scour, V_1. Second, the velocity when the scour hole is formed, V_2, defined by the research team as when the scour depth is equal to the RCP depth. The final velocity, V_3, is when the RCP rocks start to collapse. This velocity can indicate the potential flow condition that causes structural damage to the RCP. Once those velocities were obtained, the research team developed the relationship between RCP length and velocity, then compare them to the reference velocities on the Figure 1002-4 in the ODOT Location and Design (L&D) Manual Volume 2 (ODOT, 2020).

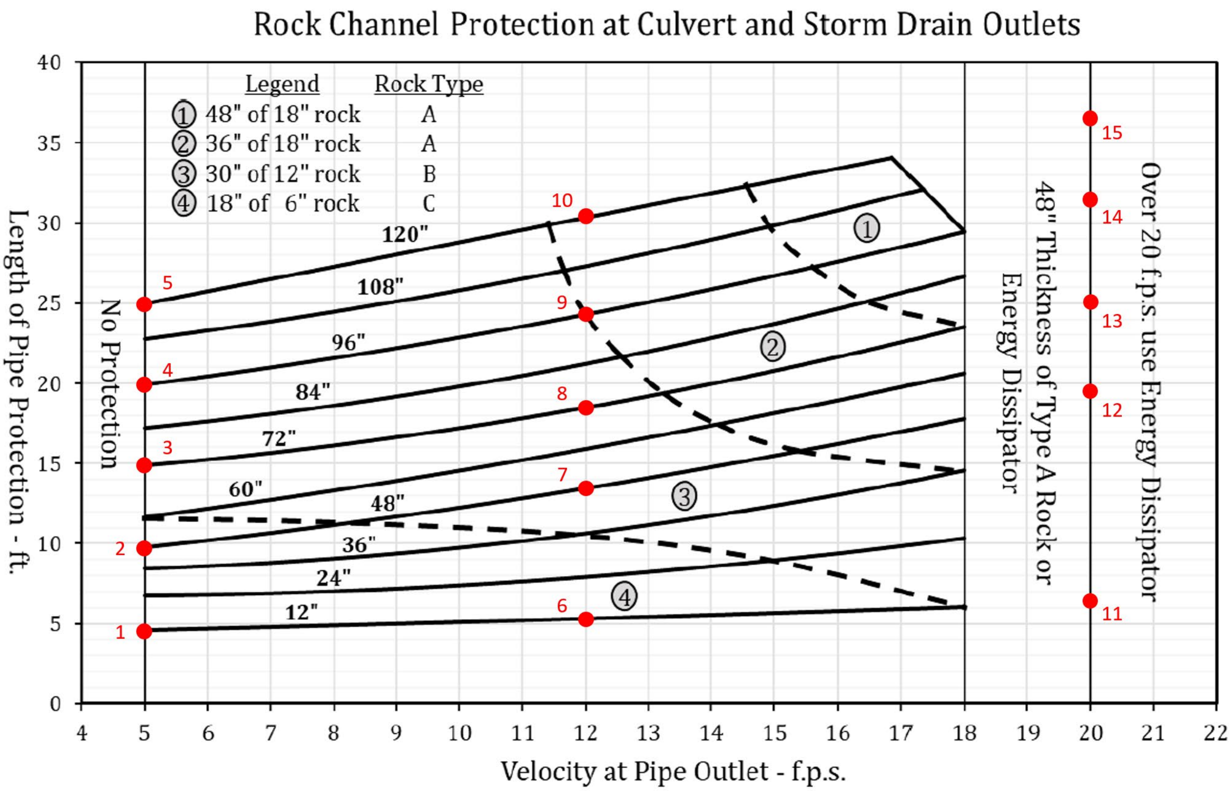


Figure 2. Red dots on the design graph of RCP represent 15 planned experiments. (12" = 1' = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

3.3 Sieve Analysis and Scaled RCP Material

The preparation of scaled RCP material first started with estimation of rocks volume required for each RCP Type and scaling factor. Volume was calculated by first multiplying length and depth of RCP layer with width of flume and then dividing it by specific weight of RCP (2.7 lb/ft^3, 43.2 kg/m^3 or 424 N/m^3). Using the RCP material specification of each RCP Type, provided in ODOT manual of Construction and Material Specifications, and applying scaling factor of 12, the material composition of each scaled RCP Type is given below:

1. Scaled Type A RCP:
    a) At least 85% of total material by weight should be less than 2.5 inch (64 mm) and greater than 1.5 inch (38 mm) in size.
    b) At least 50% of total material by weight should be greater than 2 inches (51 mm) in size.

c) At most 15% of total material by weight should be less than 1.5 inch (38 mm) in size.

2. Scaled Type B RCP:
   a) At least 85% of total material by weight should be less than 2 inch (51 mm) and greater than 1 inch (25 mm) in size.
   b) At least 50% of total material by weight should be greater than 1.5 inches (38 mm) in size.
   c) At most 15% of total material by weight should be less than 1 inch (25 mm) in size.

3. Scaled Type C RCP:
   a) At least 85% of total material by weight should be less than 1.5 inch (38 mm) and greater than 0.5 inch (13 mm) in size.
   b) At least 50% of total material by weight should be greater than 1 inch (25 mm) in size.
   c) At most 15% of total material by weight should be less than 0.5 inch (13 mm) in size.

Similarly, the volume of RCP for other two scaling factors (λ = 24, 30) is calculated for Type A and Type B as Type C material is only required for Experiments 1 and 6 (see Appendix 7.1 for more details). The scaled RCP material was prepared by first performing sieve analysis on raw aggregates to separate the aggregates of specific sizes and then mixing those aggregates in fixed percentages by weight. The sieve analysis performed for above mentioned description of RCP Types for λ = 12 is shown in Figure 3. A photograph of materials for scaled RCP is given in Figure 4.

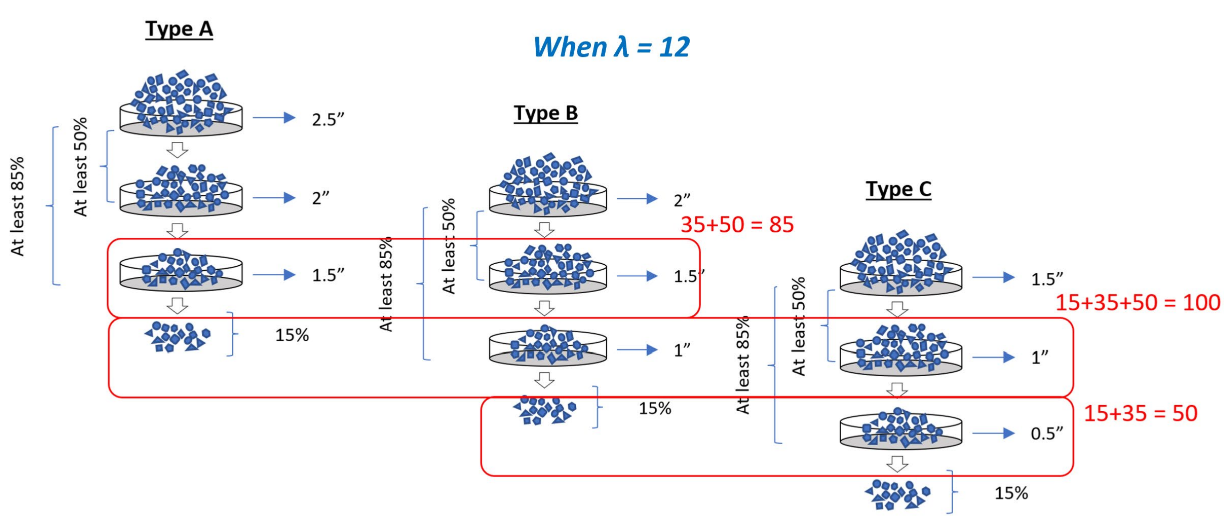


Figure 3. Composition of different RCP Types with sieve analysis at scale factor of λ = 12 (1" = 1 in = 25.4 mm)

Type A Type B Type C

Figure 4: Sample Scaled RCP Materials for λ =12

3.4 Experimental Setup at Ohio University

The experimental setup at OHIO comprises a horizontal flume with sand bed of 6 ft (1.83 m) length, 7.5 in (0.19 m) depth, and 3.5 ft (1.07 m) width as shown in Figure 5. The flume, one of the four constructed flumes used for a previous project funded by ODOT [Mitchell et al. 2010, 2010a, 2010b, 2012], is converted for the physically scaled RCP hydraulic model and built on a ground with zero bed slope. The OHIO team proposed to use 1 in (25 mm), 2 in (50 mm), 3 in (75 mm), and 4 in (100 mm) diameter pipes for the scaled model with three different scaling factors. Sand (d_{50} =8.7 mil = 0.22 mm), from one source, was chosen as bedding material for both labs. At OHIO flume, the sand bed was first saturated at low velocity, flow was then gradually increased to start the experiment. The reduced size of RCP (length and depth) for each of the 15 experiments after applying three scaling factors is presented in Table 1. The OHIO team tentatively chose these pipe sizes to make sure that the flows at culvert outlets required to run the experiments could easily be set up. A scaled RCP setup with a trapezoidal section downstream of the culvert modeled in HEC-RAS to verify that the downstream stream depth, velocity, and flow is not affected by flume width. Per the results of the HEC-RAS model, the length and width of the flume is sufficient for scaled modeling and conducting the experiments. The OHIO team developed a schedule for the scaled hydraulic modeling tests with varying variables, including different culvert outlet sizes, velocities, rock sizes, RCP lengths, and any other important factors.

The volume of the water storage tank is assessed by first calculating the scaled velocities for each experiment using scaling factors and then calculating flowrate (Q = Flow Area of model pipe cross section × scaled velocity) as shown in Table 2. With a maximum scaled flowrate of 160 gpm (606 l/min) required for Case No. 14 based on Figure 1002-4, the 600 gal (2270 l) main tank can provide flow for 3 minutes and 45 seconds. Additionally, a 300 gal (1135 l) secondary tank, installed at height of 7.5 ft (2.3 m), was also connected to the flume to provide an extra elevation head and discharge. To measure the velocities at different stages during an experiment, a flowmeter was installed in the middle of the culvert pipe. Given a known discharge and diameter of culvert pipe, velocity is calculated using the continuity equation. A geotextile sheet of required specification was placed between the RCP and sand that serves as a reference for the measurement of scour hole depth and to prevent the settlement of RCP layer caused by erosion of sand underneath the RCP. In case of partial flow in pipe at the culvert outlet, a camera is used to determine the flow depth. The camera, mounted on an adjustable stand, is placed in front of a culvert outlet to record the fluctuation in flow depth at outlet. Figure 6 is a 3D drawing of the experimental set up.

Figure 5 Experimental Setup of Physically Scaled RCP in Hydraulic Flume at Ohio University (1 gal = 3.79 l)

Table 1. Reduced RCP dimensions using three Froude scaling factors for flume at Ohio University. (12 in = 1 ft = 0.3048 m)

Case No.	**1**	**6**	**11**	**2**	**7**	**12**	**3**	**8**	**13**	**4**	**9**	**14**	**5**	**10**	**15**
Prototype Pipe Diameter (in)	12	12	12	48	48	48	72	72	72	96	96	96	120	120	120
Prototype RCP Length (ft)	4.5	5.5	6.5	9.5	13.5	19.5	15	18.5	25	20	24.5	31.5	25	30.5	36.5
Prototype RCP Thickness (in)	18	18	48	18	30	48	30	30	48	30	30	48	30	36	48
Length Scale (λ)	**12**	**12**	**12**	**12**	**12**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**30**	**30**	**30**
Model Pipe Diameter (in)	1	1	1	4	4	2	3	3	3	4	4	4	4	4	4
Model RCP Length (in)	4.5	5.5	6.5	9.5	13.5	9.75	7.5	9.25	12.5	10	12.25	15.75	10	12.2	14.6
Model RCP Thickness (in)	1.5	1.5	4	1.5	2.5	2	1.25	1.25	2	1.25	1.25	2	1	1.2	1.6

Table 2. Flowrate Estimation for OHIO flume using Froude scaling factors. (12 in = 0.3 m; 1 fps =0.3 m/s; 1 gpm = 3.79 lpm)

Case No.	**1**	**6**	**11**	**2**	**7**	**12**	**3**	**8**	**13**	**4**	**9**	**14**	**5**	**10**	**15**
Prototype Pipe Diameter (in)	12	12	12	48	48	48	72	72	72	96	96	96	120	120	120
Prototype Speed (fps)	5	12	20	5	12	20	5	12	20	5	12	20	5	12	20
Length Scale (λ)	**12**	**12**	**12**	**12**	**12**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**30**	**30**	**30**
Scaled Speed (fps)	1.44	3.46	5.77	1.44	3.46	4.08	1.02	2.45	4.08	1.02	2.45	4.08	0.91	2.19	3.65
Scaled Flowrate (gpm)	3.5	8.5	14	56.5	136	40	22.5	54	90	40	96	160	36	86	143

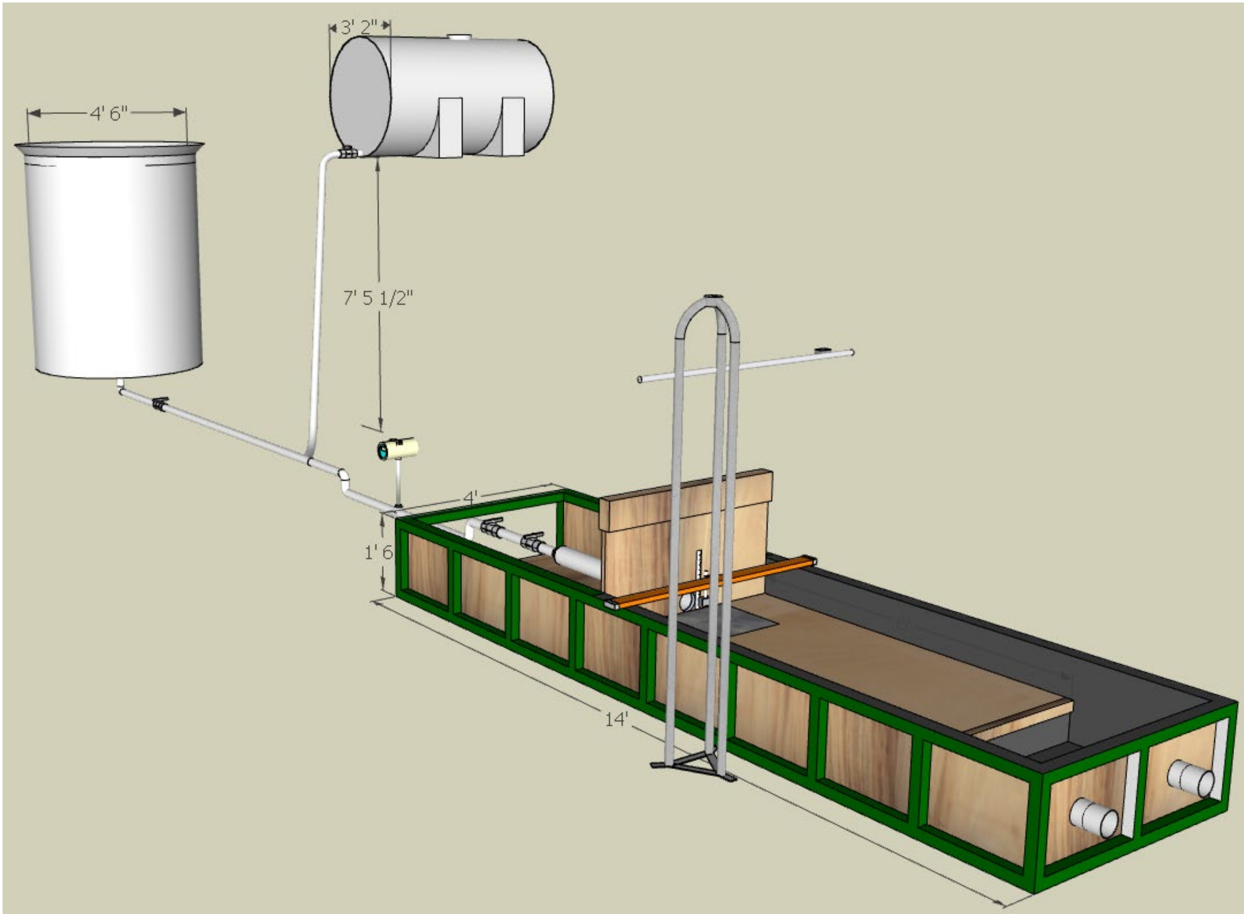


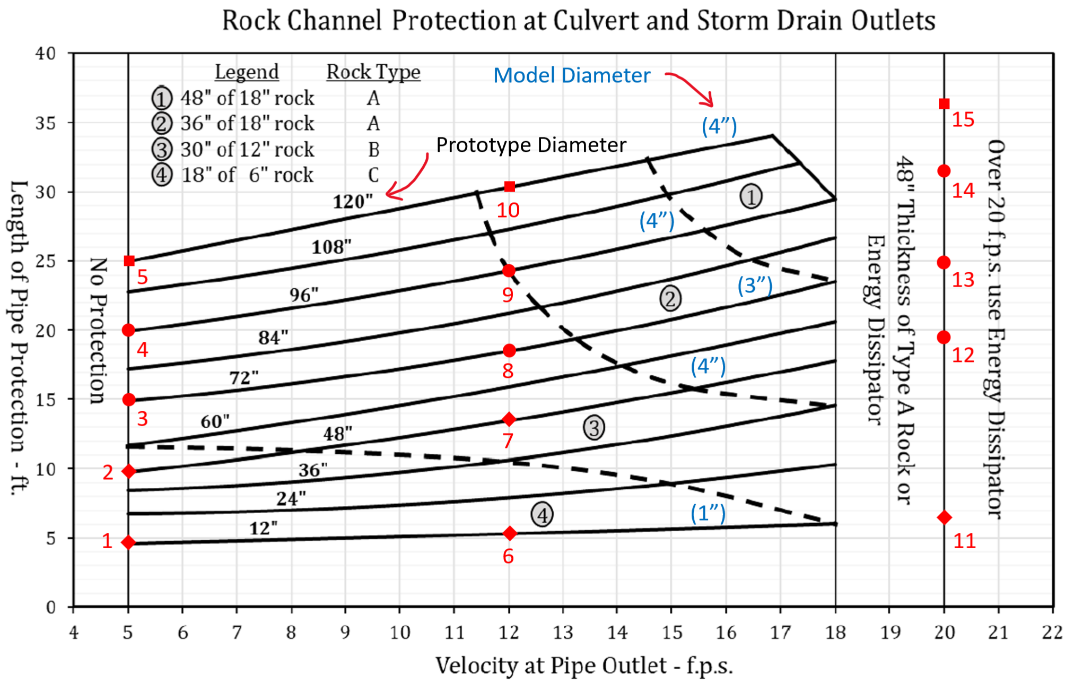
Figure 6. Drawing showing layout of experimental setup at Ohio University. (12 in = 1 ft = 0.3 m)

To analyze the geometry of scour holes, 3D scans of sand bed were recorded from a fixed location. An iPad Pro with LiDAR feature, mounted on an adjustable stand, was used to meticulously capture the geometry of the developed scour hole. To determine the depth of the scour hole, three scans were obtained. The initial scan was taken prior to the start of the experiment, serving as the reference surface. A second scan was conducted at the initiation of scour hole formation downstream of the RCP layer. The third and final scan was taken after the complete formation of the scour hole.

