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Study Title:	**Assessment of ODOT Culvert Load Rating Spreadsheets for use in Michigan FINAL REPORT**
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Research Agency:	Michigan Technological University 1400 Townsend Drive Houghton, MI 49931
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Technical Report Documentation Page

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4. Title and Subtitle **CSD – Assessment of ODOT Culvert Load Rating Spreadsheets for use in Michigan**		5. Report Date **September 28, 2012** **Revised: January 23, 2013**	
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15. Supplementary Notes		13. Type of Report and Period Covered **Final Report** 14. Sponsoring Agency Code	
16. Abstract Existing spreadsheets developed by the Ohio Department of Transportation (ODOT) for performing bridge load rating calculations on corrugated metal pipe culverts were assessed for their adherence to reference guides and then modified as required to function with Michigan legal and overload trucks.			
17. Key Words: **Bridge Load Rating, Culverts, LFR, LRFR**		18. Distribution Statement **No restrictions. This document is available to the public through the Michigan Department of Transportation.**	
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Report RC-1590

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DISCLAIMER

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Background

The project "Assessment of ODOT Culvert Load Rating Spreadsheets for use in Michigan" was a short time-frame project funded by the Michigan Department of Transportation (MDOT) through the Center for Structural Durability (CSD) at Michigan Tech. The objective of the project was to assess existing spreadsheets developed by the Ohio Department of Transportation (ODOT) for performing load rating calculations on corrugated metal pipe culverts using both Load Factor Rating (LFR) and Load and Resistance Factor Rating (LRFR) methods. The spreadsheets were assessed for their adherence to reference guides and then modified as required to function with Michigan legal and overload truck descriptions. The project did not investigate the suitability of the technical process used in the ODOT spreadsheets to produce reasonable load rating calculations. Significant structural and programing changes to the spreadsheets were considered outside the project scope. Details on the work performed for this project are described in the following sections of the report.

Task 1 – Literature Review

The technical basis of the ODOT spreadsheets references "Load Rating and Structural Evaluation of In-Service, Corrugated Steel Structures" (NCSPA 1995) and the AASHTO Standard (AASHTO 2002) and LRFD (AASHTO 2010) specifications. The spreadsheets were developed around these references and have been tested through finite element and field testing as described in "Verification of ODOT's Load Rating Analysis Programs for Metal Pipe and Arch Culverts" (Sezen, H. et. al. 2009).

ODOT and The Ohio State University conducted a detailed assessment on the culvert spreadsheets through finite element model comparisons and field testing (Sezen, H. et.al. 2009). 39 in-service culverts were assessed as part of the project. Both static and dynamic loads were applied to the culverts, and deflection and strain gage measurements were taken at several locations within each culvert. Loading was accomplished with a heavily loaded truck representative of an HS20-44 at 10 static load points and 6 dynamic load speeds ranging from 5 to 40 mph or the maximum legal speed. Each test was conducted twice with the load applied once from each direction. An instrument frame was setup inside the culverts to measure the displacement at 5 locations along the upper circumference of the culvert and 14 strain gages were installed (Sezen, H. et. al. 2009).

Numerical modeling of the culverts was performed using CANDE, a two-dimensional finite element program typically used for corrugated culvert analysis. A Level 3 analysis was performed in the study which allowed for user defined geometrical shapes, soil material zones, and structural properties (Sezen, H. et. al. 2009).

Results of the field testing showed that a significant decrease in deflection and strain measurements was found when the culverts contained more than 6.5 feet of cover. Maximum deflections caused by dynamic loading were found to be 10 to 30% less than the corresponding static loading. Soil type is generally not considered when conducting a load rating on a culvert, the effect of soil type on thrust forces was found to be negligible (Sezen, H. et. al. 2009). Specifically with regards to the spreadsheets, the researchers found:

> For the worst possible culvert condition (i.e., the reduction factors have the minimum possible values for each culvert), proposed rating factors (RF) are smaller than ODOT's RFs and are also less than 1.0 for most culverts. This suggests that the research-proposed load rating procedure is less conservative and more effective in evaluation of the existing condition of culverts.

It was suggested that the ODOT spreadsheets be improved by incorporating condition factors, based on inspection reports, to reduce the seam and buckling strengths and wall area when determining the thrust capacity of the culvert. The ODOT spreadsheets do not contain version numbers or build dates and information was not available to identify if recommendations for change to the spreadsheets were incorporated.

Task 2 – Spreadsheet Assessment and Adherence to Reference Guides

The ODOT culvert load rating spreadsheets were compared to the AASHTO Standard and LRFD Specifications and the Michigan Bridge Analysis Guide (2009). The basic principles of load rating were met along with the load factors. The general procedure used by the ODOT spreadsheet is that described by the NSCPA (1995) report.

The ODOT spreadsheets consider loading from one vehicle on the culvert and limit the width of the loaded area (transverse to the direction of travel) to the length of the culvert. Individual wheel loads are distributed from the tire contact area downward in a pyramid shape with side slopes of 1.75 times the depth of cover for the LFR method and 1.15 times the cover for the LRFR method. When these pyramids overlap the distributed area of the combined loading becomes the total area enveloped by the parameter of the pyramids as shown in Figure 1.

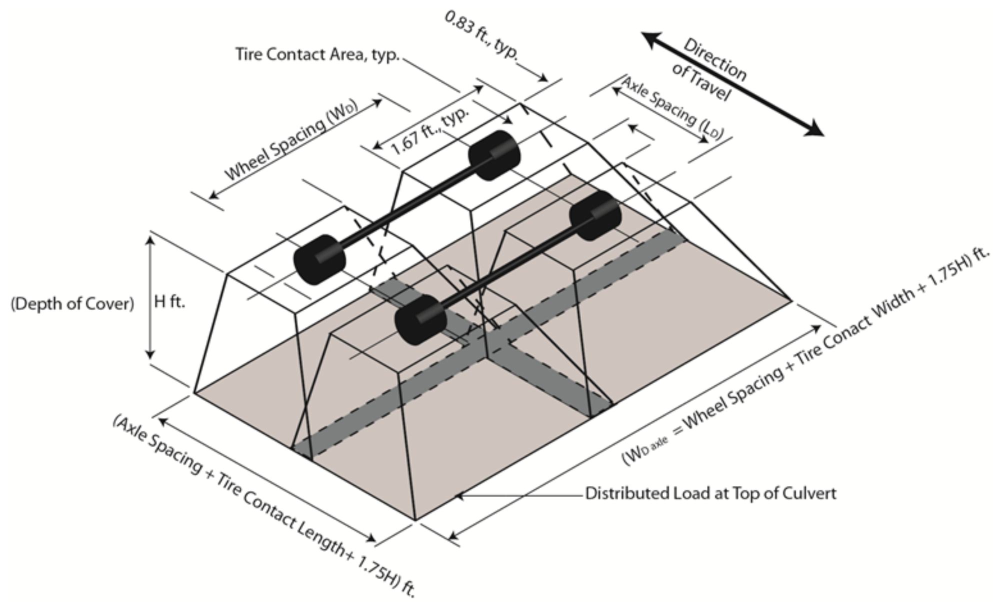

Figure 1 Distributed load (LFR) determined from axle weight

The ODOT spreadsheets use this area, however, the calculations used to determine the distributed load were based on one heavy axle and up to two adjacent axles placed within 4-feet of the heavy axle. The algorithm used to determine the distributed load from this description (up to three axle weights and spacing) was appropriate for the load configurations of ODOT trucks. However, for Michigan trucks this process would not have been appropriate and an alternative method had to be used.

The ODOT spreadsheets also do not account for the case where trucks are present in adjacent lanes. In this case, the distributed area could be further restricted depending upon the depth of cover. Modifications, explained in the next section of this report, were performed to determine the distributed load attributed to the controlling Michigan vehicle for the given depth of cover and allow for multiple loaded lanes in the Michigan modified spreadsheet.

The ODOT spreadsheets were found to meet the reference guidelines. The general procedure follows the NSCPA (1995) guidelines and AASHTO Standard and LRFD load and condition factors are utilized.

As per the project proposal, MDOT was contacted and a teleconference meeting was conducted to review the outcome of the first two project tasks prior to proceeding with Tasks 3 and 4 to modify the spreadsheets for Michigan vehicles and perform trial runs of the spreadsheet for quality control and quality assurance. Discussion with MDOT led to the decision to go forward with the project. A process was discussed for determining the controlling Michigan vehicle for each truck type at various depths which would greatly improve the functionality of the spreadsheet. This was determined to be outside the original scope of work and as such these calculations were conducted by MDOT and incorporated into the Michigan modified spreadsheets.

Task 3 – Michigan Modifications

The original spreadsheet developed by ODOT contained the analysis for Federal Trucks (HS20-44 or HL-93 Truck/Tandem) and the four Ohio Legal Trucks. This spreadsheet analyzed the heavy axle load and up to two adjacent axles provided they were located within 4-feet of the heavy axle. These axle loads were then used to calculate the average distributed load applied to the top of the culvert. The height of cover above the culvert was used to determine whether loading was based on the distributed area of an individual wheel, or one, two, or three axles. This approach worked well for the four Ohio Legal Trucks due to the legal axle configurations. However, the complexity of the Michigan trucks allowed for cases in which this approach would not have adequately represented the loading. To solve this problem, MDOT developed a spreadsheet to calculate the distributed load caused by the controlling truck for each vehicle classification (one, two, or three unit) at 0.25 foot increments from 0.25 to 2.0-feet of cover (LRFR), 0.5 foot increments from 2.0 to 4.0-feet, and 1.0 foot increments from 4.0 to 20.0 feet. Data was produced for the LRFR method for depths less than 2.0 feet because of the spreadsheet for modified minimum cover is only available for LRFR. The distributed loading was summarized in the form of a line load that represented the weight of the vehicle distributed along the length of the vehicle but not the width. The distribution of the line load over the width was handled by the Michigan modifications to the load rating spreadsheets due to the need to consider the individual properties of each culvert. A sample of the summary table for controlling trucks with the LFR method is shown in Table 1.

Table 1 Sample of MDOT controlling vehicle summary table

FEDERAL - UNFACTORED!!!							
Depth (ft)	1	1.5	2	2.5	3	3.5	4
HS-20 (k/ft)	12.39	9.25	7.38	6.14	5.26	4.60	4.09
Controlling Axles	1-Axle	1-Axle	1-Axle	1-Axle	1-Axle	1-Axle	1-Axle
MICHIGAN LEGAL - FACTORED							
Depth (ft)	1	1.5	2	2.5	3	3.5	4
1 Unit (k/ft)	9.06	6.77	5.40	4.78	4.34	3.98	3.69
Controlling Truck	Truck 1	Truck 1	Truck 1	Truck 2	Truck 2	Truck 2	Truck 4
2 Unit (k/ft)	9.06	6.77	5.40	4.78	4.42	4.30	4.18
Controlling Truck	Truck 6	Truck 6	Truck 6	Truck 6	Truck 17	Truck 17	Truck 17
3 Unit (k/ft)	9.06	6.77	5.40	4.78	4.34	3.98	3.69
Controlling Truck	Truck 19	Truck 19	Truck 19	Truck 19	Truck 19	Truck 19	Truck 22
MICHIGAN OVERLOAD Class A - FACTORED							
Depth (ft)	1	1.5	2	2.5	3	3.5	4
OverLoad (k/ft)	30.19	22.55	18.00	14.98	12.82	11.21	9.96
Controlling Truck	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1
MICHIGAN OVERLOAD Class B - FACTORED							
Depth (ft)	1	1.5	2	2.5	3	3.5	4
OverLoad (k/ft)	30.19	22.55	18.00	14.98	12.82	11.21	9.96
Controlling Truck	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1
MICHIGAN OVERLOAD Class C - FACTORED							
Depth (ft)	1	1.5	2	2.5	3	3.5	4
OverLoad (k/ft)	30.19	22.55	18.00	14.98	12.82	11.21	9.96
Controlling Truck	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1	Truck 1
Note: All loads are in k/ft along the length of the truck							

The tire contact area is specified by AASHTO for the HS20-44 and HL-93 trucks as being 10 inches in the direction of travel by 20 inches wide. The same tire contact area was used for the Michigan Legal Vehicles. Michigan Overload Vehicles could have many more tires associated with each axle, therefore, the tire contact area was assumed to be contained within the 8-foot wheel spacing.

The distributed load at the depth of the culvert was computed by using an Excel lookup function to determine the controlling truck line load from the summary table of controlling Federal and Michigan loads. This line load was distributed across the appropriate loading width. The width for each truck was determined by taking the wheel spacing on each axle (6-feet plus the tire contact area for legal vehicles and 8-feet for overload vehicles) and adding the soil distribution factor multiplied by the depth of cover. Figure 2 shows how the distributed width of each wheel was used to determine the width for an axle.

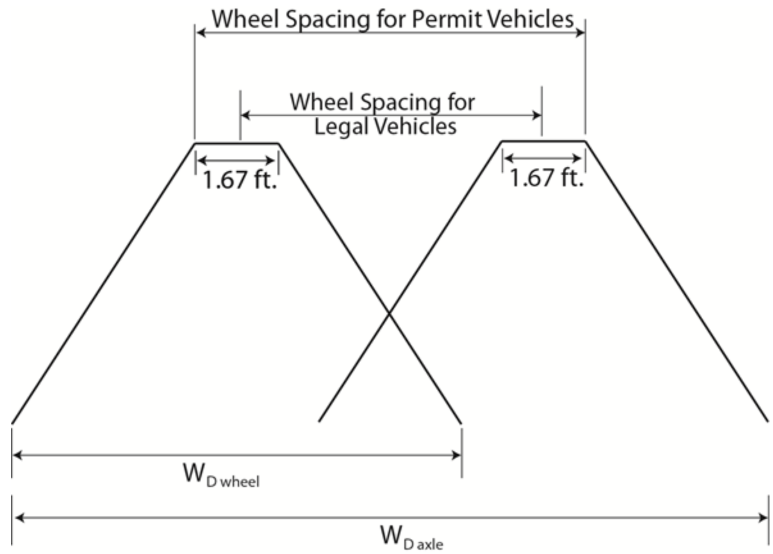

Figure 2 Distributed width from wheel spacing

The axle width was then limited by the width per lane provided by the structure which was found by taking the minimum of the structure length divided by the number of lanes and the distribution caused by a vehicle placed in each traffic lane with the outer vehicles located the minimum 2-feet from the inner lanes. Figure 3 shows a diagram of loading from multiple lanes and how it was used to determine the maximum allowable distributed width of vehicular loading.

