Structural Aspects of Field Paving of Deteriorated Metal Culvert Inverts

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Acknowledgment (slide 1)

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• **Partner:** Shaw & Halter, Inc.
Acknowledge ment (slide 2)

- **ORIL Technical Advisory Committee (TAC):**
  - Mike McColeman (ODOT hydraulics)
  - Doug Gruver (ODOT District 8)
  - Ed Herrick (Franklin Co. Engineer)
  - Warren Schlatter (Defiance Co. Engineer; ORIL Board)
  - Fred Pausch (County Engineer’s Association of Ohio)
- **Project Coordinator:**
  - Vicky Fout (ODOT Statewide Planning & Research)
Corrugated metal pipe and pipe-arch culverts have served Ohio’s roadways for decades.

Inverts of many of these metal culverts in Ohio deteriorate due to harsh water chemistry and abrasive nature of drainage flow.
Background
Invert concrete paving has been one of the rehabilitation methods available for deteriorated metal culverts.

- ODOT has CMS Item 611.11 (field paving of new or existing conduit).
- Contributions of invert paving is obvious from the hydraulic standpoint.
- What about from structural standpoint?
## Objectives

<table>
<thead>
<tr>
<th>Understand</th>
<th>Understand how much invert concrete paving contributes to the deteriorated metal culverts structurally.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examine</td>
<td>Examine if ODOT CMS Item 611.11 is adequate.</td>
</tr>
<tr>
<td>Identify</td>
<td>Identify field cases where additional steel reinforcing is needed.</td>
</tr>
<tr>
<td>Develop</td>
<td>Develop quick reference tables and guidelines concerning the field paving of steel culvert inverts.</td>
</tr>
</tbody>
</table>
Project Tasks

- Task 1 – Literature Review
- Task 2 – Survey
- Task 3 – Engineering Analysis
- Task 4 – Static Live Load Tests
- Task 5 – Extreme Load Tests
- Task 6 – Dissemination & Development of Recommendations, Procedures, Charts & Quick Reference Tables
Task 1: Literature Review

• A buried circular or near-circular shell structure maintains its shape and resists the dead/live loads by developing compressive forces all around its circumference.

→ **Hoop Action**

• Hoop Stiffness \( S_h = M^* R / E A \)

where \( M^* \) = constrained soil modulus; \( R \) = pipe radius; \( E \) = pipe material’s modulus; and \( A \) = pipe wall area per unit length.)
Task 1: Literature Review

- Functions of Culvert Inverts
  - Provides the solid surface over which water can flow while protecting the bedding layer
  - Spread the weight of the culvert structure and the dead/live loads to the bedding soil layer and subsoils below.
  - Provide continuity to the ring structure so that it can mobilize its hoop action.
Task 1: Literature Review

- Extensive literature search located no papers, reports, or book chapters that examined structural aspects of field concrete paving of deteriorated metal culvert inverts.
- This was not surprising and justified the need for the ORIL project.
Task 1: Literature Review

- Papers by Garcia & Moore (2015)
- Structural performance compared between unrehabilitated and rehabilitated CMPs
- CMPs – diameter (47”), corrugation size 2-2/3” x 1/2”, plate thickness (0.078”)
Task 1: Literature Review

• Papers by Garcia & Moore (2015)
• Rehabilitation – Fiber-reinforced spray-on mortar spayed to the CMP inside circumference
• Variations in Metal loss and Spray-on liner thickness
• Upon rehabilitation, each CMP acted like a much more rigid structure. The liner increased the bending stiffness of the steel pipes.
• The CMP treated with a 3” thick liner provided stiffer responses than the one treated with a 2” thick liner.
Task 1: Literature Review

- Recent ORITE Field Test
- Sargand, Khoury, Jordan & Hussein (2015)
Task 1: Literature Review

• 2015 ORITE Field Test
  • An ORITE team tested a 23-yr old metal pipe-arch located under a county road in Muskingum County in June 2015.
  • Rise 66”; Span 93”; Plate thickness 0.138” (gage 10); Soil cover 1’
  • The structure had its invert mostly gone due to a combination of low pH water and abrasive flow. There were some perforation holes just below the bolt lines.
Task 1: Literature Review

- 2015 ORITE Field Test
- The culvert had its invert paved only on the outlet side.
- The structure was instrumented with strain gages and wire potentiometers.
- The paved and unpaved sections of the structure were each subjected to heavy loads applied by hydraulic cylinders.
- The PI observed the test.
Task 1: Literature Review