Following the acquisition of these scans, they were processed in Scaniverse software to remove any irrelevant data. Subsequently, they were imported into MATLAB to further analyze the geometry of scour holes. Based on the empirical data obtained from these experiments, the design graphs for different types of RCP configurations were updated.

3.4.1 Experimental plan for OHIO Flume

As mentioned earlier, three scaling factors (λ = 12, 24, 30) were applied on the planned 15 experiments. For culvert diameters of 12 in (0.3 m) and 48 in (1.2 m), a scaling factor of λ = 12 was used, except for Case 12 where λ = 24 was applied. For diameters of 72 in (1.8 m) and 96 in (2.4 m), λ = 24 was applied, and for diameters of 120 in (3.0 m), λ = 30 was chosen. The OHIO experimental plan varied slightly from the Michigan plan; Michigan used a scaling factor of λ = 12 for 72 in (1.8 m) culvert diameter and Case 12. Figure 7 reproduces Figure 2 with the dot shapes representing the scaling factor (diamond shape for λ = 12, circle for λ = 24, and square for λ = 30) and the scaled model diameters listed in blue on the applicable curves. On the right under the legend for the dot shapes, is a table of the case number (C), scaled RCP length (L) in inches and scaled RCP thickness (T) in inches; these data are also in Table 2 and reproduced in the figure for convenience.



S	λ
◆	12
●	24
■	30

C	L	T
1	4.5	1.5
6	5.5	1.5
11	6	4
2	10	1.5
7	13.5	2.5
12	9.75	2
3	7.5	1.25
8	9.75	1.25
13	12.5	2
4	10	1.25
9	12	1.25
14	15.75	2
5	10	1
10	12.2	1.2
15	14.8	1.6

Figure 7. Experimental plan for OHIO Flume. S = symbol, λ = scaling factor, C = case no., L = RCP length (in), T = RCP thickness (in). (12" = 1' = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

Experimental procedure for the OHIO Flume

The experimental procedure involved a series of carefully executed steps. First, a culvert pipe of the required diameter was installed in the flume, along with the flowmeter to measure the flowrate. Next, a sheet of Type B geotextile was placed beneath the RCP at a depth equal to the thickness of the RCP layer. Type B geotextile is specifically used as filter blankets for RCP in Ohio. The RCP of required depth, length, and corresponding type was then placed over the geotextile sheet downstream of the culvert outlet. For steady flow of water, the alignment of the finished surface of the RCP and sand bed along the longitudinal centerline was verified to match with the invert level of the culvert pipe. An initial

LiDAR scan and photograph of the sand bed were taken using the Scaniverse app on the iPad Pro from its fixed overhead position before starting the experiment. Two GoPro cameras, one mounted above the sand bed and the other in front of the culvert outlet, were activated to record flow variations at the culvert outlet cross-section and the progression of scouring in the sand bed.

The experiment began by opening the primary valve and gradually increasing the flow until the scour hole started to form. The flow was then halted using a secondary valve, and a flow meter reading was taken to later calculate the initial scour velocity (V_1). A second LiDAR scan and photograph of the sand bed were then taken. The experiment was resumed by slowly reopening the secondary valve and further increasing the flow using the primary valve until either velocity V_2 or V_3 was reached. Additional scans and photographs were taken after reaching each of these velocities. Post-experiment analysis involved reviewing video recordings from the front camera to assess the flow depth at the culvert outlet at each stop point, as shown for Run 1 and Run 2 of Case 14 in Figure 8. Figure 9 shows overhead scans of the bed before each run and at the stop points for both runs of Case 14.

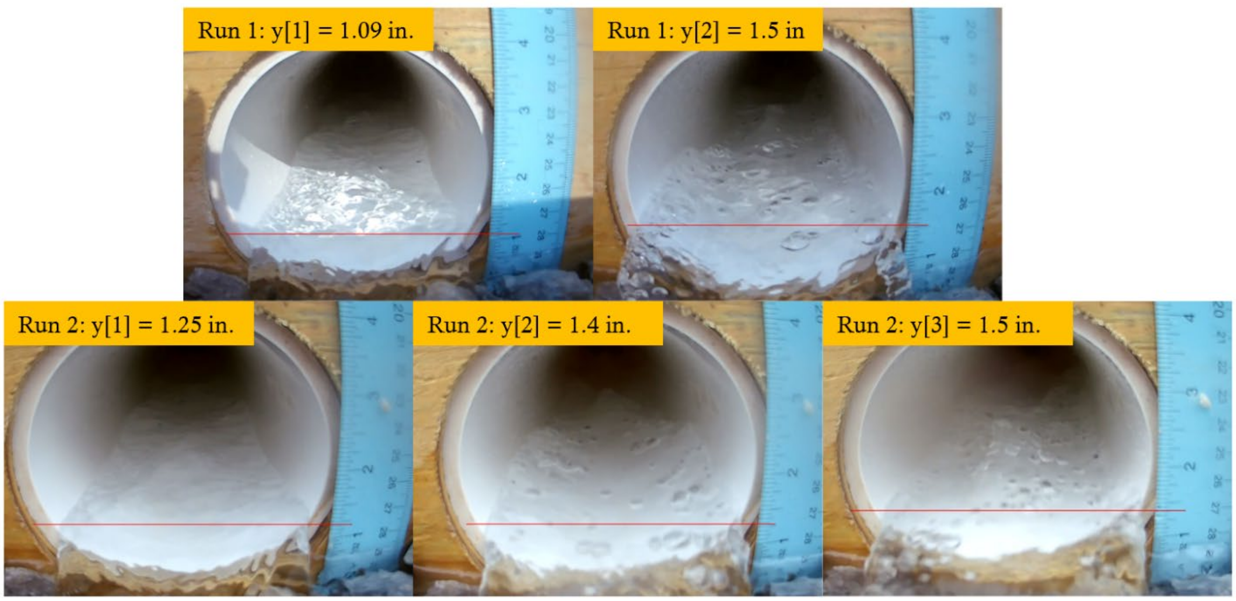


Figure 8. Flow depth determination using front camera videos for corresponding velocities of Experiment (Case) 14. A horizontal thin red line has been drawn to indicate water depth in the pipe. (1 in = 25 .4 mm)

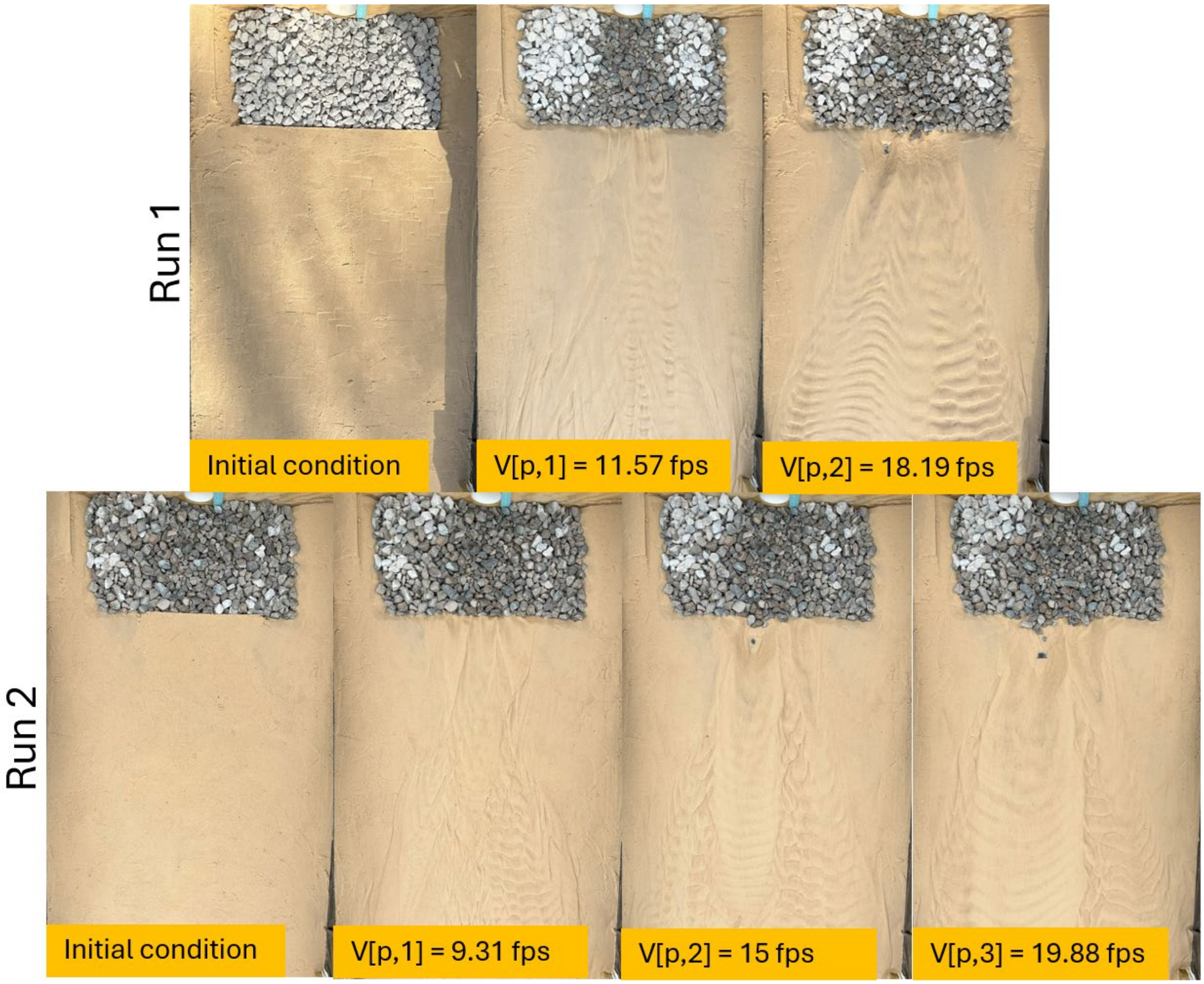


Figure 9. Scour formation, RCP failure, and corresponding prototype velocities for of Experiment (Case) 14 (1 fps = 0.305 m/s)

Finally, the velocities were calculated using the equation of continuity, $Q = AV$, where the discharge (Q) was obtained from the flowmeter and the cross-sectional area (A) of flow at the culvert outlet, considering the case of partially filled pipe, was computed using the formula $1/8(\theta - \sin\theta)d_o^2$, where d_o represents the pipe diameter and $\theta = 2\cos^{-1}(1 - 2y/d_o)$, where y as the depth of flow above the pipe invert at the outlet. Using V and the hydraulic depth $(A/2^*(y^*d_o - y^2)^{1/2})$, the Froude Number was calculated to determine the flow regime.

3.5 Experimental Setup at the University of Michigan

Figure 10 illustrates the University of Michigan flume, culvert structure, and measurement devices used in the culvert scour experiment. The flume is equipped with a circulating system and has dimensions of 0.6 m (2 ft) width, 0.8 m (2.6 m) height, and 16 m (52 ft) length. An ultrasonic flowmeter, installed on the flume supply pipe, measures the inlet flowrate, denoted as Q_{in}. The flume can be inclined to a maximum slope of 0.017. The culvert structure is positioned 5 m (16.4 ft) downstream from the inlet, and the scaled values for both the culvert pipe and RCP for each case are presented in Tables 3 and 4.

The procedure for each experiment unfolds as follows: Starting with the minimum flowrate (approximately 50 lpm (13 gal/min)), the experiment runs for 5 minutes, during which the presence of scour holes and any movement of the RCP rocks is assessed. Subsequently, the flowrate is incrementally increased until a complete scour hole is formed, and RCP rocks commence motion. This sequence is repeated until these conditions are met, and the corresponding flowrates are recorded, as illustrated in Figure 11.

The data acquisition method closely mirrors the approach used at Ohio University. It involves utilizing a known culvert outlet flowrate and water depth at the culvert outlet to calculate the velocity at the culvert outlet using the continuity equation. One notable difference in Michigan experimental setup is that Michigan's sand bed is in an unsaturated condition. To accommodate this, the end plate (Figure 10) was modified by adding 12 holes and covering these with steel mesh. This design allows water to permeate while blocking the sand, thereby maintaining an unsaturated soil condition. To determine whether the flow is uniform, a wave gauge is placed upstream to measure the upstream water depth. In instances of uniform flow, the inlet flowrate is employed as the culvert outlet flowrate. Conversely, in cases of non-uniform flow, the conservation of mass within the control volume is used to calculate the culvert outlet flowrate. To prevent the settling of the RCP layer due to the erosion of the sand beneath it, a geotextile sheet with the specified requirements is strategically positioned between the RCP and the sand. In situations of partial flow at the outlet, an ultrasonic sensor (noted in Figure 10, and shown in Figure 11) is installed on the headwall just above the culvert outlet to measure the water depth at that location. This water depth was then cross validated with the water depth captured in photographs. The geometry of the culvert scour was captured using the LiDAR scanner function of an iPad Pro, as shown in the left image of Figure 12. Post-processing using MATLAB converts this data into the form of point clouds, as depicted in the right image of Figure 12. This transformation allows the research team to determine the width, height, and length of the culvert scour, and the length of the scour will be validated by comparing it with the length measured using a camera.

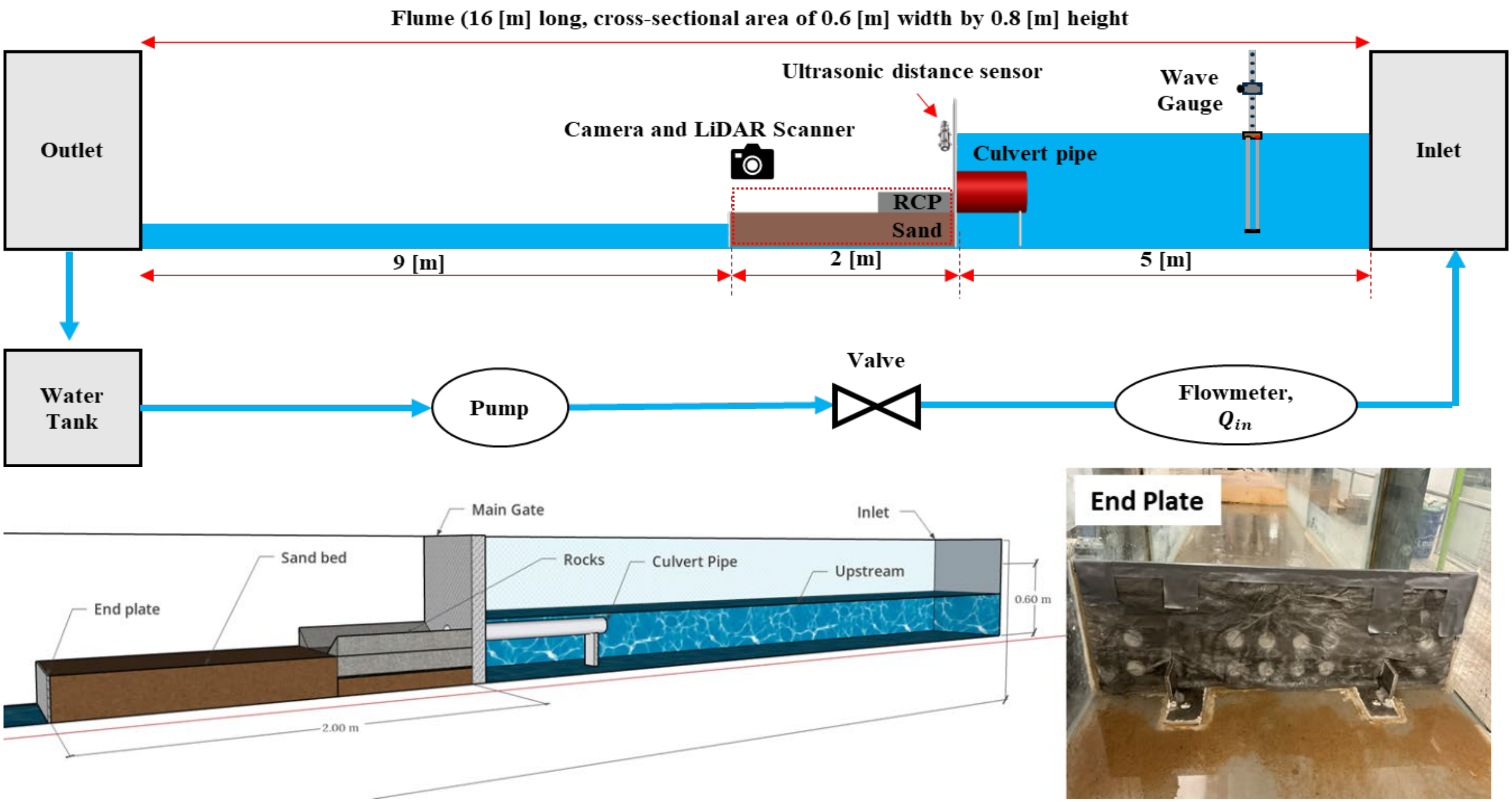


Figure 10. Flume, culvert structure, and measurement devices in the University of Michigan flume. (1 m = 0.305 ft)

Table 3. Reduced RCP dimensions using three Froude scaling factors for flume at University of Michigan. (12 in = 1 ft = 0.3048 m)

Case No.	1	6	11	2	7	12	3	8	13	4	9	14	5	10	15
Prototype Pipe Diameter (in)	12	12	X	48	48	48	72	72	72	96	96	96	120	120	120
Prototype RCP Length (ft)	4.5	5.5	X	9.5	13.5	19.5	15	18.5	25	20	24.5	31.5	25	30.5	36.5
Prototype RCP Thickness (in)	18	18	X	18	30	48	30	30	48	30	30	48	30	36	48
Length Scale (λ)	**12**	**12**	X	**12**	**12**	**12**	**12**	**12**	**12**	**24**	**24**	**24**	**30**	**30**	**30**
Model Pipe Diameter (in)	1	1	X	4	4	4	6	6	6	4	4	4	4	4	4
Model RCP Length (in)	4.5	5.5	X	9.5	13.5	19.5	15	18.5	25	10	12.25	15.75	10	12.2	14.6
Model RCP Thickness (in)	1.5	1.5	X	1.5	2.5	4	2.5	2.5	4	1.25	1.25	2	1	1.2	1.6

Table 4. Flowrate Estimation for Michigan flume using Froude scaling factors. (12 in = 0.3 m; 1 fps =0.3 m/s; 1 gpm = 3.79 lpm)