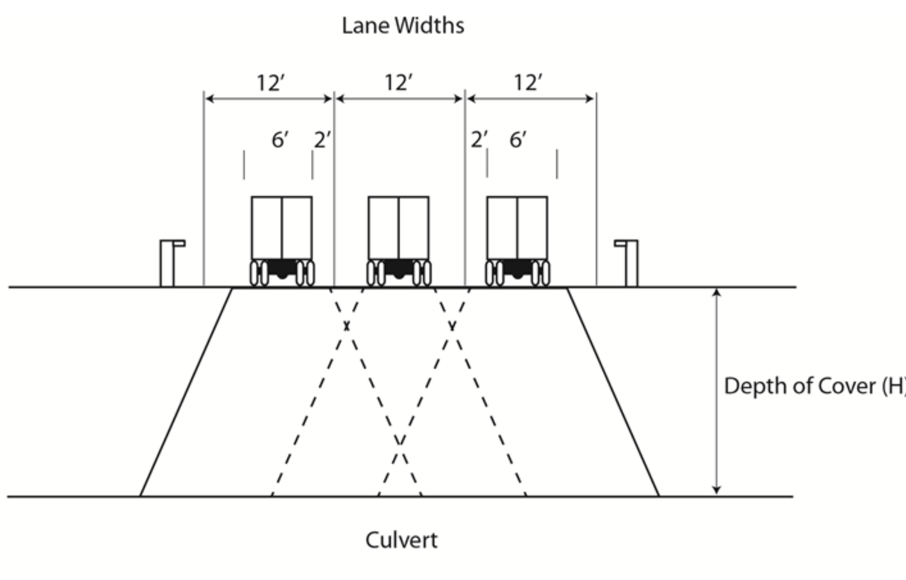

Figure 3 Distributed width limited by multiple loaded lanes

Michigan has modified live load factors for the LRFR method. Each vehicle has its own live load factor which changes with the average daily truck traffic (ADTT) of the roadway. Live load factors are determined at ADTT of 100, 1000, and 5000. The live load factors for each vehicle at an ADTT of 5000 were incorporated into the controlling vehicle spreadsheet to determine the controlling truck at each depth. For consistency, the summary table (Table 1) for the LFR controlling trucks also included factored values for the legal and overload vehicles. The Federal vehicles were left unfactored due to the need to have different live load factors for the inventory and operating ratings.

Formatting modifications were made to the Michigan modified spreadsheets to achieve consistency with other MDOT spreadsheets. Drawings showing loading details were redone and labels were updated to agree with the values contained within the spreadsheet. Several new figures were added to show how the axle loads were used to determine the distributed load applied to the top of the culvert (Figures 1-3).

The NCSPA Design Data Sheet No. 19 had been scanned and included within the ODOT spreadsheet. The scanned copy was out of focus and hard to read. This worksheet was redone for the MDOT Modified version of the spreadsheets.

Task 4 – Trial Runs

The modified spreadsheets (Appendix A) were run through several validation processes during QA/QC. Two researchers reviewed the spreadsheets; one focused on an analysis of the programing within the spreadsheet and checked cell references and functions. The other researcher checked the technical content and verified the spreadsheet calculations with hand calculations and then performed analysis on a variety of in-service culverts.

Results of the QA/QC are included in Appendix B. No errors were found in the programing; however, some suggestions were noted for improvement on the programing under a future project. Analysis of the technical content also found no errors but proved to be a good source for comments on updates that could be made to the program in the future under another project.

Task 5 – Final Report and Deliverables

Deliverables for this project consist of the following three Excel 2010 files along with this report:

- Michigan modified load factor rating method for corrugated metal pipe, Version 1.0
  - MDOT_CMP_LFR.xlsx
- Michigan modified load and resistance rating method for corrugated metal pipe, Version 1.0
  - MDOT_CMP_LRFR.xlsx
- Michigan modified load and resistance rating method for corrugated metal pipe with a modification for minimum cover requirements, Version 1.0
  - MDOT_CMP_LRFR_modified_minimum_cover.xlsx

Future Work

- As with any program, future updates will be required to keep the spreadsheet up to date on changes in the specifications and to make improvements on the usability and to meet the needs of those using the spreadsheets. Attempts were made to increase the efficiency of the programing and improve the layout within the spreadsheets. However, more work could be done to further improve efficiency, usability, and reporting format although a complete rewrite was out of the scope of this project.
- These Excel spreadsheets meet the immediate needs for the load rating of culverts through both the LFR and LRFR methods. However, the ability to store culvert data in a database that could be accessed through a standalone culvert program or web application would allow for updates to the programing without the need to re-input large amounts of data into individual spreadsheets. A standalone program would also eliminate the likelihood of users accidently making changes to the program, however, it could be written to include user defined values where engineers may desire to allow their own calculations to be used instead of those within the program. Database storage would also allow for better organization of the culvert files for agencies with large numbers of culverts in their inventory.

References

AASHTO (2002) Standard Specifications for Highway Bridges, 17th Edition. American Association of State Highway and Transportation Officials.

AASHTO (2010) AASHTO LRFD Bridge Design Specifications, 5th Edition. American Association of State Highway and Transportation Officials.

AASHTO (2011) The Manual for Bridge Evaluation, 2nd Edition. American Association of State Highway and Transportation Officials.

MDOT (2009) Bridge Analysis Guide, 2005 Edition with 2009 Interim Update. Michigan Department of Transportation, Construction and Technology Support Area.

NSCPA (1995) Load Rating and Structural Evaluation of In-Service, Corrugated Steel Structures, NCSPA Design Data Sheet No. 19, National Corrugated Steel Pipe Association, Dallas, TX.

Sezen, H., Fox, P., and Yeau, K. (2009) Verification of ODOT's Load Rating Analysis Programs for Metal Pipe and Arch Culverts. The Ohio State University, Ohio Department of Transportation State Job Number 134225.

Appendices

OWNER	MDOT/Superior	SPREADSHEET VERSION		1.0	10/12/2012
SECTION	B01 of 11111	COMP. BY	ABC	DATE	10/1/2012
DESCRIPTION	Pleasant Road Over Raging River	CHECK BY	DEF	DATE	10/9/2012

Load Factor Rating (LFR):

CORRUGATED METAL STRUCTURE (CIRCULAR & PIPE ARCH) & ARCHES

Adapted by MDOT from the original spreadsheets developed by the Ohio DOT

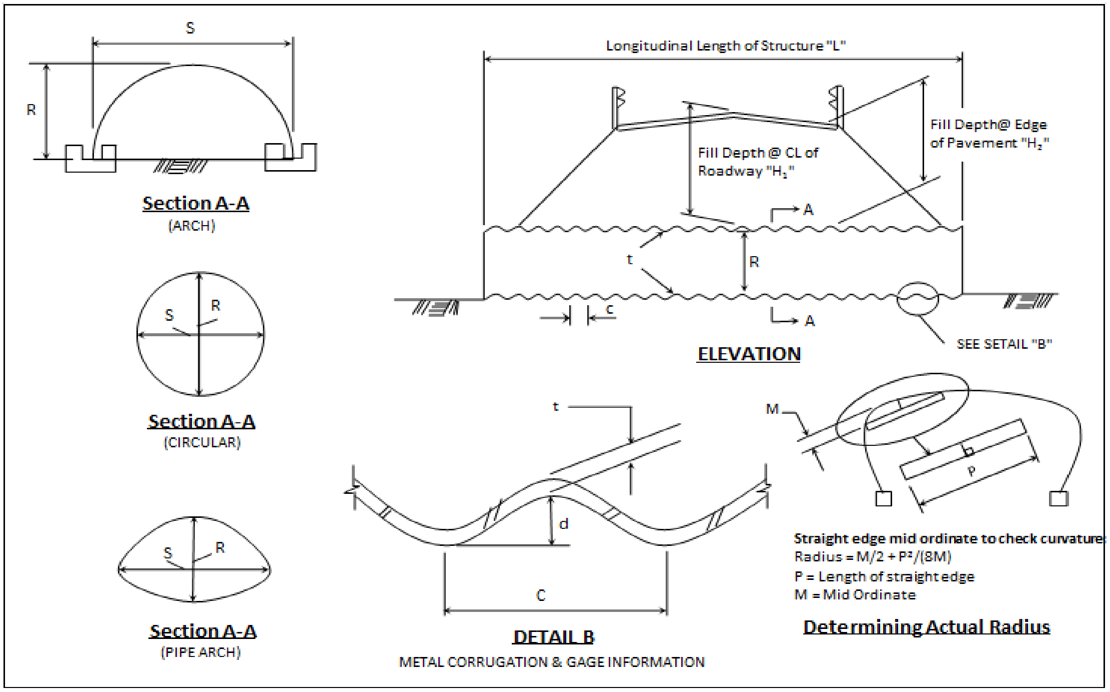

Figure 1: Measurement of Culvert Properties

* For unsymmetrical structures, structures deflected more than 5% from design shape, or those that show localized distortions require that the actual maximum radius be determined in those distorted areas as show above. Use two times the actual maximum radius rather than the span in structural design checks. Typically this provides a conservative evaluation of the structure. Calculate maximum existing top radius by taking measurements around the upper periphery of the culvert using a ruler of length "P" to obtain values of "M". This should be done at selected stations along length of culvert, particularly at locations with noticeable sag.

Structure Information (from existing bridge plans & field measurements):

Structure Type (to determine Minimum Cover):		Corrugated Metal Pipe (AASHTO 12.4)	←: choose from a drop-down list
Seam Type (to determine Seam Strength):		Annular pipe w/ spot welded, riveted or bolted seam	←: choose from a drop-down list
Structure Category (based on NCSPA Design Data Sheet No. 19)		Typical (NCSPA design data sheet No. 19, II. A. 1.)	←: choose from a drop-down list
Fill Depth at Centerline of Roadway "H_1" (ft) =		1.25	Minimum cover measured from top of rigid pavement, bottom of flexible pavement, AASHTO12.4.1.5 (Minimum for this spreadsheet is 1.0 ft)
Fill Depth at Edge of Pavement "H_2" (ft) =		1.25	
Span Length "S" (ft) =		10.00	
Rise "R" (ft) =		6.00	(For documentation purposes, not used in calculations)
Longitudinal Length of Structure "L" (ft) =		46.00	
Clear Roadway Width (Face to face of gaurdrail) (ft) =		36.00	
Determine Actual Top Radius "R_t" (ft) = (can be determined by field measurements* or hand calculations)		0.00	see * above
Metal Corrugation & Gage Information:	Metal Type:	Steel	←: choose from a drop-down list
	Corrugation (if known):	6 x 2 (steel structural plate pipe)	←: choose from a drop-down list
	Gage number (if known):	3	←: choose from a drop-down list
	c (in) =		**Note**: if corrugation & gage number are known, leave the input cells for "c", "d" & "t" blank; if corrugation & gage number are unknown, field measurements of "c", "d" & "t" are required.
	d (in) =		
	t (in) =		
Pipe Crown Deflection** (if any) =		0%	
Metal Loss based on materials field evaluation (if any) =		0%	

** reduction in rise divided by the span length from design shape in the unit of percentage

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Load Factor Load Rating of In-Service, Corrugated Metal Pipe Structures

Based on NCSPA Design Data Sheet No. 19 & AASHTO Standard Specification for Highway Bridges
Adapted by MDOT from the original spreadsheets developed by the Ohio DOT

DO NOT use this spreadsheet to load rate Structural Plate Box Culverts

Design Dimensions

1. For **typical structures**, use the actual field measured span for calculations.
2. For **unsymmetrical structures or those deflected over 5%**:
   a. use 2 x the top radius (2 R_t) in lieu of span for calculations.
   b. base critical buckling stress calculations on the theoretical design span, reducing the resulting allowable buckling stress by the appropriate buckling strength reduction factor " f " (NCSPA Design Data Sheet No. 19, Figure B.1.1).
3. For all **long span structures** (horizontal ellipse, low and high profile arches, inverted pear shapes and pear arches), as well as other horizontal ellipses, use 2 x actual top radius ($2R_t$) in all cases.

For typical structures :	Design Span = Actual Span "S" (ft) =	10.00
For unsymmetrical or deflect more than 5% structures:	Design Span (ft) = $2R_t$ =	0.00
	Pipe Crown Deflection =	0%
	Buckling Strength Reduction Factor, f =	0.95
long span structures:	Design Span (ft) = $2R_t$ =	0.00

Structure Category:	Typical (NCSPA design data sheet No. 19, II. A. 1.)