- 2015 ORITE Field Test
  - The culvert cross-section was more flexible in the unpaved test section than in the invert-paved section.
  - Concreting the invert made the thrust response more magnified and bending moment response reduced.
  - Also, invert paving caused the structural responses to become more symmetric about the vertical centerline of the culvert.
Task 1: Literature Review

- ODOT CMS Item 611.11
- Paving 3 inches thick over plate corrugations
- Use 2” x 2” - W0.9 x W0.9 galvanized wire mesh or equivalent
- Wire mesh width 4 inches less than the paving width
- Wire mesh securely fastened to the conduit near each edge and at the center
- Wire mesh attached to the conduit at points no more than 4 ft apart along the flow line
- Use galvanized steel support chairs under the wire mesh, if necessary, to keep the position of the mesh in place
Task 2: Survey

• Survey forms were developed to gather information related to metal culvert invert paving policies and practice.

• The forms were mailed to Ohio county engineers, ODOT district offices, and other state DOTs.

• Responses were received from 28 county engineers, 8 ODOT districts, and 25 state DOTs.

• No entities had comprehensive structural procedures established for field paving of metal culvert inverts.
Task 2: Survey County Engineers Who Responded
Task 2: Survey

- **Survey Among Ohio County Engineers**
- Only 50% of respondents have paved metal culvert inverts.
- County engineers in NW Ohio have never paved their metal culverts.
- Among the county engineers who pave metal culvert inverts, most indicate they do so shortly after the first perforations appear.
- More than 50% of the county engineers who pave metal culvert inverts have their own invert paving specifications.
- Pavement thickness, use of steel reinforcement, and vertical extent of paving all vary among counties.
- County engineers who paved metal culvert inverts are mostly very positive about this rehabilitation method.
Task 2: Survey ODOT District Engineers Who Responded
**Task 2: Survey**

- **Survey Among ODOT District Engineers**
  - ODOT district engineers all follow CMS Item 611.11 specifications when paving metal culvert inverts.
  - However, ODOT district engineers have varied opinions about when metal culvert inverts should be paved.
  - One district (District 8) adds steel rebars to wire mesh prior to field paving.
  - ODOT district engineers who paved metal culvert inverts are mostly positive about this rehabilitation method.
Task 2: Survey

- **ODOT District 1**
  - Invert paving extended up to the boltline to protect bolts from rust due to condensation

- **ODOT District 8**
  - Developed plan notes & details to show the size of rebar, rebar spacing, and length of welds; amount of rebar for restoring original hoop stiffness
Task 2: Survey

Other State ODOT Engineers Who Responded
Task 2: Survey

- Survey Among Other State DOTs
  - Sixteen (16) out of 25 responding state DOTs have applied invert paving to metal culverts.
  - State DOTs in arid regions (ex. Arizona, New Mexico, ...) have had no experience with invert paving.
  - DOT engineers in different states share varied opinions about when metal culvert inverts should be paved.
  - Thirteen (13) state DOTs have their own specifications for invert paving. Among them, nine (9) have standard plan drawings.
Task 2: Survey

- Survey Among Other State DOTs
  - Invert pavement thickness commonly range from 4” to 6”.
  - At least seven (7) state DOTs require studs and/or rebars in addition to wire mesh.
  - No consistent trend was found concerning vertical extent of invert paving.
  - State DOT engineers who have paved metal culvert inverts are mostly positive about this rehabilitation method.
Task 1: Literature Review

• CalTrans (2013)

- #10 Welded Wire Mesh
- Welding rebars: Every 4” (transv.) Every 30” (longitud.)
- Grout Ports @ 6” Spacing @ 5 & 7 o’clock
- 4” Thick Concrete
- Existing CMP
- 60°
- 120°
Task 2: Survey

Pictures supplied by NHDOT
Task 2: Survey

1. REBAR PAVED INVERT ARCH DETAIL (RPI)

   4" OR 6" LONG STUD SHEAR CONNECTORS SEEN TABLES, SHEET CD-3
   REINFORCEMENT (SEE TABLE), TIE TO STUD SHEAR CONNECTORS
   4" SPACING BETWEEN ROWS FOR 1/4" AND 5/8" CONNECTORS, 6" SPACING FOR 3/4" CONN.
   SEE TABLE ON DWG, CD-3 FOR MINIMUM NUMBER OF ROWS.