Case No.	1	6	11	2	7	12	3	8	13	4	9	14	5	10	15
Prototype Pipe Diameter (in)	12	12	X	48	48	48	72	72	72	96	96	96	120	120	120
Prototype Speed (fps)	5	12	X	5	12	20	5	12	20	5	12	20	5	12	20
Length Scale (λ)	**12**	**12**	X	**12**	**12**	**12**	**12**	**12**	**12**	**24**	**24**	**24**	**30**	**30**	**30**
Scaled Speed (fps)	1.44	3.46	X	1.44	3.46	5.77	1.44	3.46	5.77	1.02	2.45	4.08	0.91	2.19	3.65
Scaled Flowrate (gpm)	3.5	8.5	X	56.5	136	40	22.5	54	90	40	96	160	36	86	143

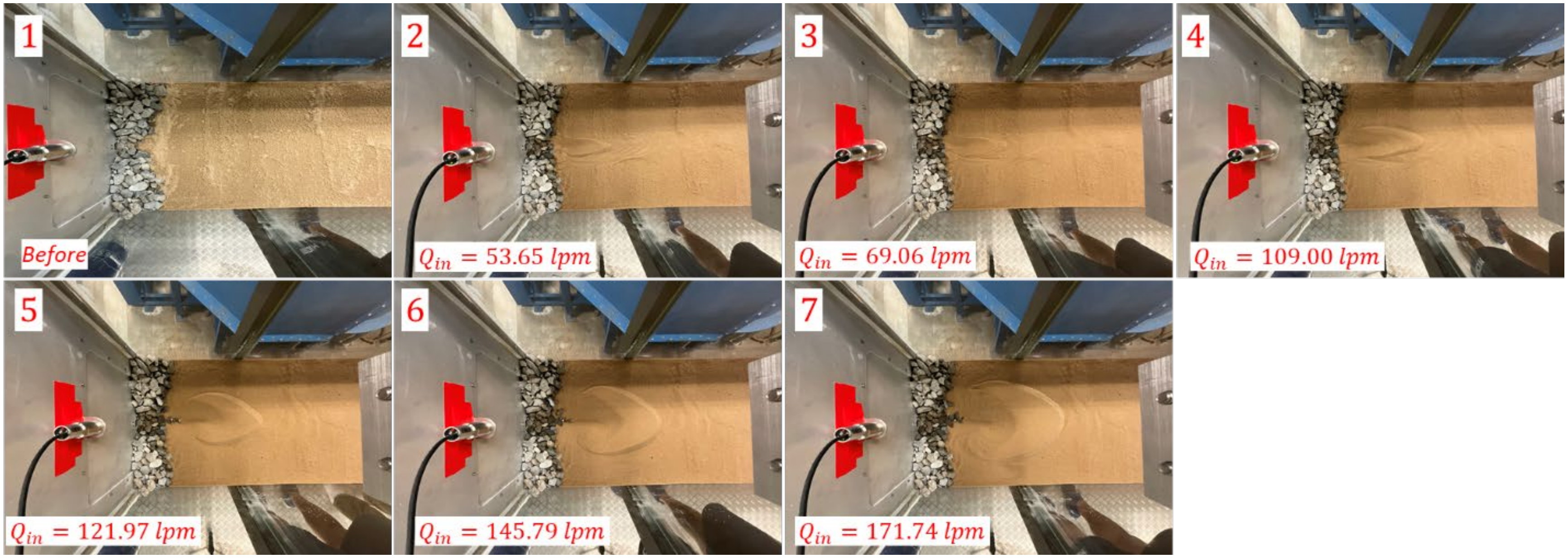


Figure 11. Culvert scour formation (#5), RCP rock movement (#7), and corresponding flowrates (1 lpm = 0.264 gal/min)

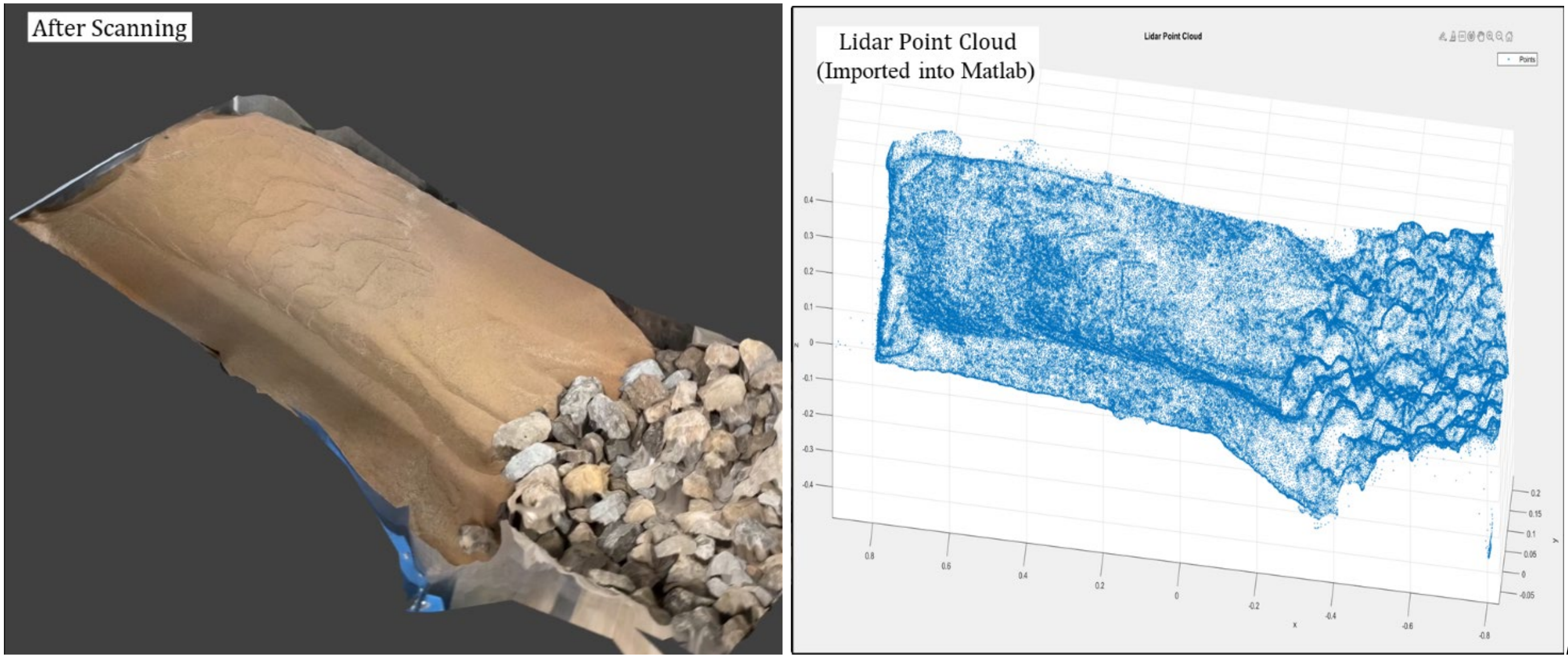
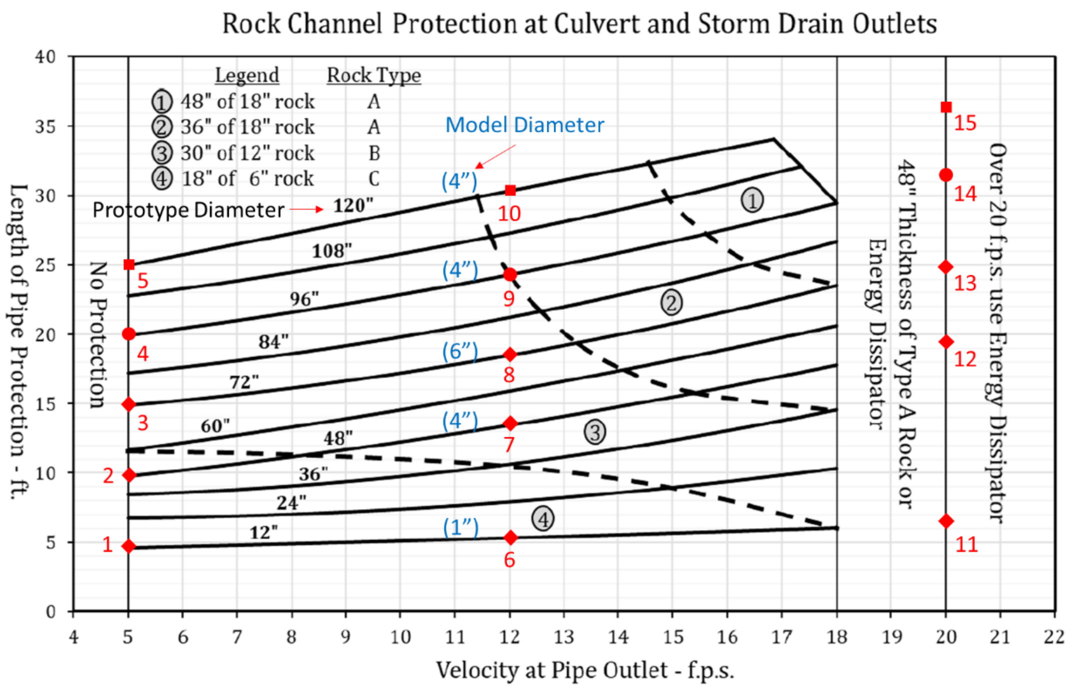


Figure 12. Culvert scour LiDAR scan (top) and its geometry after importation into MATLAB (bottom). Water flows from left to right.

3.5.1 Experimental plan for Michigan Flume

Similar to the Ohio flume setup, three scaling factors (λ = 12, 24, 30) were applied. However, Case 11 was excluded from the Michigan experimental plan due to limitations in upstream depth. As mentioned in Section 3.4.1, the scaling factors used in the Michigan experiment differ slightly from those in the Ohio experimental plan. For culvert diameters of 12 in (0.3 m), 48 in (1.2 m), and 72 in (1.8 m), a scaling factor of λ = 12 was used. For diameters of 96 in (2.4 m), λ = 24 was applied, and for diameters of 120 in (3.0 m), λ = 30 was chosen. Figure 13 reproduces Figure 2, with the dot shapes representing the scaling factor (diamond shape for λ = 12, circle for λ = 24, and square for λ = 30), and the scaled model diameters listed in blue on the applicable curves. On the right, under the legend for the dot shapes, there is a table of the case number (C), scaled RCP length (L) in inches, and scaled RCP thickness (T) in inches. These data are also in Table 3 and reproduced in the figure for convenience.



S	λ
◆	12
●	24
■	30

C	L	T
1	4.5	1.5
6	5.5	1.5
11	X	X
2	9.5	1.5
7	13.5	2.5
12	19.5	4
3	15	2.5
8	18.5	2.5
13	25	4
4	10	1.25
9	12.25	1.25
14	15.75	2
5	10	1
10	12.2	1.2
15	14.6	1.6

Figure 13. Experimental plan for Michigan Flume. S = symbol, λ = scaling factor, C = case no., L = RCP length (in), T = RCP thickness (in). (12" = 1' = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

4 Research Findings and Conclusions

4.1 Experimental Results from OHIO Flume

The experimental data for three threshold velocities (V_1, V_2, V_3) was plotted against the corresponding RCP lengths. The graph of V_1 data in Figure 14 showed no clear pattern, likely due to the inherent challenge in accurately identifying the onset of scour hole formation because of the absence of an objective criterion. For instance, 72 in (1.8 m) diameter pipes did not reveal a direct relationship between velocity and RCP length. However, the velocity data of 48 in (1.2 m) pipes displayed a perfect linear relationship between velocity and RCP length. In contrast, increasing the RCP length from 20 ft (6.1 m) to 31.5 ft (9.6 m) for 96 in (2.4 m) culvert pipes had a marginal effect on V_1 velocity, which changed slightly from 8.24 fps (2.51 m/s) to 9.31 fps (2.84 m/s).

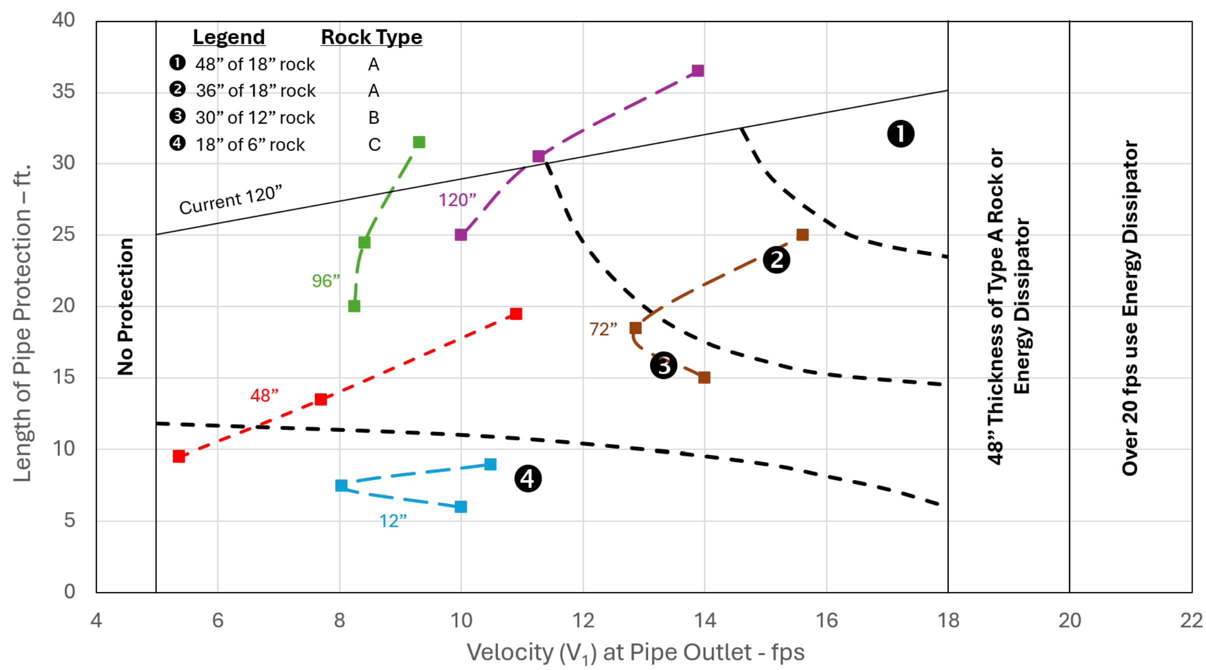


Figure 14. RCP design graph based on V_1 ***data of OHIO flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)***

In some cases, the values of V_2 and V_3 were identical (Figure 15 and Figure 16), indicating that the point of RCP failure coincided with the completion of the scour hole. The graph for 96 in (2.4 m) and 120 in (3.0 m) diameter culvert pipes demonstrated a linear relationship between RCP length and V_3, although the lines are intersecting. Additionally, the relationships for 48 in (1.2 m) and 72 in(1.8 m) pipes could be linearly regressed, leading to their intersection as well. In the case of 12 in (0.3 m) pipes, the V_3 velocities exceeded 20 fps (6.1 m/s), highlighting the necessity of implementing energy dissipators.

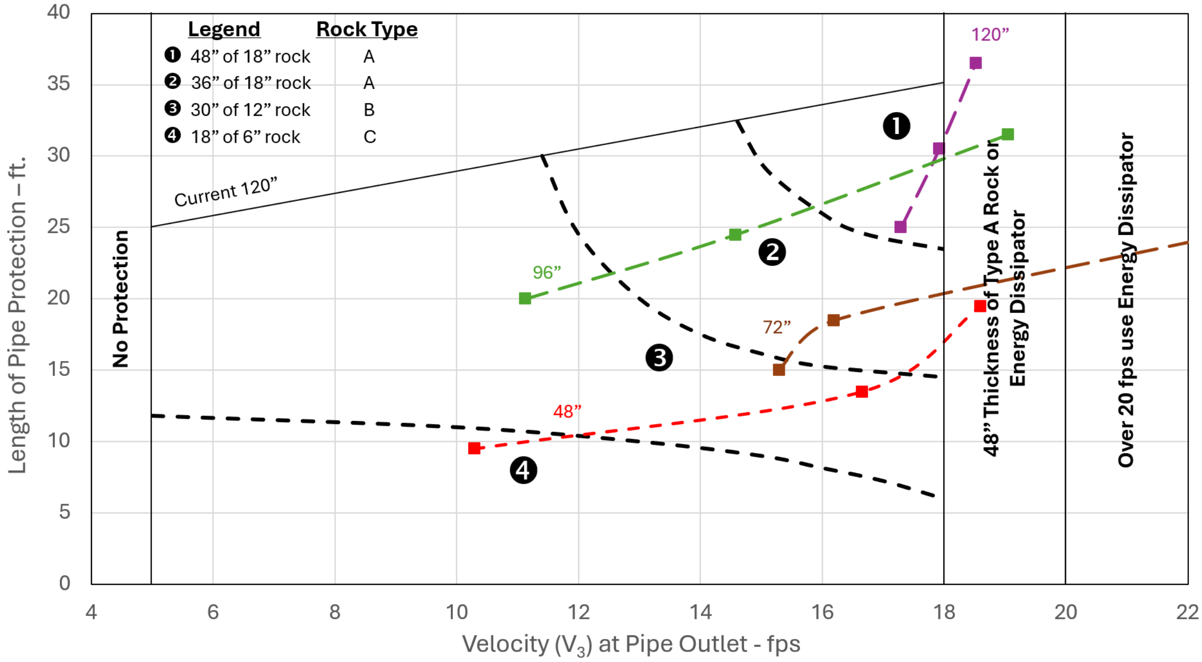


Figure 15. RCP design graph based on V_3 data of OHIO flume. (12" = 1' = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

The general trend obtained from the experimental findings indicates that RCP lengths obtained from the current ODOT design are conservative, especially for larger pipe diameters at lower design velocities (Figures 15 & 17). This observation was obtained following the application of regression on V_2 data. Also, to make these findings applicable in the field, regression curves were drawn for each pipe size which are shown in Figure 17and the details of the regression equation for each pipe size can be viewed in Appendix 7.3. For instance, in the case of larger pipe diameters (96 in (2.4 m) and 120 in (3.0 m)) with lower design velocities (<15 fps (4.6 m/s)), the ODOT-recommended RCP lengths are longer compared to experimental findings. Furthermore, the ODOT design approach suggests RCP lengths of 23 ft (7.0 m) and 29 ft (8.8 m) for design velocities of 10 fps (3 m/s) in pipes with diameters of 96 in (2.4 m) and 120 in (3.0 m), respectively. However, experimental findings from the OHIO flume suggest that shorter RCP lengths of 21.5 ft (6.6 m) and 23 ft (7.0 m) would suffice for the respective pipe sizes. Similarly, for 48 in (1.2 m) and 72 in (1.8 m) diameter pipes, the ODOT design method appears more conservative for both low and high velocities when compared to the experimental results. However, the RCP length recommended by the ODOT design procedure for 12 in (0.3 m) diameter pipes aligns closely with the lengths determined through experimental results.

