Appendix C
Proposed Revisions to AASHTO Specifications

National Cooperative Highway Research Program
Project 15-29

Limited Use Document

This Final Report is furnished only for review by members of the NCHRP project panel and is regarded as fully privileged. Dissemination of information included herein must be approved by the NCHRP.

CNA Consulting Engineers
Simpson, Gumpertz & Heger

April 2009

Table of Contents

1 Introduction

Recommended changes to the AASHTO LRFD Design Specifications are presented in Appendix C.1 and C.2. We have recommended changes to Sections 3 and 12, based on the Simplified Design Equations presented in the main body of the report. Table 1 summarizes the changes to each section for the six culvert types.

Table 1—Proposed Changes to AASHTO LRFD Design Specifications

Culvert Type	Section 3 Changes	Section 12 Changes
All types	Eliminate $LLDF$ dependence on soil type Effect of fill ignored < 1 ft for round culverts Effect of fill ignored for < 2 ft for flat-top and 3-sided culverts Added equations for rectangular area calculation	N.A.
Concrete Box	Add $0.06 \cdot D_i$ factor (e.g. Eqns (2) & (3))	None
Concrete Pipe	$LLDF$ varies from 1.15 to 1.75 Add $0.06 \cdot D_i$ factor Add $L_{t,gov}$ factor	Change live load bedding factor for indirect design to 2.2
Corrugated Metal Pipe	Add $0.06 \cdot D_i$ factor	Eqn (147)-(149)
Thermoplastic Pipe (profile wall)	Add $0.06 \cdot D_i$ factor	Eqn (153)-(155)
Corrugated Metal Arch	Add $0.06 \cdot D_i$ factor	Eqn (161)-(162)
Concrete Arch	Add $0.06 \cdot D_i$ factor	None

Note: Equation numbers refer to equations in the main report.

Appendix C.1
Proposed Revisions to AASHTO Specifications Section 3

SECTION 3: LOADS AND LOAD FACTORS

TABLE OF CONTENTS

3.6.1.2.6 Distribution of Wheel Loads Through Earth Fills

Where the depth of fill is less than 2.0 ft., the effect of the fill on the distribution of live load shall be neglected. Live load distribution for culvert tops may be based on provisions for deck slabs spanning parallel to traffic as specified in Articles 4.6.2.1 and 4.6.3.2.

When the depth of fill over round culverts is greater than 1.0 ft, or when the depth of fill over flat top, three sided or long-span concrete arch culverts is greater than 2.0 ft the live load shall be distributed to the structure as specified herein.

Live load shall be distributed to the top slabs of flat top, three sided, or long-span concrete arch culverts with less than 2.0 ft of fill as specified in Article 4.6.2.10. Round culverts with less than 1.0 ft of fill shall be analyzed with more comprehensive methods.

In lieu of a more precise analysis, or the use of other acceptable approximate methods of load distribution permitted in Section 12, where the depth of fill exceeds 2.0 ft., wheel loads may be considered to be uniformly distributed over a rectangular area with sides equal to the dimension of the tire contact area, as specified in Article 3.6.2.1.5, and increased by either 1.15 times the depth of the fill in select granular backfill, or the depth of the fill in all other cases. The provisions of Articles 3.6.1.1.2 and 3.6.1.3 shall apply.

In lieu of a more precise analysis, or the use of other acceptable approximate methods of load distribution permitted in Section 12, wheel loads may be considered to be uniformly distributed over a rectangular area with sides equal to the dimension of the tire contact area, as specified in Article 3.6.1.2.5, and increased by the factors listed in Table 3.6.1.2.6-1. The provisions of Articles 3.6.1.1.2 and 3.6.1.3 shall apply.

Table 3.6.1.2.6-1 Increase in Rectangular Area Dimension with Increasing Fill Depth

Culvert Type	Transverse	Longitudinal
Reinforced Concrete Pipe	1.15, diameter#2 ft. 1.75, diameter.8 ft. Linearly interpolated between these limits	Same as transverse, plus 0.06 times the span
All others	1.15	1.15 plus 0.06 times the span

The rectangular area shall be calculated from:

C3.6.1.2.6

Elastic solutions for pressures produced within an infinite half-space by loads on the ground surface can be found in Poulos and Davis (1974), NAVFAC DM-7.1 (1982), and soil mechanics textbooks.

