Assessment of Dynamic Load Allowance for Buried Culverts

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ABSTRACT

In the past, research on buried culverts has focused on looking at live load distribution through soil onto buried culverts and given little attention to the dynamic amplification of moving loads. The few studies that looked at the dynamic amplification of buried culverts idealized the load-soil-culvert problem using a plane-strain assumption. Under such conditions, the finite area axle loads are erroneously modeled as strip loads acting over the entire width of the culvert. In this study, the plane-strain assumption is removed and the load-soil-culvert system is modeled and analyzed a three-dimensional problem. Dynamic load allowance (*DAF*) was determined from field measurements, two-dimensional finite element method (2-D FEM), and three-dimensional finite element method (3-D FEM). The 2-D and 3-D FEM models resulted in an average *DAF* of 1.099 and 1.048, respectively. The average *DAF* calculated from field measurements and the American Association of State Highway and Transportation Officials (AASHTO) recommended formula are 0.963 and 1.295, respectively. Overall, the AASHTO *DAF*s are the highest and the field *DAF*s are the lowest. The plain strain assumption adopted in the 2-D FEM models resulted in *DAF* values that are higher than the 3-D FEM and field evaluated *DAF*s. The *DAF* calculated from three-dimensional models is the closest to the field measured *DAF*s.

Citation information: please cite this work as follows

Kadivar, M., N. Manahiloh Kalehiwot, N. Kaliakin Victor, and W. Shenton Harry, *Assessment of Dynamic Load Allowance for Buried Culverts*, in IFCEE 2018.

Link to published article: https://ascelibrary.org/doi/abs/10.1061/9780784481608.018

BACKGROUND

The Federal Highway Administration (FHWA) defines culverts as structures that are designed to drain water and have span lengths smaller than bridges (FHWA 1995). Design of culverts is commonly done following the procedures stipulated in the American Association of State Highway and Transportation Officials (AASHTO) standards (AASHO 1962; AASHTO 2012). The live load carrying capacity of a culvert is determined by performing a load rating, which includes the effect of dynamic loads on the culvert. AASHTO defines the Dynamic Amplification Factor (*DAF*) as:

$$DAF = \frac{R_{Dyn}}{R_{stat}} \tag{1}$$

where, R_{Dyn} is some measure of the dynamic response and R_{stat} is some measure of the static response of the structure. AASHTO recommends a *DAF* value of 1.33 for culverts with no fill above the slab surface. When there is fill, the *DAF* is decreases as a function of fill depth (D_E) and can be calculated according to Equation 2, where D_E is measured in feet.

$$DAF = 1 + 0.33(1.0 - 0.125D_E) \geq 1 \tag{2}$$

Noting the discrepancies between observations made during field tests of culverts and the values of *DAF* from AASHTO, Wells (2016) concluded that AASHTO recommended values of *DAF* are too conservative. In addition, by performing a parametric study, Wells et al. (2016) showed that parameters other than the fill depth affect *DAF* significantly. In a pioneering study, Turneaure et al. (1911) reported the *DAF's* strong dependency on the span length of culverts. Similar conclusions were drawn by other researchers as well (e.g. Fleming and Romualdi 1961; Smith 1969; Coussy et al. 1989; Manko and Beben 2008; Wekezer et al. 2010). In addition to the bridge span length, the vehicle speed, axle spacing, and fundamental frequency affect the *DAF* value of bridges (Smith 1969). Surface roughness has also been shown to have role in deciding the magnitude of *DAF* (Wekezer et al. 2010).

