STRUCTURAL ANALYSIS DOCUMENATION
Design Division
Bridge Management Section

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SUBJECT: *MDOT CMP LFR (ver. 1.0).xlsx* Structural Analysis Documentation (SAD)

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This spreadsheet is designed to aid a qualified engineer in completing the bridge load rating analysis of a corrugated metal pipe culvert structure. Sound engineering judgment and familiarity with the analysis are required to choose appropriate input values and to recognize situations that may deviate from the standard case on which these spreadsheets are based. The following documentation provides information concerning the calculations in order for the engineer to determine if the spreadsheet is suitable for the culvert in question, and to aid in modifications for unique circumstances. This documentation describes the steps needed to complete the load rating analysis using the load factor rating (LFR) method for corrugated metal pipe culverts.

This spreadsheet is comprised of seven worksheets; *Input-Structure Info*, *CMP Rating Calculations*, *Reference Tables*, *MI Trucks*, *Section Property Tables*, *Seam Strength Tables*, and *NCSPA Design Data Sheet No. 19*.

"AASHTO" specification sections noted below refer to the AASHTO Standard Specifications for Bridge Construction, 17th Edition, 2002.

Cells are highlighted according to the following:

Input Parameters
Header Information
Informational Values
Intermediate Calculations
Summary of Final Calculations
Warnings or Special Notes

The analysis portion of the spreadsheet is protected. To unprotect, choose Tools – Protection – unprotect Sheet. The password is "password".

Input-Structure Info Worksheet

The general information entered in rows 1-3 is used to generate the header information on subsequent pages.

Structure Type is selected from a drop down list sourced from the *Reference Tables* worksheet. This input is used to determine the appropriate minimum cover as described in AASHTO (12.4.1.5, 12.5.3.3, 12.6.1.5, or 12.7.2.1). The minimum cover for each structure type is listed alongside the structure type in the *Reference Tables* worksheet and a lookup function finds the minimum cover for the selected structure type.

Seam Type is selected from a drop down list referenced from the *Reference Tables* worksheet. This is used in the calculations to determine the appropriate capacity modification factor for seam strength according to AASHTO 12.6.1.3

Structure Category is selected from a dropdown list and is used to determine the appropriate span length (**Span Length (S)** is used for typical structures, two times the **Actual Top Radius (R_t)** is used for unsymmetrical/deflected or long-span structures) and whether or not the buckling strength reduction factor should be used when determining the wall buckling strength.

Fill Depth at Centerline of Roadway (H_1) and **Fill Depth at Edge of Pavement (H_2)** are used to determine the minimum cover applied above the top of the culvert and to determine the distribution of vehicle loads to the top of the culvert.

Span Length (S) (transverse to the longitudinal length) for the culvert is entered along with the **Rise (R)** (vertical height) of the structure. These measurements are explained in Figure 1.

Longitudinal Length of the Structure (L) (length of the culvert) and **Clear Roadway Width** (face to face of guardrail) are used to limit the width of distributed area applied to the culvert from multiple loaded lanes. The calculated distribution width is not allowed to exceed that provided by the length of the structure or an equal division of the sum of lane widths and soil distribution width by the number of lanes.

Actual Top Radius may be calculated according to Figure 1 in the worksheet. The **Actual Top Radius** is only used to determine span length for load rating if the **Structure Category** is" unsymmetrical/deformed more than 5%" or for "Long Span". For these cases, the **Span Length** used for the load rating is taken as two times the **Actual Top Radius**. **Actual Top Radius** is not use for the "typical" **Structure Category**.

Metal Type is selected from a menu and can be steel or aluminum. Aluminum is broken down into several thicknesses and alloy types. The material type is used to determine general material

properties; yield point, tensile strength, and modulus of elasticity. This information is stored in lookup tables within the *Reference Tables* worksheet.

Corrugation and **Gage Number** for the corrugated pipe or plates are selected from a drop down menu. The **Gage Number** is used to lookup the thickness of the CMP from the *Reference Tables* worksheet. The **Corrugation** type is used to determine the cross sectional area of the wall, the radius of gyration of corrugation, and the moment of inertia of the pipe. These values must be looked up and entered by the user in the *CMP Rating Calculations* worksheet. "N/A" must be selected from the lists if the values are not known, in which case values for **c**, **d**, and **t** must be entered. "N/A" triggers the calculations to use the values for **c**, **d**, and **t**.

c,**d**, & **t** values are required to be measured on the structure if the **Corrugation** and **Gage Number** are not known. Detail B in Figure 1 shows how these measurements are made. **c** is the distance between peaks in the corrugation (spacing). **d** is the distance from the peak to the valley (depth) of the corrugation. **t** is the thickness of the material. The user must use these values to determine a Corrugation and Gage thickness as shown in the Reference Tables worksheet and enter the appropriate properties in the *CMP Rating Calculations* worksheet.