Then, **Span Length** used in Load Rating Calculation(ft) =	10.00	Warnings:
Then, $\mathbf{R_t}$ used in Load Rating Calculation (ft) =	0.00	
$\mathbf{R}_{t\,(max)}$ * (ft) =		

* Maximum Plate Radius allowed if Long Span Structural Plate Structures Selected

Design Properties

Mechanical Properties:

Metal Type:	Steel	
F_y = Minimum Yield Point of the Metal	33	ksi
F_u = Minimum Tensile Strength of the Metal	45	ksi
E_m = Modulus of elasticity of metal	29000	ksi

Section Properties:

Corrugation:	6 x 2 (steel structural plate pipe)	
Gage Number:	3	
c (in) =		
d (in) =		Warnings:
t (in) =	0.249	
$t_{(min)}$** (in) =		

** Required Minimum Top Arc Thickness if Long Span Structural Plate Structures Selected

A_s (in^2/ft) =	2.003	input these values based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "section property tables".
r* (in) =	0.6840	
I x 10^{-3} (in^4/in) =	78.175	

* r =radius of gyration of corrugation (in)

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Design Calculations:

Structure Type:	Corrugated Metal Pipe (AASHTO 12.4)	
Seam Type:	Annular pipe w/ spot welded, riveted or bolted seam	
Longitudinal Length of Structure "L" (ft) =	46.00	Warnings:
AASHTO minimum cover, h (ft) =	1.25	
Height of cover above crown "H" (ft) = (the lowest cover over the structure in a traffic area based on field measurement)	1.25	
φ_{loss} = Section Properties reduction factor on the basis of metal loss from the materials field evaluation =	1.00	
φ_1 = capacity modification factor for wall area and buckling (AASHTO Std. 12.6.1.3)	1.0	
φ_2 = capacity modification factor for seam strength (AASHTO Std. 12.6.1.3)	0.67	
δ = Soil density (k/ft^3)	0.120	
k = soil stiffness factor =	0.22	

Calculate the F_{cr} (critical buckling stress) :

if: $S < \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}, then\ F_{cr} = F_u - \frac{F_u^{\ 2}}{48E_m}\left(\frac{kS}{r}\right)^2$

if: $S > \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}, then\ F_{cr} = \frac{12E_m}{(kS/r)^2}$

Compare: S (in) = 120.00 < $\frac{r}{k}\sqrt{\frac{24E_m}{F_u}}$ = 386.66

So: **F_{cr}** = 42.83 ksi

Calculate the T_{cap} (thrust capacity of the wall) :

Seam Strength (k/ft) = ***62.0*** Input the seam strength value based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "seam strength tables"

T_{cap} = less of:	1. wall yield strength = $\varphi_1\ \varphi_{loss}\ F_y\ A_s$ =	66.1
	2. wall buckling strength = f $\varphi_1\ \varphi_{loss}\ F_{cr}\ A_s$ =	85.8
	3. seam strength = φ_2 x (seam strength) =	41.5

So: **T_{cap}** = 41.5 k/ft

Calculate the T_E (pipe wall thrust due to earth cover) :

T_E = higher value of :	1. δ H (S/2) =	0.75	k/ft
	2. δ H R_t =	0.00	k/ft

So: **T_E** = 0.75 k/ft

Calculate the $T_{(L+I)}$ (pipe wall thrust due to live load plus impact) :

$T_{(L+I)}$ = higher value of :	1. $\rho_{(L+I)}$ (S/2) =	k/ft
	2. $\rho_{(L+I)}$ R_t =	k/ft

Based on **AASHTO 3.8.2.3**:	Live load Impact, I =	30%	for 0'-0" < H < 1'-0"
		20%	for 1'-1" < H < 2'-0"
		10%	for 2'-1" < H < 2'-11"
		0%	for H ≥ 3'-0"

So, for this structure: Depth of Fill, **H**=	1.25	ft
I =	20%	
(1+**I**) =	1.20	

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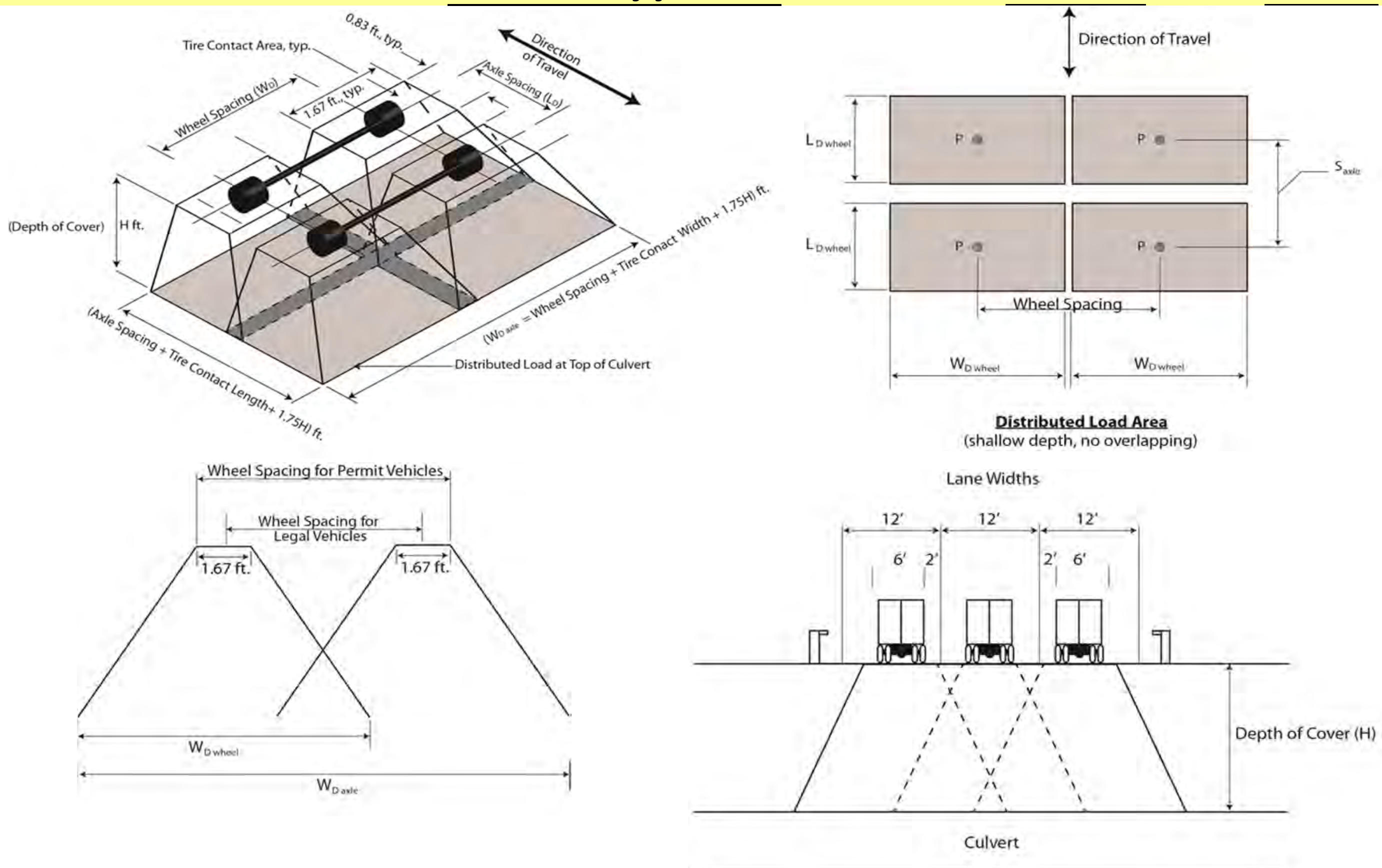

Figure 2: Load distribution through structural fill

Pressure on the tire contact area is distributed on the culvert through the cover depth, Dimension as:

$W_D = W_W + 1.75H$

$L_D = L_W + 1.75H$

The surface tire contact area for HS20 loading (per AASHTO 3.30)**:**

W_W = 20" =	1.67	ft
L_W = 10" =	0.83	ft

The tire surface contact area for Legal MI Trucks is assumed to be the same as the HS 20 truck.

The tire surface contact area for MI overload vechicles is considered to be part of the measurement for wheel spacing on axle (out to out)

Fill depth, H (ft) =	1.25
Structure Total Length, L (ft) =	46.00
Clear Roadway Width (Face to face of gaurdrail) (ft) =	36.00
Lane Width (ft) =	12.00
Number of Lanes =	3

Factored Truck Load at Depth

	HS20	MI 1-Unit	MI 2-Unit	MI 3-Unit	MI Overload
Controling Truck	**1-Axle**	**Truck 1**	**Truck 6**	**Truck 19**	**Class A** ←
wheel spacing on axle	6.00	6.00	6.00	6.00	8.00
$W_{D\ wheel}$ (ft)	3.85	3.85	3.85	3.85	
$W_{D\ axle(total)}$	7.71	7.71	7.71	7.71	10.19
Max W_D/lane provided by structure	10.06	10.06	10.06	10.06	38.19
Rating W_D	7.71	7.71	7.71	7.71	10.19
Reduction in Load Intensity	1.00	1.00	1.00	1.00	
Operating Truck Line Load + Impact (k/ft)	14.86	10.87	10.87	10.87	36.23
Load on Culvert, $\rho_{(L+I)}$	1.93	1.41	1.41	1.41	3.56
$T_{(L+I)}$ (k/ft)	9.64	7.05	7.05	7.05	17.78

Longitudinal pressure overlaps are considered for each MI truck configuration

Multi-lane overlap is assumed for MI legal and HS-20 trucks

Single-lane is assumed for MI overload vehicles

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Load Rating Factors for Ring Compression Structures:

Operating Load Rating Factor (RF_O):

a. RF_O based on wall strength

$$RF_{O-W} = \frac{T_{cap} - 1.95T_E}{T_{(L+I)}}$$

*Note: $T_{(L+I)}$ is factored

b. RF_O based on minimum cover requirements

$$RF_{O-C} = \frac{H^2}{C(h)^2}$$

Where, $C = 2.36\frac{H}{S} + 0.528 \leq 1.0 =$ 0.82

Warning:

Operating Load Rating Factors, *RF O*					
	HS20	**MI 1-Unit**	**MI 2-Unit**	**MI 3-Unit**	**MI Overload**
T_{cap}	41.54	41.54	41.54	41.54	41.54
T_E	0.75	0.75	0.75	0.75	0.75
Live Load Factor	1.30	1.00	1.00	1.00	1.00
Factored $T_{(L+I)}$	12.53	7.05	7.05	7.05	17.78
Is culvert burried deep enough to neglect LL?	NO	NO	NO	NO	NO
RF_{O-W}	3.20	5.68	5.68	5.68	2.25
RF_{O-C}	1.22	1.22	1.22	1.22	1.22
RF_O	1.22	1.22	1.22	1.22	1.22

Note:

2. Inventory Load Rating Factor (RF_i):

a. RF_i based on wall strength

$$RF_{i-w} = \frac{3}{5}RF_{O-W}$$

b. RF_i based on minimum cover requirements

$$RF_{i-c} = \frac{H^2}{h^2}$$

Inventory Load Rating Factor, *RF i*	
	HS20
RF_{i-w}	1.92
RF_{i-c}	1.00
RF_i	1.00

Load Rating Summary:				
		Controling Truck	***Rating Factor***	Warnings:
Inventory	Federal	HS20	RF=1.00	
Operating	Federal	HS20	RF=1.22	
	MI 1-Unit	Truck 1	RF=1.22	
	MI 2-Unit	Truck 6	RF=1.22	
	MI 3-Unit	Truck 19	RF=1.22	
	MI Overload	Class A	RF=1.22	

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MDOT

Load & Resistance Factor Rating (LRFR)

CORRUGATED METAL STRUCTURE (CIRCULAR & PIPE ARCH) & ARCHES

Adapted by MDOT from the original spreadsheets developed by the Ohio DOT

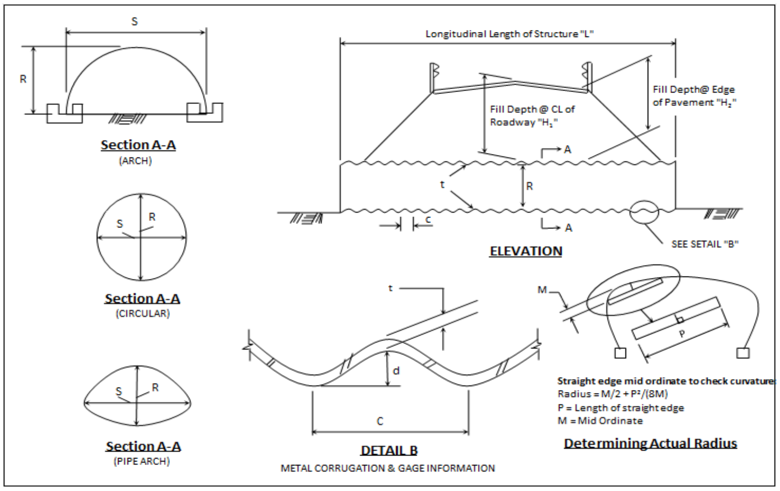

Figure 1: Measurement of Culvert Properties

* For unsymmetrical structures, structures deflected more than 5% from design shape, or those that show localized distortions require that the actual maximum radius be determined in those distorted areas as show above. Use two times the actual maximum radius rather than the span in structural design checks. Typically this provides a conservative evaluation of the structure. Calculate maximum existing top radius by taking measurements around the upper periphery of the culvert using a ruler of length "P" to obtain values of "M". This should be done at selected stations along length of culvert, particularly at locations with noticeable sag.

Structure Information (from existing bridge plans & field measurements):

Structure Type (to determine Minimum Cover):		Corrugated Metal Pipe	← choose from a drop-down list	
Seam Type (to determine Seam Strength):		Annular pipe w/ spot welded, riveted or bolted seam	← choose from a drop-down list	
Structure Category (based on NCSPA Design Data Sheet No. 19)		Typical (NCSPA design data sheet No. 19, II. A. 1.)	← choose from a drop-down list	
* Depth of Fill "H" (ft) = (fill depth used for dead load calculations)		3.60	Warnings:	
* Minimum Cover Depth "H_{min}" (ft) = (fill depth used to check minimum cover requirement)		3.60		
Span Length "S" (ft) =		10.00		
Rise "R" (ft) =		6.00	(For documentation purposes, not used in calculations)	
Longitudinal Length of Structure "L" (ft) =		46.00		
Clear Roadway Width (Face to face of gaurdrail) (ft) =		36.00		
Actual Top Radius "R_t" (ft) = (can be determined by field measurements or hand calculations)		0.00	see * above	
Metal Corrugation & Gage Information:	Metal Type	Steel	← choose from a drop-down list	
	Corrugation (if known)	6 x 2 (steel structural plate pipe)	← choose from a drop-down list	
	Gage number (if known)	8	← choose from a drop-down list	
	c (in) =		**Note**: if corrugation & gage number are known, leave the input cells for "c", "d" & "t" blank; if corrugation & gage number are unknown, field measurements of "c", "d" & "t" are required.	
	d (in) =			
	t (in) =			
Pipe Crown Deflection ** (if any) =		0%		
Metal Loss based on materials field evaluation (if any) =		0%		
Pipe Cross-Section Properties	A_s (in^2/ft) =	2.003	input these values based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "**section property tables**".	
	r (in) =	0.6840		
	I x 10^{-3} (in^4/in) =	78.175		
Pipe Seam Strength	Seam Strength (k/ft) =	62.0	input the seam strength value based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "**seam strength tables**"	
Backfill	δ = Soil density (k/ft^3) =	0.120		
	φ_E = Factor for Distribution of Live Load with Depth of Fill based on Backfill Type (per AASHTO LRFD 3.6.1.2.6)	1.15	1.15 used here for select granular backfill, change the factor φ_E to 1.0 for all other cases.	
Load Factors	η_R (for nonredundant members) =	1.05	AASHTO LRFD 12.5.4. & 1.3.4	
	γ_{EV} (Vertical Earth Pressure for CMPs) =	1.95	input the load factors based on the "**LRFR Load Factors**" table on the right	
	γ_{LL} (HL-93 Loading - Inventory) =	1.75		
	γ_{LL} (HL-93 Loading - Operating) =	1.35		
Condition Factor	ϕ_c =	1.00	AASHTO MBE 2nd Edition Table 6A.4.2.3-1 & C6A.4.2.3-1	
System Factor	ϕ_s =	1.00	AASHTO MBE 2nd Edition Table 6A.4.2.4-1	
	$\phi_c\ \phi_s \geq 0.85$ =	1.00		

** reduction in rise divided by the span length from design shape in the unit of percentage

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LRFR of In-Service, Corrugated Metal Pipe Structures

Based on AASHTO LRFD Bridge Design Specifications, Section 3, 4 & 12 & NCSPA Design Data Sheet No. 19

Adapted by MDOT from the original spreadsheets developed by the Ohio DOT

Do NOT use this spreadsheet to load rate Structural Plate Box Culverts

Design Dimensions

1. For **typical structures**, use the actual field measured span for calculations.
2. For **unsymmetrical structures or those deflected over 5%**:
   - **a.** use 2 x the top radius (2 R_t) in lieu of span for calculations.
   - **b.** base critical buckling stress calculations on the theoretical design span, reducing the resulting allowable buckling stress by the appropriate buckling strength reduction factor " f " (NCSPA Design Data Sheet No. 19, Figure B.1.1).
3. For all **long span structures** (horizontal ellipse, low and high profile arches, inverted pear shapes and pear arches), as well as other horizontal ellipses, use 2 x actual top radius (2Rt) in all cases.