The behavior of culverts under dynamic loading conditions has not been extensively explored. Recently, however, the topic of dynamic behavior of culverts seems to have gained interest (e.g., Chen and Harik 2012; Beben 2013; Wells 2016; Wells et al. 2016). Among these studies, the experimental investigation performed by Beben (2013) found out that the value of *DAF* for culverts increases with increasing span length and decreasing fill depth. In his work, the range of *DAF* values for culverts spanned between 1.11 and 1.29. Performing a two dimensional (2-D) finite element analysis, Chen and Harik (2012) showed that *DAF* values for culverts increase with increasing vehicle speed and decrease with increasing surface roughness. Recently (Wells 2016; Wells et al. 2016), by performing 2-D FEM analysis and in situ testing, determined that the AASHTO recommended *DAF* values are too conservative. The latter two studies recommended that the calculation of *DAF* should account for span length, slab thickness, asphalt rigidity, and Young’s modulus of the soil in addition to the AASHTO specified fill depth. Although 2-D FEM analyses simplify problem solving and reduce computational time, they do not fully account for actual field conditions. Because of the plane-strain assumptions, 2-D finite element analyses lead to erroneous and overly conservative estimation of *DAF* values. In this work, it is attempted to see how much information is lost when analyses are performed using a 2-D (plane strain) idealization. Four culverts, located in the New Castle county of Delaware, are modeled using 3-D and 2-D finite elements and analyzed using ABAQUS® computer program. Calculated *DAF* values are compared with each other and with those estimated from in situ load rating tests and AASHTO procedures.

CULVERT DESCRIPTION

Figure 1 schematically shows a typical culvert that was modeled and analyzed with ABAQUS®. The figure represents quarter of the load-structure-soil system, with a plane of symmetry along the front and left surfaces. All dimensions, as measured in the field, are presented in Table 1. The four culverts selected for field testing and FEM analysis were named as shown in the first column of Table 1. Culverts BR-1 and BR-2 do not have any backfill on top of their slabs. Their slabs are in direct contact with the asphalt layer. Culverts BR-3 and BR-4 have layers of backfill soil, crushed stone and asphalt over their slabs. The cross-sectional shape of the first two culverts is similar to a simple frame (i.e., an inverted U-shape) and the latter two culverts have a box type cross-section. The schematic illustrations of typical culverts in the 2-D and 3-D spaces are shown in Figures 2 and 3, respectively.

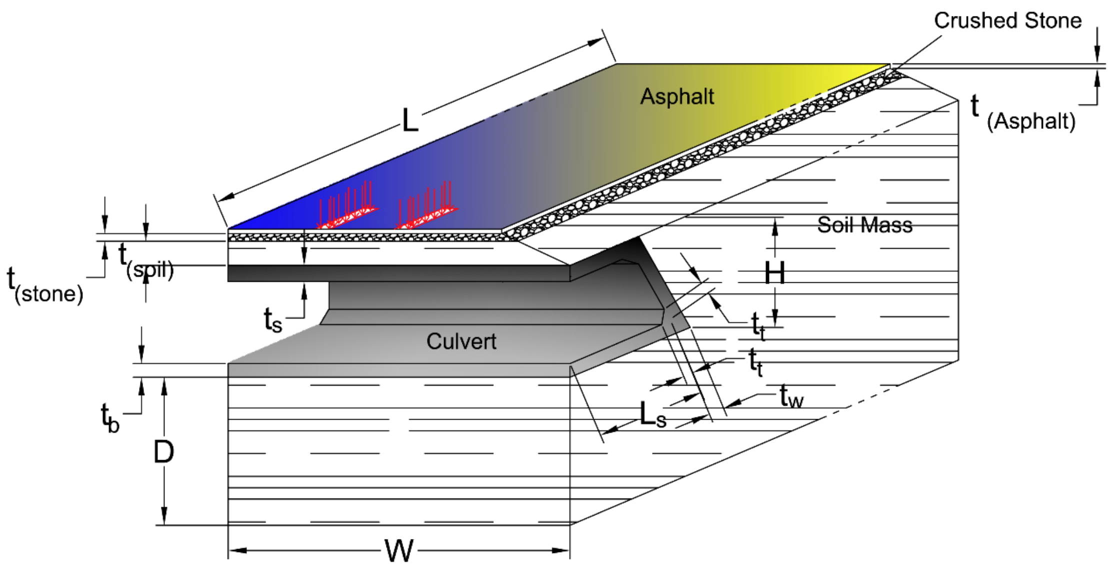
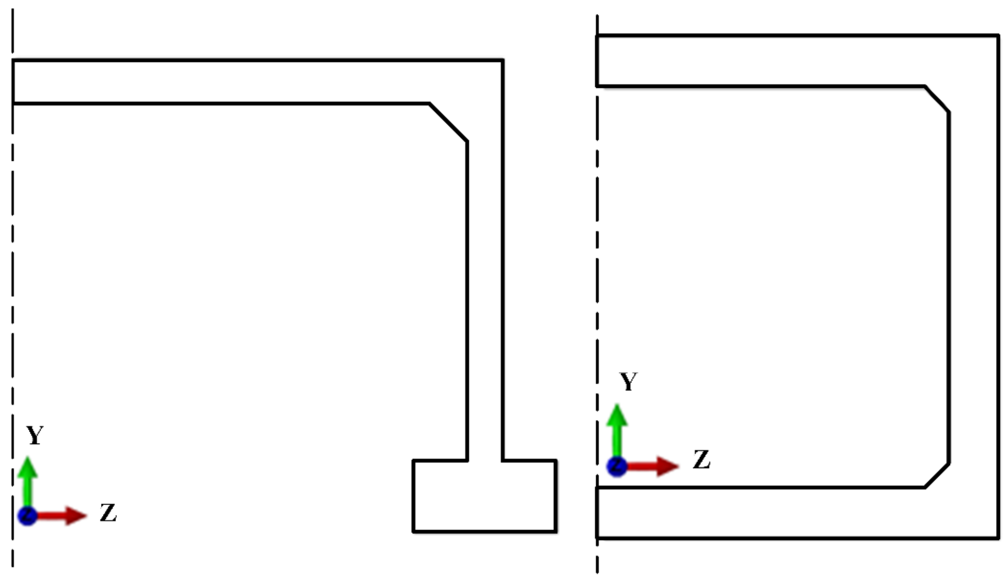