Pipe Crown Deflection is measured as the reduction in **Rise** divided by the **Span Length** from the design shape, entered as a percentage. This is only used if Structure Category is "unsymmetrical/deformed". The pipe crown deflection is used to determine the buckling strength reduction factor.

Metal Loss Based on Materials Field Evaluation is used to determine the section properties reduction factor on the basis of metal loss. *NCSPA Design Data Sheet No. 19* Section B.2 provides guidance on measuring and assessing metal loss.

CMP Rating Calculations Worksheet

Design Dimensions reproduces information entered in *Input-Structure Info*.

For typical structures the **Design Span** is reported from the **Span Length (S)** entered in the *Input-Structure Info* worksheet. For unsymmetrical, deflected long span structures **Design Span** is calculated as two times the **Actual Top Radius** entered in the *Input-Structure Info* worksheet.

Buckling Strength Reduction Factor is calculated based on **Pipe Crown Deflection**, if entered. The formula is based on figure B.1.1 on page 7 of NCSPA Design Data Sheet No 19.

Structure Category is displayed as entered in the *Input-Structure Info* worksheet.

The appropriate **Span Length** is determined based on the **Structure Category**. The **Top Radius** and the $R_{t(max)}$(maximum top radius for long-span structures) are shown and used, as appropriate, to determine the thrust on the culvert wall.

Design Properties displays material and section properties for the culverts.

Metal Type is displayed as selected in the *Input-Structure Info* worksheet.

F_y (minimum yield point), **F_u** (minimum tensile strength), and **E** (modulus of elasticity) for the material are determined from the *Reference Tables* worksheet based on the **Metal Type**.

Corrugation and **Gage Number** will be displayed if entered in the *Input-Structure Info* worksheet. If these were not entered then the values for **c** and **d** will appear. The thickness (**t**) will be displayed as entered in Input-Structure Info or as determined from the *Reference Tables* worksheet based on the entry for **Gage Number**.

Minimum Thickness (t_{min}) is displayed only if a long-span structure is selected. The value for **t_{min}** is determined from AASHTO Table 12.7.2A I.

The user is required to enter values for cross-sectional area (**A_s**), radius of gyration (**r**), and the moment of inertia (**I**) for the cross section of the structure. The S*ection Property Tables* worksheet contains these values for steel and aluminum culverts of various seam types, corrugation, and gage number.

The ***Design Calculations*** section contains the calculations associated with the load rating of a culvert.

Structure, **Seam Type**, and **Longitudinal Length of Structure** entered in the *Input-Structure Info* worksheet are displayed.

AASHTO Minimum Cover is calculated in the *Reference Tables* worksheet based on the **Structure Type** entered on the *Input-Structure Info* worksheet.

Height of Cover above Crown (H) is equal to the minimum of the **Fill Depth at Centerline of Roadway** and **Fill Depth at Edge of Pavement** values entered in the *Input-Structure Info* worksheet.

Section Properties Reduction Factor (φ_{loss}) is a direct reduction in the cross sectional thickness due to material loss and is calculated by subtracting the **Metal Loss Based on Field Evaluation** in the *Input-Structure Info* worksheet from 100%.

Capacity Modification Factor for Wall Area and Buckling (φ_1) is to be entered from AASHTO 12.6.1.3.

Capacity Modification Factor for Seam Strength (φ_2) is determined from AASHTO 12.6.1.3 based on the **Seam Type**.

Soil Density (δ) of the material placed above the culvert is to be entered by the user.

Soil Stiffness Factor (k) of the soil is entered by the user from AASHTO 12.3.2.

Critical Buckling Stress (F_{cr}) is calculated determined from AASHTO 12.3.2, Equations 12-8 and 12-9.

Seam Strength is entered based on **Metal Type**, **Corrugation**, and **Gage Number** from the S*eam Strength Tables* worksheet. In some cases, the number of bolts per foot must be field measured to determine the proper **Seam Strength**.

