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Construct and Test Scale Model Box Culvert Design project

Prepared by:
University of New Mexico
Department of Civil Engineering - Hydraulics Laboratory
MSC01 1070
Albuquerque, NM 87131-0001

Prepared for:
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16. Abstract

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The UNM research team tested the culvert's capacity and ability to reduce velocities to match existing conditions. This included evaluating *HEC 14* roughness element design and proposing alternatives.

Researchers determined that NMDOT design performed sufficiently, conveying 100-year flows and reducing velocities. UNM researchers also propose a design alternative that has fewer roughness elements and roughness elements in fewer culvert sections, allowing for easier maintenance. The modeling process and results have been discussed in this report.

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By:

Kyle Shour
Julie Coonrod
Kent Steinhaus
Mark Stone

At the
University of New Mexico
Department of Civil Engineering – Hydraulics Laboratory
Albuquerque, New Mexico

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NMDOT Research Bureau
7500B Pan American Freeway NE
Albuquerque, NM 87109
PO Box 94690
Albuquerque, NM 87199-4690
(505) 841-9145
http://nmshtd.state.nm.us/main.asp?secid=11071
Research.Bureau@state.nm.us

PREFACE

The research reported herein describes construction and testing of a scale model box culvert design project near Jemez Springs, New Mexico. The purpose of this work was to test the effectiveness of a culvert to convey 100-year flows and roughness elements to reduce outlet velocities to pre-construction conditions.

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This report presents the results of research conducted by the author(s) and does not necessarily reflect the views of the New Mexico Department of Transportation. This report does not constitute a standard or specification.

ABSTRACT

The research team at the University of New Mexico's (UNM) hydraulics lab designed, constructed, and tested a 1:20 scale physical model of a proposed culvert in Jemez Springs, New Mexico. The culvert design was developed by the New Mexico Department of Transportation (NMDOT). The culvert receives supercritical flow from the Church Canyon Arroyo. As a result of existing structures, complex arroyo planform, and variable slopes, the culverts response to a supercritical flow regime was difficult to know. Therefore, physical modeling was performed.

The UNM research team tested the culvert's capacity and ability to reduce velocities to match existing conditions. This included evaluating *HEC 14* roughness element design and proposing alternatives.

Researchers determined that NMDOT design performed sufficiently, conveying 100-year flows and reducing velocities. UNM researchers also propose a design alternative that has fewer roughness elements and roughness elements in fewer culvert sections, allowing for easier maintenance. The modeling process and results have been discussed in this report.

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1. INTRODUCTION

A *Notice to Proceed* on the *Construct and Test Scale Model Box Culvert Design* project, Research Project No. NM10DSN-02 was received on May 14, 2010. The New Mexico Department of Transportation (NMDOT) contracted the UNM Hydraulics Laboratory (UNM) to develop a model of the proposed culvert located at the intersection of Church Canyon and NM Route 4 on the north side of Jemez Springs, NM (**Figure 1**).