Figure 1 Schematic illustration of the load-culvert-soil system.

Table 1 Dimensions of the culvert systems (All measurement in meters).

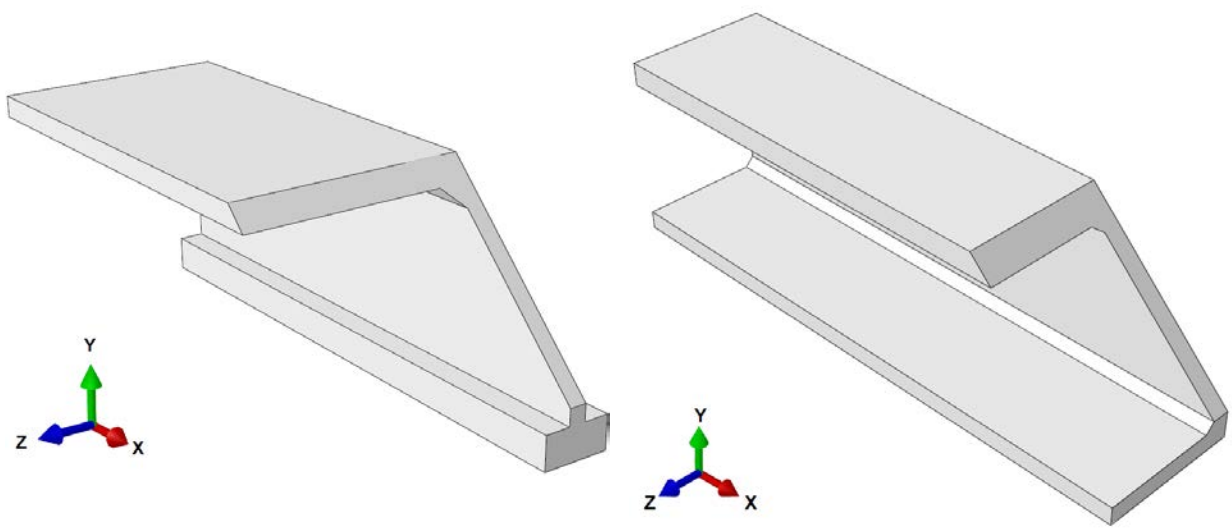
Culvert	$t_{(soil)}$	$t_{(stone)}$	$t_{(asphalt)}$	t_w	t_s	t_b	t_t	L_s	H	W	L	D
BR-1	0	0	0.13	0.30	0.38	0	0.30	3.20	2.44	7.72	23.50	5.00
BR-2	0	0	0.13	0.30	0.38	0	0.30	3.86	4.04	10.62	24.16	5.00
BR-3	0.32	0.26	0.11	0.30	0.30	0.30	0.15	2.13	3.05	9.80	22.43	5.00
BR-4	0.25	0.20	0.13	0.30	0.30	0.36	0.15	1.52	1.88	14.25	21.82	5.00