   VOIDS IN EXISTING INVERT SHALL BE COMPLETELY FILLED IN WITH ITEM 602.2001.

   NOTE:
   1. THIS REPAIR DETAIL IS NOT TO BE USED FOR SPANS GREATER THAN 10' OR FILL HEIGHTS OVER 3'6" AND OVER 10" OF DEPRESSED KEYS OF CIRCULAR PIPES, THIS REPAIR IS NOT TO BE USED WHERE CONCRETE WOULD EXTEND ABOVE THE MIDPOINT OF CIRCULAR PIPES. THIS REPAIR IS NOT TO BE USED FOR PIPE ARCHES WHERE THE CONCRETE PAVING WOULD NEED TO EXTEND ABOVE THE SPRING LINE OF THE ARCH.

   2. ITEM 602.2001 SHALL COMPLETELY COVER THE DETERIORATED SURFACE OF THE PIPE INVERT, AND AT LEAST 6" BEYOND TOP RUN OF STUD SHEAR CONNECTORS. STUD SHEAR CONNECTORS SHALL BE WELDED ACCORDING TO THE STEEL CONSTRUCTION MANUAL (SCM) TO THE PIPE ABOVE THE AREA OF SECTION LOSS, AJOUE. THIS ITEM SHALL INCLUDE ALL MATERIALS AND WORK SHOWN TO REPAIR THE CULVERTS.

   3. ALL PROVISIONS OF SECTION 650 OF THE NYSDOT STANDARD SPECIFICATIONS APPLY TO THE WORK DETAINED AS APPLICABLE.

   4. ANY ASPHALT COATING AND GALVANIZING ARE TO BE REMOVED TO BASE METAL BEFORE WELDING. REPAIR GALVANIZING IN WELD AREAS ACCORDING TO SECTION 710.4-1 OF THE STANDARD SPECIFICATIONS. COST TO BE INCLUDED IN UNIT EST PRICE FOR ITEM 602.2001.

   5. EFFECTIVELY ATTACHED STUD SHEAR CONNECTORS SHALL BE LEFT IN PLACE AND REPLACED WITH AN ADDITIONAL STUD SHEAR CONNECTOR ADJOUE.

   6. CONCRETE SHALL MEET REQUIREMENTS OF SECTION 555, CLASS A OR

   7. REINFORCEMENT TABLE

<table>
<thead>
<tr>
<th>SPAN</th>
<th>TRANSVERSE</th>
<th>LONGITUDINAL</th>
<th>&quot;1&quot;</th>
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<tbody>
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<td>6'</td>
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<td>$4 @ 12''</td>
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<td>7'</td>
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<tr>
<td>10'</td>
<td>$5 @ 6''</td>
<td>$5 @ 12''</td>
<td>8''</td>
</tr>
</tbody>
</table>

   ALL DIMENSIONS ARE IN FEET UNLESS OTHERWISE NOTED.

STATE OF NEW YORK
DEPARTMENT OF TRANSPORTATION
Task 3: Engineering Analysis

- AASHTO LRFD Design Method
- Analytical methods for corrugated metal culverts are presented in Section 12: Buried Structures and Tunnel Liners.
- The live load and load combination are set up according to Section 3: Loads and Load Factors.
Task 3: Engineering Analysis

- AASHTO LRFD Design Method
- Corrugated Metal Culverts
- Failure Mode 1: Wall Crushing
- Culvert wall will crush if thrust stress reaches the yield strength of metal.
- Max. thrust stress may be calculated at the springline, considering soil dead load and live loads resting above the culvert structure.
Task 3: Engineering Analysis

- AASHTO LRFD Design Method
- Factor of Safety Against Wall Crushing

\[(FS)_{wc} = 24F_y A/(P_f S)\]

- where \(F_y\) = yield strength of metal (33 ksi for steel); \(A\) = wall area per unit length (in\(^2\)/ft); \(P_f\) = vertical crown pressure due to dead and live loads (ksf); and \(S\) = culvert span (in).
Task 3: Engineering Analysis

- AASHTO LRFD Design Method
- Corrugated Metal Culverts
- Failure Mode 2: Wall Buckling
- Culvert wall will buckle prematurely if thrust stress reaches the critical buckling stress.
- The critical buckling stress depends on several factors (properties of culvert wall, soil stiffness, vertical pressure acting on culvert).
Task 3: Engineering Analysis