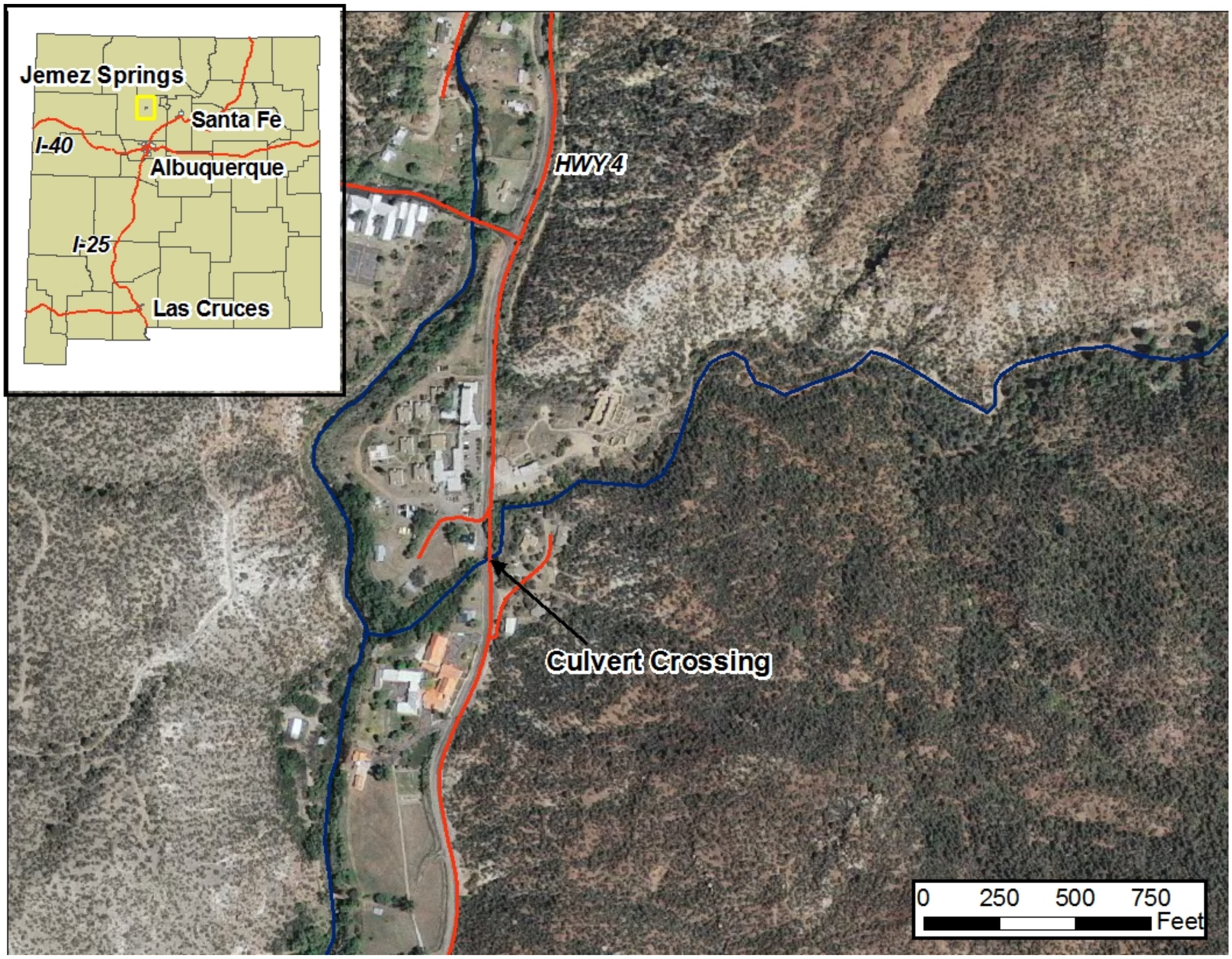

FIGURE 1: Project Location

Due to the existing spatial constraints along with arroyo planform and profile, the culvert design was complex. The supercritical flow regime in the culvert further complicated the design of the culvert. To decrease proposed condition velocities to pre-construction velocities, the NMDOT applied *HEC 14* methods. This method allowed engineers to size roughness elements and determine appropriate spacing to reduce velocities. However, *HEC 14* was developed for subcritical flow regimes. For these reasons, the NMDOT contracted UNM to test the design effectiveness and examine alternatives.

2. SCOPE

The UNM research team conducted modeling with the following goals:

- The culvert must convey the 100-year flow without headwater or tailwater overtopping the headwall or tailwall or flooding surrounding buildings.
- Velocities at the culvert outlet could not exceed fourteen (14) feet per second (fps).
- Alternative roughness designs would be considered.

3. MODEL DESIGN AND CONSTRUCTION

Model design was aided by NMDOT design documents (**Figure 2**) and *Replacement Structure Sizing for Bridges 441 and 442* by URS. With information from these documents, two HEC-RAS models were created. The first model was created by estimating the total headloss in the proposed culvert, including roughness elements and bends. An effective length was calculated for the culvert such that the same total headloss, as estimated with design documents, would be achieved with a single Manning's n-value. The second model treated the culvert as an open channel with each section of culvert having its own Manning's n-value, length, and slope (**Figure 3**). This model was developed with a higher degree of certainty and would allow UNM to determine the exact location of any hydraulic jump occurring in the model; however, this model could not handle pressure flow conditions like the first model.