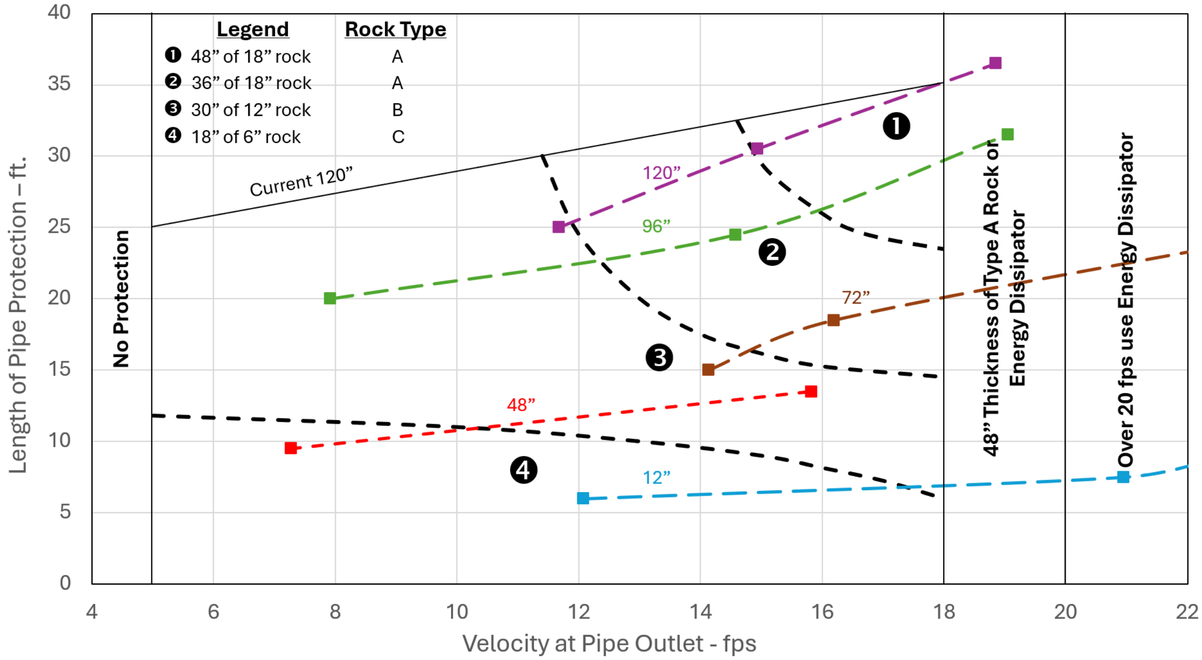


Figure 16. RCP design graph based on V_2 data of OHIO flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

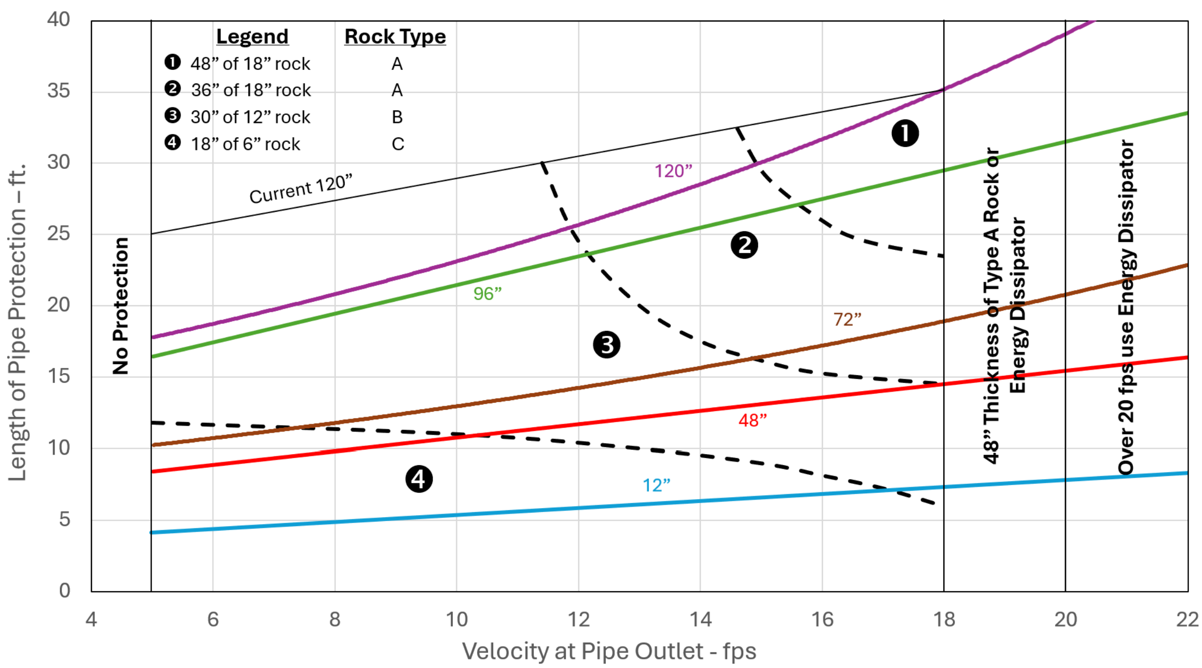


Figure 17. RCP design graph based on the regression of V_2 data of OHIO flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

Notes: Supercritical flow over saturated soil

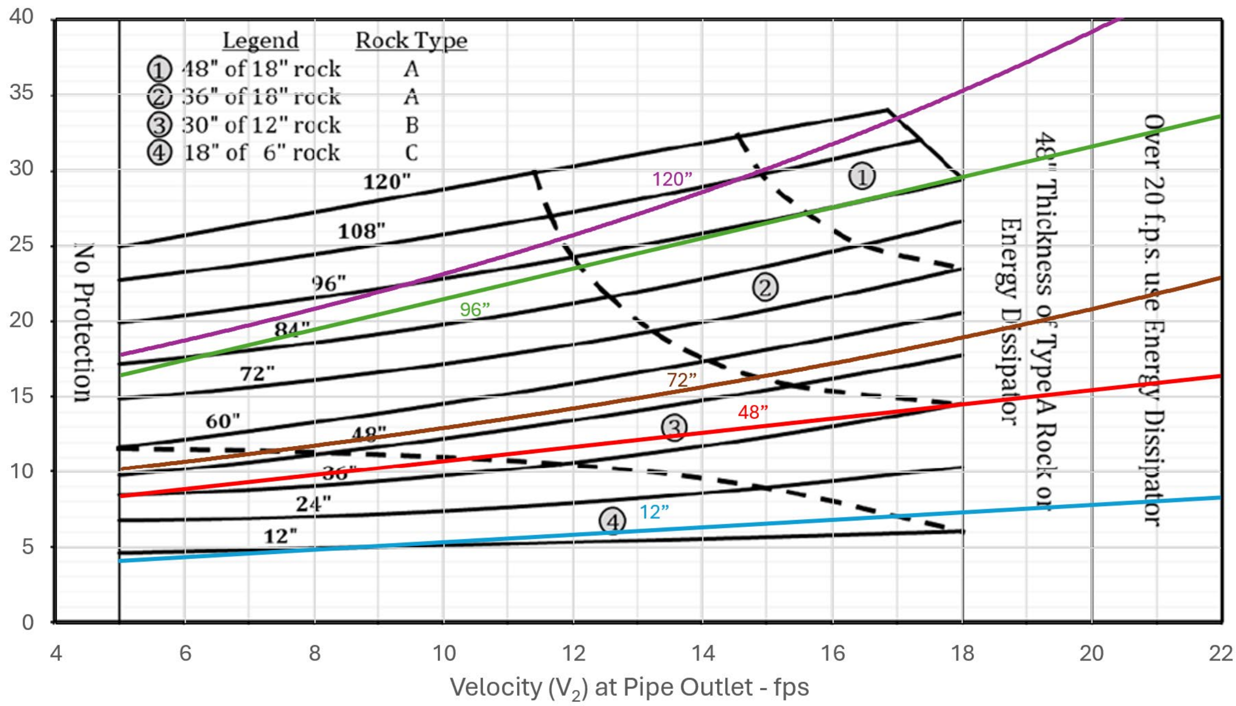


Figure 18. Comparison of ODOT RCP design procedure with RCP design graph based on V_2 data of OHIO flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

4.2 Experimental Results of the Michigan Flume

The design graphs derived from the experimental data of Michigan flume for threshold velocities V_1, V_2 and V_3 are different from one another. The design graph plotted from V_1 data (Figure 19), like the OHIO data trend, does not provide a clear guidance for field implementation. For instance, the design curve for the 120 in (3.0 m) pipe diameter shows an inverse relationship between outlet velocity and RCP length, with an increase in velocity from 7.8 fps (2.4 m/s) to 9 fps (2.7 m/s) resulting in a significant reduction in RCP length from 35 ft (10.7 m) to 25 ft (7.6 m). For 96 in (2.4 m) pipe, change in RCP length has no effect on outlet velocity. A linear relationship is found between RCP length and outlet velocity for the 72 in (1.8 m) and 48 in (1.2 m) pipe sizes. However, extrapolation of these curves leads to intersections, yielding no insight for field applications. For 12 in (0.3 m) pipe, an increase in velocity will require shorter lengths of RCP.

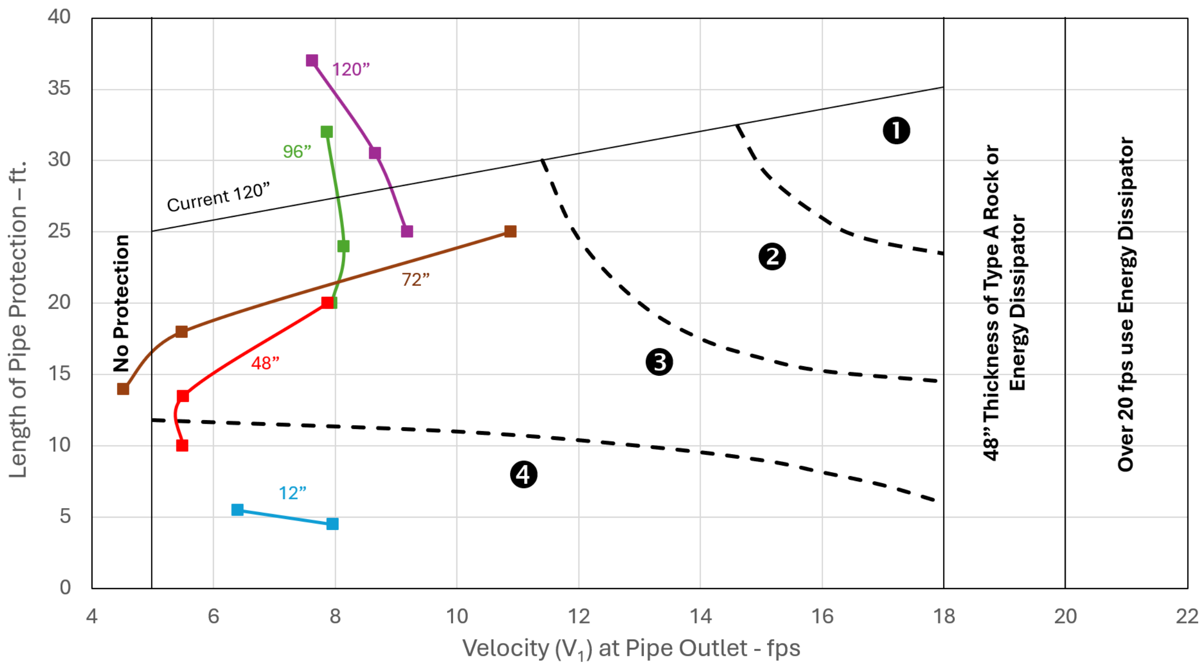


Figure 19. RCP design graph based on V_1 ***data from Michigan flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)***

The design graph for V_3 (Figure 20) shows that as pipe size increases, RCP length also increases. Moreover, the relationship between outlet velocity and RCP length varies for each pipe varies. For instance, the design curve for the 120 in (3.0 m) pipe size shows an increase in velocity from 9.5 fps (2.9 m/s) to 12 fps (3.7 m/s)) will require a significant increase in RCP length from 25 ft (7.6 m) to 37 ft (11.3 m). However, the extrapolation of this curve will result in its intersection with other curves, making the design graph inapplicable in the field.

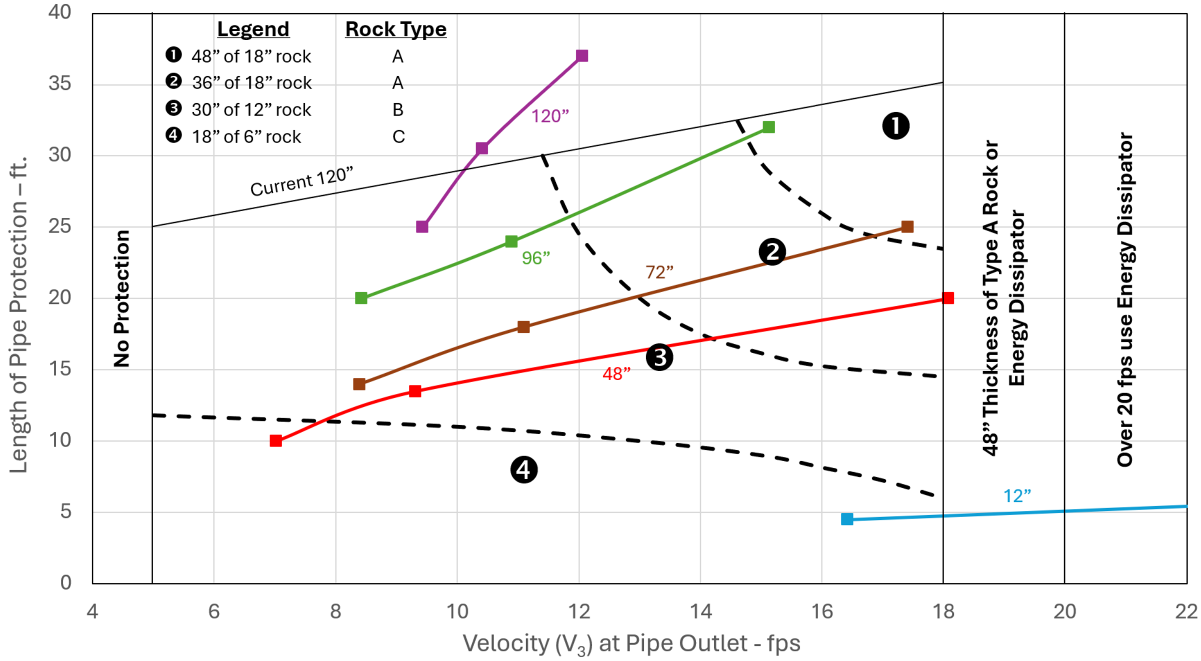


Figure 20. RCP design graph based on V_3 ***data of Michigan flume. (12" = 1' = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)***

The design graph for V_2 (Figure 21) shows that, at lower velocities, the ODOT design procedure is more conservative compared to experimental findings of the Michigan flume. It is obvious from the regression curves of V_2 data as demonstrated in Figure 22 (see Appendix 7.3 for the equations). However, as the velocity increases (V > 10 fps (3 m/s)), this trend reverses. As pipe size increases, the slope in the linear relationship between velocity and RCP length increases, indicating that larger pipes need more RCP protection length as outlet velocity increases (Figure 23). The design curves for the 48 in (1.2 m), 72 in (1.8 m), and 96 in (2.4 m) pipe sizes are similar to those of V_3. The reason behind this similarity is the removal of sand support from RCP after V_2 is reached, which leads to immediate RCP failure.

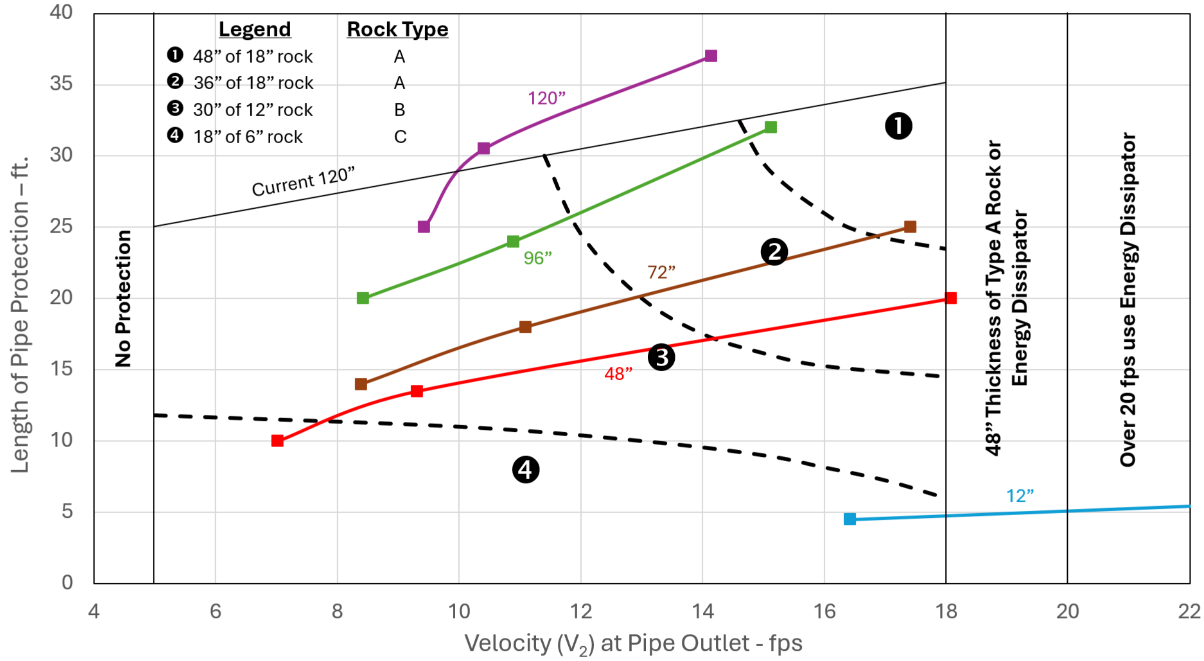


Figure 21. RCP design graph based on V_2 data of Michigan flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