- AASHTO LRFD Design Method
- Factor of Safety Against Wall Buckling
  \[(FS)_{wb} = \frac{2F_{cr}A}{P_fS}\]
- where \(F_{cr}\) = critical buckling stress (ksi); \(A\) = wall area per unit length (in\(^2\)/in); \(P_f\) = vertical crown pressure due to dead and live loads (ksi); and \(S\) = culvert span (in).
Task 3: Engineering Analysis

- AASHTO LRFD Design Method
- The culvert’s plate thickness affects the soil fill height that induces wall crushing in a proportional manner.
- The AASHTO equation for wall crushing is simple to use and can be applied to assess the impacts of metal loss in the culvert wall section.
- This approach, originally intended for the springline location, may be applicable also to the invert region.
Task 3: Engineering Analysis

- AASHTO LRFD Design Method
  - The AASHTO equation for examining wall buckling failure does not work well for CMPs having deteriorated wall sections. This is because the equation is based on the radius of gyration, which changes little as the wall deteriorates.
  - The current AASHTO methodology does not describe a step that can be taken to calculate the combined stresses (due to thrust and bending moment effects) to predict when/where a plastic hinge forms.
Task 3: Engineering Analysis

- Computer Simulations
  - Culvert Analysis & Design (CANDE) computer software, based on the finite element method (FEM)
  - Abaqus – more flexible, general purpose FEM simulation software
Task 3: Engineering Analysis

• **Computer Simulations**
  • Culvert represented by a series of column/beam elements
  • Soils represented by a number of quadratic elements
  • Soils are assumed to be bonded to the culvert.
  • Each simulation requires a detailed mesh with material properties, boundary conditions, construction sequences, and loading instructions
Task 3: Engineering Analysis

• Computer Simulations
• 2-D Simulations by CANDE & Abaqus (0% metal loss, varied metal loss over invert, invert paved)
• CMP (60” diameter, corrugation size 6” x 2”, plate 0.11” thick) and CMPA (84” span x 61” rise, same corrugation & plate) analyzed under different loading conditions
• Abaqus is more powerful, since it allows an intact culvert to be installed in the ground. Then, the user can modify its invert.
Task 3: Engineering Analysis

- Computer Simulations (60” dia. CMP)

Overall Half-Mesh

Metal Loss over Invert

Concrete Pavement over Invert
Task 3: Engineering Analysis

- Computer Simulations (60” dia. CMP)

Thrust N, Soil Cover H = 10 ft

Distance from 1st node @ crown (in)

Thrust Force (lb/in)

Intact
Invert Paved
75% det
95% det

Invert Region
Task 3: Engineering Analysis

- Computer Simulations (60” dia. CMP)

Bending Moment $M$, Soil Cover $H = 10$ ft

- Intact
- Invert Paved
- 75% det
- 95% det

Invert Region
Task 3: Engineering Analysis

- Computer Simulations (60” dia. CMP)
Task 3: Engineering Analysis

• Computer Simulations
• As the invert section experiences 50%, 75%, and 95% metal loss, the load carrying capacity of corrugated metal pipes drops to 68%, 33%, and 6% of that of the intact pipe.
• Under the same increments of metal loss, the load capacity of pipe-arches drops to 96%, 47%, and 8% of that of the intact structure.
• For both pipes and pipe-arches, the most critical region for wall crushing remains just above the springline when the metal loss in the invert is less than 50%. The critical area shifts to the invert when the metal loss there becomes more than 50%.
Task 3: Engineering Analysis

• Computer Simulations

• As the degree of metal deterioration worsens, bending moment response decreases in the deteriorated region. The thrust force carried by the wall is less sensitive to the effects of invert deterioration.

• The more severe the invert deterioration is, the larger the deflections.