For typical structures :	Design Span = Actual Span "S" (ft) =	10.00
For unsymmetrical or deflect more than 5% structures:	Design Span (ft) = 2R_t =	0.00
	Pipe Crown Deflection =	0%
	Buckling Strength Reduction Factor, f * =	0.95

* reduction factor f is based on NCSPA Design Data Sheet No 19, II Structural Evaluation A.2.b & Appendix B.1, Figure B.1.1 for Unsymmetrical structures or structures deflected over 5% only.

long span structures:	Design Span (ft) = 2R_t =	0.00
Structure Category:	Typical (NCSPA design data sheet No. 19, II. A. 1.)	

Then, **Span Length** used in Load Rating Calculation (ft)=	10.00	Warnings:
Then, **R_t** used in Load Rating Calculation (ft)=	0.00	
$R_{t\ (max)}$ * (ft) =		

* Maximum Plate Radius allowed if Long Span Structural Plate Structures Selected

Design Properties

Conduits Mechanical & Section Properties:

Mechanical Properties:

Metal Type:	Steel	
F_y = Minimum Yield Point of the Metal	33	ksi
F_u = Minimum Tensile Strength of the Metal	45	ksi
E_m = Modulus of elasticity of metal	29000	ksi

Section Properties:

Corrugation:	6 x 2 (steel structural plate pipe)	
Gage Number:	8	
c (in) =		
d (in) =		Warnings:
t (in) =	0.170	
$t_{(min)}$** (in) =		

** Required Minimum Top Arc Thickness if Long Span Structural Plate Structures Selected

A_s (in^2/ft) =	2.003
r (in) =	0.6840
I x 10^{-3} (in^4/in) =	78.175

Design Calculations:

Structure Type:	Corrugated Metal Pipe	
Seam Type:	Annular pipe w/ spot welded, riveted or bolted seam	
Longitudinal Length of Structure "L" (ft) =	46.00	Warnings:
AASHTO minimum cover, "h" (ft) =	1.25	
Depth of cover used to check AASHTO minimum cover requirment "H_{min}" (ft) =	3.60	
φ_{loss} = Section Properties reduction factor on the basis of metal loss from the materials field evaluation =	1.00	
φ_1 = Resistance Factor for **wall area and buckling** (Table 12.5.5-1)	1.00	
φ_2 = Resistance Factor for **seam strength** (Table 12.5.5-1)	0.67	
δ = Soil density (k/ft^3)	0.120	
k = soil stiffness factor =	0.22	
φ_E = Factor for Distribution of Live Load with Depth of Fill based on Backfill	1.15	

Calculate the f_{cr} (critical buckling stress) : (AASHTO LRFD 12.7.2.4)

if: $$S < \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}, then\ f_{cr} = F_u - \frac{F_u{}^2}{48E_m}\left(\frac{kS}{r}\right)^2$$

if: $$S > \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}, then\ f_{cr} = \frac{12E_m}{(kS/r)^2}$$

Compare: S (in) = 120.00 < $\frac{r}{k}\sqrt{\frac{24E_m}{F_u}} =$ 386.66

Therefore, f_{cr} = 42.83 ksi

Calculate the T_{cap} (thrust capacity of the wall) :

Seam Strength (k/ft) = 62.0

T_{cap} = less of:	1. wall yield strength = $\varphi_1\ \varphi_{loss}\ F_y\ A$ =	66.1
	2. wall buckling strength = f $\varphi_1\ \varphi_{loss}\ f_{cr}\ A$ =	85.8
	3. seam strength = φ_2 x (seam strength) =	41.5

Therefore, **T_{cap}** = 41.5 k/ft

Calculate the T_E (pipe wall thrust due to earth cover) :

T_E = higher value of :	1. δ H (S/2) =	2.16	k/ft
	2. δ H R_t =	0.00	k/ft

Therefore, **T_E** = 2.16 k/ft

Calculate the $T_{(L+I)}$ (pipe wall thrust due to live load plus dynamic load allowance) :

$T_{(L+IM)}$ = higher value of :	1. $\rho_{(L+IM)}$ (S/2) =	k/ft
	2. $\rho_{(L+IM)}$ R_t =	k/ft

$\rho_{(L+IM)}$: pressure at crown due to live load plus dynamic load allowance

Based on **AASHTO LRFD 3.6.2.2:**

Live load Dynamic Load Allowance, **IM** = 33(1.0-0.125 D_E) ≥ 0%

where, D_E = the minimum depth of earth cover above the structure (ft)

For this structure: Depth of Fill, D_E = **H**=	3.60	ft
IM =	18%	
(1+**IM**) =	1.18	

Calculations based on AASHTO LRFD 3.6.1.2.5 & 6:

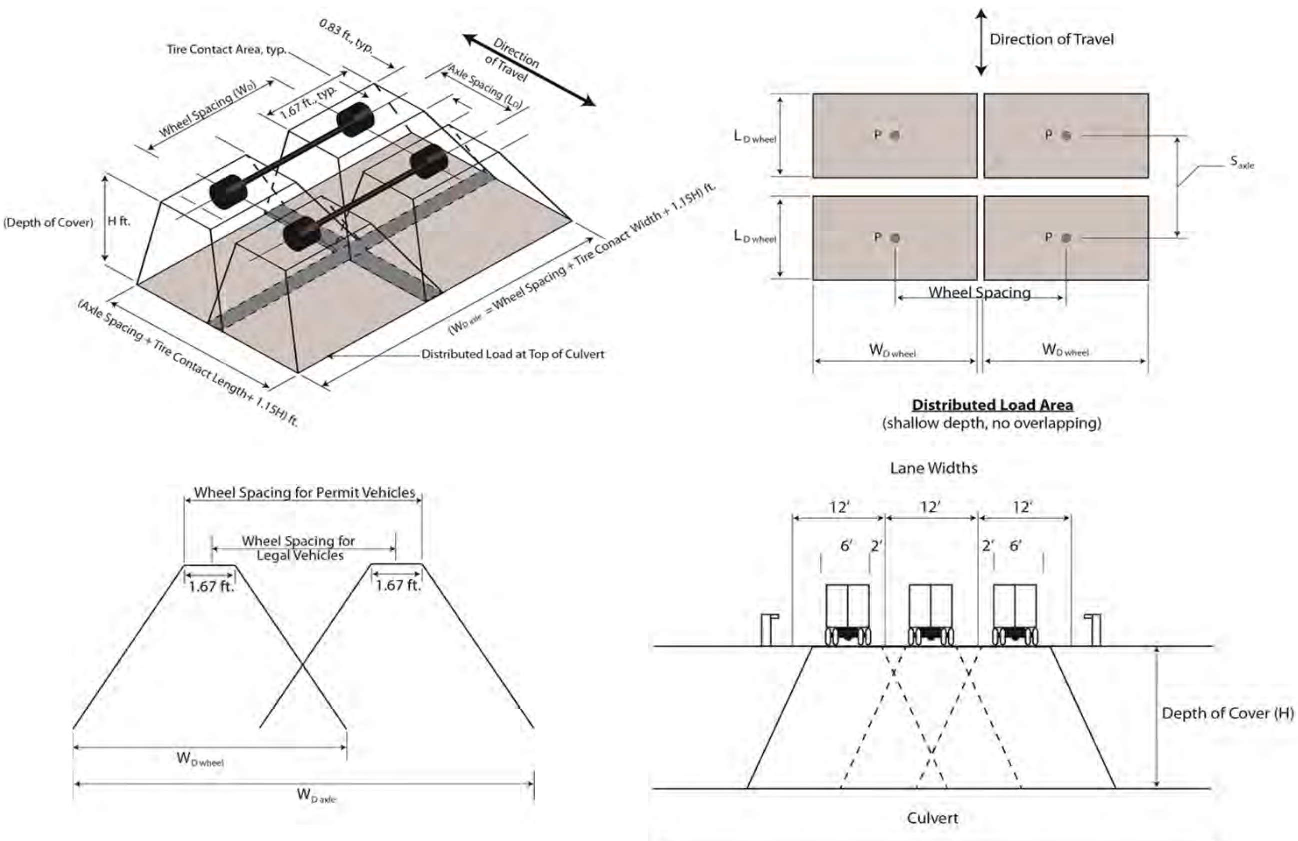

Figure 2: Load distribution through structural fill

Where, $\mathbf{W_T}$ = Tire contact width, $\mathbf{L_T}$ = Tire contact length, $\mathbf{W_D}$ = Distributed load width, $\mathbf{L_D}$ = Distributed load length

The surface tire contact area for HL-93 loading (also applied to MI trucks) (per AASHTO LRFD 3.6.1.2.5)**:**

$\mathbf{W_T}$ = 20" =	1.67	ft
$\mathbf{L_T}$ = 10" =	0.83	ft

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Distribution of wheel loads through earth fills (per AASHTO LRFD 3.6.1.2.6):

for **HL-93** Design Truck (also applied to MI trucks)

$W_D = 1.67 + \varphi_E H =$ 5.81 ft

$L_D = 0.83 + \varphi_E H =$ 4.97 ft

Depth of Fill, H (ft) =	3.60
Structure Total Length, L (ft) =	46.00
Clear Roadway Width (Face to face of gaurdrail) (ft) =	36.00
Lane Width (ft) =	12.00
Number of Lanes =	3

Truck Load at Depth

	HL-93 Truck/Tandem	MI 1-Unit	MI 2-Unit	MI 3-Unit	MI Overload
	(Unfactored)	(Factored)	(Factored)	(Factored)	(Factored)
Controling Truck	**1-Axle**	**Truck 2**	**Truck 10**	**Truck 20**	**Class A**
wheel spacing on axle	6.00	6.00	6.00	6.00	8.00
$W_{D\ Wheel}$(ft)	5.81	5.81	5.81	5.81	
Controlling number of loaded lanes	1	1	1	1	1
Controlling $W_{D\ axle(total)\ (ft)}$	11.61	11.61	11.61	11.61	12.14
Max W_D provided by structure (ft)	40.14	40.14	40.14	40.14	40.14
Rating W_D	11.61	11.61	11.61	11.61	12.14
Multiple Presence Factor	1.20	1.20	1.20	1.20	1.20
Impact + Operating Truck Line Load (k/ft)	7.78	8.14	8.14	7.49	20.28
Load on Culvert, $\rho_{(L+IM)}$	0.80	0.84	0.84	0.77	2.00
$T_{(L+IM)}$ (k/ft)	4.02	4.21	4.21	3.87	10.02

Load factors have not been applied to the HL-93 Truck and Tandem but will be in the next section

Transverse pressure overlaps are considered. Longitudinal pressure overlaps are considered for each MI truck configuration

Load Rating Factors for Ring Compression Structures:

1. **Operating** Load Rating Factor (RF_O):

a. RF_O based on wall strength

$$RF_{O-W} = \frac{\varphi_c \varphi_s T_{cap} - \gamma_{EV} \eta_R T_E}{\gamma_{LL} T_{(L+IM)}}$$

b. RF_O based on minimum cover requirements

$$RF_{O-C} = \frac{H_{\min}^{\ 2}}{C(h)^2}$$

Where, $C = 2.36 \frac{H_{\min}}{S} + 0.528 \leq 1.0 =$ 1.00

Operating Load Rating Factors, RF_O					
	HL-93 Truck/Tandem	**MI 1-Unit**	**MI 2-Unit**	**MI 3-Unit**	**MI Overload**
T_{cap}	41.54	41.54	41.54	41.54	41.54
$\phi_c\ \phi_s$	1.00	1.00	1.00	1.00	1.00
T_E	2.16	2.16	2.16	2.16	2.16
γ_{EV}	1.95	1.95	1.95	1.95	1.95
η_R	1.05	1.05	1.05	1.05	1.05
$T_{(L+IM)}$	4.02	4.21	4.21	3.87	10.02
γ_{LL}	1.35	1.00	1.00	1.00	1.00
Is culvert burried deep enough to neglect LL?	NO	NO	NO	NO	NO
RF_{O-W}	6.84	8.82	8.82	9.60	3.70
RF_{O-C}	8.29	8.29	8.29	8.29	8.29
RF_O	6.84	8.29	8.29	8.29	3.70
Note:					

2. Inventory Load Rating Factor (RF_i):

a. RF_i based on wall strength

$$RF_{i-W} = \frac{\varphi_c \varphi_s T_{cap} - \gamma_{EV} \eta_R T_E}{\gamma_{LL} T_{(L+IM)}}$$

b. RF_i based on minimum cover requirements

$$RF_{i-c} = \frac{H_{\min}{}^2}{h^2}$$

Inventory Load Rating Factor, *RF i*	
	HL-93 Truck/Tandem
T_{cap}	41.54
$\phi_c\ \phi_s$	1.00
T_E	2.16
γ_{EV}	1.95
η_R	1.05
$T_{(L+IM)}$	4.02
γ_{LL}	1.75
$RF_{i\text{-}w}$	5.28
$RF_{i\text{-}c}$	8.29
RF_i	5.28