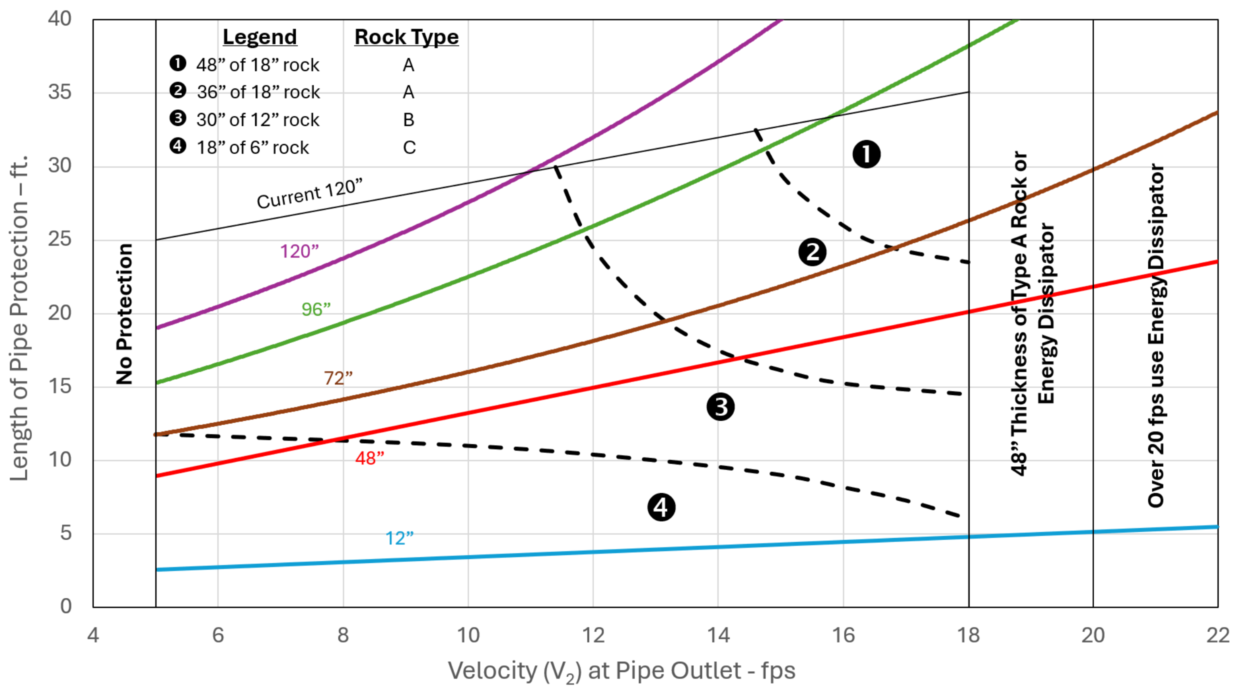


Figure 22. RCP design graph based on the regression of V_2 data of Michigan flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

Notes: Subcritical flow over unsaturated soil

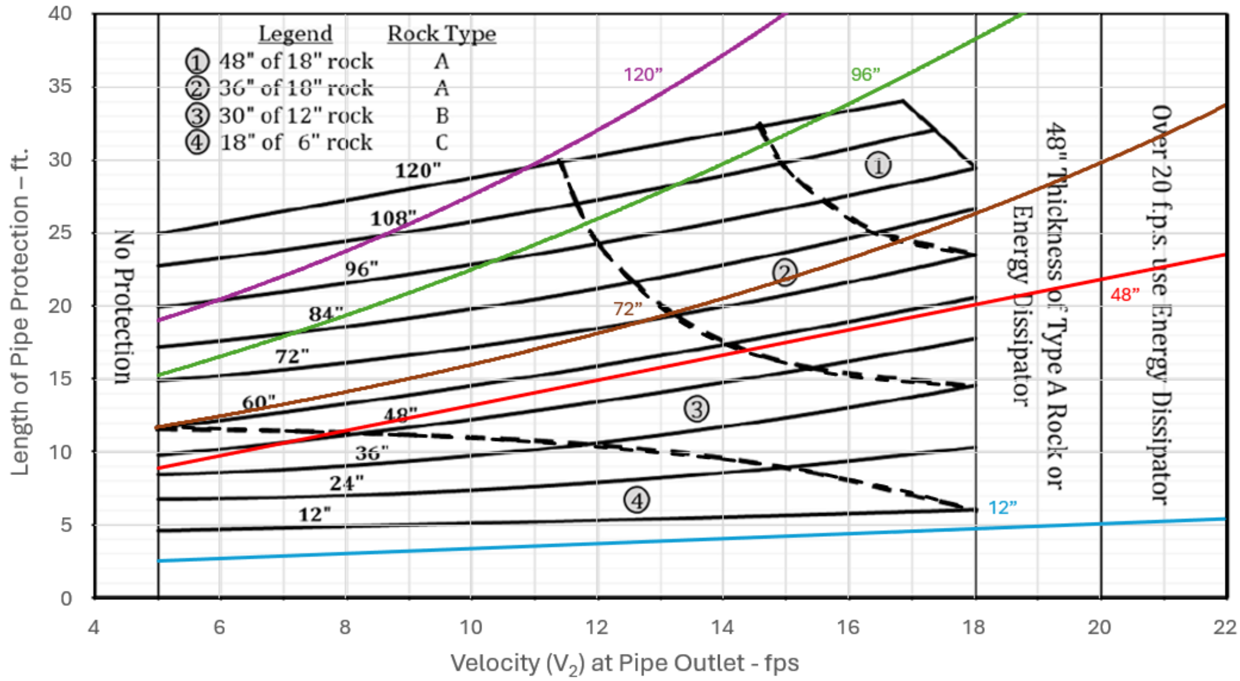


Figure 23: Comparison of ODOT RCP design procedure with RCP design graph based on V_2 data of Michigan flume. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

4.3 Conclusions

The empirical investigations, conducted independently at OHIO and Michigan, collectively unveil a discernible relationship between RCP length and scour hole completion velocity V_2. However, the findings regarding V_1 and V_3 yield scant insight into the optimal design of RCP length. Despite discerning a logical correlation between RCP length and outlet velocity V_2 in the studies, the design graphs derived from the data of both institutions exhibit significant disparities. Specifically, the RCP design curves derived from the Michigan data are situated to the left on the graph compared to the OHIO curves, which occupy the right side, except for the blue curves (12 in (0.3 m) prototype culvert) where the Michigan design curve necessitates less RCP material than the OHIO curve for a given velocity, as observed in Figure 24.

In essence, RCP lengths based on Michigan data tend to be generally longer compared to those derived from OHIO data. These discrepancies can be ascribed to fundamental differences in the experimental setups at each laboratory, as follows:

a) In the Michigan flume, flow at the culvert outlet was impelled by gravity, with the water head behind the culvert propelling the flow through the pipe. The water level seldom exceeded the top of the pipe cross-section. Conversely, in the OHIO flume, flow was driven by a stable water head in a 600 gaL (2271 l) tank, which was continuously replenished by a constant water supply.
b) At Michigan, a constant flow was sustained for 5 minutes to observe changes in the sand bed, after which it was significantly increased (e.g., by 50 lpm (13 gpm)). Meanwhile, at OHIO, flow was gradually adjusted using a primary valve until the target velocity (V_2) was attained.
c) The sand bed in the Michigan flume exhibited either partial saturation or remained unsaturated, whereas the sand bed in the OHIO flume was fully saturated.
d) The outlet flow regime in the Michigan flume was predominantly subcritical, or the Froude Number was close to 1, whereas supercritical flow conditions were observed in the OHIO flume.
e) The sand bed width in the Michigan flume (2 ft (0.6 m)) was narrower compared to that of the OHIO flume (3.75 ft (1.1 m)).
f) The Michigan flume incorporated a recirculating water system, while the OHIO flume lacked such a mechanism.
g) The water storage capacity at the Michigan flume was comparatively larger than that of the OHIO flume (600 + 300 gal (2271 + 1135 l)).

The design curves, showing the RCP lengths for all pipe sizes, based on the interpolation of the regression of culvert sizes tested in OHIO and Michigan flume are shown in Figures 25 and 26 respectively.

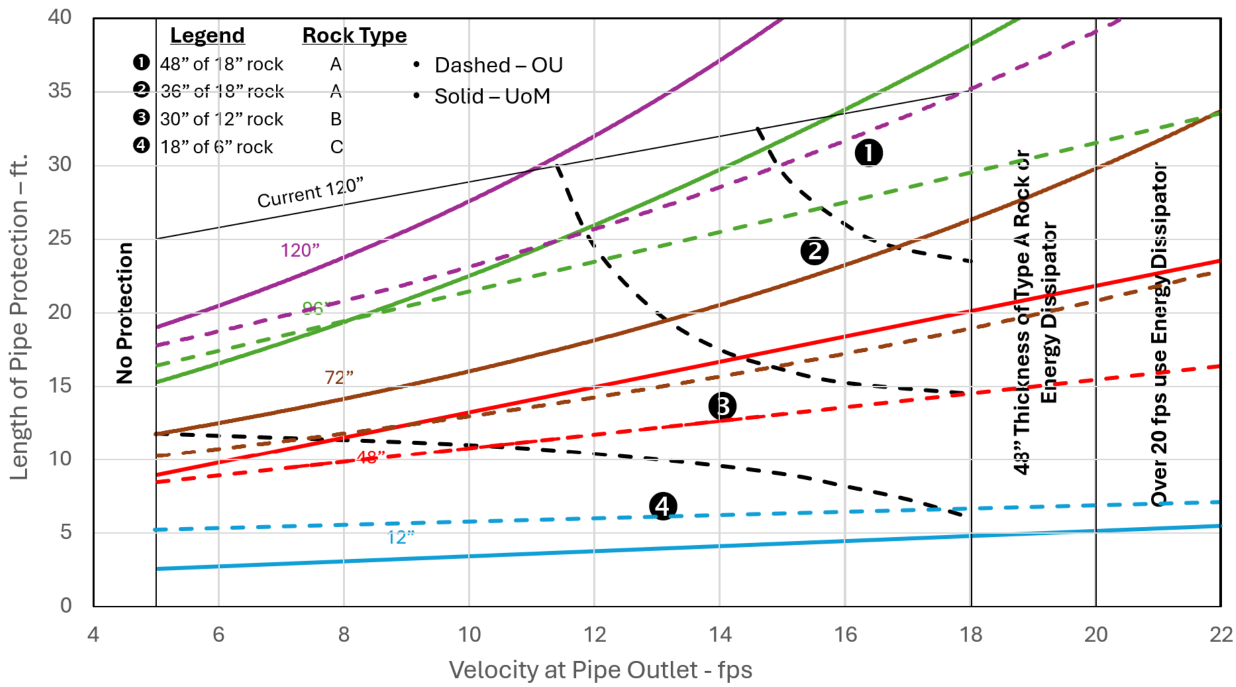


Figure 24. Comparison of RCP Length Designs based on OHIO and Michigan V_2 Data. (12” = 1’ = 1 ft = 0.305 m; 1 fps = 1 ft/s = 0.305 m/s)

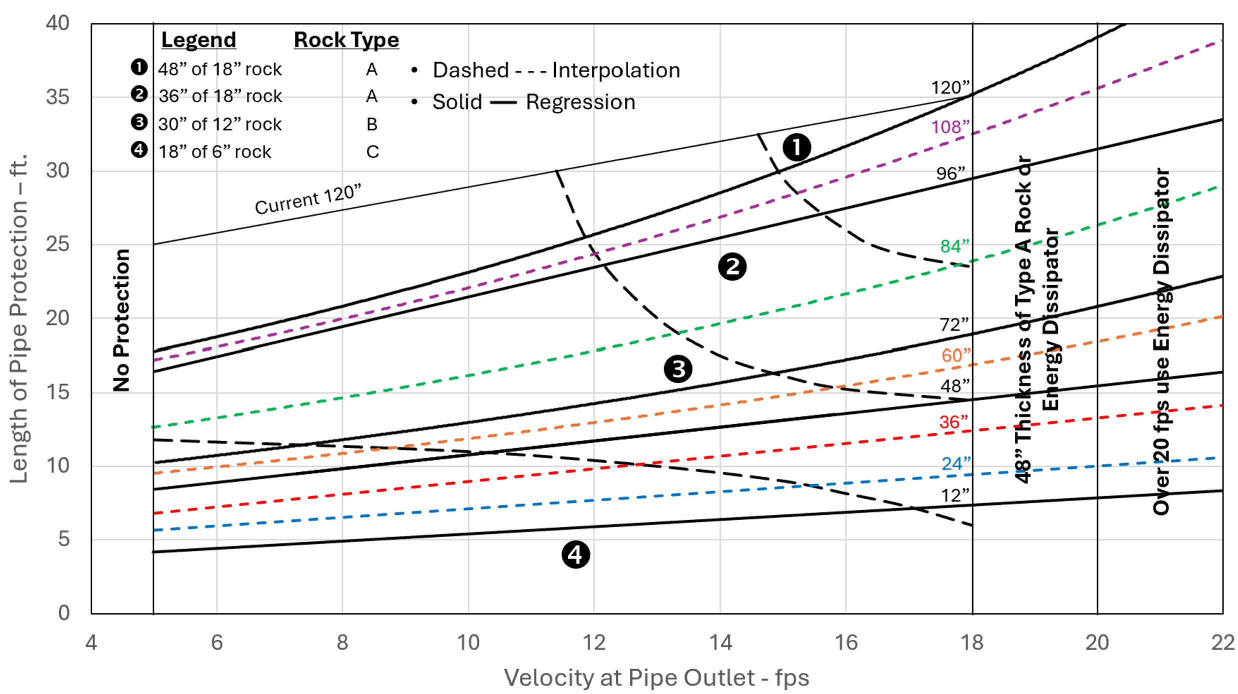


Figure 25. RCP design graph based on the regression and interpolation of V2 data of OHIO flume.

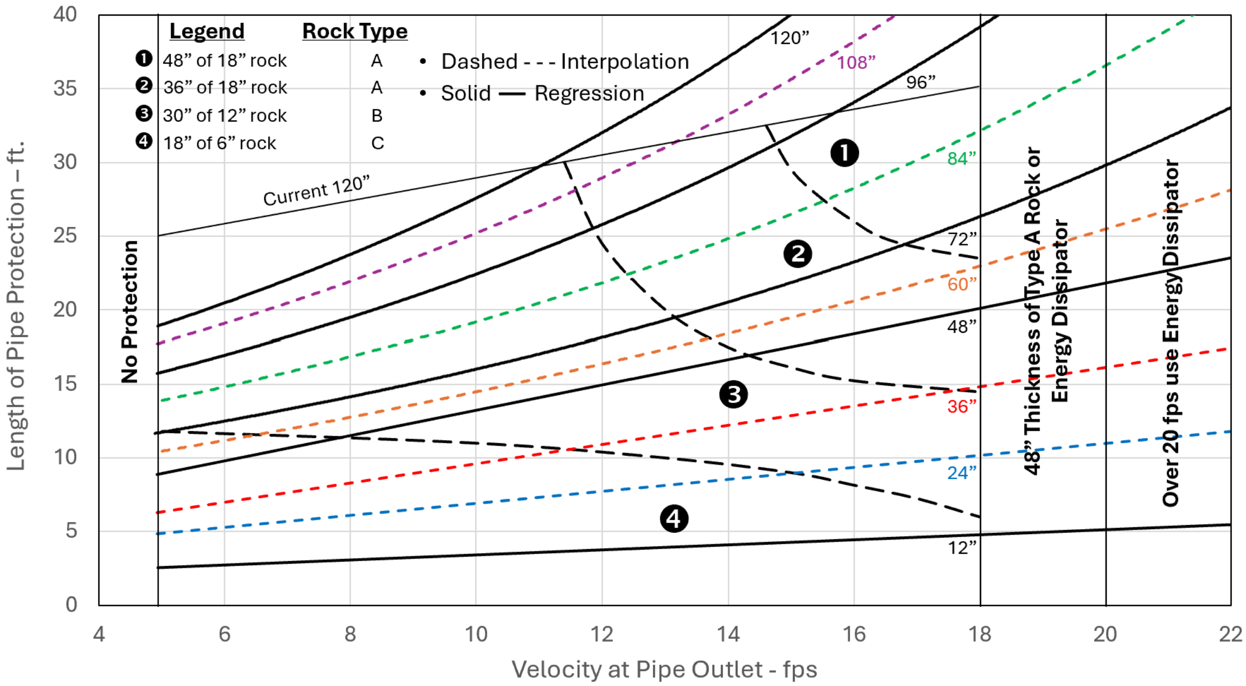


Figure 26. RCP design graph based on the regression and interpolation of V2 data of Michigan flume.

5 Recommendations for Implementation

The divergence between the RCP design graphs derived from the experimental outcomes of the OHIO and Michigan flumes, as well as their deviation from the ODOT design graph, underscores the need for an integrated approach. These insights hold promise for refining the RCP design procedure for practical application in the field, and the following recommendations aim to facilitate this integration:

a) Tailoring to Flow Regimes: The design graph from the Michigan flume proves apt for scenarios characterized by subcritical outlet flow regimes, whereas the OHIO flume design graph is better suited for designing RCP under supercritical flow conditions at culvert outlets.
b) Soil Considerations: Accounting for soil conditions is paramount. Sites with saturated soil may benefit from utilizing the OHIO graph, whereas those with unsaturated soil could find the Michigan graph more applicable.
c) Establishing Bounds: The experimental results from both universities offer valuable bounds for RCP length. For instance, for a design velocity of 12 fps (3.6 m/s) in a 48 in (1.2 m) pipe, the RCP length should ideally range between 12 ft (2.6 m) and 15 ft (4.6 m), accommodating varying conditions.
d) Consideration for Inlet and Outlet Control: Both OHIO and Michigan flume results should inform designs for both inlet and outlet control-based culverts. For Type (c) inlet control designs, as illustrated in Figure 27, emphasis should be on outlet velocities in supercritical flow regimes, whereas for Type (e) outlet control, focus should be on subcritical flow regimes.
e) Exploration of Flow Rate: Future research endeavors should prioritize the exploration of flow rate as a critical parameter, offering deeper insights into its influence on RCP design.
f) Targeted Research on Flow Regimes and Soil Conditions: Future investigations should be strategically directed towards examining specific flow regimes and soil conditions, refining our understanding, and improving the applicability of RCP design methodologies.
g) Post-Installation Inspection: It is strongly advised that RCP designed based on the outcomes of this experimental investigation undergo immediate inspection following high-intensity rainfall events that may lead to outlet velocities surpassing the design thresholds. This proactive measure ensures the ongoing effectiveness and integrity of the RCP installations.