• Wall buckling may not become an issue unless the degree of metal loss exceeds 95% under both H-20 live loading through shallow covers and soil loading under deeper covers.
Task 3: Engineering Analysis

- **Computer Simulations**
- The invert region becomes more flexible and starts deforming upward as the culvert’s bottom region loses more metal.
- Having severe metal deteriorations at the interface region (usually located just below the springline) can be just as damaging to the entire culvert structure as having severe metal deteriorations over the invert.
- Invert concrete paving can restore the original structural integrity of the metal culvert. This is supported by the fact that thrust and deflection responses become closer to (actually less than) those of the intact pipe once the invert is paved.
Task 3: Engineering Analysis

• Computer Simulations

• For both metal pipes and pipe-arches, use of a heavier reinforcement can lead to decreased tensile stresses in the concrete. The effect of heavier reinforcement on the culvert responses is observed more clearly when the steel reinforcement is tied to the culvert wall.
Task 4: Static Live Load Tests

- Site 1:
- HOC-93-11.29 CMP
  - Age = Unknown
  - Diameter = 108” (9’-0”)
  - Soil Cover = 3.5’
  - Corrugation Size = 3” x 1”
  - Plate Thick. = 0.078” (gage 14)
  - Full bituminous coating
Task 4: Static Live Load Tests

• Site 1:
  • HOC-93-11.29 CMP
  • Bituminous coat cracked and detached, especially at inlet.
  • Exposed metal plate heavily rusted with some perforation holes.
Task 4: Static Live Load Tests

- Site 1:
- HOC-93-11.29 CMP
- 1/3 of bottom removed under one traffic lane’s wheel path to simulate a badly deteriorated invert condition.
Task 4: Static Live Load Tests

- Site 1:
- HOC-93-11.29 CMP
- Static live loads were applied by positioning front axle or center of rear axles of a 29-ton dump truck over the culvert.
Task 4: Static Live Load Tests

- Site 1:
- HOC-93-11.29 CMP
- Invert was paved according to ODOT CMS item 611.11.
- The structure was subjected to the same static live load tests, 46 days after the field paving.
- The truck weighed 25 tons during the retesting.
Task 4: Static Live Load Tests

- Live Load Tests @ Local Culvert Sites
- Live Loading

[Note] SG = Strain Gage; LP = Linear Potentiometer
Task 4: Static Live Load Tests

- Site 1 (HOC-93-11.29 CMP)

Rear Axles over Crown
Task 4: Static Live Load Tests

- Site 1 (HOC-93-11.29 CMP)

Rear Axles over Crown

![Graph showing thrust force vs distance from crown with data points for unpaved and paved surfaces.](image)
Task 4: Static Live Load Tests

- Site 1 (HOC-93-11.29 CMP) Rear Axles over Crown

![Graph showing bending moment vs distance from crown for unpaved and paved surfaces.](image-url)
Task 4: Static Live Load Tests

- Site 2:
- Pipe-Arch in Defiance County, OH
  - Age = 31 yrs (1985)
  - Span = 125” (10’-5”)
  - Rise = 85” (7’-1”)
  - Soil Cover = 8”
  - Corrugation = 2-2/3” x 1/2”
  - Plate = 0.17” (gage 8)
Task 4: Static Live Load Tests

- Site 2:
  - Pipe-Arch in Defiance County
  - Heavy rust & scale below the interface area, with some perforation holes, especially in the inlet section.
  - Some voids seen in the backfill soil through the perforation holes.
Task 4: Static Live Load Tests

- Site 2:
- Pipe-Arch in Defiance County
- The culvert was instrumented with strain gages and linear potentiometers in the same way.
Task 4: Static Live Load Tests

- Site 2:
- Pipe-Arch in Defiance County
- The culvert was load-tested in the same way as the HOC-93 CMP was.
- Dump truck’s gross weight was 28 tons
Task 4: Static Live Load Tests

- Site 2:
  - Pipe-Arch in Defiance County
  - Test 1 = Original Culvert
  - Test 2 = Bottom 1/3 Removed
  - Test 3 = Invert Paved
Task 4: Static Live Load Tests

- Site 2:
- Pipe-Arch in Defiance County
- Invert paved on the inlet side on Nov. 7 according to ODOT Item 611.11
- Structure retested on Nov. 22, using the same dump truck.
Task 4: Static Live Load Tests

- Site 2 (Defiance Co. CMPA)
Task 4: Static Live Load Tests

- Site 2 (Defiance Co. CMPA)
Task 4: Static Live Load Tests

• Site 2 (Defiance Co. CMPA)
Task 4: Static Live Load Tests

- Site 2 (Defiance Co. CMPA)

![Graph of Thrust Force, Front Tire Loading over Shoulder 2]

- As-is
- Invert Removed
- Invert Paved
Task 4: Static Live Load Tests

- Site 2 (Defiance Co. CMPA)
Task 4: Static Live Load Tests

- Site 2 (Defiance Co. CMPA)