T_{cap} (thrust capacity of the wall)is the minimum capacity of the structure considering wall yield, wall buckling, and seam strength. These are determined from the equations presented in AASHTO 12.3.1,12.3.2 and 12.3.3 respectively.

T_E (pipe wall thrust due to earth cover is determined from the weight of soil placed above the culvert. For typical structures the **Actual Span (S)** is used for determining the wall thrust. For unsymmetric/deformed or long-span structures the maximum thrust determined from either the **Actual Span (S)** or the **R_t (**Actual Top Radius).

Depth of Fill (H) is the **Height of Cover Above Crown (H).**

Live Load Impact is determined from AASHTO 3.8.2.3 based on **Height of Cover Above Crown (H)**.

The **Surface Tire Contact Area** for the HS20 truck was determined from AASHTO 3.30. This same tire contact area was taken as the tire contact area for the Michigan Legal Vehicles (1, 2, and 3-unit).

Fill Depth (H), **Structure Total Length (L)**, and **Clear Roadway Width** are all shown as entered in the *Input-Structure Info* worksheet.

Lane Width is calculated for the roadway as per AASHTO 3.6.

The **Number of Lanes** is calculated as the **Clear Roadway Width/Lane Width**.

The **Truck Load at Depth** table is used to determine the live load effect on the wall thrust of the culvert for the HS20 truck, each of the controlling Michigan Legal Trucks (1, 2, and 3-unit), and Michigan Overload Trucks. A spreadsheet, a summary of which is contained in the *MI trucks* worksheet, was used to determine the controlling vehicle for each truck classification at depths from one to twenty feet.

Controlling Truck is reported from the *MI Trucks* worksheet based on **Fill Depth** for the HS20 and Michigan Legal Trucks. The Michigan Overload Truck classification must be selected by the user. The user should start with “Class A”. If Class A produces a load rating less than 1.0, then “Class B” should be selected. If “Class B” produces a rating less than 1.0 then select “Class C”.

Wheel Spacing on Axle is 6.0 feet for the HS20 and Michigan Legal Trucks but may be selected by the user for the Michigan Overload Truck and is the distance, center-to-center of wheel. The wheel spacing on the Michigan Overload Truck should include the out to out of the tire contact area for these vehicles as a tire contact area is not assumed given the variability in the number of wheels that may be used per axle. A diagram of wheel spacing for legal and overload is shown in Figure 2.

$W_{D\ Wheel}$ is the width of the wheel load distributed through the soil at the culvert depth (see Figure 2) and is calculated based on the AASHTO distribution factor of 1.75(H) plus the width of the **Surface Tire Contact Area** per AASHTO 6.4.1. Note this is not used for Michigan Overload Trucks given variability in the number of wheels that may be used per axle.

$W_{D\ axle}$ is the total distributed load width for the axle. The distributed width is dependent on whether the individual wheel loads on an axle overlap at depth as described in AASHTO 6.4.2. **$W_{D\ axle}$** is calculated as the minimum of the **Wheel Spacing on Axle** + **$W_{D\ wheel}$** or two times **$W_{D\ wheel}$**.

Max W_D/Lane Provided by Structure is used to limit the live load distribution width to the overall structure length divided by the number of lanes. The minimum of the **Structure Total Length** divided by the **Number of Lanes** or the distributed width associated with a truck occupying each lane as shown in Figure 2 divided by the **Number of Lanes**. The Michigan Overload Trucks are treated with one loaded lane.

Rating W_D is the minimum of **$W_{D\ axle(total)}$** and **Max W_D/Lane Provided by Structure** and is used to determine the distributed load on the culvert per lane.

Reduction in Load Intensity (AASHTO 3.12) is used to reduce the loading if three or more lanes are loaded. The effect of multiple loaded lanes at **Depths of Fill** ranging from 1 to 20 feet and 1 to 4 loaded lanes was studied. It was found that 2 loaded lanes at 100% of their load would control to 10 of fill depth. From 11 to 20 ft of fill, 3 loaded lanes (90%) controls.

NOTE: The formulas used for **Rating W_D** and **Reduction in Load Intensity** may be unconservative if the clear roadway width exceeds 72 feet for depths greater than 14 feet. If there are three or more lanes of traffic, the spreadsheet will assume two loaded lanes for depths up to and including 10 feet, and three loaded lanes for depths from 11 to 20 feet.

The Michigan Overload Trucks are treated with one loaded lane therefore there is no reduction in load intensity for these trucks.