Load Rating Summary:

		Controling Truck	Rating Factor	Warnings:
Inventory	Federal	HL-93	RF=5.28	
Operating	Federal	HL-93	RF=6.84	
	MI 1-Unit	Truck 2	RF=8.29	
	MI 2-Unit	Truck 10	RF=8.29	
	MI 3-Unit	Truck 20	RF=8.29	
	MI Overload	Class A	RF=3.70	

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Load & Resistance Factor Rating (LRFR) - Modified for Minimum Cover

CORRUGATED METAL STRUCTURE (CIRCULAR & PIPE ARCH) & ARCHES

Adapted by MDOT from the original spreadsheets developed by the Ohio DOT

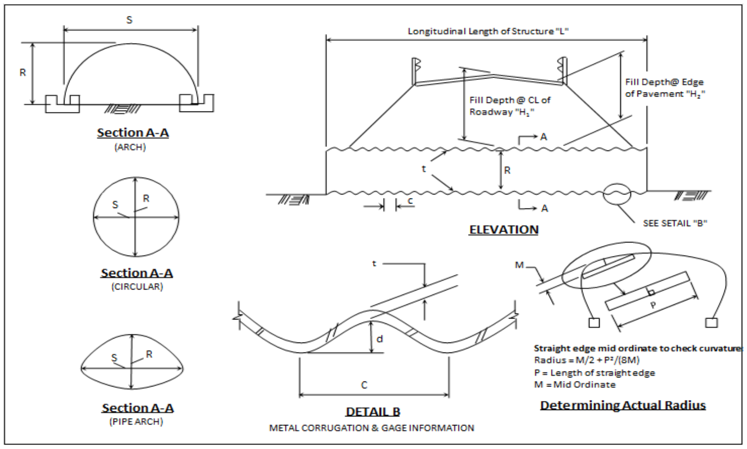

Figure 1: Measurement of Culvert Properties

* For unsymmetrical structures, structures deflected more than 5% from design shape, or those that show localized distortions require that the actual maximum radius be determined in those distorted areas as show above. Use two times the actual maximum radius rather than the span in structural design checks. Typically this provides a conservative evaluation of the structure. Calculate maximum existing top radius by taking measurements around the upper periphery of the culvert using a ruler of length "P" to obtain values of "M". This should be done at selected stations along length of culvert, particularly at locations with noticeable sag.

Structure Information (from existing bridge plans & field measurements):

	Structure Type (to determine Minimum Cover):	Corrugated Metal Pipe	← choose from a drop-down list	
	Seam Type (to determine Seam Strength):	Annular pipe w/ spot welded, riveted or bolted seam	← choose from a drop-down list	
	Structure Category (based on NCSPA Design Data Sheet No. 19)	Typical (NCSPA design data sheet No. 19, II. A. 1.)	← choose from a drop-down list	
	* Depth of Fill "H" (ft) = (fill depth used for dead load calculations)	3.60	Warnings:	
	* Minimum Cover Depth "H_{min}" (ft) = (fill depth used to check minimum cover requirement)	3.60		
	Span Length "S" (ft) =	10.00		
	Rise "R" (ft) =	6.00		
	Longitudinal Length of Structure "L" (ft) =	46.00		
	Clear Roadway Width (Face to face of gaurdrail) (ft) =	36.00		
	Actual Top Radius "R_t" (ft) = (can be determined by field measurements or hand calculations)	0.00	see * above	
Metal Corrugation & Gage Information:	Metal Type	Steel	← choose from a drop-down list	
	Corrugation (if known)	6 x 2 (steel structural plate pipe)	← choose from a drop-down list	
	Gage number (if known)	8	← choose from a drop-down list	
	c (in) =		**Note**: if corrugation & gage number are known, leave the input cells for "c", "d" & "t" blank; if corrugation & gage number are unknown, field measurements of "c", "d" & "t" are required.	
	d (in) =			
	t (in) =			
	Pipe Crown Deflection ** (if any) =	0%		
	Metal Loss based on materials field evaluation (if any) =	0%		
Pipe Cross-Section Properties	A_s (in^2/ft) =	2.003	input these values based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "**section property tables**".	
	r (in) =	0.6840		
	I x 10^{-3} (in^4/in) =	78.175		
Pipe Seam Strength	Seam Strength (k/ft) =	62.0	input the seam strength value based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "**seam strength tables**"	
Backfill	δ = Soil density (k/ft^3) =	0.120		
	φ_E = Factor for Distribution of Live Load with Depth of Fill based on Backfill Type (per AASHTO LRFD 3.6.1.2.6)	1.15	1.15 used here for select granular backfill, change the factor φ_E to 1.0 for all other cases.	
Load Factors	η_R (for nonredundant members) =	1.05	AASHTO LRFD 12.5.4. & 1.3.4	
	g_{EV} (Vertical Earth Pressure for CMPs) =	1.95	input the load factors based on the "**LRFR Load Factors**" table on the right	
	g_{LL} (HL-93 Loading - Inventory) =	1.75		
	g_{LL} (HL-93 Loading - Operating) =	1.35		
	g_{LL} (Ohio Legal Loads - Operating - based on ADTT) =	1.65		
Critical Load Parameter for Arch	$Rise\ and\ Span\ Ratio\ \frac{R}{S} =$	0.60		
	$Critical\ Load\ Parameter\ \gamma_4 = \frac{q_{cr}S^3}{EI} =$	24	input the value obtained from the worksheet "**Critical Load Parameter Table**" based on rise to span ratio and support type, **when R/S ≥0.5, input the value for R/S = 0.5**	
Condition Factor	ϕ_c =	1.00	AASHTO MBE 2nd Edition Table 6A.4.2.3-1 & C6A.4.2.3-1	
System Factor	ϕ_s =	1.00	AASHTO MBE 2nd Edition Table 6A.4.2.4-1	
	$\phi_c\ \phi_s \geq 0.85$ =	1.00		

** reduction in rise divided by the span length from design shape in the unit of percentage

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LRFR of In-Service, Corrugated Metal Pipe Structures - Modified for Minimum Cover

Based on AASHTO LRFD Bridge Design Specifications, Section 3, 4 & 12 & NCSPA Design Data Sheet No. 19
Adapted by MDOT from the original spreadsheets developed by the Ohio DOT

DO NOT use this spreadsheet to load rate Structural Plate Box Culverts

Design Dimensions

1. For **typical structures**, use the actual field measured span for calculations.
2. For **unsymmetrical structures or those deflected over 5%**:
   a. use 2 x the top radius (2 R_t) in lieu of span for calculations.
   b. base critical buckling stress calculations on the theoretical design span, reducing the resulting allowable buckling stress by the appropriate buckling strength reduction factor " f " (NCSPA Design Data Sheet No. 19, Figure B.1.1).
3. For all **long span structures** (horizontal ellipse, low and high profile arches, inverted pear shapes and pear arches), as well as other horizontal ellipses, use 2 x actual top radius (2Rt) in all cases.

For typical structures :	Design Span = Actual Span "S" (ft) =	10.00
For unsymmetrical or deflect more than 5% structures:	Design Span (ft) = $2R_t$ =	0.00
	Pipe Crown Deflection =	0%
	Buckling Strength Reduction Factor, f * =	0.95

* reduction factor f is based on NCSPA Design Data Sheet No 19, II Structural Evaluation A.2.b & Appendix B.1, Figure B.1.1 for Unsymmetrical structures or structures deflected over 5% only.

long span structures:	Design Span (ft) = $2R_t$ =	0.00
Structure Category:	Typical (NCSPA design data sheet No. 19, II. A. 1.)	

Then, **Span Length** used in Load Rating Calculation (ft)=	10.00	Warnings:
Then, $\mathbf{R_t}$ used in Load Rating Calculation (ft)=	0.00	
$\mathbf{R}_{t\ (max)}$ * (ft) =		

* Maximum Plate Radius allowed if Long Span Structural Plate Structures Selected

Design Properties

Conduits Mechanical & Section Properties:

Mechanical Properties:

Metal Type:	Steel	
F_y = Minimum Yield Point of the Metal	33	ksi
F_u = Minimum Tensile Strength of the Metal	45	ksi
E_m = Modulus of elasticity of metal	29000	ksi

Section Properties:

Corrugation:	6 x 2 (steel structural plate pipe)	
Gage Number:	8	
c (in) =		
d (in) =		Warnings:
t (in) =	0.170	
$t_{(min)}$ ** (in) =		

** Required Minimum Top Arc Thickness if Long Span Structural Plate Structures Selected

A_s (in^2/ft) =	2.003
r (in) =	0.6840
I x 10^{-3} (in^4/in) =	78.175

Design Calculations:

Structure Type:	Corrugated Metal Pipe	
Seam Type:	Annular pipe w/ spot welded, riveted or bolted seam	
Longitudinal Length of Structure "L" (ft) =	46.00	Warnings:
AASHTO minimum cover, "h" (ft) =	1.25	
Depth of cover used to check AASHTO minimum cover requirment "H_{min}" (ft) =	3.60	
φ_{loss} = Section Properties reduction factor on the basis of metal loss from the materials field evaluation =	1.00	
φ_1 = Resistance Factor for **wall area and buckling** (Table 12.5.5-1)	1.00	
φ_2 = Resistance Factor for **seam strength** (Table 12.5.5-1)	0.67	
δ = Soil density (k/ft^3)	0.120	
k = soil stiffness factor =	0.22	
φ_E = Factor for Distribution of Live Load with Depth of Fill based on Backfill Type (per	1.15	

Calculate the f_{cr} (critical buckling stress) : (AASHTO LRFD 12.7.2.4)

if: $$S < \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}, then\ f_{cr} = F_u - \frac{F_u^{\ 2}}{48E_m}\left(\frac{kS}{r}\right)^2$$

if: $$S > \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}, then\ f_{cr} = \frac{12E_m}{(kS/r)^2}$$

Compare: S (in) = 120.00 < $\frac{r}{k}\sqrt{\frac{24E_m}{F_u}}$ = 386.66

Therefore, f_{cr} = 42.83 ksi

Calculate the T_{cap} (thrust capacity of the wall) :

Seam Strength (k/ft) = 62.0

T_{cap} = less of:	1. wall yield strength = $\varphi_1\ \varphi_{loss}\ F_y\ A$ =	66.1
	2. wall buckling strength = f $\varphi_1\ \varphi_{loss}\ f_{cr}\ A$ =	85.8
	3. seam strength = φ_2 x (seam strength) =	41.5

Therefore, T_{cap} = 41.5 k/ft

Calculate the T_E (pipe wall thrust due to earth cover) :

T_E = higher value of :	1. δ H (S/2) =	2.16	k/ft
	2. δ H R_t =	0.00	k/ft

Therefore, T_E = 2.16 k/ft

Calculate the $T_{(L+I)}$ (pipe wall thrust due to live load plus dynamic load allowance) :

$T_{(L+IM)}$ = higher value of :	1. $\rho_{(L+IM)}$ (S/2) =	k/ft
	2. $\rho_{(L+IM)}$ R_t =	k/ft

$\rho_{(L+IM)}$: pressure at crown due to live load plus dynamic load allowance

Based on **AASHTO LRFD 3.6.2.2:**

Live load Dynamic Load Allowance, **IM** = 33(1.0-0.125 D_E) ≥ 0%

where, D_E = the minimum depth of earth cover above the structure (ft)

For this structure: Depth of Fill, D_E = **H**=	3.60	ft
IM =	18%	
(1+**IM**) =	1.18	

Calculations will be based on **AASHTO LRFD 3.6.1.2.5 & 6**:

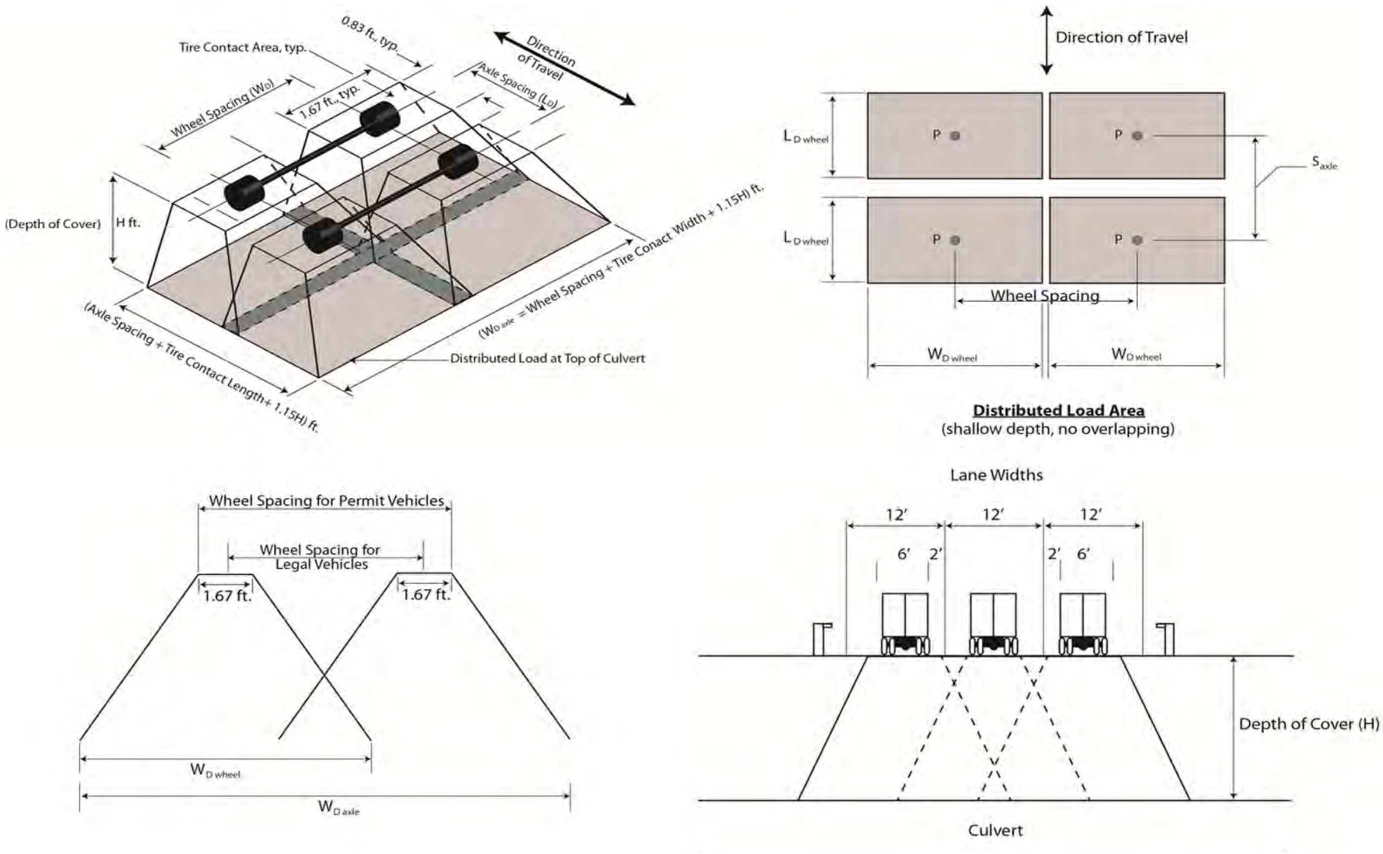


Figure 2: Load distribution through structural fill

Where, $\mathbf{W_T}$ = Tire contact width, $\mathbf{L_T}$ = Tire contact length, $\mathbf{W_D}$ = Distributed load width, $\mathbf{L_D}$ = Distributed load length