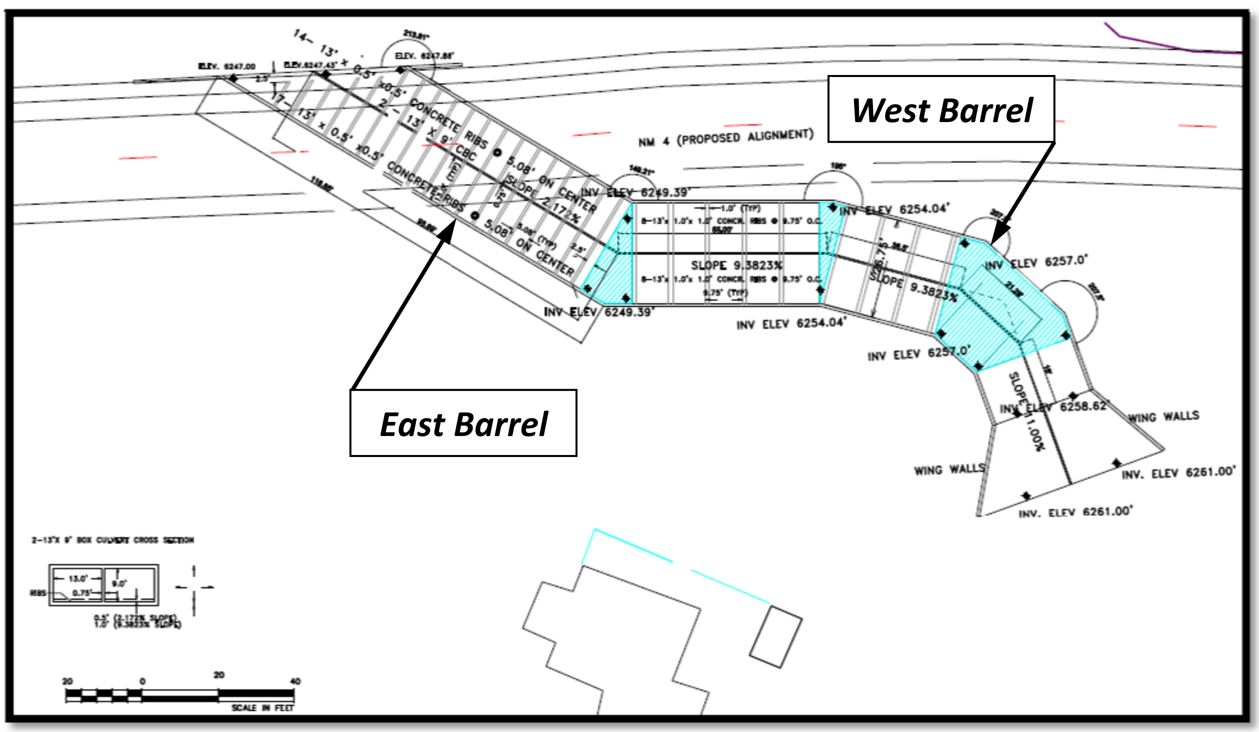

FIGURE 2: NMDOT Culvert Design

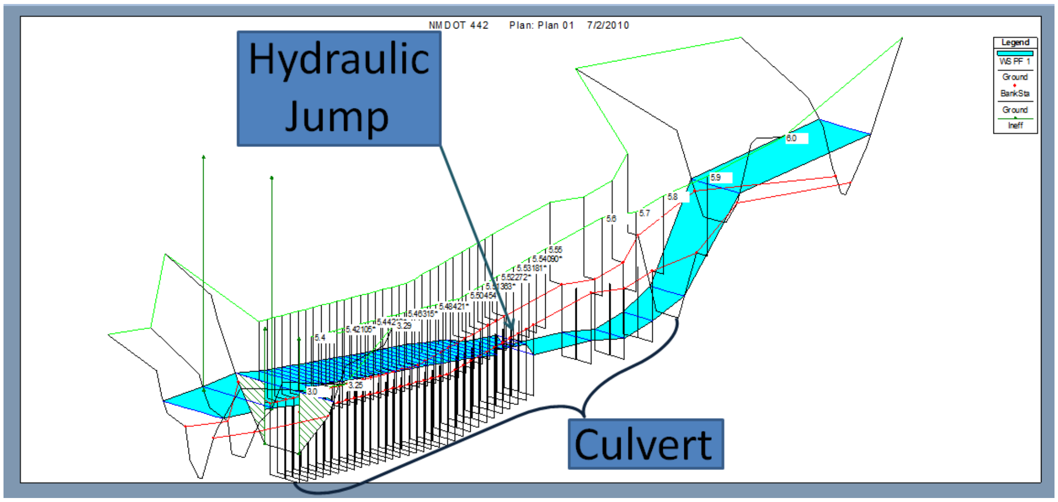

FIGURE 3: Section of Open Channel HEC-RAS Model

The model design was a mirror of the actual design because UNM was constrained by the location of plumbing in the lab. For the purposes of this report, the right barrel will be referred to as the west barrel and the left barrel, the east barrel. UNM researchers determined that applying a 1:20 scale would result in the largest model given available space in the lab. Model lengths, velocities, and flows were determined with use of Froude similitude equations (See Appendix). Froude similitude is typically applied to open channel models because the Froude number is the same in both the actual culvert (prototype) and the model.

The channel upstream and downstream of the culvert was designed to replicate the natural arroyo as best as practically possible using topographic maps provided by the NMDOT. The depth of each channel piece was determined by simulating the 100-year flow in the two HEC-RAS models. The model producing the greatest depth at a given cross-section was used to determine the required depth of that cross-section.

Channel cross-sections were fabricated by an outside source using UNM designs. The culvert was built from wood and acrylic sheets. The acrylic sheets were used to make the outside walls so that hydraulics could be observed while the model was operating. The model was built with a removable top so that velocities could be measured and hydraulics better observed at lower flows. **Figure 4** shows the completed model.

FIGURE 4: Completed Model

A wide range of flows were simulated through the model and measured, allowing UNM to determine what flows were possible. The UNM research team decided to simulate the 2 and 100-year flows (**Table 1**).

TABLE 1: Tested Flowrates

Return Period	NMDOT Flow (cfs)	Pump Flows	
		Prototype (cfs)	Model (cfs)
2 Yr	572	567	0.32
100 Yr	2160	2190	1.22

4. FIRST MODEL

In the first model, the east barrel (left barrel) was initially un-roughened, while the west barrel (right barrel) was roughened with baffles according to the NMDOT design (**Figure 5**); thereby, providing some means of quantifying and qualifying the effects of the roughening elements. Direct comparison of the impacts of the baffles is difficult, however, because the barrels are not identical.