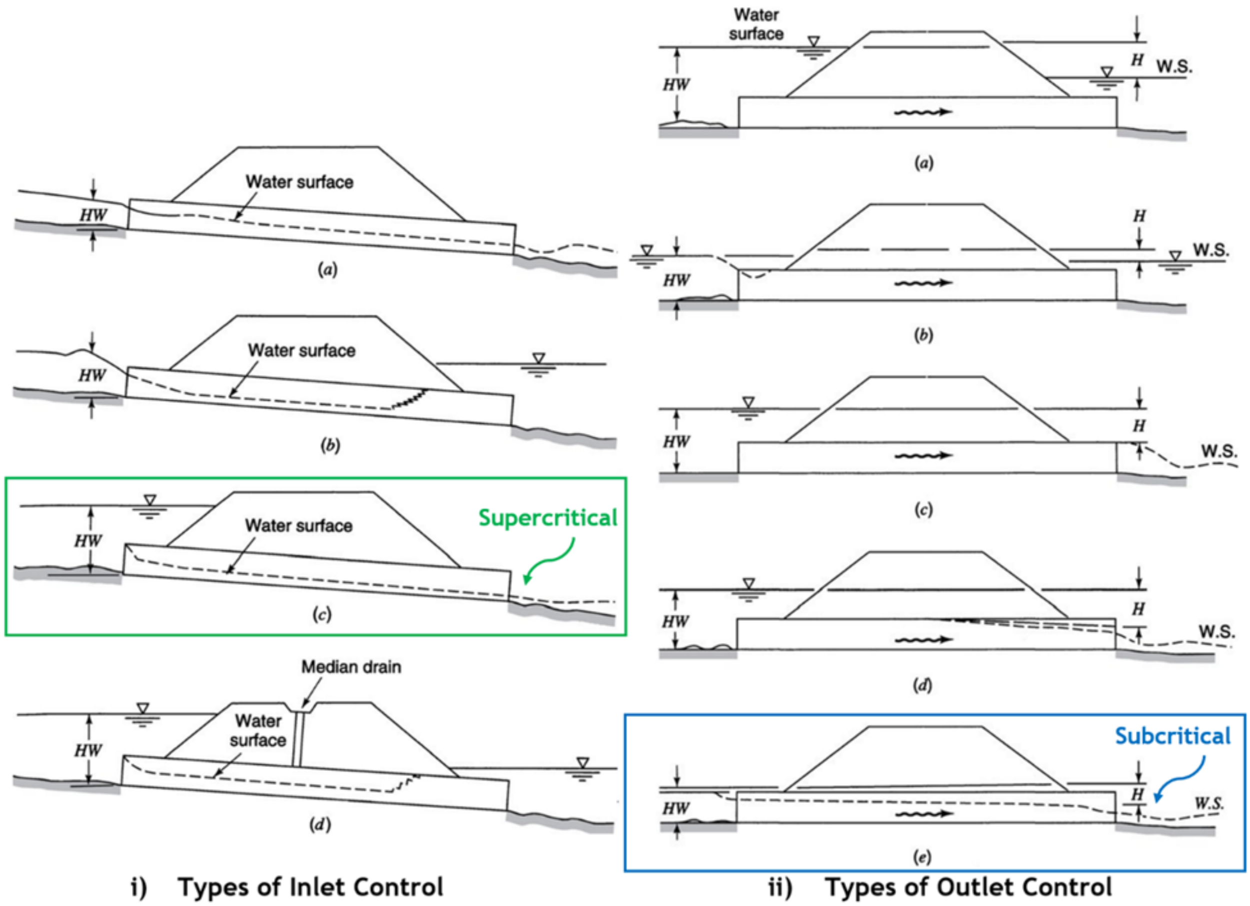


Figure 27. Design of RCP length based on Type (c) inlet control and Type (e) outlet control using design procedures proposed by Ohio University and University of Michigan [adapted from FHWA, 1985].

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7 Appendices

7.1 Scaled RCP Materials

The RCP material specification for various sizes of Rock Types is provided in ODOT Construction and Material Specification 703.19 [ODOT, 2023, p. 719-720] which states:

1. Type A material has at least 85 percent of the total material by weight larger than an 18-inch (0.5 m) but less than a 30-inch (0.8 m) square opening and at least 50 percent of the total material by weight larger than a 24-inch (0.6 m) square opening. Furnish material smaller than an 18-inch (0.5 m) square opening that consists predominantly of rock spalls and rock fines, and that is free of soil.

2. Type B material has at least 85 percent of the total material by weight larger than a 12-inch (0.3 m) but less than a 24-inch (0.6 m) square opening and at least 50 percent of the total material by weight larger than an 18-inch (0.5 m) square opening. Furnish material smaller than a 12-inch (0.3 m) square opening that consists predominantly of rock spalls and rock fines, and that is free of soil. 719

3. Type C material has at least 85 percent of the total material by weight larger than a 6-inch (150 mm) but less than an 18-inch (0.5 m) square opening and at least 50 percent of the total material by weight larger than a 12-inch (0.3 m) square opening. Furnish material smaller than a 6-inch (150 mm) square opening that consists predominantly of rock spalls and rock fines, and that is free of soil.

Using the scale factor of 24 and 30, and assigning percentages to the material retained on smaller sieves and passed through larger sieves for each Type, the scaled RCPs are presented in the following table:

For λ = 24	For λ = 30
• Scaled Type A RCP: a) At least 85% of total material by weight should be less than 1.25 in (32 mm) and greater than 0.75 in (19 mm) in size. b) At least 50% of total material by weight should be greater than 1 in (25mm) in size. c) At most 15% of total material by weight should be less than 0.75 in (19 mm) in size. • Scaled Type B RCP: a) At least 85% of total material by weight should be less than 1 in (25 mm) and greater than 0.5 in (13 mm) in size. b) At least 50% of total material by weight should be greater than 0.75 in (19 mm) in size.	• Scaled Type A RCP: a) At least 85% of total material by weight should be less than 1 in (25 mm) and greater than 0.6 in (15 mm) in size. b) At least 50% of total material by weight should be greater than 0.8 in (20 mm) in size. c) At most 15% of total material by weight should be less than 0.6 in (15 mm) in size. • Scaled Type B RCP: a) At least 85% of total material by weight should be less than 0.8 in (20 mm) and greater than 0.4 in (10 mm in size. b) At least 50% of total material by weight should be greater than 0.6 in (15 mm) in size. c) At most 15% of total material by weight should be less than 0.4 in (10 mm) in size.

c) At most 15% of total material by weight should be less than 0.5 in (13 mm) in size.	

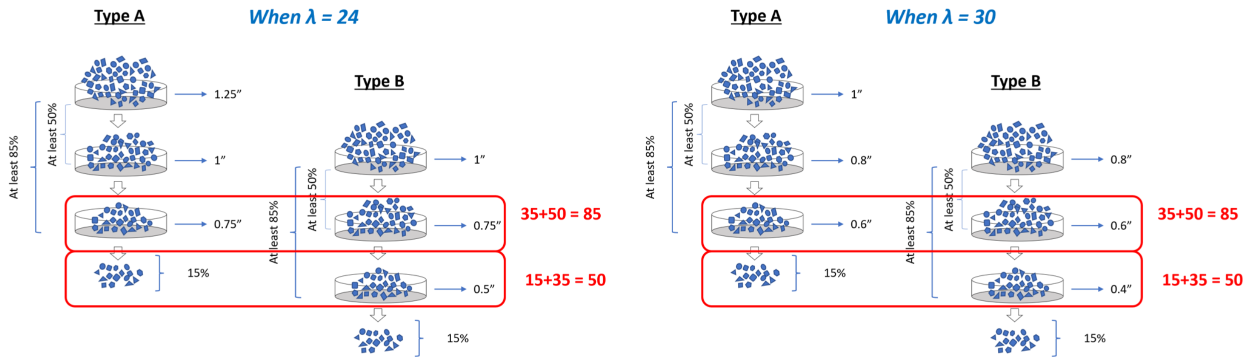


Figure 28. Composition of different RCP Types with sieve analysis at scale factor of λ = 24 (left) and 30 (right). (1” = 25.4 mm)

7.2 RCP dimensions (SI Units)

Table 5. Reduced RCP dimensions (SI Units) using three Froude scaling factors for OHIO flume

Case No.	Prototype Pipe Diameter (mm)	Prototype RCP Length (m)	Prototype RCP Thickness (mm)	Scaling Factor (λ)	Model Pipe Diameter (mm)	Model RCP Length (mm)	Model RCP Thickness (mm)
1	300	1.37	450	12	25	114	37.5
6	300	1.68	450	12	25	140	37.5
11	300	1.83	1200	12	25	152	100
2	1200	3.05	450	12	100	254	37.5
7	1200	4.11	750	12	100	343	62.5
12	1200	5.94	1200	24	50	248	50
3	1800	4.57	750	24	75	190.5	31.25
8	1800	5.94	750	24	75	248	31.25
13	1800	7.62	1200	24	75	317.5	50
4	2400	6.10	750	24	100	254	31.25
9	2400	7.32	750	24	100	305	31.25
14	2400	9.60	1200	24	100	400	50
5	3000	7.62	750	30	100	254	25
10	3000	9.30	900	30	100	310	30
15	3000	11.28	1200	30	100	376	40

7.3 Regression Equations

The empirical data of scour hole formation is converted into regression curves to design RCP length using outlet velocity. To draw these design curves, three types of regression were applied on V_2 data. In these equations, '*L*' and '*V*' represent the length of pipe protection in feet and culvert outlet velocity in feet per second, respectively. Using OHIO flume data, the regression equations for each pipe size are below:

a) Exponential Equation for 120 in (3.0 m) Pipe Diameter

$$L = 13.685\, e^{0.0525V}$$

b) Linear Equation for 96 in (2.4 m) Pipe Diameter

$$L = 1.0055V + 11.407$$

c) Exponential Equation for 72 in (1.8 m) Pipe Diameter

$$L = 8.0862e^{0.0473V}$$

d) Linear Equation for 48 in (1.2 m) Pipe Diameter

$$L = 0.4678V + 6.0988$$

e) Linear Equation for 12 in (0.3 m) Pipe Diameter

$$L = 0.1116V + 4.6496$$

Following regression equation were obtained for Michigan flume data:

a) Exponential Equation for 120 in (3.0 m) Pipe Diameter

$$L = 13.087e^{0.0745V}$$

b) Polynomial Equation for 96 in (2.4 m) Pipe Diameter

$$L = 0.0398V^2 + 0.85V + 10.018$$

c) Exponential Equation for 72 in (1.8 m) Pipe Diameter

$$L = 8.6069e^{0.0621V}$$

d) Linear Equation for 48 in (1.2 m) Pipe Diameter

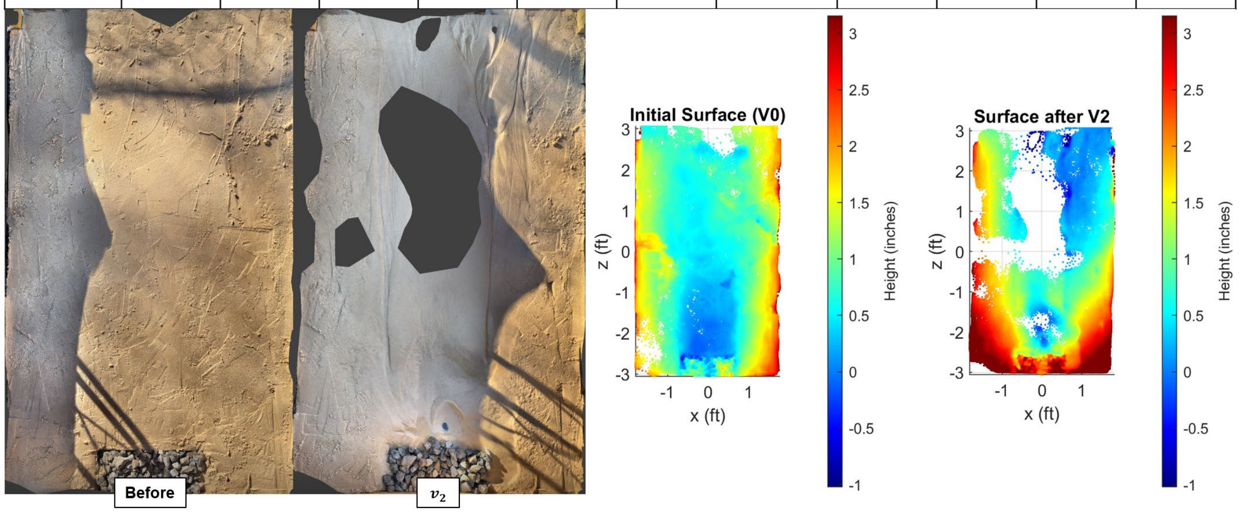
$$L = 0.8589V + 4.6489$$

e) Linear Equation for 12 in (0.3 m) Pipe Diameter

$$L = 0.1704V + 1.70$$

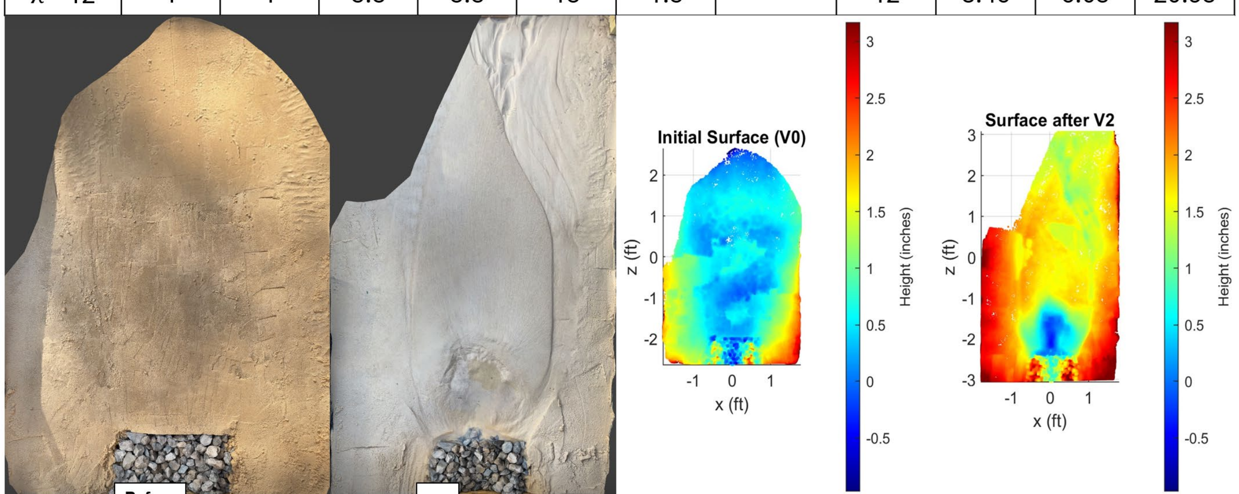
7.4 LiDAR Scanning Results from OHIO Flume

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
01	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	C	P (fps)	M (fps)	M (fps)	P (fps)
λ = 12	1	1	4.5	4.5	18	1.5		5	1.44	3.49	12.08



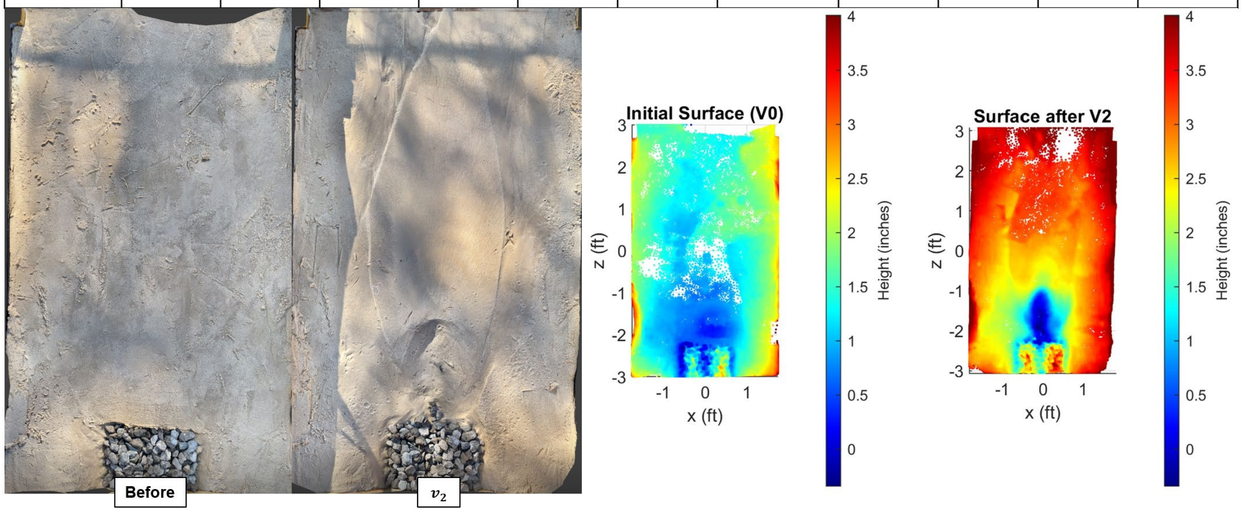
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
06	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	C	P (fps)	M (fps)	M (fps)	P (fps)
λ = 12	1	1	5.5	5.5	18	1.5		12	3.46	6.05	20.95



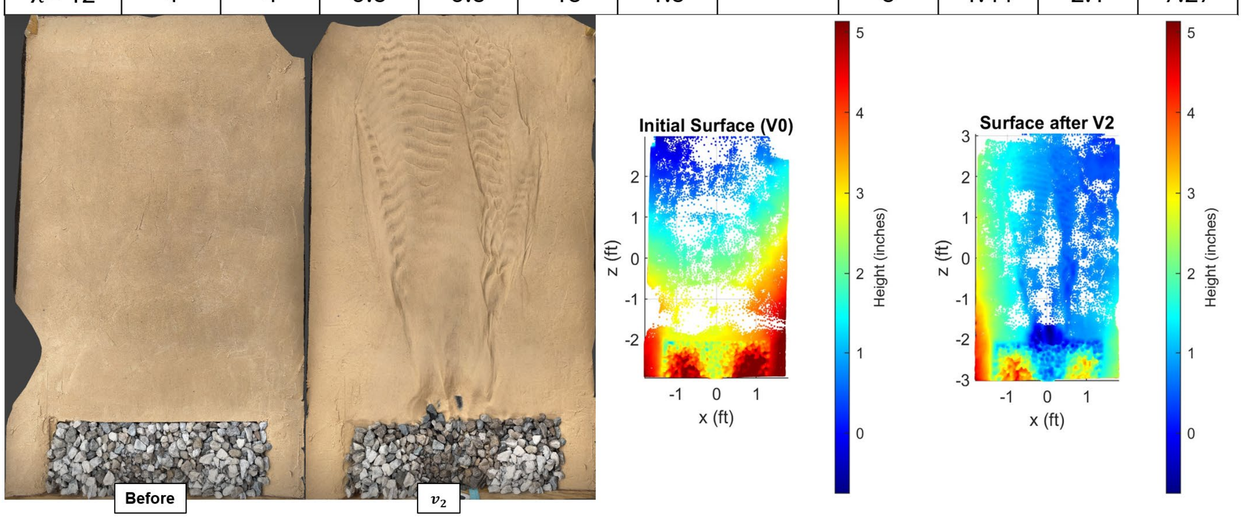
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
11	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	C	P (fps)	M (fps)	M (fps)	P (fps)
λ = 12	1	1	6.5	6.5	48	1.5		20	5.77	6.52	22.59