The surface tire contact area for HL-93 loading (also applied to MI trucks) (per AASHTO LRFD 3.6.1.2.5)**:**

$\mathbf{W_T}$ = 20" =	1.67	ft
$\mathbf{L_T}$ = 10" =	0.83	ft

Distribution of wheel loads through earth fills (per AASHTO LRFD 3.6.1.2.6):

for **HL-93** Design Truck (also applied to MI trucks)

$W_D = 1.67+\varphi_E H =$ 5.81 ft

$L_D = 0.83 + \varphi_E H =$ 4.97 ft

Depth of Fill, H (ft) =	3.60
Structure Total Length, L (ft)=	46.00
Clear Roadway Width (Face to face of gaurdrail) (ft) =	36.00
Lane Width (ft) =	12.00
Number of Lanes =	3

Truck Load at Depth

	HL-93 Truck/Tandem	MI 1-Unit	MI 2-Unit	MI 3-Unit	MI Overload
	(Unfactored)	(Factored)	(Factored)	(Factored)	(Factored)
Controling Truck	**1-Axle**	**Truck 2**	**Truck 10**	**Truck 20**	**Class A**
wheel spacing on axle	6.00	6.00	6.00	6.00	8.00
$W_{D\ Wheel}$ (ft)	5.81	5.81	5.81	5.81	
Controlling Number of Loaded Lanes	1	1	1	1	1
Controlling $W_{D\ axle\ (total)}$	11.61	11.61	11.61	11.61	12.14
Max W_D/lane provided by structure	40.14	40.14	40.14	40.14	40.14
Rating W_D	11.61	11.61	11.61	11.61	12.14
Multiple Presence Factor	1.20	1.20	1.20	1.20	1.20
Impact + Operating Truck Line Load (k/ft)	7.78	8.14	8.14	7.49	20.28
Load on Culvert, $\rho_{(L+IM)}$	0.80	0.84	0.84	0.77	2.00
$T_{(L+IM)}$ (k/ft)	4.02	4.21	4.21	3.87	10.02

Load factors have not been applied to the HL-93 Truck and Tandem but will be in the next section

Transverse pressure overlaps are considered. Longitudinal pressure overlaps are considered for each MI truck configuration

Check Minimum Earth Cover

Calculate The Critical Intensity of Distributed Load q_{cr}

(Based on "Theory of Elasticity by Timoshenko" & "Guide to Stability Design Criteria for Metal Structures, 5th Edition")

This check considers the Federal and MI Legal Trucks, Overload trucks are not used in the main calculations, however a check of q_{max} is shown for consideration

$$\gamma_4 = \frac{q_{cr} S_c^{\ 3}}{EI} = \quad 24.0$$

$$q_{cr} = \gamma_4 \frac{EI}{S_c^{\ 3}}$$

Where,

E =	29000	ksi
I =	78.18	in^4/in
S_c (span length) =	10.00	ft

q_{cr} = **31.49** ksi

Calculate Maxmium Distributed Load q_{max}

$$q_{max} = \gamma_{EV} H\delta + \gamma_{LL}\rho_{(L+IM)} = \quad 27.78 \text{ ksi}$$

For Permit Trucks:

52.21 ksi

WARNING! Overload Truck Exceeds qmax)

Compare q_{cr} and q_{max}:

q_{max} < q_{cr}

AASHTO minimum cover, h (ft) =	1.25	
H_{min} (ft) =	3.60	**cover depth meet AASHTO requirment**
Modified minimum cover, h_{mod} (ft) =	1.25	**modified minimum cover = AASHTO minimum cover**

Load Rating Factors for Ring Compression Structures:

1. **Operating** Load Rating Factor (RF_O):

   a. RF_O based on wall strength

$$RF_{O-W} = \frac{\varphi_c \varphi_s T_{cap} - \gamma_{EV} \eta_R T_E}{\gamma_{LL} T_{(L+IM)}}$$

   b. RF_O based on minimum cover requirements

$$RF_{O-C} = \frac{H_{\min}^{\;2}}{C(h_{\mathrm{mod}})^2}$$

Where, $C = 2.36\dfrac{H_{\min}}{S} + 0.528 \le 1.0 =$ 1.00

Operating Load Rating Factors, ***RF*** *O*					
	HL-93 Truck	**MI 1-Unit**	**MI 2-Unit**	**MI 3-Unit**	**MI Overload**
T_{cap}	41.54	41.54	41.54	41.54	41.54
$\phi_c\ \phi_s$	1.00	1.00	1.00	1.00	1.00
T_E	2.16	2.16	2.16	2.16	2.16
γ_{EV}	1.95	1.95	1.95	1.95	1.95
η_R	1.05	1.05	1.05	1.05	1.05
$T_{(L+IM)}$	4.02	4.21	4.21	3.87	10.02
γ_{LL}	1.35	1.00	1.00	1.00	1.00
Is culvert burried deep enough to neglect LL?	NO	NO	NO	NO	NO
RF_{O-W}	6.84	8.82	8.82	9.60	3.70
RF_{O-C}	8.29	8.29	8.29	8.29	8.29
RF_O	6.84	8.29	8.29	8.29	3.70

Note:

2. **Inventory** Load Rating Factor (RF_i):

   a. RF_i based on wall strength

$$RF_{i-W} = \frac{\varphi_c \varphi_s T_{cap} - \gamma_{EV} \eta_R T_E}{\gamma_{LL} T_{(L+IM)}}$$

   b. RF_i based on minimum cover requirements

$$RF_{i-c} = \frac{H_{\min}^{\;2}}{h_{\mathrm{mod}}^{\;2}}$$

Inventory Load Rating Factor, ***RF*** *i*	
	HL-93 Truck
T_{cap}	41.54
$\phi_c\ \phi_s$	1.00
T_E	2.16
γ_{EV}	1.95
η_R	1.05
$T_{(L+IM)}$	4.02
γ_{LL}	1.75
RF_{i-w}	5.28
RF_{i-c}	8.29
RF_i	5.28

Load Rating Summary:				
		Controling Truck	**Rating Factor**	Warnings:
Inventory	Federal	HL-93	RF=5.28	
Operating	Federal	HL-93	RF=6.84	
	MI 1-Unit	Truck 2	RF=8.29	
	MI 2-Unit	Truck 10	RF=8.29	
	MI 3-Unit	Truck 20	RF=8.29	
	MI Overload	Class A	RF=3.70	

Double Checking Cell References:

Drop down menus

All drop-down menus functioned properly and referenced the correct ranges in "Reference tables".

Sheet	Tested Cell	Referenced Cell/Table Range	Passed?
input-structure info	C28	'Reference tables'!structure_type	Yes
input-structure info	C29	'Reference tables'!seam_type	Yes
input-structure info	C30	'Reference tables'!structure_category	Yes
input-structure info	D38	'Reference tables'!metal_type	Yes
input-structure info	D39	'Reference tables'!corrugation_all	Yes
input-structure info	D40	'Reference tables'!Gage_number	Yes
CMP Rating Calculations	F131	'Reference tables'!$B$67:$B$69	Yes

Auto-filled data

No critical errors were found on the auto-filled data-fields. The only area of concern I had was that many of the formulas had important values embedded in them, which may make the sheet hard to update. See the attached spreadsheet for comments on individual cells.

Sheet	Tested Cell	Referenced Cell/Table Range	Passed?	Notes
CMP Rating Calculations	E15	'input-structure info'!C33	Yes	
CMP Rating Calculations	E17	'input-structure info'!C37	Yes	
CMP Rating Calculations	E18	'input-structure info'!C44	Yes	
CMP Rating Calculations	E19	E18	Yes	
CMP Rating Calculations	E21	'input-structure info'!C37	Yes	Same formula as E17
CMP Rating Calculations	C23	'input-structure info'!C30	Yes	
CMP Rating Calculations	D25	C23, E15, E17	Yes	
CMP Rating Calculations	D26	'input-structure info'!C37	Yes	
CMP Rating Calculations	D27	'input-structure info'!C28	Yes	
CMP Rating Calculations	C33	'input-structure info'!D38	Yes	
CMP Rating Calculations	E34	C33, 'Reference tables'!B32:E36	Yes	
CMP Rating Calculations	E35	C33, 'Reference tables'!B32:E36	Yes	
CMP Rating Calculations	E36	C33, 'Reference tables'!B32:E36	Yes	
CMP Rating Calculations	B39	'input-structure info'!D39	Yes	
CMP Rating Calculations	B40	'input-structure info'!D40	Yes	
CMP Rating Calculations	B41	B39, 'input-structure info'!D41	Yes	
CMP Rating Calculations	B42	B39, 'input-structure info'!D42	Yes	
CMP Rating Calculations	B43	B40, 'input-structure info'!D43, 'Reference tables'!A39:B48	Yes	More significant figures in this field than in other fields
CMP Rating Calculations	B44	input-structure info'!C28, 'Reference tables'!B17	Yes	Only one value in the lookup table
CMP Rating Calculations	C53	'input-structure info'!C28	Yes	
CMP Rating Calculations	C54	input-structure info'!C29	Yes	
CMP Rating Calculations	E55	'input-structure info'!C35	Yes	
CMP Rating Calculations	E56	input-structure info'!C28, 'Reference tables'!B2:C6	Yes	
CMP Rating Calculations	E57	input-structure info'!C31, 'input-structure info'!C32	Yes	
CMP Rating Calculations	E58	'input-structure info'!C45	Yes	
CMP Rating Calculations	E60	input-structure info'!C29, 'input-structure info'!C29		Maybe it's a better idea to have formulas point to a value in a reference table rather than having the string literal in the formula.
CMP Rating Calculations	C72	C70,D70,E35,E36,E62,B48	Yes	

1/5

Sheet	Tested Cell	Referenced Cell/Table Range	Passed?	Notes
CMP Rating Calculations	F77	E34, B47, E59, E58	Yes	
CMP Rating Calculations	C70	D25	Yes	Cell is not highlighted grey OK, CG
CMP Rating Calculations	F70	B48, E62, E36, E35	Yes	Cell is not highlighted grey, factor of 1000 in numerator and denominator is unnessesary OK, CG
CMP Rating Calculations	F78	C23,C72, B47,E59,E58,E19	Yes	Formula if false doesn't match the formula specified in C78 OK, should not include Buckling Strength Reduction Factor CG
CMP Rating Calculations	F79	E60, C75	Yes	
CMP Rating Calculations	C81	F77, F78, F79	Yes	
CMP Rating Calculations	D84	E61, E57, D25	Yes	
CMP Rating Calculations	D85	E61, E57, D26	Yes	
CMP Rating Calculations	C87	D84, D85	Yes	
CMP Rating Calculations	D97	E57	Yes	
CMP Rating Calculations	D98	D97	Yes	literals embedded in the formula
CMP Rating Calculations	D99	D98	Yes	Do we really need this?
CMP Rating Calculations	B117	None	Yes	Literals in the formula
CMP Rating Calculations	B118	None	Yes	Literals in the formula
CMP Rating Calculations	E123	D97	Yes	Doesn't reference the origional entry for 'H'
CMP Rating Calculations	E124	'input-structure info'!C35	Yes	
CMP Rating Calculations	E125	'input-structure info'!C36	Yes	
CMP Rating Calculations	E126	E125	Yes	Literals in the formula
CMP Rating Calculations	E127	E125	Yes	Literals in the formula
CMP Rating Calculations	C131	$E$123,'MI Trucks'!$C$7:$R$13	Yes	
CMP Rating Calculations	D131	$E$123,'MI Trucks'!$C$7:$R$13	Yes	
CMP Rating Calculations	E131	$E$123,'MI Trucks'!$C$7:$R$13	Yes	
CMP Rating Calculations	C135	$B$117,$E$123	Yes	suspicous formula fill depth + Wheel width?
CMP Rating Calculations	D135	$B$117,$E$123	Yes	suspicous formula fill depth + Wheel width?
CMP Rating Calculations	E135	$B$117,$E$123	Yes	suspicous formula fill depth + Wheel width?
CMP Rating Calculations	B136	B135, B134	Yes	
CMP Rating Calculations	C136	C135,C134	Yes	
CMP Rating Calculations	D136	D135, D134	Yes	

OK, depth multipled by Soildistribution factor.