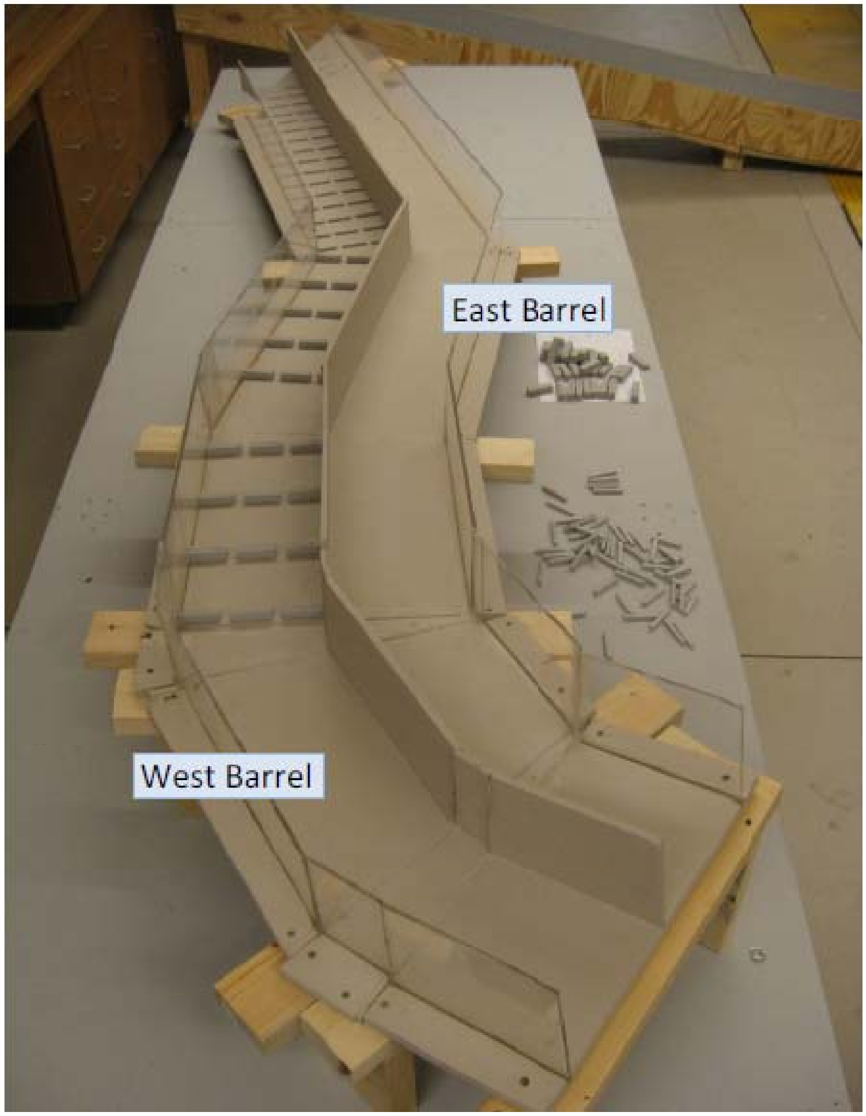

FIGURE 5: First Model without Top

The first model was observed at both the low and high flows. The culvert had sufficient capacity. Water depth reached the top of the culvert in three locations at the high flow. However, water did not transition from open channel flow to pressure flow. The depth was the result of the supercritical flow regime hydraulics. Given the low depth of the un-roughened barrel, UNM's velocity meter could not be used. Therefore, outlet velocities (**Table 2**) were measured by timing a ping-pong ball over a known distance (surface measurement method). This method is expected to over-predict average velocities because surface velocities are typically higher than the depth averaged velocity. Initial results suggest that the west barrel might not require additional roughness adjustment. The baffles also help mitigate the adverse impacts of supercritical hydraulics, supporting more uniform flow in the transverse and longitudinal directions (**Figure 6**).

TABLE 2: Measured Outlet Velocities in First Model

		Surface Measurement Method	
Event (Yr)	**Barrel**	**Model Vel. (fps)**	**Prototype Vel. (fps)**
2	West	2.0	8.9
	East	2.1	9.3
100	West	2.8	12.3
	East	3.9	17.5