Operating Truck Line Load + Impact is a line load (along the length of the truck in the direction of travel) representation of the controlling truck at the depth of the culvert. This value is retrieved from the *MI Trucks* worksheet based on the **Depth of Fill (H)**.

Load on Culvert, $\rho_{(L+I)}$ is the **Operating Truck Line Load + Impact** times the **Reduction in Load Intensity** divided by the **Rating W_D**.

$T_{(L+I)}$, is determined using the **Actual Span** for typical structures and the maximum of the **Actual Span** or the **Actual Top Radius** for unsymmetric/deformed or long-span structures.

The **Operating Load Rating Factors, RF_O** table calculates the operating rating factors based on live load and culvert strength.

T_{cap} and **T_E** were calculated previously in this worksheet and are reproduced in the summary table for Operating Load Rating Factors.

A **Live Load Factor** must be entered for the operating load rating. The *MI Trucks* tables include operating level live load factors for the Michigan Legal and Overload Trucks; however, the HS20 trucks were left unfactored due to the need to conduct both Inventory and Operating ratings. The appropriate live load factor for the HS20 truck should be entered. Values of 1.0 should be used for the Michigan Legal and Overload Trucks since the live load factor for these trucks has already been applied.

Factored $T_{(L+I)}$ applies the **Live Load Factor** to the value for **$T_{(L+I)}$** calculated in the Factored Truck Load at Depth table.

Is culvert buried deep enough to neglect LL? (AASHTO 6.4.2) This row of the table will say YES if the **Depth of Fill** is greater than both 8 feet and the **Span Length.**

Operating Load Rating Factor **(RF_O)** is the minimum value calculated based on wall strength (**RF_{O-W}**) and minimum cover requirements (**RF_{O-C}**) as described in *NCSPA Design Data Sheet No. 19.* If **Is culvert buried deep enough to neglect LL?** Is equal to YES, calculated rating factors are ignored, and a rating factor of 99.9 is used for all vehicles.

Inventory Load Rating Factor **(RF_I)** is the minimum value calculated based on wall strength (**RF_{I-W}**) and minimum cover requirements (**RF_{I-C}**) as described in *NCSPA Design Data Sheet No. 19*. The rating factor is determined by simply applying a ratio of 3/5 to the operating ratings. If **Is culvert buried deep enough to neglect LL?** Is equal to YES, calculated rating factors are ignored, and a rating factor of 99.9 is used for all vehicles.

The **Load Rating Summary** table presents a summary of the controlling Rating Factors along with the controlling truck for both Federal Inventory and Operating levels, Michigan 1-Unit, 2 Unit and 3 Unit at operating level and MI Overload.

The controlling Michigan Overload Vehicle is presented as Class A, B, or C depending on what was entered in the Truck Load at Depth table. If Class C was used and the rating factor was found to be less than 1.0, Class D will be displayed as per the Michigan Bridge Analysis Guide (2009).

MI Trucks Worksheet

The ***MI Trucks*** worksheet includes a summary of the calculated line loads for Federal, Legal and Overload trucks at depths ranging from 1' to 20'. This summary is taken from a larger spreadsheet that is not included in the CMP spreadsheet due to its size and complexity. The larger spreadsheet "Truck Combinations (10-16-12).xlsx" is available on the website.

Section Property Tables Worksheet

The ***section property tables*** worksheet is a reference table that is reproduced from AASHTO tables 12.4.3.1 and 12.4.3.2. This worksheet is used to determine the Area (A_s), Radius of Gyration (r) and moment of inertia (I) of the culvert section used. If Gage Number and Corrugation are known, A_s, r & I can be taken directly. If only c, d & t are known, the Corrugation can be determined from the table, and A_s, r & I can be determined.

Seam Strength Tables Worksheet

The ***seam strength tables*** worksheet is a reference table that is reproduces from AASHTO tables in section 12.4.2. The seam strength can be determined based on **Gage Number** or thickness **(t)**, **Corrugation**, **Metal Type, Seam Type,** and in some cases, measured bolt diameter.

NCSPA Design Data Sheet No 19 Worksheet

The **NCSPA Design Data Sheet No 19** worksheet is a full reproduction of the National Corrugated Steel Pipe Association data sheet for load rating and structural evaluation for in-service corrugated steel structures. This sheet, along with AASHTO Standard Specifications for Bridge Construction, 17th edition, is the basis for the MDOT CMP spreadsheet.