In Table 1, $t_{(soil)}$, $t_{(stone)}$, $t_{(asphalt)}$, t_w, t_s, and t_b represent the soil fill, crushed stone, asphalt, culvert wall, culvert top slab, and culvert bottom slab thicknesses, respectively. The quantity t_t is the chamfer width; L_s is half of the culvert span length; H is the culvert height; W is half of the road width; L is the full longitudinal length of the modeled system; D is the depth of the soil mass below the bottom of the culvert.



(a) **(b)**

Figure 2 Typical 2-D culvert cross-section: (a) BR-1 and BR-2; (b) BR-3 and BR-4.



(a) **(b)**

Figure 3 Typical 3-D culvert cross-section: (a) BR-1 and BR-2; (b) BR-3 and BR-4.

MODEL DESCRIPTION

Dynamic and static models for both 3-D and 2-D conditions were developed in ABAQUS®, using 8-node elements. Analyses of these models were performed on the University of Delaware parallel computing cluster system. This system consists of 200 computer nodes which total 5160 AMD "Interlagos" cores, 14.5TB RAM, a 180TB Lustre filesystem, and a QDR InfiniBand network backplane. The typical run time for the 3-D models was about one hour and 10 minutes for dynamic and static analyses, respectively. For 2-D (plane strain) idealizations, approximately five minutes were required for dynamic analyses and less than one minute for static analyses.

Table 2 presents the parameters that are used in the models. These parameters are based on the linear elastic approach and are adopted from the work of Wu et al. (2014).

Table 2 Selected Material Properties

Material	Elastic Modulus (MPa)	Poisson's Ratio	Density (kg/m^3)
Asphalt	1200	0.15	2400
Stone	300	0.35	2300
Concrete	31000	0.25	2400
Soil	50	0.40	1800

The specified mesh size adjacent to the tire loads was 0.1 meter and gradually increased to approximately 1 meter near the locations where no significant changes occur. The locations of no significant change are determined by performing mesh sensitivity analysis. These boundaries were identified at 20 m longitudinal distance and five-meter depth. The total number of nodes was typically between 80,000 to 120,000 for the 3-D models and 3,000 to 4,000 for the 2-D ones. Typical meshed 2-D and 3-D models are shown in Figures 4 and 5, respectively.

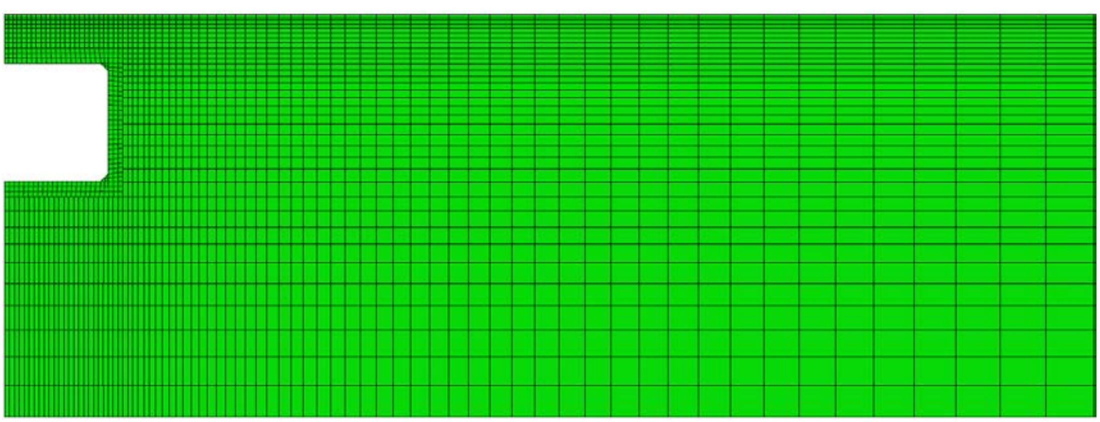


Figure 4 Typical mesh in 2-D.