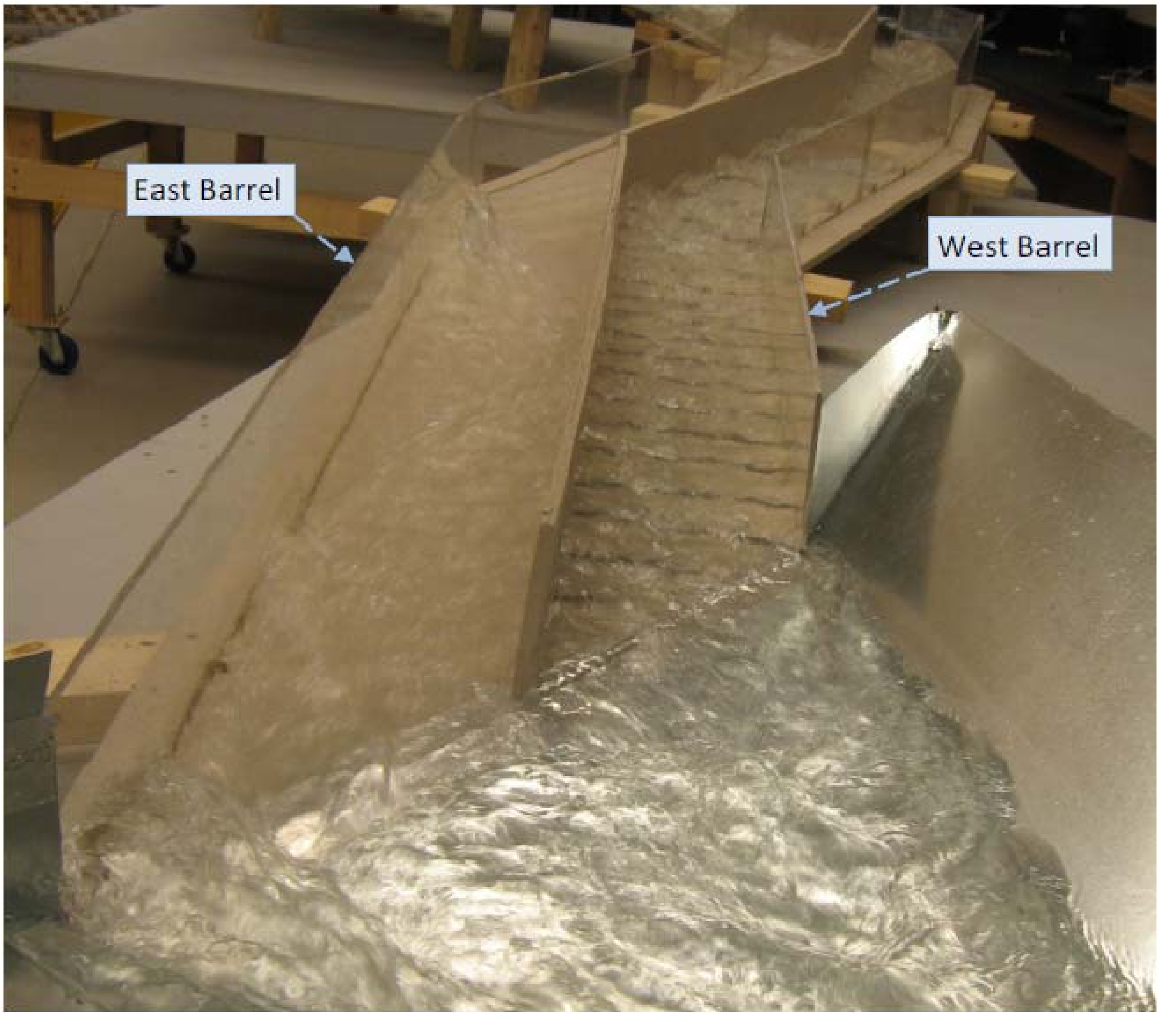

FIGURE 6: Baffles Improving Flow Uniformity in First Model (Conveying 2-year Flow)

5. SECOND MODEL

For the second model iteration, one by one-foot (1'x1') elements with 5.08-foot center-to-center spacing (prototype dimensions) were added to the most downstream section of the east barrel (**Figure 7**). This would result in greater roughness in the final culvert section and was done to test alternative roughness designs. UNM hoped that this would sufficiently reduce outlet velocities while decreasing the length of culvert containing baffles, allowing for easier maintenance.