This approximation is similar to the 60° rule found in many texts on soil mechanics. The dimensions of the tire contact area are determined at the surface based on the dynamic load allowance of 33 percent at depth = 0. They are projected through the soil as specified. The pressure intensity on the surface is based on the wheel load without dynamic load allowance. A dynamic load allowance is added to the pressure on the projected area. The dynamic load allowance also varies with depth as specified in Article 3.6.2.2. The design lane load is applied where appropriate and multiple presence factors apply.

$$H_{int} = \frac{s_w - \frac{w_t}{12} - \frac{0.06D_i}{12}}{LLDF} \quad (3.6.1.2.6\text{-}1)$$

For $H < H_{int}$:

$$w_w = \frac{w_t}{12} + LLDF \cdot H + 0.06 \cdot \frac{D_i}{12} \quad (3.6.1.2.6\text{-}2)$$

$$l_w = \frac{l_t}{12} + LLDF \cdot H \quad (3.6.1.2.6\text{-}3)$$

For $H \geq H_{int}$

$$w_w = \frac{w_t}{12} + s_w + LLDF \cdot H + 0.06 \cdot \frac{D_i}{12} \quad (3.6.1.2.6\text{-}4)$$

$$A_{LL} = l_w \cdot w_w \quad (3.6.1.2.6\text{-}5)$$

where:

$A_{LL} =$ rectangular area at depth H, ft.^{2}

$H =$ depth of fill over culvert, ft.

H_{int} wheel interaction depth, ft.

$w_t =$ tire patch width, 20 in.

$l_t =$ tire patch length, 10 in.

$w_w =$ live load patch width at depth H, ft.

$l_w =$ live load patch length depth H, ft.

$LLDF =$ live load distribution factor per Table 1

$D_i =$ inside diameter/span of the culvert, in.

$s_w =$ wheel spacing, 6 ft

Where such areas from several wheels overlap, the total load shall be uniformly distributed over the area.

For single-span culverts, the effects of live load may be neglected where the depth of fill is more than 8.0 ft. and exceeds the span length; for multiple span culverts, the effects may be neglected where the depth of fill exceeds the distance between faces of end walls.

Where the live load and dynamic load allowance ~~impact~~ moment in concrete slabs, based on the distribution of the wheel load through earth fills, exceeds the live load and dynamic load allowance~~impact~~ moment calculated according to Articles 4.6.2.1 and 4.6.3.2, the latter moment shall be used.

This provision applies to relieving slabs below grade and to top slabs of box culverts.

Appendix C.2
Proposed Revisions to AASHTO Specifications Section 12

12.7 METAL PIPE, PIPE ARCH, AND ARCH STRUCTURES

12.7.2.2 Thrust

The factored thrust, T_L, per unit length of wall shall be taken as:

$$T_L = P_L\left(\frac{S}{24}\right) \quad (12.7.2.2\text{-}1)$$

where:

T_L = factored thrust per unit length (kip/ft.)

S = pipe span (in.)

P_L = factored crown pressure (ksf)

$$T_L = \frac{P_{LD}S}{2} + \frac{P_{LL}\cdot\min(S, l_t + LLDF\cdot H)\cdot F_1}{2} \quad (12.7.2.2\text{-}1)$$

where:

T_L = factored thrust per unit length (kip/ft.)

S = culvert span (ft.)

P_{LD} = factored dead-load crown pressure (ksf)

P_{LL} = factored live-load crown pressure (ksf)

In which, for corrugated metal pipe:

$$F_{1,\lim} = \max\left(\frac{15}{S/12}, 1\right) \quad (12.7.2.2\text{-}2)$$

$$F_1 = \max\left(F_{1,\lim}, \left(\frac{0.75\cdot S}{l_t/12 + LLDF\cdot H}\right)\right) \quad (12.7.2.2\text{-}3)$$

where:

H = depth of fill (ft.)

$LLDF$ = live load distribution factor per Article 3.6.1.2

l_t = tire patch length, per Article 3.6.1.2.5

or in which, for long-span corrugated metal structures:

$$F_1 = \frac{0.54\cdot S}{\frac{w_t}{12} + LLDF\cdot H + 0.03\cdot S} \quad (12.7.2.2\text{-}4)$$

where:

w_t = is the tire patch width, per Article 3.6.1.2.5.