The horizontal displacement, normal to the symmetry planes, and vertical displacement at the bottom of the system were restrained. Since relative movement between the layers is negligible, no sliding is assumed and all interfaces are constrained with ties.

As per the specification in AASHTO, a standard HL-93 truck rear tire load is applied to the models (AASHTO 2012). The magnitude of applied truck load, on the pavement surface, is 142.3 kN (32 kips). This load is divided between the two axles of the rear tires that are 1.83 m (6') from each other. Each wheel touches the ground with a contact-area of 0.25 × 0.5 m (10" × 20"). The tire load is applied at the mid span of culverts, where the maximum deflection is expected. In order to simulate the truck crossing the road, a symmetrical triangular pulse is selected for the dynamic load time-history (Figure 6). The duration of the assigned load is dependent on the culvert span length.

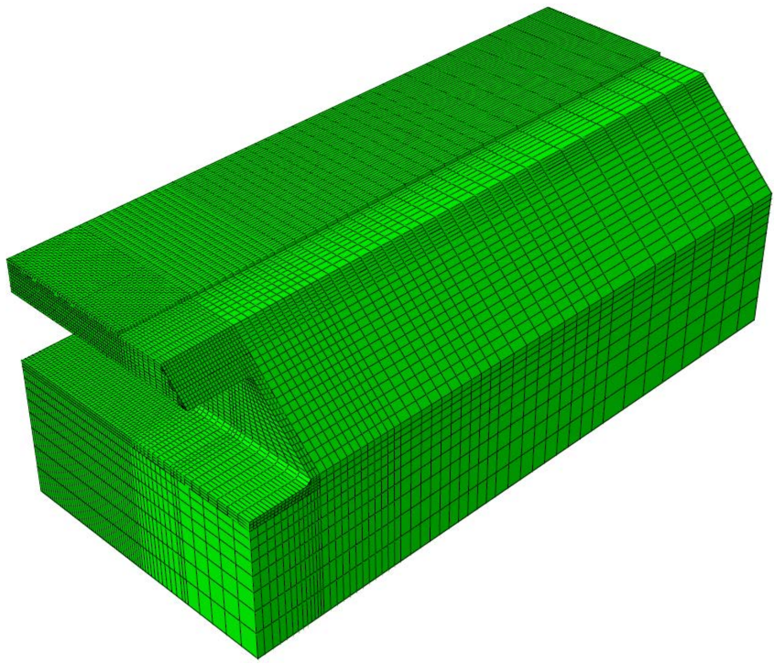


Figure 5 Typical mesh in 3-D.