![Graph showing vertical deflection with distance from crown. The graph compares 'As-is', 'Invert Removed', and 'Invert Paved' conditions.]
Task 4: Static Live Load Tests

• Live Load Tests @ Local Culvert Sites
• Metal culvert’s structural responses to static live load magnified when 1/3 of invert was removed.
• Metal culvert’s structural responses to static live load became reduced back to or less than where they used to be upon paving the invert.
• Concrete slab placed on the invert can remain relatively stress/strain free.
Task 5: Extreme Load Tests

- Controlled Load Tests @ ORITE Load Frame, Located in Athens, OH
Task 5: Extreme Load Tests

- Controlled Extreme Load Tests @ ORITE Load Frame
- 60” diameter CMP specimens (12-gage, corrugation size 2-2/3” x 1/2”)
- Crushed limestone backfill
- Instrumentations for culverts included strain gages, wire potentiometers, and soil pressure cells
- Invert pavement was instrumented with strain transducers.
Task 5: Extreme Load Tests

- Extreme Load Tests @ ORITE Load Frame
- Test 1: CMP unaltered & unpaved
- Test 2: CMP invert removed
- Test 3: CMP invert removed & standard paving
- Test 4: CMP invert removed & heavily-reinforced paving
- [Note] Each CMP was first backfilled in compacted layers of dense crushed limestone material until a cover of 12” was placed over the crown. Then, its invert was modified (not in Test 1).
Task 5: Extreme Load Tests

- CMP Ready for Extreme Loading in Test 1
Task 5: Extreme Load Tests

- CMP Invert Alteration for Tests 2-4

- Bottom 1/3 section removed after backfilling the culvert
Task 5: Extreme Load Tests

- CMP Invert Paving for Test 3

- Std. wire mesh (2” x 2” – W0.9 x W0.9) attached to culvert wall (screws every 2.5’), covering bottom 1/3 area
Task 5: Extreme Load Tests

- CMP Invert Paving for Test 3

- 3”-thick concrete layer poured on top of corrugated plate
Task 5: Extreme Load Tests

- CMP Invert Paving for Test 4

- #4 rebars spot-welded to culvert plates in transverse and longitudinal directions.
Task 5: Extreme Load Tests

- CMP Invert Paving for Test 4

- Std. wire mesh (2” x 2” – W0.9 x W0.9) applied over rebars
Task 5: Extreme Load Tests

- CMP Invert Paving for Test 4
Task 5: Extreme Load Tests

• Field Instrumentation & Loading
Task 5: Extreme Load Tests

• Field Instrumentation

Soil Pressure Cell

Strain Gages & Wire Potentiometer
## Task 5: Extreme Load Tests

### Summary: Max. Load Capacity

<table>
<thead>
<tr>
<th>Test No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max. Load Applied to Cause Failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>924 kips (100%)</td>
<td>677 kips (73%)</td>
<td>800 kips (87%)</td>
<td>924 kips (100%)</td>
</tr>
<tr>
<td></td>
<td>Max. Vert. Pressure Needed to Cause Failure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>126 psi</td>
<td>92 psi</td>
<td>109 psi</td>
<td>126 psi</td>
</tr>
</tbody>
</table>

[Note] Test 1: CMP unaltered & unpaved  
Test 2: CMP invert removed  
Test 3: CMP invert removed & received standard paving  
Test 4: CMP invert removed & received heavily-reinforced paving
Task 5: Extreme Load Tests

- Failure Mode
- Test 1
- Wall Crushing/Buckling (just above springline)
- Settling of Loading Plate
Task 5: Extreme Load Tests

- Failure Mode
- Test 2
- Ovaling & Seam Splitting
- Settling of Loading Plate
- Backfill soil started infiltration (through the opening in the invert)
Task 5: Extreme Load Tests

- Failure Mode
- Test 3
- Detachment & lifting of Concrete Pavement
- Seam Splitting
- Settling of Loading Plate
Task 5: Extreme Load Tests

- Failure Mode
- Test 4

- Detachment & Lifting of Concrete Pavement
- Wall Crushing/ Buckling (just above springline)
- Settling of Loading Plate

- [Note] No Seam Splitting observed.
Task 5: Extreme Load Tests

- Comparison Plots
- Soil Pressure Cell Readings
- Top – Vertical Pressure @ Crown
- Bottom – Lateral Pressure @ Springline
Task 5: Extreme Load Tests

- Comparison Plots
- Loading Platform Settlement
Task 5: Extreme Load Tests

When a metal pipe’s invert region is badly deteriorated, ...