Sheet	Tested Cell	Referenced Cell/Table Range	Passed?	Notes
CMP Rating Calculations	E136	E135, E134	Yes	
CMP Rating Calculations	F136	F134, E123	Yes	
CMP Rating Calculations	B137	E126, E127, E123, E127	Yes	
CMP Rating Calculations	C137	E126, E127, E123, E127	Yes	Same formula as B137
CMP Rating Calculations	D137	E126, E127, E123, E127	Yes	Same formula as B137
CMP Rating Calculations	E137	E126, E127, E123, E127	Yes	Same formula as B137
CMP Rating Calculations	F137	E126, E127, E123, E127	Yes	Same formula as B137
CMP Rating Calculations	B134	none	Yes	should this value be in a reference table somewhere or is it always the same?
CMP Rating Calculations	C134	none	Yes	should this value be in a reference table somewhere or is it always the same?
CMP Rating Calculations	D134	none	Yes	should this value be in a reference table somewhere or is it always the same?
CMP Rating Calculations	E134	none	Yes	should this value be in a reference table somewhere or is it always the same?
CMP Rating Calculations	B138	B136, B137	Yes	
CMP Rating Calculations	C138	C136, C137	Yes	
CMP Rating Calculations	D138	D136, D137	Yes	
CMP Rating Calculations	E138	E136, E137	Yes	
CMP Rating Calculations	F138	F136, F137	Yes	
CMP Rating Calculations	B139	B132, B118, E123	Yes	
CMP Rating Calculations	C139	$E$123,'MI Trucks'!$C$7:$R$13	Yes	
CMP Rating Calculations	D139	$E$123,'MI Trucks'!$C$7:$R$13	Yes	
CMP Rating Calculations	E139	$E$123,'MI Trucks'!$C$7:$R$13	Yes	
CMP Rating Calculations	F139	F131, $E$123,'MI Trucks'!C17:R19, 'MI Trucks'!C23:R25, 'MI Trucks'!C29:R31	Yes	
CMP Rating Calculations	B140	B139, B138	Yes	
CMP Rating Calculations	C140	C139, C138	Yes	
CMP Rating Calculations	D140	D139, D138	Yes	
CMP Rating Calculations	E140	E139, E139	Yes	
CMP Rating Calculations	F140	F139, F138	Yes	

OK, Based on lanes & other fixed properties, not truck dependent ✓

Sheet	Tested Cell	Referenced Cell/Table Range	Passed?	Notes
CMP Rating Calculations	B141	B140, D25, D26	Yes	
CMP Rating Calculations	C141	C140, D25, D26	Yes	
CMP Rating Calculations	D141	D140, D25, D26	Yes	
CMP Rating Calculations	E141	E140, D25, D26	Yes	
CMP Rating Calculations	F141	F140, D25, D26	Yes	
CMP Rating Calculations	C154	E56, E57, D153	Yes	
CMP Rating Calculations	B158	C81	Yes	
CMP Rating Calculations	C158	C81	Yes	
CMP Rating Calculations	D158	C81	Yes	
CMP Rating Calculations	E158	C81	Yes	
CMP Rating Calculations	F158	C81	Yes	
CMP Rating Calculations	B159	C87	Yes	
CMP Rating Calculations	C159	C87	Yes	
CMP Rating Calculations	D159	C87	Yes	
CMP Rating Calculations	E159	C87	Yes	
CMP Rating Calculations	F159	C87	Yes	
CMP Rating Calculations	B160	B141	Yes	
CMP Rating Calculations	C160	C141	Yes	
CMP Rating Calculations	D160	D141	Yes	
CMP Rating Calculations	E160	E141	Yes	
CMP Rating Calculations	F160	F141	Yes	
CMP Rating Calculations	B161	B158, B159, B160	Yes	
CMP Rating Calculations	C161	B158, B159, C160	Yes	formula references B159/160 instead of same value for its own unit.
CMP Rating Calculations	D161	B158, B159, D160	Yes	formula references B159/160 instead of same value for its own unit.
CMP Rating Calculations	E161	B158, B159, E160	Yes	formula references B159/160 instead of same value for its own unit.
CMP Rating Calculations	F161	B158, B159, F160	Yes	formula references B159/160 instead of same value for its own unit.
CMP Rating Calculations	B162	C154	Yes	
CMP Rating Calculations	C162	C154	Yes	
CMP Rating Calculations	D162	C154	Yes	

UPDATED!

Sheet	Tested Cell	Referenced Cell/Table Range	Passed?	Notes
CMP Rating Calculations	E162	C154	Yes	
CMP Rating Calculations	F162	C154	Yes	
CMP Rating Calculations	B163	B161, B162	Yes	
CMP Rating Calculations	C163	B161, C162	Yes	formula references B161 instead of same value for its own unit
CMP Rating Calculations	D163	B161, D162	Yes	formula references B161 instead of same value for its own unit
CMP Rating Calculations	E163	B161, E162	Yes	formula references B161 instead of same value for its own unit
CMP Rating Calculations	F163	B161, F162	Yes	formula references B161 instead of same value for its own unit
CMP Rating Calculations	B174	B161	Yes	
CMP Rating Calculations	B175	E123, E56	No	Lookup table could return "-" which would cause an error in the formula
CMP Rating Calculations	B176	B174, B175	No	Error could cascade from B175

UPDATED CG

9/28/12 JAK

MDOT CMP LFR

1) BUCKLING STRENGTH REDUCTION FACTOR

NCSPA DESIGN DATA SHEET No. 19 UPDATED, CG

PAGE 7, FIGURE B.1.1 * MISSING

2) CMP RATING CALCULATIONS

DESIGN CALCULATIONS

CG AASHTO Std 12.6.1.3 ϕ_1 = CAPACITY MODIFICATION FACTOR FOR WALL AREA AND BUCKLING

* NOTE WHERE TO LOOK UP IN CODE

CG AASHTO STD. SP. 12.6.1.3 ϕ_2 = CAPACITY MODIFICATION FACTOR FOR SEAM STRENGTH

* NOTE WHERE TO LOOK UP IN CODE

CALCULATE THE T_{CAP}

CG * FOR CONSISTENCY IN FORMULA REPLACE A WITH A_s

DESIGN DIMENSIONS

CG * PROVIDE DEFINITION-"LONG SPAN STRUCTURE"

- Defined from NCSPA definition of Design Dimensions, 3. for all long span structures . . . (

GENERAL COMMENT

IF IN THE FUTURE IT WOULD BE POSSIBLE TO PROVIDE THE ABILITY TO CLEAR THE FORM OF USER INPUTS (GREEN CELLS) IT MIGHT MINIMIZE THE POTENTIAL FOR MIXING OLD AND NEW DATA.

* NOTE THAT IN EXAMPLE CROSS SECTION PROPERTIES & SEAM STRENGTH ARE BASED ON 10 GAGE INSTEAD OF 3 GAGE MATERIAL

CHECK CALCULATION FOR ORIGINAL EXAMPLE

FOR F_{cr} $\quad S = 10\,ft = 120\,in$

$$\text{IF} \quad S < \frac{0.6840}{0.22}\sqrt{\frac{24(29000)}{45}} \Rightarrow 45 - \frac{(45)^2}{48(29000)}\left(\frac{0.22(120)}{0.6840}\right)^2$$

OK

$120 < 387$ THEN $F_{cr} = 42.83$ ksi

FOR T_{CAP} $\quad$ LESS OF

$(1.0)(1.00)(33)(2.003) = 66.1$

$(0.95)(1.0)(1.00)(42.83)(2.003) = 81.5$ $\quad 85.8$ OK

* f ONLY USE IF C24 IS UNSYMMETRICAL OR DEFLECT OVER 5%

$(0.67)(62) = 41.5$

$T_{CAP} = 41.5$

FOR T_E $\quad$ HIGHER OF

$(0.120)(3.6)(10/2) = 2.16$

$(0.120)(3.6)(15) = 6.48$

$T_E = 6.48$

FOR RF_{O-W}

$$\frac{41.5 - 1.95(6.48)}{7.84} \quad \text{(HS20 TRUCK)}$$

$= 3.68$ OK

ADDED NOTE REGARDING THIS CG

IF ≤ 1.0 USE NUMBER
IF ≥ 1.0 USE 1.00

USE NO

FOR RF_O

$$C = 2.36\left(\frac{3.6}{10}\right) + 0.528 = \boxed{1.38} \leq 1.0 \ \cancel{\text{THEN}} = 1.00$$

$$RF_{O-C} = \frac{(3.6)^2}{\cancel{1.38}(1.25)^2}$$

$= \cancel{6.04}\ 8.29$

* ADD NOTE TO CLARIFY WHAT C VALUE TO USE BASED ON ≤

9/28/12 JAK

USING PORTIONS OF KENT CRC DATA

PAGE 3 OF 7

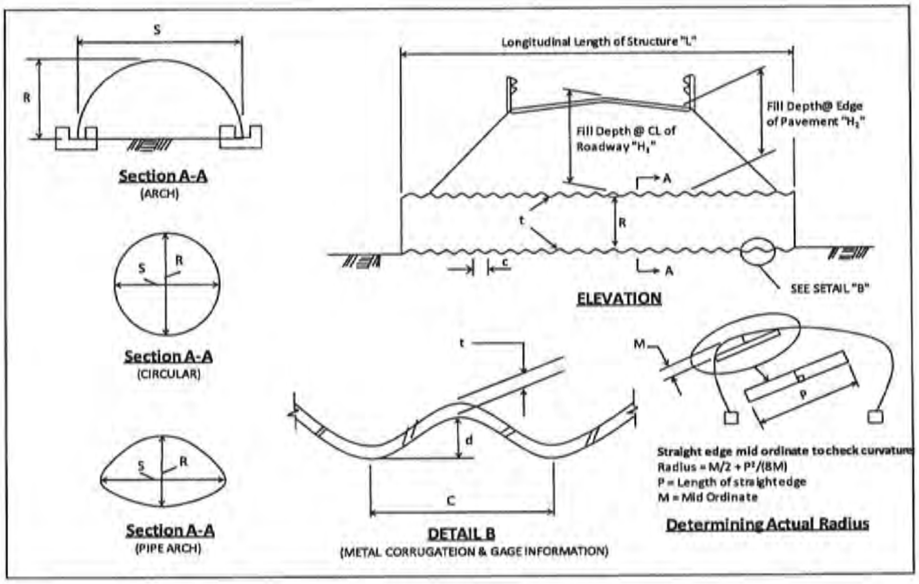
WITH ASSUMPTIONS FOR MISSING INFORMATION

OWNER		SHEET NO 1	OF 1
SECTION		COMP. BY JAK	DATE 9/24/2012
DESCRIPTION	Test 1	CHECK BY	DATE

MDOT

Load Factor Rating (LFR):
CORRUGATED METAL STRUCTURE (CIRCULAR & PIPE ARCH) & ARCHES

Adapted by MDOT from the original spreadsheets developed by the Ohio DOT



* For unsymmetrical structures, structures deflected more than 5% from design shape, or those that show localized distortions require that the actual maximum radius be determined in those distorted areas as show above. Use two times the actual maximum radius rather than the span in structural design checks. Typically this provides a conservative evaluation of the structure. Calculate maximum existing top radius by taking measurements around the upper periphery of the culvert using a ruler of length "P" to obtain values of "M". This should be done at selected stations along length of culvert, particularly at locations with noticeable sag.

Structure Information (from existing bridge plans & field measurements) :

Structure Type (to determine Minimum Cover):	Corrugated Metal Pipe (AASHTO 12.4)		←: choose from a drop-down list
Seam Type (to determine Seam Strength):	Annular pipe w/ spot welded, riveted or bolted seam		←: choose from a drop-down list
Structure Category (based on NCSPA Design Data Sheet No. 19):	Typical (NCSPA design data sheet No. 19, II. A. 1.)		←: choose from a drop-down list
Fill Depth at Centerline of Roadway "H_1" (ft) =	7.00		ASSUMED
Fill Depth at Edge of Pavement "H_2" (ft) =	7.00		
Span Length "S" (ft) =	15.33		
Rise "R" (ft) =	9.25		
Longitudinal Length of Structure "L" (ft) =	114.00		
Clear Roadway Width (Face to face of gaurdrail) (ft) =	43.00		
Determine Actual Top Radius "R_t" (ft) = (can be determined by field measurements* or hand calculations)			see * above
Metal Corrugation & Gage Information:	Metal Type:	Steel	ASSUMED ←: choose from a drop-down list
	* Corrugation (if known):	6 x 2 (steel structural plate pipe)	←: choose from a drop-down list
	Gage number (if known):	10	←: choose from a drop-down list
	c (in) =		Note: if corrugation & gage number are known, leave the input cells for "c", "d" & "t" blank; if corrugation & gage number are unknown, field measurements of "c", "d" & "t" are required.
	d (in) =		
	t (in) =		
Pipe Crown Deflection ** (if any) =	0%		
Metal Loss based on materials field evaluation (if any) =	0%		

** reduction in rise divided by the span length from design shape in the unit of percentage

Drop down list contains more options than just the standard configurations that AASHTO gives properties for. Only AASHTO sections were reproduced, would have to use other source for other configurations. CK

* DROP DOWN LIST FOR "CORRUGATION" AND SEAM STRENGTH TABLE (USED FOR VALUE ON PAGE 3) DO NOT CONTAIN THE SAME SECTIONS. AASHTO STD. SPEC. FOR HWY BR, DIVISION I, SECTION 12.4.2 DIFFERS FROM TABLE HERE

MDOT			
OWNER		SHEET NO 1	OF 4
SECTION		COMP. BY JAK	DATE 9/24/2012
DESCRIPTION	Test 1	CHECK BY	DATE

Load Factor Load Rating of In-Service, Corrugated Metal Pipe Structures

Based on NCSPA Design Data Sheet No. 19 & AASHTO Standard Specification for Highway Bridges
Adapted by MDOT from the original spreadsheets developed by the Ohio DOT

Spreadsheet last modified: September 28, 2012

DO NOT use this spreadsheet to load rate Structural Plate Box Culverts

Design Dimensions

1. For **typical structures**, use the actual field measured span for calculations.
2. For **unsymmetrical structures or those deflected over 5%**:
   a. use 2 x the top radius (2 R_t) in lieu of span for calculations.
   b. base critical buckling stress calculations on the theoretical design span, reducing the resulting allowable buckling stress by the appropriate multiplier to account for deflection " f " (NCSPA Design Data Sheet No. 19, Figure B.1.1).
3. For all **long span structures** (horizontal ellipse, low and high profile arches, inverted pear shapes and pear arches), as well as other horizontal ellipses, use 2 x actual top radius ($2R_t$) in all cases.

For typical structures :	Design Span = Actual Span "S" (ft) =	15.33
For unsymmetrical or deflect more than 5% structures:	Design Span (ft) = $2R_t$ =	0.00
	Pipe Crown Deflection =	0%
	Buckling Strength Reduction Factor, f =	0.95
long span structures:	Design Span (ft) = $2R_t$ =	0.00

Structure Category:	Typical (NCSPA design data sheet No. 19, II. A. 1.)