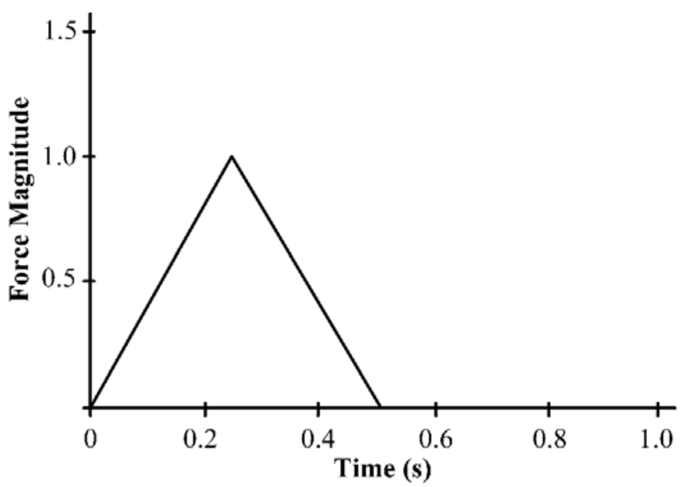
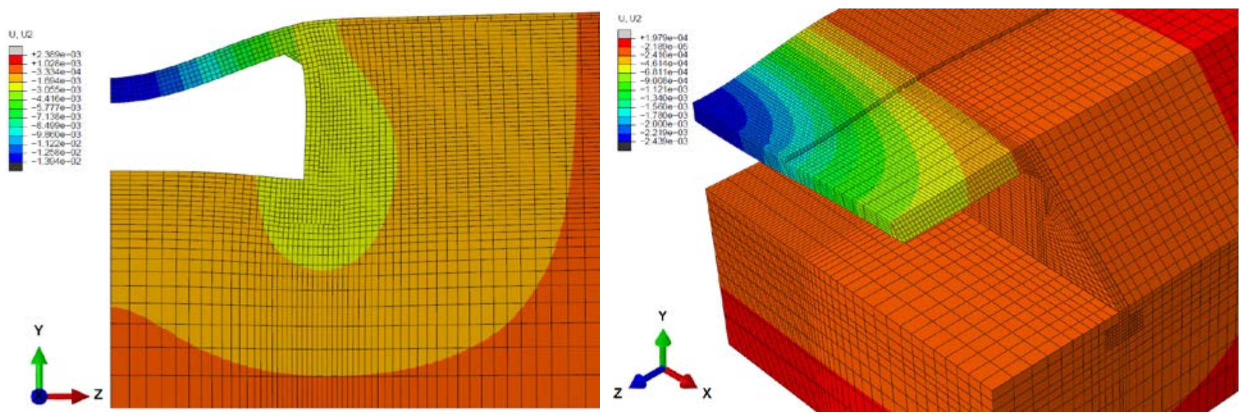


Figure 6 Symmetric triangular pulse load.

MODEL RESULTS

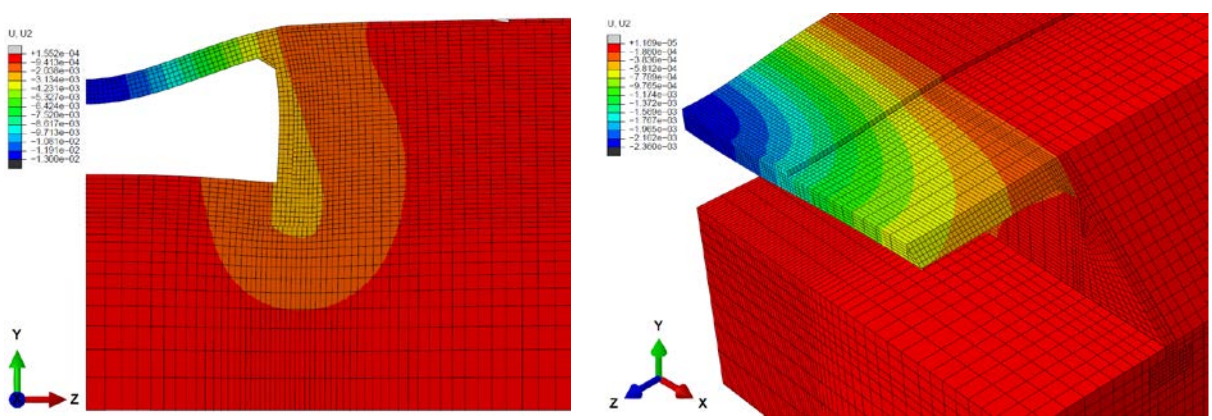
Due to their physical similarity, culverts BR-1 and BR-2 behave in a similar fashion, but at varying magnitudes of response to the applied loads. The same applies to culverts BR-3 and BR-4. Hence, the static and dynamic behavior of only one of each group is discussed here. As the main objective of this work is to obtain the *DAF* from 2-D and 3-D analyses, attention is given to simulated displacements. Accordingly, the displacement contours of the systems under static and dynamic loading conditions for 2-D and 3-D models are presented.