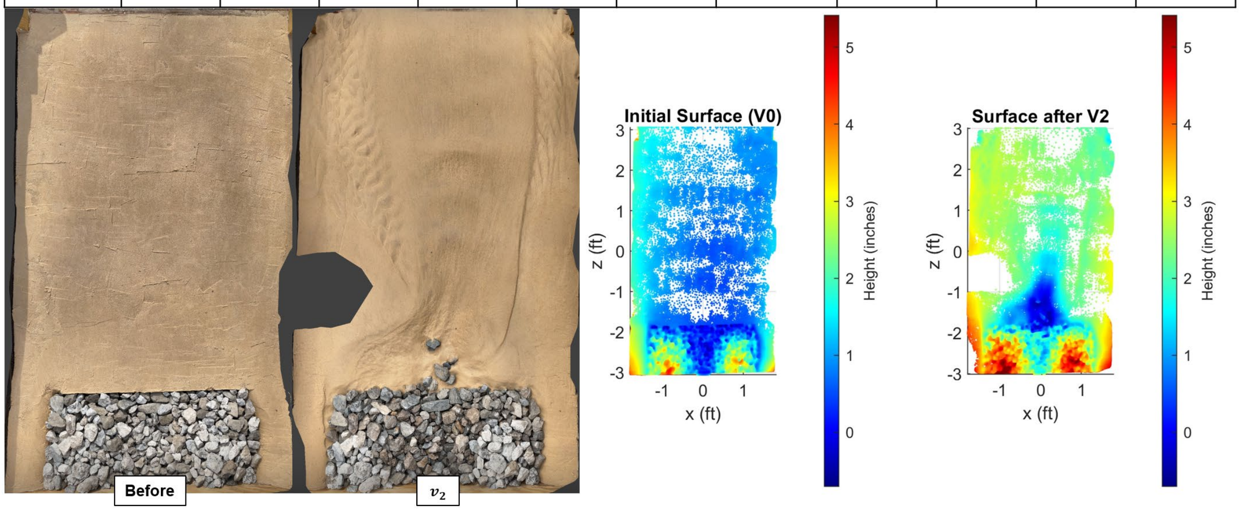
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
02	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	C	P (fps)	M (fps)	M (fps)	P (fps)
λ = 12	4	4	9.5	9.5	18	1.5		5	1.44	2.1	7.27



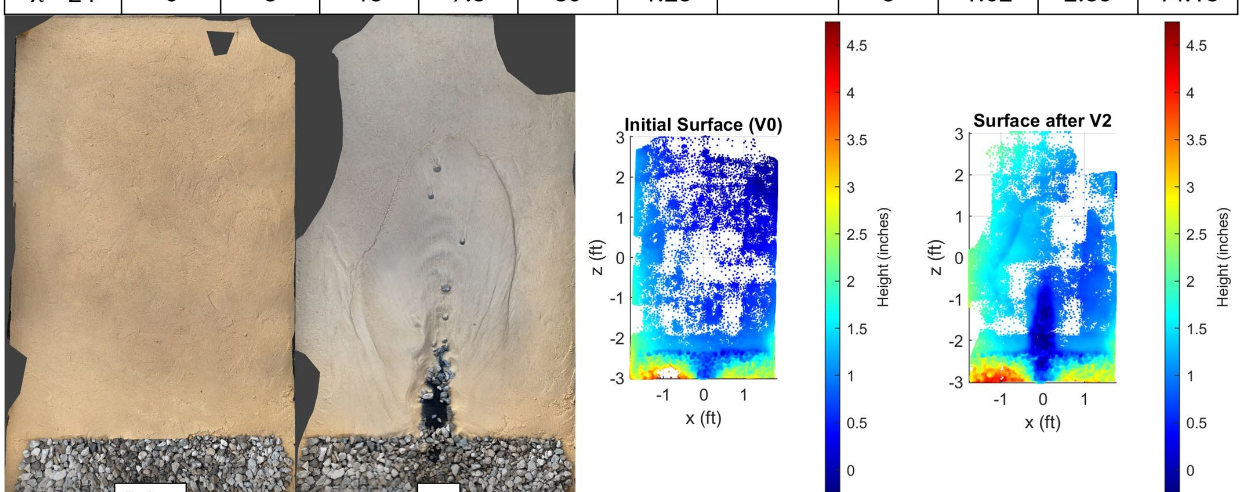
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
07	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	B	P (fps)	M (fps)	M (fps)	P (fps)
λ = 12	4	4	13.5	13.5	30	2.5		12	3.46	4.57	15.82



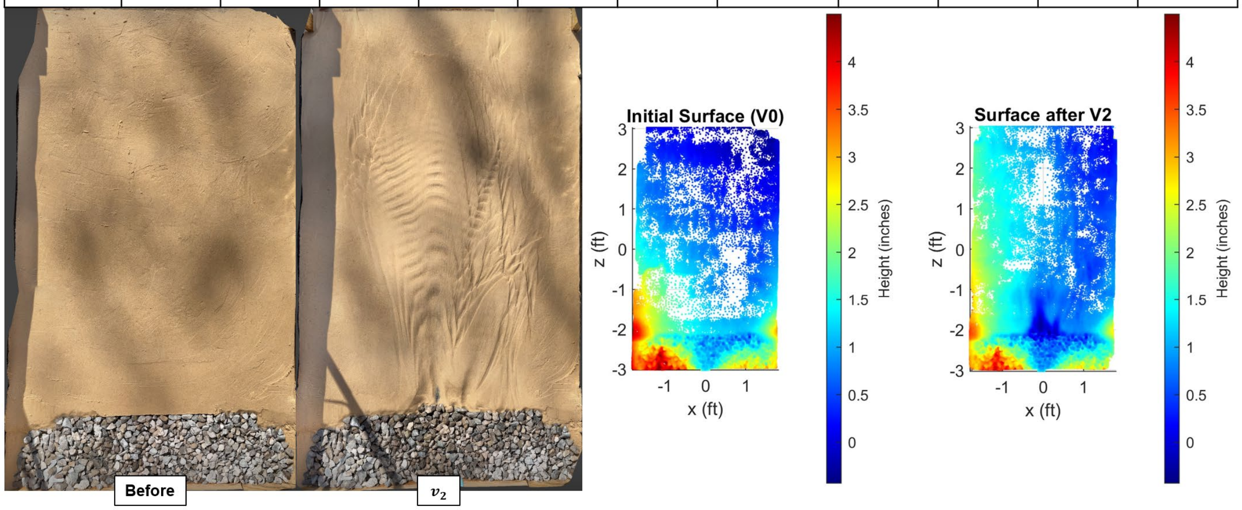
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
03	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	B	P (fps)	M (fps)	M (fps)	P (fps)
λ = 24	6	3	15	7.5	30	1.25		5	1.02	2.89	14.13



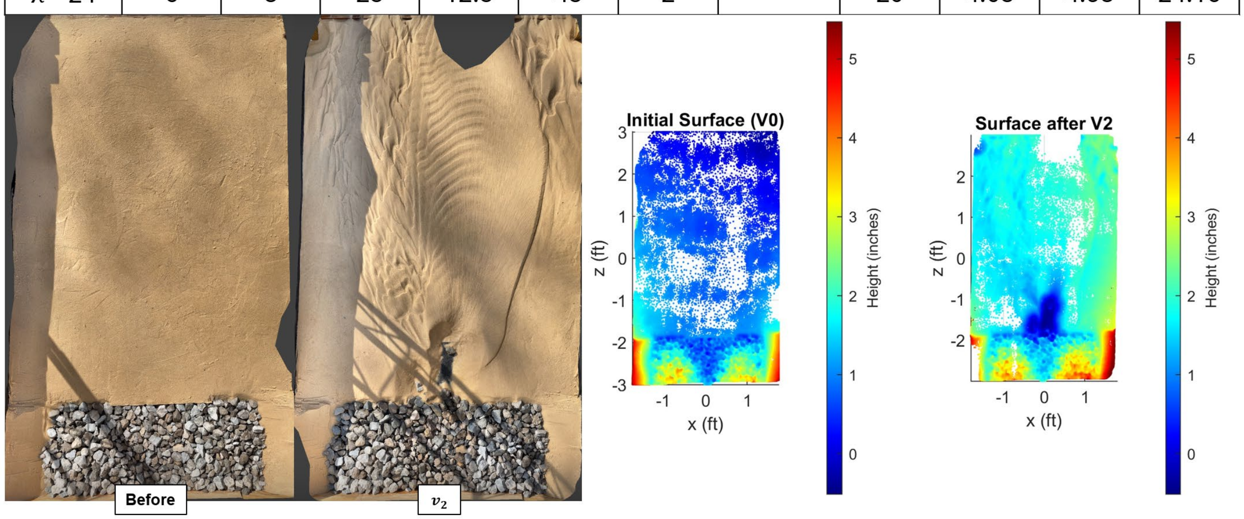
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
08	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	B	P (fps)	M (fps)	M (fps)	P (fps)
λ = 24	6	3	18.5	9.25	30	1.25		12	2.45	3.3	16.19



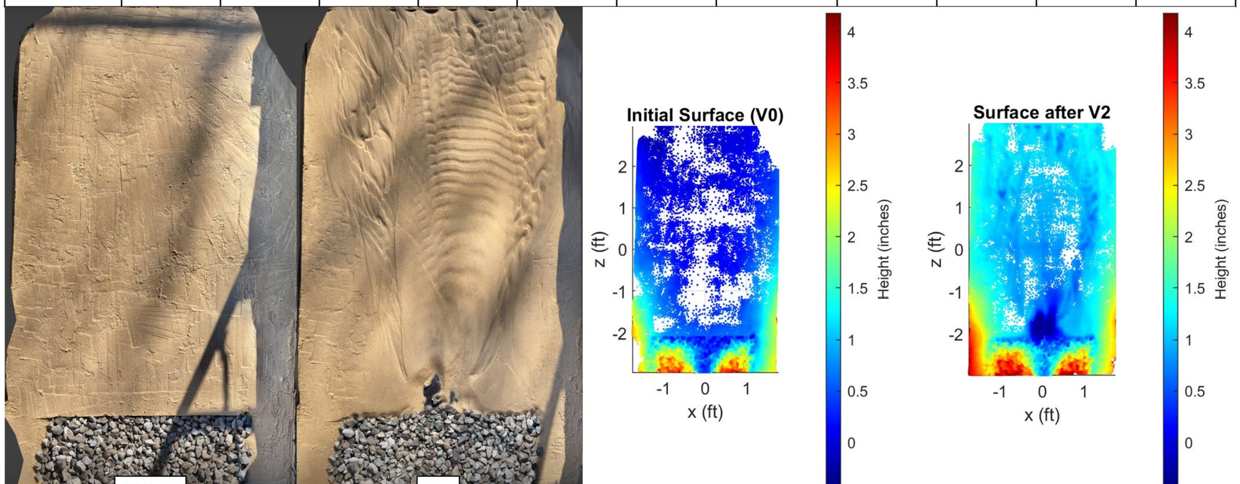
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
13	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	A	P (fps)	M (fps)	M (fps)	P (fps)
λ = 24	6	3	25	12.5	48	2		20	4.08	4.93	24.16



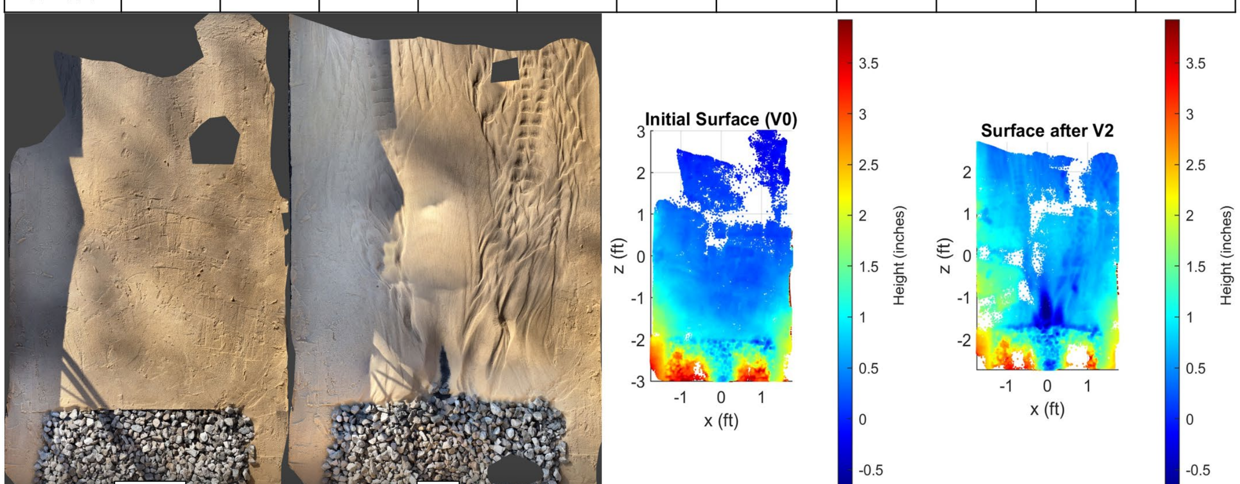
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
04	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	B	P (fps)	M (fps)	M (fps)	P (fps)
λ = 24	8	4	20	10	30	1.25		5	1.02	1.62	7.92



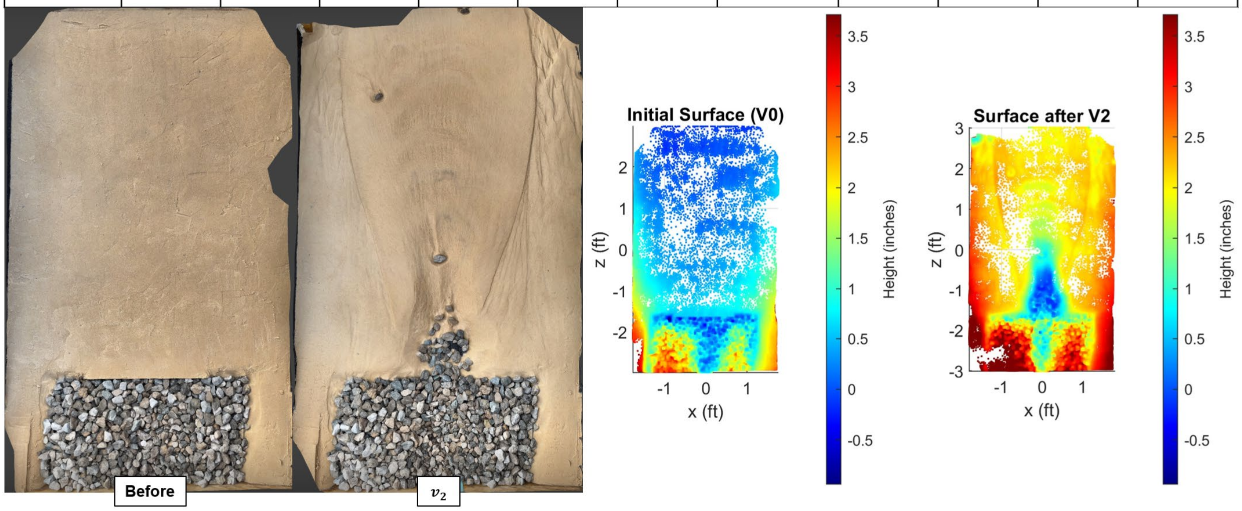
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
09	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	B	P (fps)	M (fps)	M (fps)	P (fps)
λ = 24	8	4	24.5	12.25	30	1.25		12	2.45	2.98	14.58



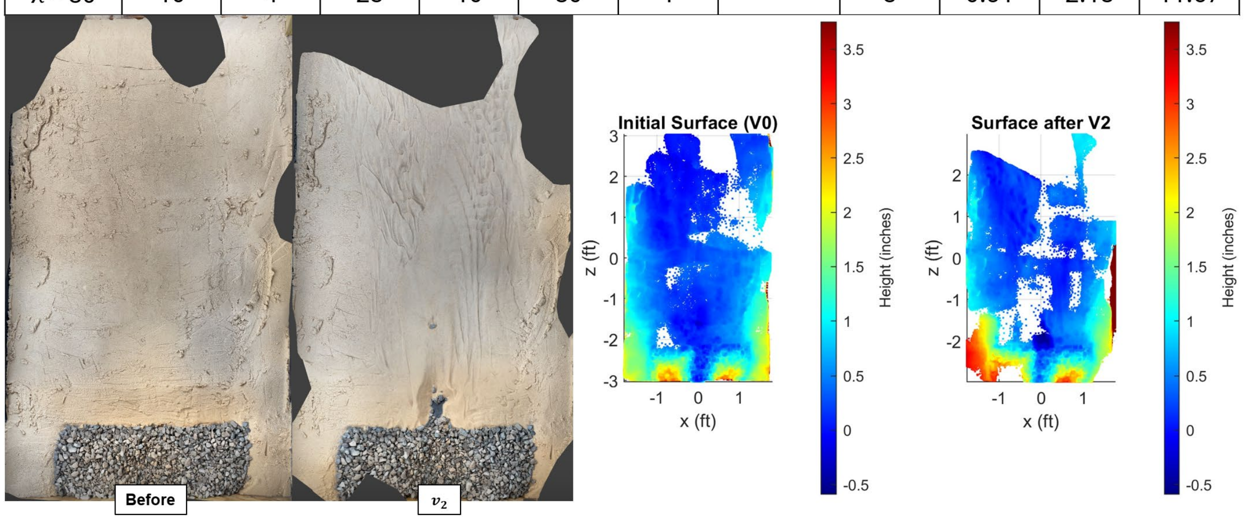
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
14	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	A	P (fps)	M (fps)	M (fps)	P (fps)
λ = 24	8	4	31.5	15.75	48	2		20	4.08	3.89	19.05



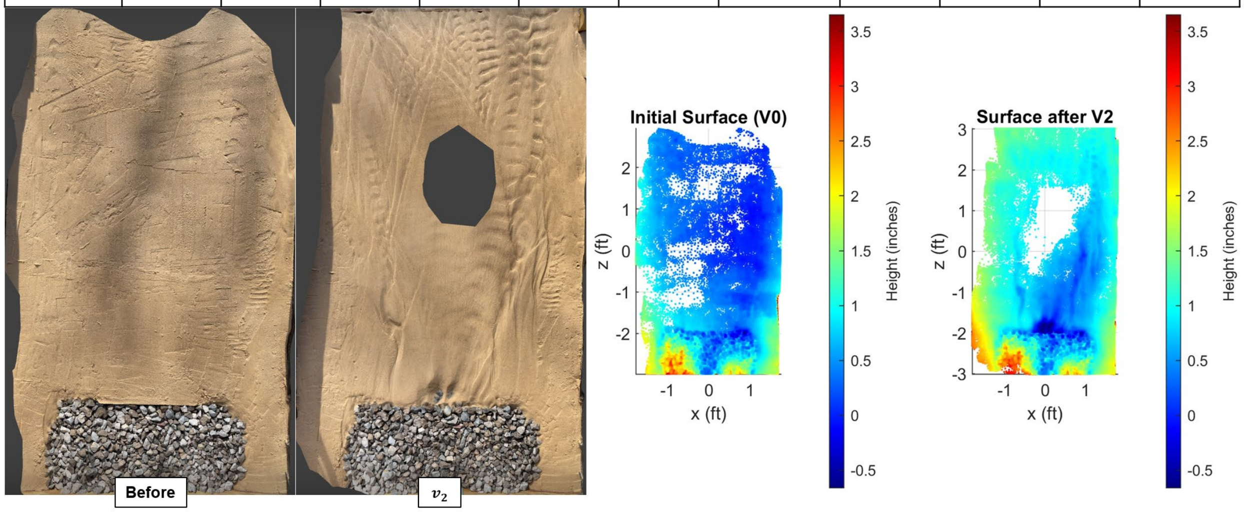
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
05	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	B	P (fps)	M (fps)	M (fps)	P (fps)
λ = 30	10	4	25	10	30	1		5	0.91	2.13	11.67