Then, **Span Length** used in Load Rating Calculation(ft) =	15.33	Warnings:
Then, R_t used in Load Rating Calculation (ft) =	0.00	
$R_{t\,(max)}$ * (ft) =		

* Maximum Plate Radius allowed if Long Span Structural Plate Structures Selected

Design Properties

Mechanical Properties:

Metal Type:	Steel	
F_y = Minimum Yield Point of the Metal	33	ksi
F_u = Minimum Tensile Strength of the Metal	45	ksi
E_m = Modulus of elasticity of metal	29000	ksi

Section Properties:

Corrugation:	6 x 2 (steel structural plate pipe)	
Gage Number:	10	
c (in) =		
d (in) =		Warnings:
t (in) =	0.138	
$t_{(min)}$** (in) =		

** Required Minimum Top Arc Thickness if Long Span Structural Plate Structures Selected

A_s (in^2/ft) =	***2.003***	input these values based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "section property tables".
r* (in) =	***0.6840***	
175	***78.175***	

* r =radius of gyration of corrugation (in)

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Design Calculations:

Structure Type:	Corrugated Metal Pipe (AASHTO 12.4)	
Seam Type:	Annular pipe w/ spot welded, riveted or bolted seam	
Longitudinal Length of Structure "L" (ft) =	114.00	Warnings:
AASHTO minimum cover, h (ft) =	1.92	
Height of cover above crown "H" (ft) = (the lowest cover over the structure in a traffic area based on field measurement)	7.00	
φ_{loss} = Section Properties reduction factor on the basis of metal loss from the materials field evaluation =	1.00	
φ_1 = capacity modification factor for wall area and buckling	1.0	
φ_2 = capacity modification factor for seam strength	0.67	
δ = Soil density (k/ft^3)	0.120	
k = soil stiffness factor =	0.22	

Calculate the F_{cr} (critical buckling stress) :

if: $S < \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}$, then $F_{cr} = F_u - \frac{F_u^2}{48E_m}\left(\frac{kS}{r}\right)^2$

if: $S > \frac{r}{k}\sqrt{\frac{24E_m}{F_u}}$, then $F_{cr} = \frac{12E_m}{(kS/r)^2}$

Compare: S (in) = 183.96 < $\frac{r}{k}\sqrt{\frac{24E_m}{F_u}}$ = 386.66

So: F_{cr} = 39.91 ksi

Calculate the T_{cap} (thrust capacity of the wall) :

Seam Strength (k/ft) = 62.0

Input the seam strength value based on metal type, corrugation, gage number or pipe wall thickness, see tables in worksheet "seam strength tables"

T_{cap} = less of:	1. wall yield strength = $\varphi_1\,\varphi_{loss}\,F_y\,A$ =	66.1
	2. wall buckling strength = f $\varphi_1\,\varphi_{loss}\,F_{cr}\,A$ =	79.9
	3. seam strength = φ_2 x (seam strength) =	41.5

So: T_{cap} = 41.5 k/ft

Calculate the T_E (pipe wall thrust due to earth cover) :

T_E = higher value of :	1. δ H (S/2) =	6.44	k/ft
	2. δ H R_t =	0.00	k/ft

So: T_E = 6.44 k/ft

Calculate the $T_{(L+I)}$ (pipe wall thrust due to live load plus impact) :

$T_{(L+I)}$ = higher value of :	1. $\rho_{(L+I)}$ (S/2) =		k/ft
	2. $\rho_{(L+I)}$ R_t =		k/ft

Based on **AASHTO 3.8.2.3**:	Live load Impact, I =	30%	for 0'-0" < H < 1'-0"
		20%	for 1'-1" < H < 2'-0"
		10%	for 2'-1" < H < 2'-11"
		0%	for H ≥ 3'-0"

So, for this structure: Depth of Fill, H=	7.00	ft
I =	0%	
(1+I) =	1.00	

9/28/12 JAK

MDOT

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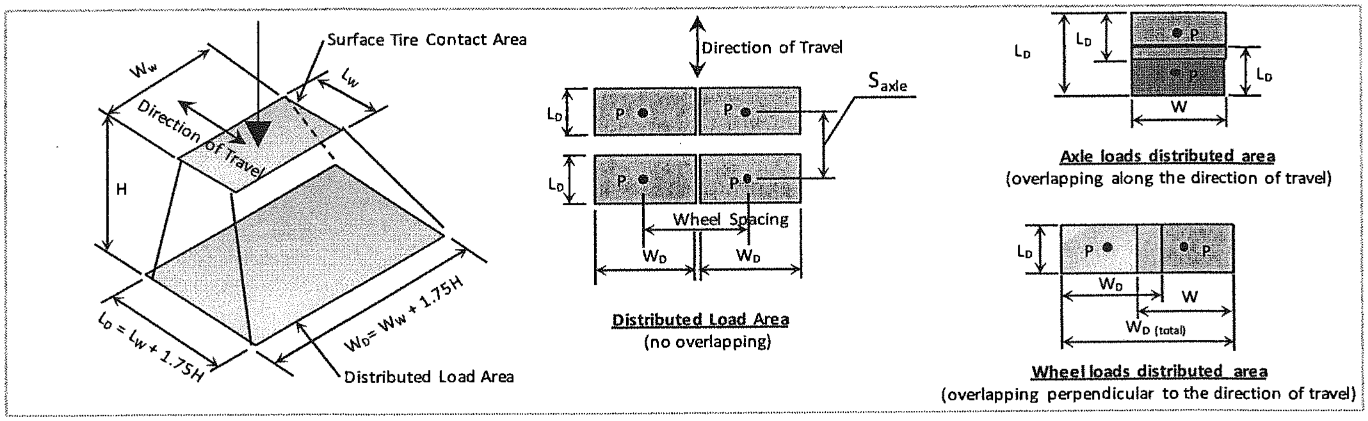
SECTION		COMP. BY	JAK	DATE	9/24/2012
DESCRIPTION	Test 1	CHECK BY		DATE	



Pressure on the tire contact area is distributed on the culvert through the cover depth, Dimension as:

$W_D = W_W + 1.75H$

$L_D = L_W + 1.75H$

The surface tire contact area for HS20 loading (per AASHTO 3.30):

W_W = 20" =	1.67	ft
L_W = 10" =	0.83	ft

The tire surface contact area for Legal MI Trucks is assumed to be the same as the HS 20 truck.

The tire surface contact area for MI overload vechicles is considered to be part of the measurement for wheel spacing on axle (out to out)

Fill depth, H (ft) =	7.00
Structure Total Length, L (ft) =	114.00
Clear Roadway Width (Face to face of gaurdrail) (ft) =	43.00
Lane Width (ft) =	12.00
Number of Lanes =	3

Factored Truck Load at Depth

	HS20	MI 1-Unit	MI 2-Unit	MI 3-Unit	MI Overload
Controling Truck	1-Axle	Truck 4	Truck 17	Truck 23	Class A ←
wheel spacing on axle	6.00	6.00	6.00	6.00	8.00
$W_{D\ wheel}$ (ft)	13.92	13.92	13.92	13.92	
$W_{D\ axle(total)}$	19.92	19.92	19.92	19.92	20.25
Max W_D/lane provided by structure	13.42	13.42	13.42	13.42	55.25
Rating W_D	13.42	13.42	13.42	13.42	20.25
FACTORED Operating Truck Line Load + Impact (k/ft)	3.18	2.87	3.60	3.12	7.00
Factored Load on Culvert, $\rho_{(L+I)}$	0.24	0.21	0.27	0.23	0.35
Factored $T_{(L+I)}$ (k/ft)	1.82	1.64	2.06	1.78	2.65

Transverse pressure overlaps are considered. Longitudinal pressure overlaps are considered for each MI truck configuration

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Load Rating Factors for Ring Compression Structures:

Operating Load Rating Factor (RF_O):

a. RF_O based on wall strength

$$RF_{O-W} = \frac{T_{cap} - 1.95T_E}{T_{(L+I)}}$$

*Note: $T_{(L+I)}$ is factored

b. RF_O based on minimum cover requirements

$$RF_{O-C} = \frac{H^2}{C(h)^2}$$

Where, $C = 2.36\frac{H}{S} + 0.528 \le 1.0 =$ 1.00

Note: The equation has an upper limit of 1.0, therefore if the calculation is greater than 1.0 a value of 1.0 is to be used.

So, $RF_{O\text{-}C}$ = 13.34

Operating Load Rating Factors, RF_O					
	HS20	MI 1-Unit	MI 2-Unit	MI 3-Unit	MI Overload
T_{cap}	41.54	41.54	41.54	41.54	41.54
T_E	6.44	6.44	6.44	6.44	6.44
Factored $T_{(L+I)}$	1.82	1.64	2.06	1.78	2.65
Is culvert burried deep enough to neglect LL?	NO	NO	NO	NO	NO
$RF_{O\text{-}W}$	15.96	17.70	14.10	16.24	10.94
$RF_{O\text{-}C}$	13.34	13.34	13.34	13.34	13.34
RF_O	13.34	13.34	13.34	13.34	10.94

Note:

2. Inventory Load Rating Factor (RF_i):

a. RF_i based on wall strength

$$RF_{i-w} = \frac{3}{5}RF_{O-W}$$

b. RF_i based on minimum cover requirements

$$RF_{i-c} = \frac{H^2}{h^2}$$

Inventory Load Rating Factor, RF_I	
	HS20
$RF_{I\text{-}w}$	9.57
$RF_{I\text{-}c}$	13.34
RF_I	9.57

Load Rating Summary:			
		Controling Truck	Rating Factor
Inventory	Federal	HS20	RF=9.57
Operating	Federal	HS20	RF=13.34
	MI 1-Unit	Truck 4	RF=13.34
	MI 2-Unit	Truck 17	RF=13.34
	MI 3-Unit	Truck 23	RF=13.34
	MI Overload	Class A	RF=10.94

Warnings:

MDOT CMP LEFR

INPUT - STRUCTURE INFO

LOAD FACTORS

REMOVE g_{LL} (OHIO LEGAL LOADS - OPERATING - BASED ON AADT)

FROM SPREADSHEET & LEFR LOAD FACTORS TABLE

gLL could be removed because it is different for each MI truck and was removed for state specific vehicles, not for the design truck CG

ϕ_S & TABLE 6A.4.2.4-1

DO NOT SEE A SUPERSTRUCTURE TYPE THAT MATCHES CMP

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FORMULA FOR "OPERATING LOAD RATING FACTOR" AND "INVENTORY LOAD RATING FACTOR" AND OPERATING LOAD RATING FACTORS, RF_0" TABLE

Updated, CG

* SYMBOLS SHOULD BE UNIFORM

$\gamma_{EV} = g_{EV}$

$\gamma_{LL} = g_{LL}$

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FOR C

Updated, CG

NOTE THAT IF ≤ 1.0 USE CALCULATED NUMBER

IF > 1.0 USE 1.00

LRFR SPREAD SHEET HAND CALCULATIONS CHECK

CRITICAL BUCKLING STRESS

$S = 15.33' = 183.96''$

$$\text{IF } S < \frac{0.6840}{0.22}\sqrt{\frac{24(29{,}000)}{45}} = 386.7 \text{ IN}$$

$$\text{THEN } f_{cr} = 45 - \frac{(45)^2}{48(29{,}000)}\left(\frac{0.22(183.96)}{0.6840}\right)^2$$

$$f_{cr} = 39.91 \checkmark$$

FOR HL-93 TRUCK TANDEM

T_{CAP}
(1.) 62.8 (3.) 41.5
(2.) 75.9

$T_{CAP} = 0.67(62) = 41.5 \checkmark$

$T_E = 6.44 \checkmark$
(1.) 6.44
(2.) 0.00

$W_D = 1.67 + 1.15(7)$

$W_D = 9.72 \checkmark$

$L_D = 0.83 + 1.15(7)$

$L_D = 8.88 \checkmark$

$$P_{(L+IM)} = \frac{4.04}{12.02} = 0.34 \checkmark \qquad T_{(L+IM)} = 0.34\left(\frac{15.33}{2}\right) = 2.61$$

$$= (0.34)(15.33) = 5.21 \checkmark \quad 5.16 \checkmark$$

ROUNDING ISSUE

$T_{(L+IM)}$ TRUCK LOAD DEPTH TABLE
CHECKED OTHER TRUCKS OK

OPERATING LOAD RATING FACTOR

$$RF_{O-W} = \frac{(1.00)(41.5) - 1.95(1.05)(6.44)}{1.35(2.58)}$$

$$= 8.13 \checkmark \qquad 8.15 \text{ OK}$$

OPERATING RF OK

$$RF_{O-C} = \frac{(7.0)^2}{1.00(1.92)^2}$$

$$= 13.29 \checkmark \qquad 13.34 \text{ OK}$$

✓ CG

$$C = 2.36\left(\frac{7.00}{15.33}\right) + 0.52$$

$$= 1.61 \leq 1.00$$

*ADD NOTE:
IF ≤ 1.0 USE NUMBER
IF > 1.0 USE 1.00

INVENTORY LOAD RATING FACTOR (RF_i)

$$RF_{i\text{-}W} = \frac{1.00(41.5) - (1.95)(1.05)(6.44)}{1.75(2.58)}$$

$$= 6.27 \checkmark \qquad 6.29 \checkmark$$

$$RF_{i\text{-}C} = \frac{(7)^2}{(1.92)^2} = 13.29 \checkmark \qquad 13.34 \checkmark$$

INVENTORY RF

$$RF_i = MIN = 6.29 \checkmark$$

OK

FOR MI OVERLOAD

f_{cr} = 39.91 ← FROM PREVIOUS CALC.

T_{CAP} = 41.5 T_E = 6.44

$W_{D\,WHEEL}$ = 9.72

$W_{D\,AXLE}$ = 16.05 ✓

OPERATING LOAD FACTOR

$$RF_{O-W} = \frac{(1.00)(41.5) - 1.95(1.05)(6.44)}{(1.00)(4.67)}$$

= 6.06 ✓ 6.07 ✓

RF_{O-C} = 13.34 FROM PREVIOUS CALC. C = 1.00 FROM PREVIOUS CALC

RF_O = 6.07 ✓ ← OPERATING

INVENTORY LOAD FACTOR

$$RF_{i-W} = \frac{(1.00)(41.5) - (1.95)(1.05)(6.44)}{(1.75)(2.58)}$$

= 6.27 ✓ 6.29 ✓ ← INVENTORY

RF_{i-C} = 13.34 ✓ FROM PREVIOUS CALC.