• the structure can become more flexible and deflect horizontally more than when its invert is intact.

• the bending moment response can become enhanced while the thrust response diminished

• the backfill soil can get pushed into the bottom hole and become looser.

• the structure can fail prematurely through seam splitting and excessive deflections.

• the load capacity can drop to 73% of the intact structure.
When a metal pipe’s deteriorated invert region is paved with concrete, ...

- the structure’s load capacity improves to 87% (w/ ODOT CMS item 611.11 method) and 100% (w/ addition of #4 rebars) of the intact one.
- The structure’s failure mode becomes more similar to that of the intact version (wall crushing/buckling).
- Better bonding is achieved between the concrete slab and CMP plate when rebars are welded.
Task 6: Dissemination

- Recommendations to ODOT CMS Item 611.11
- Grout voids that were detected in the backfill material, prior to field paving.
- The paving must extend to 6 inches above the highest location of severe metal deterioration.
- Place appropriate size and number of steel reinforcing bars in the corrugation valleys and weld them to the culvert plates if – 1) early signs of wall crushing/wall buckling are detected inside the culvert; 2) the quick reference tables indicate additional reinforcement is required; or 3) the factor of safety against wall crushing is calculated to be less than 1.5 for the springline/interface or invert per the engineering procedure.
Task 6: Dissemination

- Recommendations to ODOT CMS Item 611.12 & 13

- Inspect the area where the water and air meets (interface area) to assess the degree of rusting/scaling. Strike hard the metal surface with a prospector’s pick a few times, and note the material response. If perforation holes are present, note the size and frequency of the hole (over a specified distance). Note the size of voids that are developing in the backfill material. Also, observe if signs of wall crushing (cracking) or wall buckling (warping, bulging) are present.
Task 6: Dissemination

- Recommendations to ODOT CMS Item 611.12 & 13

- Inspect the invert region of the culvert to assess the degree of rusting/scaling. Strike the metal surface hard with a prospector’s pick a few times, and note the material response. If perforation holes are present, note the size and frequency of the hole (over a specified distance and width). Note the size of voids that are developing in the bedding material. Also, observe if signs of wall buckling (warping, bulging), soil infiltration, and seam separation are present.
Task 6: Dissemination

• **Quick Reference Tables**

• A series of quick reference tables were prepared for various sizes of CMP and CMPA. These tables can indicate the amount of steel needed for invert paving, depending on the field conditions (corrugation size, plate thickness, % metal loss, soil cover thickness).

• The tables should be useful to hydraulic engineers and culvert inspectors.
Task 6: Dissemination

• Quick Reference Tables (sample)
• 8’-0” Dia. CMP – Corrugation Size 3” x 1”
• Plate Thickness 0.079” (Gage 14)

<table>
<thead>
<tr>
<th>Metal Loss</th>
<th>1’ Cover</th>
<th>2’ Cover</th>
<th>4’ Cover</th>
<th>6’ Cover</th>
<th>8’ Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>12%</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
</tr>
<tr>
<td>25%</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
</tr>
<tr>
<td>33%</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
</tr>
<tr>
<td>50%</td>
<td>#3 (4p)</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
</tr>
<tr>
<td>67%</td>
<td>#4 (3p)</td>
<td>#4 (11p)</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
</tr>
<tr>
<td>75%</td>
<td>#4 (2p)</td>
<td>#4 (5p)</td>
<td>Std.</td>
<td>Std.</td>
<td>Std.</td>
</tr>
</tbody>
</table>

[Note] Std. = Standard wire mesh 2” x 2” – W0.9 x W0.9 (per ODOT CMS item 611.11). #4 (3p) = #4 rebars welded to plates with spacing of 3 corrugation pitches (= 9”).
Task 6: Dissemination

• Welding of Steel Reinforcing Bars

Spacing = 2p
Task 6: Dissemination

- **Recommended Engineering Procedure**
- **Step 1**: Identify the culvert shape (circular, pipe-arch), nominal size (diameter, rise & span), material type, corrugation size, and wall thickness. The Step-1 data must be verified in the field.
- **Step 2**: Assess the degree of worst metal loss (0%, 25%, 33%, 50%, 67%, 85%) in the water-air interface area or over the invert. Based on this, select a suitable wall area value from Table 1.
Task 6: Dissemination