12.10.4.3.2c Live Load Bedding Factors

The bedding factor~~s~~ B_{FLL} for live load, W_L, for both circular pipe and arch and for elliptical pipe shall be 2.2 for all fill heights and culvert diameters. ~~are given in Table 1. If B_{FE} is less than B_{FLL}, use B_{FE} instead of B_{FLL}, for the live load bedding factor. For pipe diameters not listed in Table 1, the bedding factor may be determined by interpolation.~~

~~**Table 12.10.4.3.2c-1 Bedding Factors, B_{FLL}, for the Design Truck.**~~

Fill Ht., Ft.	Pipe Diameter, in.										
	12	24	36	48	60	72	84	96	108	120	144
0.5	2.2	1.7	1.4	1.3	1.3	1.1	1.1	1.1	1.1	1.1	1.1
1.0	2.2	2.2	1.7	1.5	1.4	1.3	1.3	1.3	1.1	1.1	1.1
1.5	2.2	2.2	2.1	1.8	1.5	1.4	1.4	1.3	1.3	1.3	1.1
2.0	2.2	2.2	2.2	2.0	1.8	1.5	1.5	1.4	1.4	1.3	1.3
2.5	2.2	2.2	2.2	2.2	2.0	1.8	1.7	1.5	1.4	1.4	1.3
3.0	2.2	2.2	2.2	2.2	2.2	2.2	1.8	1.7	1.5	1.5	1.4
3.5	2.2	2.2	2.2	2.2	2.2	2.2	1.9	1.8	1.7	1.5	1.4
4.0	2.2	2.2	2.2	2.2	2.2	2.2	2.1	1.9	1.8	1.7	1.5
4.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9	1.8	1.7
5.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9	1.8
5.5.	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.0	1.9
6.0	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.1	2.0
6.5	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2

12.12 THERMOPLASTIC PIPES

12.12.3.4 Thrust

12.12.3.4

The factored thrust per unit length of wall of buried plastic pipe structures shall be taken as:

~~$T_L = P_F\left(\frac{D_O}{2}\right)$ 12.12.3.4-1~~

$$T_L = \frac{P_{FD}D_0}{2} + \frac{P_{FL}\min(D_0, l_t + LLDF \cdot H)F_1F_2}{2}$$ (12.12.3.4-1)

where:

T_L = factored thrust per unit length (kip/ft.)

D_O = outside diameter of pipe (ft.)

~~P_F = factored vertical crown pressure (ksf)~~

P_{FD} = factored dead-load vertical crown pressure (ksf)

P_{FL} = factored live-load vertical crown pressure (ksf)

In~~For~~ which~~, the factored vertical crown pressure, P_F, shall be taken as~~:

~~$P_F = \eta_{EV}(\gamma_{EV}VAF \cdot P_{SP} + 1.3\gamma_{WA}P_W) + \eta_{LL}\gamma_{LL}C_LP_L$ 12.12.3.4-2~~

~~in which:~~

$$P_{FD} = \eta_{EV}(\gamma_{EV}VAF \cdot P_{SP} + 1.3\gamma_{WA}P_W)$$ (12.12.3.4-2)

$$P_{FL} = \eta_{LL}\gamma_{LL}P_L$$ (12.12.3.4-3)

$$VAF = 0.76 - 0.71 \cdot \left(\frac{S_H - 1.17}{S_H + 2.92}\right)$$ 12.12.3.4-4~~3~~

$$S_H = \frac{\phi_s M_s R}{EA}$$ 12.12.3.4-5~~4~~

$$P_w = \gamma_w H_s$$ 12.12.3.4-6~~5~~

$$F_{1,\lim} = \max(15/D_i, 1)$$ (12.12.3.4-7)

$$F_1 = \max\left(F_{1,\lim}, 0.75 \cdot \left(\frac{D_o}{l_t/12 + LLDF \cdot H}\right)\right)$$ (12.12.3.4-8)

In Eq. 2, a factor of 1.3 is applied to water load to account for uncertainty of the level of the groundwater. The Engineer may vary this factor based on knowledge of actual site conditions.

For η factors, refer to Article 12.5.4 regarding assumptions about redundancy for earth loads and live loads.