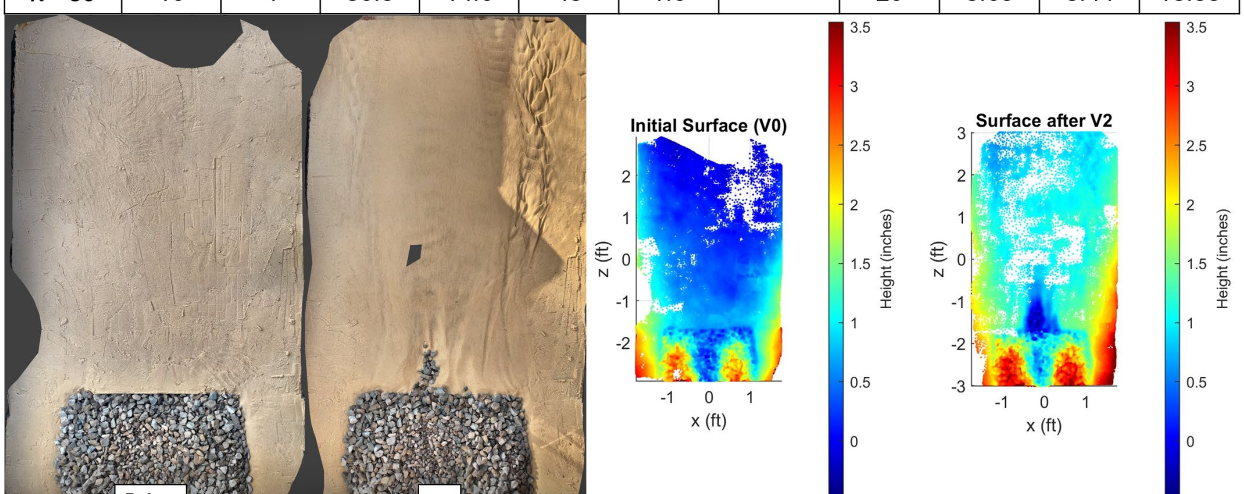
Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
10	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	A	P (fps)	M (fps)	M (fps)	P (fps)
λ = 30	10	4	30.5	12.2	36	1.2		12	2.19	2.73	14.93



Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

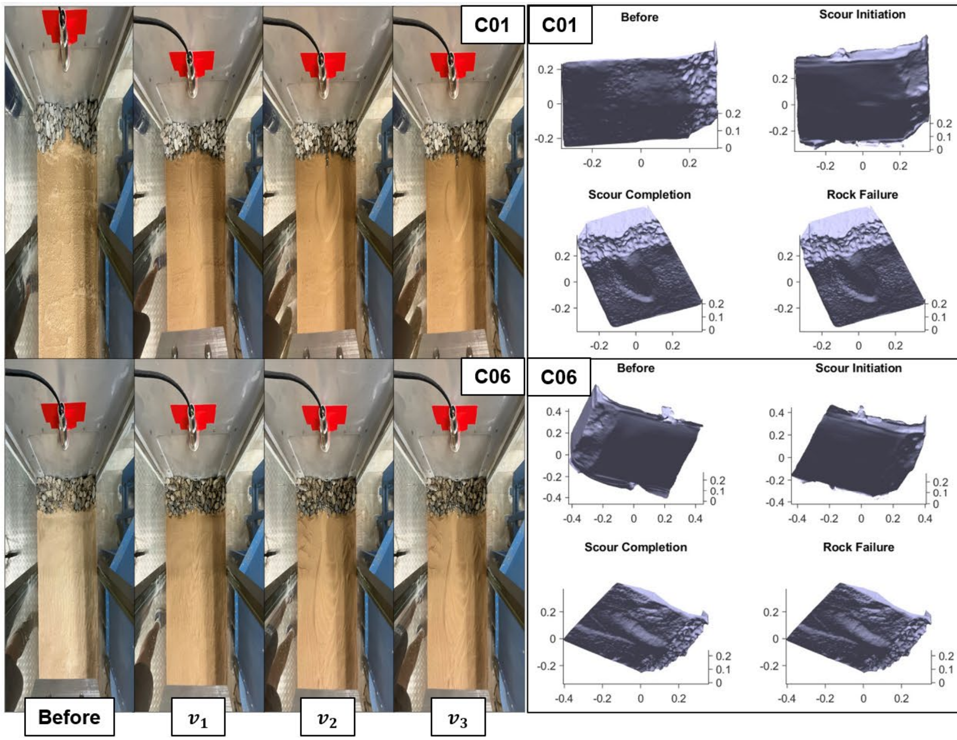
Case No	Pipe Diameter		RCP Length		RCP Thickness		RCP Type	Threshold Velocity from ODOT Design		Threshold Velocity from Experiment	
15	P (ft)	M (in)	P (ft)	M (in)	P (in)	M (in)	A	P (fps)	M (fps)	M (fps)	P (fps)
λ = 30	10	4	36.5	14.6	48	1.6		20	3.65	3.44	18.85



Top: Case Specification, Left: Top View of LiDAR Scan, Right: MATLAB Plot

7.5 LiDAR Scanning Results of Michigan Flume

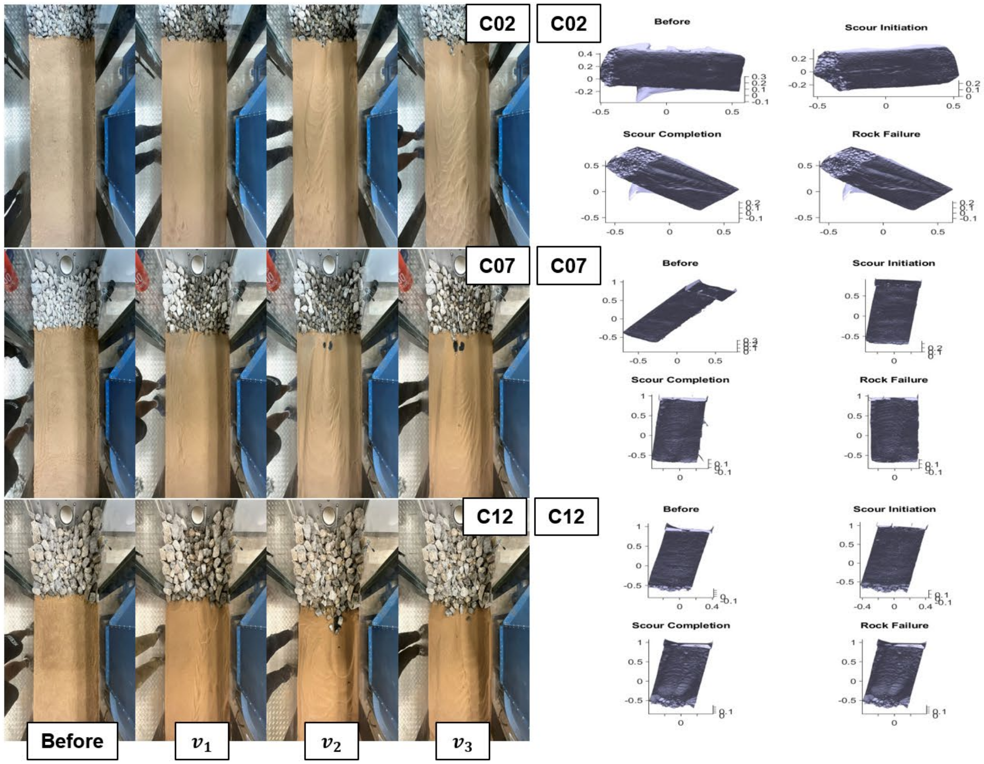
Pipe Size: D = 1 ft



Case	Pipe Size	RCP Length	RCP Type	RCP Thickness	Threshold Velocity from Experiment	Threshold Velocity from Chart
01	1 ft	4.5 ft	C	1.5 ft	$v_1 \approx 7.96\ fps$ $v_2 \approx 16.43\ fps$ $v_3 \approx 16.43\ fps$	$4\ fps$
06	1 ft	5.5 ft	C	1.5 ft	$v_1 \approx 6.39\ fps$ $v_2 \approx 22.30\ fps$ $v_3 \approx 22.30\ fps$	$12\ fps$

Left: Top Views, Center: LiDAR Scanning, Right: Detailed Results

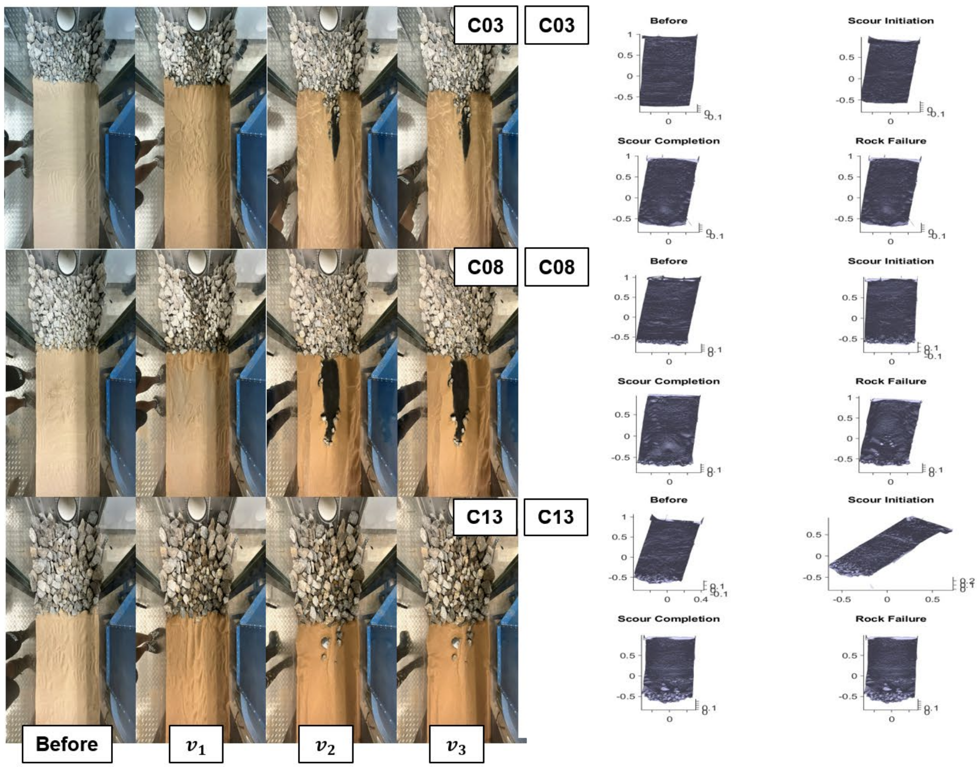
Pipe Size: D = 4 ft



Case	Pipe Size	RCP Length	RCP Type	RCP Thickness	Threshold Velocity from Experiment	Threshold Velocity from Chart
02	4 ft	10 ft	C	1.5 ft	$v_1 \approx 5.49\ fps$ $v_2 \approx 7.02\ fps$ $v_3 \approx 7.02\ fps$	$4\ fps$
07	4 ft	13.5 ft	B	2.5 ft	$v_1 \approx 5.50\ fps$ $v_2 \approx 9.31\ fps$ $v_3 \approx 9.31\ fps$	$12\ fps$
12	4 ft	20 ft	A	4 ft	$v_1 \approx 7.87\ fps$ $v_2 \approx 18.08\ fps$ $v_3 \approx 18.08\ fps$	$20\ fps$

Left: Top Views, Center: LiDAR Scanning, Right: Detailed Results

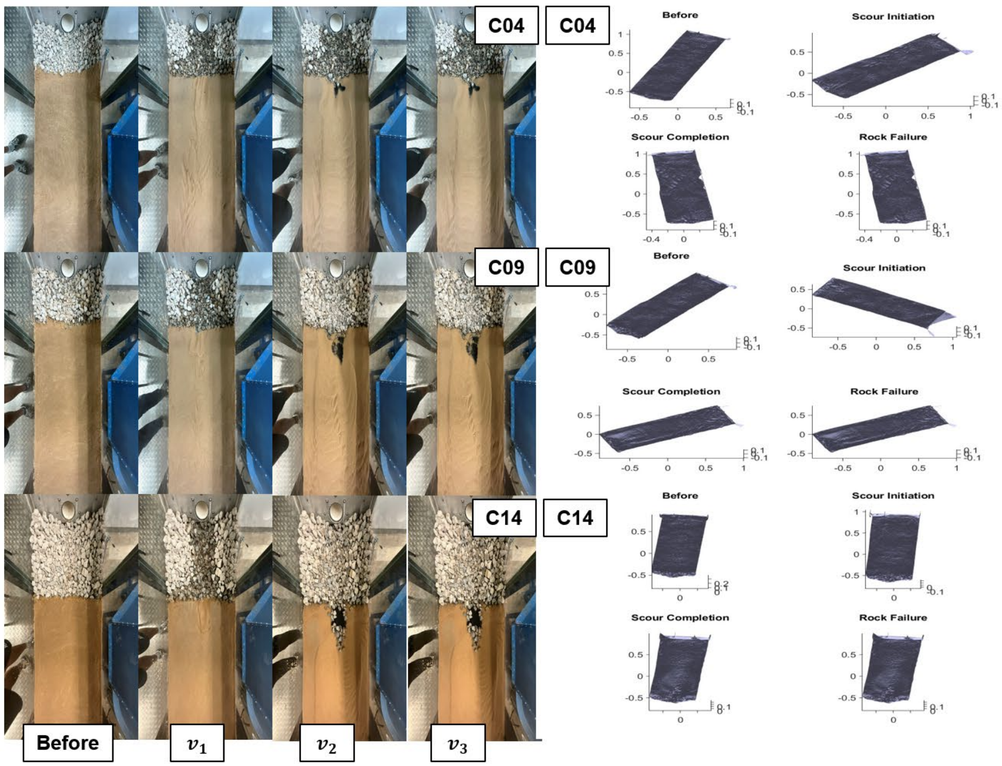
Pipe Size: D = 6 ft



Case	Pipe Size	RCP Length	RCP Type	RCP Thickness	Threshold Velocity from Experiment	Threshold Velocity from Chart
03	6 ft	14 ft	B	2.5 ft	$v_1 \approx 4.52\ fps$	$4\ fps$
					$v_2 \approx 8.39\ fps$	
					$v_3 \approx 8.39\ fps$	
08	6 ft	18 ft	B	2.5 ft	$v_1 \approx 5.48\ fps$	$12\ fps$
					$v_2 \approx 11.09\ fps$	
					$v_3 \approx 11.09\ fps$	
13	6 ft	25 ft	A	4 ft	$v_1 \approx 10.88\ fps$	$20\ fps$
					$v_2 \approx 17.41\ fps$	
					$v_3 \approx 17.41\ fps$	

Left: Top Views, Center: LiDAR Scanning, Right: Detailed Results

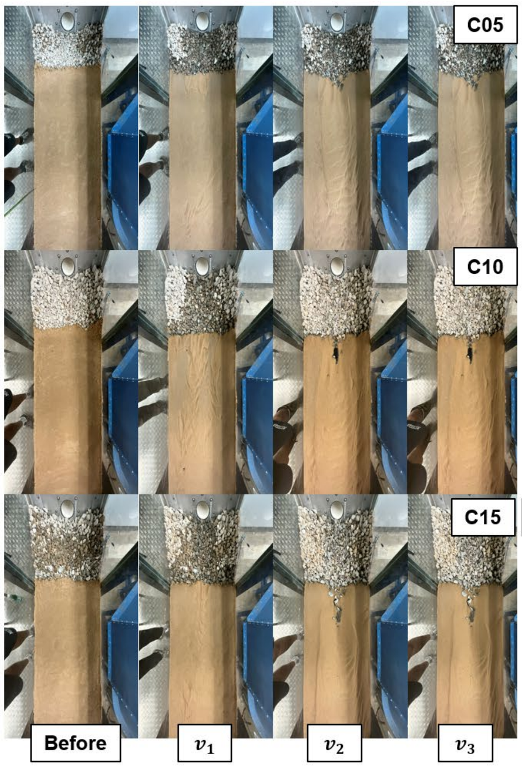
Pipe Size: D = 8 ft

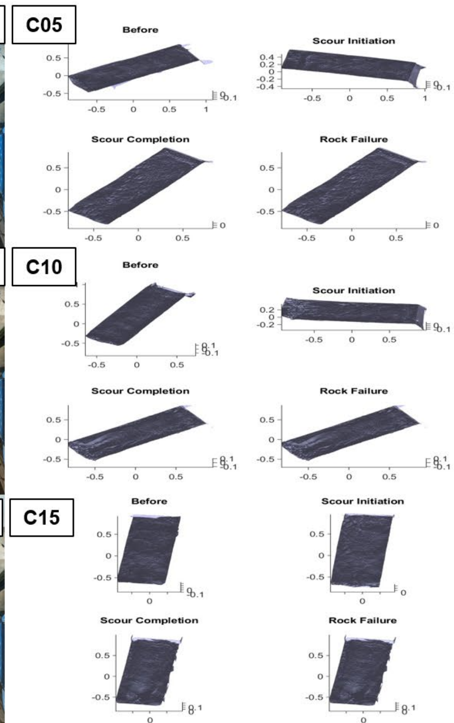


Case	Pipe Size	RCP Length	RCP Type	RCP Thickness	Threshold Velocity from Experiment	Threshold Velocity from Chart
04	8 ft	20 ft	B	2.5 ft	$v_1 \approx 7.94\ fps$	4 fps
					$v_2 \approx 8.42\ fps$	
					$v_3 \approx 8.42\ fps$	
09	8 ft	24 ft	B	2.5 ft	$v_1 \approx 8.14\ fps$	12 fps
					$v_2 \approx 10.89\ fps$	
					$v_3 \approx 10.89\ fps$	
14	8 ft	32 ft	A	4 ft	$v_1 \approx 7.86\ fps$	20 fps
					$v_2 \approx 15.13\ fps$	
					$v_3 \approx 15.13\ fps$	

Left: Top Views, Center: LiDAR Scanning, Right: Detailed Results

Pipe Size: D = 10 ft





Case	Pipe Size	RCP Length	RCP Type	RCP Thickness	Threshold Velocity from Experiment	Threshold Velocity from Chart
05	10 ft	25 ft	B	2.5 ft	$v_1 \approx 9.18\ fps$	$4\ fps$
					$v_2 \approx 9.43\ fps$	
					$v_3 \approx 9.43\ fps$	
10	10 ft	30.5 ft	A	3 ft	$v_1 \approx 8.66\ fps$	$12\ fps$
					$v_2 \approx 10.41\ fps$	
					$v_3 \approx 10.41\ fps$	
15	10 ft	37 ft	A	4 ft	$v_1 \approx 7.95\ fps$	$20\ fps$
					$v_2 \approx 14.14\ fps$	
					$v_3 \approx 14.14\ fps$	

Left: Top Views, Center: LiDAR Scanning, Right: Detailed Results

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