- **Recommended Engineering Procedure**
- **Step 3**: Measure the average soil cover height $H$ over the culvert crown.
- **Step 4**: Calculate the factored vertical crown pressure $P_F$ by following one of the procedures outlined in Appendix F.
- **Step 5**: Compute the factor of safety against wall crushing $(FS)_{wc}$ that could occur in or near the springline region, using the AASHTO method ...
Task 6: Dissemination

- **Recommended Engineering Procedure**
  - For assessing the wall crushing potential in the invert region, take 75% of the $P_F$ value calculated above. If $(FS)_{wc} \geq 1.5$, then there is no need to add additional reinforcement when performing field paving or other repairs. Proceed to Step 6.
  - If $(FS)_{wc} < 1.5$, then the culvert’s wall needs to be bulked up by welding steel rebars. Select the rebar size & spacing from Quick Reference Tables.
Task 6: Dissemination

• **Recommended Engineering Procedure**

• Obtain the adjusted wall area value $A'$.

• Recalculate $(FS)_{wc}$ by using the adjusted wall area $A'$ in place of $A$. Unless $(FS)_{wc} \geq 1.5$, revise the rebar size or rebar spacing and repeat the FS calculation.

• **Step 6:** Assess the degree of worst metal loss (0%, 25%, 50%, ...) in the invert area. Based on this, pick suitable wall area and wall moment of inertia values from Tables 1 and 2, respectively. Divide the wall area selected by 12 to convert it to the unit of in$^2$/in.

• **Step 7:** Calculate the critical buckling stress and the factor of safety against wall buckling $(FS)_{wb}$ using the following formulas.
Task 6: Dissemination

• **Recommended Engineering Procedure**
  • If $(FS)_{wb} \geq 1.5$, then there is no need to add additional reinforcement prior to field paving.
  • If $(FS)_{wb} < 1.5$, then the culvert’s wall needs to be bulked up by welding steel rebars. Select the rebar size & spacing from Quick Reference Tables.
  • Obtain the adjusted wall area value $A'$. 
  • Recalculate the neutral axis location and moment of inertia $I'$. 
  • Recalculate $(FS)_{wc}$ by using $A'$ and $I'$. Unless $(FS)_{wb} \geq 1.5$, revise the rebar size or spacing and repeat the FS calculation.
Task 6: Dissemination

• **Recommended Engineering Procedure**
  
  • Factor of safety against wall crushing failure, $(FS)_{wc}$ is almost always slightly higher than that against wall buckling failure, $(FS)_{wb}$.
  
  • Therefore, adding rebars to make $(FS)_{wc} > 1.5$ automatically takes care of the concern for wall buckling.
Task 6: Dissemination

- No additional steel reinforcement is needed for CMPs under shallow (< 2’) covers, as long as the field paving is done before the degree of metal loss advances beyond 33%.
- No additional steel reinforcement is needed for CMPs under intermediate (2’-8’) covers, as long as the field paving is done before the degree of metal loss reaches 60%.

[Note] These statements can be extended to pipe-arches as well.
Task 6: Dissemination

CMP is having a deteriorated invert

Is metal loss 30% or more over the middle? 1/3?

No

Voids forming under the invert or next to the culvert?

No

Monitor the culvert structure periodically

Yes

Apply CMS Item 611.11 soon

CMP is having a deteriorated area at interface (just below springline)

Is metal loss 30% or more in the interface area?

Yes

Are there early signs of wall crushing or wall buckling? Is the pipe deformed? Are the plates coming apart at seams? Has the roadway been settling?

Yes

Weld rebars & Apply CMS Item 611.11 Immediately

No

Apply CMS Item 611.11 Immediately

Case 1

$\text{(FS)}_{wc} \geq 1.5$

Case 2

$\text{(FS)}_{wc} < 1.5$

Consult Tables Attached; Carry out engineering calculations for wall crushing & wall buckling (using % metal loss identified)
Thank you 😊

- Please refer to the 434-page final report (T. Masada, June 2017, FHWA/OH-2017-21) for further details.

- ORIL is currently accepting research ideas from representatives of local public agencies for funding consideration. Ideas can be submitted through the ORIL website (http://oril.transportation.ohio.gov) and the deadline is November 9, 2017.