Figures 7 and 8 present the displacement contours for culverts BR-1 and BR-2, under dynamic (at the time when maximum displacement occurs) and static loading conditions in 2-D and 3-D, respectively. The displacement contours for culverts BR-3 and BR-4 are shown in Figures 9 and 10. In the figures, it can be seen that the maximum displacement occurs at the mid span, close to the left boundary. This displacement is recorded at the asphalt and crushed stone layers immediately under the wheel loaded area. Comparing results of the dynamic and static models, it can be said that the displacement was distributed over a larger area under dynamic loading conditions.



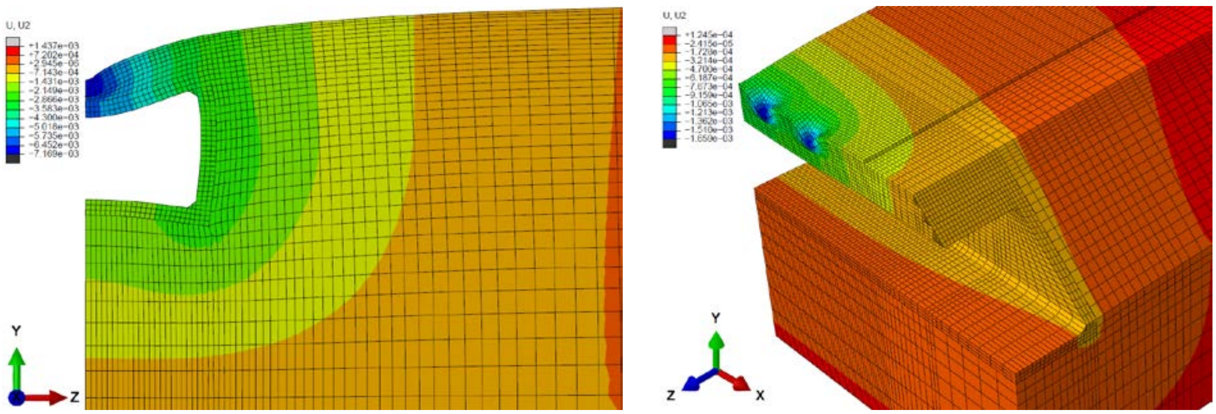
(a) **(b)**

Figure 7 Dynamic response in BR-1 and BR-2 at maximum displacement conditions: (a) 2-D model (magnified 100 times); (b) 3-D model (magnified 300 times).



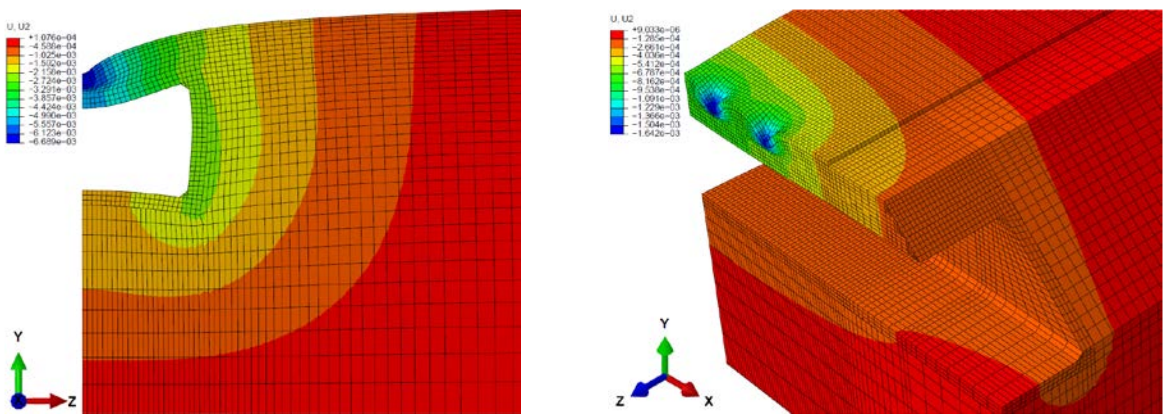
(a) **(b)**

Figure 8 Static response in BR-1 and BR-2 at maximum displacement conditions: (a) 2-D model (magnified 100 times); (b) 3-D model (magnified 300 times).