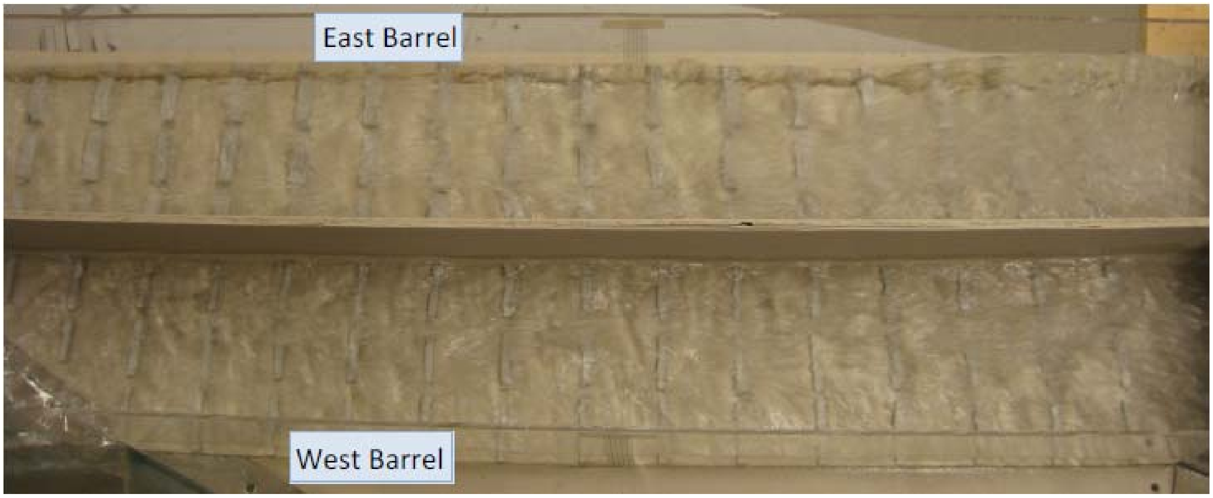

FIGURE 7: Second Model with Coarser Roughness Elements Added to East Barrel

Once again the culvert conveyed the 100-year event without problems (**Figure 8**). Again, water was deep enough to hit the top of the culvert. Velocity measurements were acquired (**Table 3**) with the surface measurement method and by using a SonTek FlowTracker Acoustic Doppler Velocimeter (ADV). The ADV seemed to slightly under-predict velocities. The additional roughness in the east barrel was not quite sufficient. Velocities were slightly high in the east barrel and sufficiently low in the west barrel.

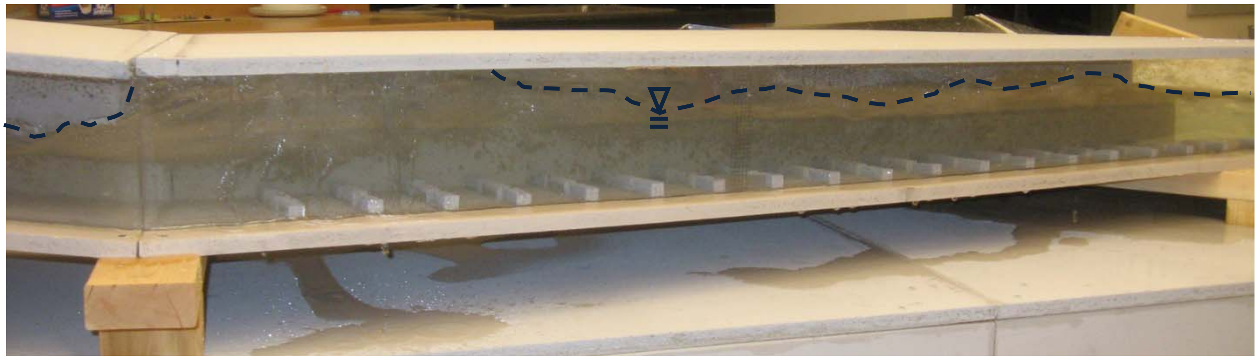

FIGURE 8: Second Model East Barrel Conveying 100-year Flow

TABLE 3: Measured Outlet Velocities in Second Model

		Surface Measurement Method		Velocity Meter	
Event (Yr)	**Barrel**	**Model Vel. (fps)**	**Prototype Vel. (fps)**	**Model Vel. (fps)**	**Prototype Vel. (fps)**
2	West	2.2	9.9	1.4	6.1
	East	2.2	9.7	1.5	6.8
100	West	2.7	11.9	2.0	9.0
	East	3.0	13.5	2.3	10.1

6. THIRD MODEL

The third, and final, model iteration added more 1’x1’ elements with a 9.75’, center-to-center spacing (prototype dimensions) to the east barrel in the next section upstream (**Figure 9**). These new roughness elements match the original design for that section of the culvert. Velocities were once again measured at both low and high flows (**Table 4**). The additional roughness elements reduced the velocity in the east barrel to an acceptable value. Prototype velocities at the outlet of both barrels were below the maximum of 14 fps. The culvert also conveyed both low and high events without excessive head water or tail water (**Figure 10**).