Figure C3.11.3-1 shows the effect of groundwater on the earth pressure. P_{sp} does not include the hydrostatic pressure. P_{sp} is the pressure due to the soil above and below the water table directly above the pipe. See Table 3.5.1-1 for common unit weights.

$$F_2 = \frac{0.95}{1 + 0.6S_H} \qquad (12.12.3.4\text{-}9$$

where:

P_F = factored vertical crown pressure (ksf)

η_{EV} = load modifier, specified in Article 1.3.2, as they apply to vertical earth loads on culverts

γ_{EV} = load factor for vertical pressure from dead load of earth fill, as specified in Article 3.4.1

γ_{WA} = load factor for hydrostatic pressure, as specified in Article 3.4.1

VAF = vertical arching factor

P_{SP} = geostatic earth pressure *(EV)* as specified in Section 3. Does not include hydrostatic pressure (ksf)

P_W = hydrostatic water pressure (ksf)

H_S = depth of water table above springline of pipe (ft.)

γ_w = unit weight of water (kcf)

η_{LL} = load modifier, as specified in Aricle 1.3.2, as they apply to live loads on culverts

γ_{LL} = load factor for live load, as specified in Article 3.4.1

P_L = pressure due to live load *(LL)*, and dynamic load allowance *(IM)* impact and multiple presence loads as specified in Article 3.6.1.2.6 (ksf)

C_L = live load distribution coefficient $L_W / D_o \leq 1$

L_W = horizontal live load distribution width in the circumferential direction, at the elevation of the crown (ft.)

S_H = hoop stiffness factor

ϕ_S = resistance factor for soil stiffness, $\phi_S = 0.9$

M_S = constrained soil modulus specified in Table 1 (ksi)

R = radius to centroid of culvert wall (in.)

E = initial or long-term modulus of elasticity as specified in Table 12.12.3.3-1 (ksi)

H = depth of fill (ft.)

$LLDF$ = live load distribution factor per Article 3.6.1.2.6

l_t = tire patch length, per Article 3.6.1.2.5

The use of the vertical arching factor is based on the behavior demonstrated by Burns and Richard *(1964)*, that pipe with high hoop stiffness ratios (ratio of soil stiffness to pipe hoop stiffness) carry substantially less load than the weight of the prism of soil directly over the pipe. This behavior was demonstrated experimentally by Hashash and Selig *(1990)* and analytically by Moore *(1995)*. McGrath *(1999)* developed the simplified form of the equation presented in Eq. 3.

If evaluating the short-term loading conditions, then use the initial modulus of elasticity to compute S_H. Similarly, if evaluating the long-term loading conditions, then use the 5-year modulus of elasticity to compute S_H.

The initial modulus should be used when checking short-term thrust demands. The long-term modulus should be used when checking long-term thrust demands.

If the structural backfill material is compacted or uncompacted crushed stone then M_s values for Sn-100 and Sn-85, respectively, may be used.

Suggested practice is to design for a standard Proctor backfill density 5 percent less than specified by the contract documents.

If the structural backfill does not extend for one diameter on each side of culverts under 10 or more ft. of fill, or one-half diameter, but not less than 18.0 in. each side of culverts under depths of fill up to 10.0 ft., then the value of M_s used may be a composite value representative of the structural backfill and the material at the sides of the structural backfill (see *AWWA 1996)*.

The secant constrained modulus may also be determined experimentally using the stress-strain curve resulting from a uniaxial strain test on a sample of soil compacted to the field specified density. The constrained modulus is the slope of the secant from the origin of the curve to a point on the curve corresponding to the geostatic earth pressure, P_{sp}.

Note that the units for wall area are in.^{2}/in. in this article. In other articles wall area is usually specified in in.^{2}/ft.

A = wall area (in.²/in.)

In the absence of site-specific data, the secant constrained soil modulus, M_s, may be selected from Table 1 based on the backfill type and density, and the geostatic earth pressure, P_{sp}. Linear interpolation between soil stress levels may be used for the determination of M_s.

For culverts under depths of fill up to 10.0 ft., the soil type and density selected for Table 1 should be representative of the conditions for a width of one-half diameter each side of the culvert, but never less than 18.0 in. each side of the culvert.

For culverts under depths of fill greater than 10.0 ft., the soil type and density selected from Table 1 should be representative of the conditions for a width of one diameter each side of the culvert.