(a) (b)

Figure 9 Dynamic response in BR-3 and BR-4 at maximum displacement conditions: (a) 2-D model (magnified 200 times); (b) 3-D model (magnified 500 times).



(a) (b)

Figure 10 Static response in BR-3 and BR-4 at maximum displacement conditions: (a) 2-D model (magnified 200 times); (b) 3-D model (magnified 500 times).

Table 3, summarizes the maximum values of displacement and the corresponding *DAF* calculated for all models. In the table, it can be observed that 2-D models undergo much larger displacements than the 3-D models. This phenomenon is attributed to the plane strain assumption used in the 2-D models. In addition, the *DAF* values obtained in 2-D models are typically bigger than those obtained in 3-D models.

Table 3 Summary of maximum displacements and related *DAF* for the modeled culverts.

Culvert	2-D FEM			3-D FEM		
	Static (mm)	Dynamic (mm)	*DAF*	Static (mm)	Dynamic (mm)	*DAF*
BR-1	8.785	9.300	1.059	1.709	1.762	1.031
BR-2	12.970	13.922	1.073	2.350	2.435	1.036
BR-3	5.220	5.819	1.115	0.750	0.795	1.061
BR-4	4.991	5.528	1.108	0.979	1.041	1.063
Average	7.992	8.642	1.099	1.447	1.508	1.048

DAF FROM FIELD AND AASHTO PROCEDURES

Field results of *DAF* for the modeled culverts are taken from Wells (2016). AASHTO recommends *DAF* for culverts BR-1 and BR-2, for which there is no fill, is 1.33. For culverts BR-3 and BR-4, which are overlain by fill, the AASHTO recommended *DAF* values are computed using Equation 2. *DAF* values calculated from field measurements and AASHTO procedures are summarized in Table 4.

Table 4 *DAF* values calculated from field and AASHTO procedures.

Culvert	AASHTO	Field
BR-1	1.33	1.01
BR-2	1.33	0.96
BR-3	1.25	0.92
BR-4	1.27	0.98
Average	1.295	0.963

CONCLUSIONS AND RECOMMENDATIONS

As shown in Table 4, AASHTO recommended values of *DAF* were found to be approximately 30 percent larger than the field calculated values. The *DAF* values obtained from 2-D FEM models were in a range of 1.06 to 1.15. These values were smaller than AASHTO values, while still larger than the field obtained *DAF*s. Among all *DAF*s, those obtained from 3-D FEM analysis were the closest to the field-measured values. The *DAF* values in 3-D FEM models were in the range of 1.03 to 1.06, with a maximum deviation of 6% from the field measurements. Recalling the *DAF* values of Table 3, it is concluded that the AASHTO procedure for calculating *DAF* is too conservative. Even though 2-D FEM models did not capture the real culvert behavior, their *DAF* results have been found more accurate than those obtained from AASHTO procedures. The displacements obtained in the 2-D FEM analyses were conservative, relative to the 3-D analysis results. Lastly, it is concluded that the asphalt-culvert-soil interaction can more reasonably be captured using 3-D FEM analyses, where the least amount of simplification is required.

It is known that load rating tests are expensive to run on a regular basis. They usually require traffic diversion and road blockage to avoid test disturbances. Attributed to these inconveniences, *DAF*s are commonly calculated analytically by following the AASHTO provisions. Following the results observed in this study, it is recommended to use 3-D FEM modeling to determine *DAF*s numerically. The modeling aspects and the computational time involved in running 3-D FEM analysis are not as intensive as one might think. Once a working model is developed, the analysis takes a matter of few hours. In cases where 3-D FEM analysis could not be justified, the 2-D FEM analysis could be used. Even though the obtained results are not ideal, *DAF*s from 2-D FEM are still closer to the actual *DAF* values when compared to what AASHTO procedures give.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the Delaware Department of Transportation. Any opinions, findings, and conclusions expressed herein are those of the authors and do not necessarily reflect the views of the Delaware Department of Transportation.

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