FIGURE 9: Third Model Roughness Elements (Left)
FIGURE 10: Third Model Conveying 100-year (Right)

TABLE 4: Measured Outlet Velocities in Third Model

		Surface Measurement Method		Velocity Meter	
Event (Yr)	**Barrel**	**Model Vel. (fps)**	**Prototype Vel. (fps)**	**Model Vel. (fps)**	**Prototype Vel. (fps)**
2	West	2.2	9.9	1.4	6.1
	East	2.2	9.7	1.5	6.8
100	West	2.7	11.9	2.0	9.0
	East	3.0	13.5	2.3	10.1

The open channel HEC-RAS model was used for verification because n-values in this model were known to a greater level of confidence, the culvert never transitioned to pressure flow, and the open channel model allowed the UNM research team to see the location of the hydraulic jump. The open channel model better predicted hydraulics. The results of the final physical model were compared to the open channel HEC-RAS model (**Table 5**). HEC-RAS and modeled results show reasonable agreement. The HEC-RAS model also accurately predicted the location of the hydraulic jump (**Figure 3**).

TABLE 5: Comparison of Third Model and HEC-RAS Velocities

Event	**Average Prototype Velocity (fps)**		
(Yr)	**Surface Measurement**	**Velocity Meter**	**HEC-RAS**
2	9.8	6.4	4.0
100	12.7	9.6	9.3

7. CONCLUSIONS AND RECOMMENDATIONS

The UNM research team made the following general observations:

- Roughness elements reduced outlet velocities below 14 fps in the prototype.
- Roughness elements created more uniform flow in the culvert and at the outlet, reducing the effects of the supercritical flow regime.
- Roughness elements will likely collect debris and may be difficult to maintain. The UNM research team did not test the culvert capacity or effectiveness of the culvert in reducing velocities with the area behind the elements filled.
- The *HEC 14* method used to design roughness elements was created for a subcritical flow regime. Therefore, velocities calculated with this method are different than those measured in the model.
- The flow was approximately equally divided in both barrels at both low and high flows (**Table 6**).

TABLE 6: East and West Barrel Flow Distributions

	% of Flow in Barrel	
Barrel	2 Yr Event	100 Yr Event
West	37.5	41.6
East	62.5	58.4

The UNM research team recommends changing only the design of the roughness elements. The modified design would include 1-foot by 1-foot elements in the two most downstream sections with 5.03-foot spacing in the most downstream section and 9.75-foot spacing in the second most downstream section (prototype dimensions given). This design is recommended because it performs sufficiently, is simpler to construct, will result in easier maintenance, and will likely minimize the adverse effects resulting from back-filling of debris behind elements. UNM researchers should note, however, that the current NMDOT design performs adequately and that the recommended design requires a greater volume of concrete.

APPENDIX

FROUDE SIMILITUDE

The Froude number (**F**) is a dimensionless ratio of inertial forces to gravitational forces (**Equation 1**). For supercritical flow, as is common in this model, this value is greater than one. This essentially says that a greater portion of the energy in the flow stored in kinetic energy (velocity) than is stored in potential energy (depth). This type of similitude is applied to open channel modeling.

$$\boldsymbol{F} = \frac{V}{\sqrt{gL}}$$

EQUATION 1: Froude number Defined

In this equation, V is velocity, g gravitational acceleration, and L a length dimension, typically hydraulic depth. Scale calculations begin by setting the Froude number of the prototype (actual structure) equal to the Froude number of the model (**Equation 2**).

$$\boldsymbol{F_m} = \boldsymbol{F_p} = \left[\frac{V_m}{\sqrt{gL_m}}\right] = \left[\frac{V_p}{\sqrt{gL_p}}\right]$$

EQUATION 2: Definition of Froude Similitude Equation

The scale factor (L_r) is the ratio of prototype to model length and is by definition a linear relationship (**Equation 3**). With some manipulation the scale factor can be substituted into Equation 2. The results are two equations that can be used to scale velocities (**Equation 4**) and flow (**Equation 5**).

$$L_r = \frac{L_p}{L_m}$$

EQUATION 3: Scale Factor Equation

$$V_p = V_m\sqrt{L_r}$$

EQUATION 4: Velocity Scaling Equation

$$Q_p = Q_m * L_r^{5/2}$$

EQUATION 5: Flow Scaling Equation