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Field testing and numerical modeling of a low-fill box culvert under a flexible pavement subjected to traffic loading

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Abstract. This paper presents field study and numerical modeling results for a single-cell low-fill concrete box culvert under a flexible pavement subjected to traffic loading. The culvert in the field test was instrumented with displacement transducers to capture the deformations resulting from different combinations of static and traffic loads. A low-boy truck with a known axle configuration and loads was used to apply seven static load combinations and traffic loads at different speeds. Deflections under the culvert roof were measured during loading. Soil and pavement samples were obtained by drilling operation on the test site. The properties of the soil and pavement layers were determined in the laboratory. A 3-D numerical model of the culvert was developed using a finite difference program FLAC3D. Linear elastic models were used for the pavement layers and soil. The numerical results with the material properties determined in the laboratory were compared with the field test results. The observed deflections in the field test were generally smaller under moving loads than static loads. The maximum deflections measured during the static and traffic loads were 0.6 mm and 0.41 mm respectively. The deflections computed by the numerical method were in good agreement with those observed in the field test. The deflection profiles obtained from the field test and the numerical simulation suggest that the traffic load acted more like a concentrated load distributed over a limited area on the culvert. Elastic models for culverts, pavement layers, and surrounding soil are appropriate for numerical modeling of box culverts under loading for load rating purposes.

Keywords: culvert; deflection; numerical method; pavement; stress

1. Introduction

Culverts are major units of a highway system. They can be installed at shallow to great depths depending upon terrain conditions. The influence of traffic load is greater when the culverts are buried under shallow depths compared to those under great depths (Abdel-Karim *et al.* 1990, 1993). Engineers are required to evaluate and maintain the shallow cover culverts in a serviceable condition. This need is often addressed by load rating of culverts.

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American Association of State Highway and Transportation Officials (AASHTO) defines load rating as the maximum truck tonnage, expressed in terms of HS load designation, permitted across a culvert (AASHTO 2011). The Kansas Department of Transportation Bridge Design Manual (2011) describes load rating as analyses of culverts and bridges performed to determine the live load that structures can safely carry. Load rating is carried out based on the existing culvert condition and requires analyses and engineering judgment by comparing the culvert structure's capacity and dead load demand to live load demand (Lawson *et al*. 2009). Therefore, load rating depends on three major factors: culvert load capacity, dead load demand, and live load demand for moment, shear or thrust. Among these factors, the live load is the governing factor in load rating of the low-fill culverts. The traffic load is prominent on culverts with a fill depth of 2.4 m or less (Abdel-Karim *et al*. 1990, 1993).

The distribution of the applied load on the culvert to the surrounding soil is a complex soil-structure interaction problem. Soil-structure interaction problem has been of interest to researchers for a few decades (James and Brown 1987, Tadros *et al*. 1987, Bloomquist and Gutz 2002, McGrath *et al*. 2005, Yoo *et al*. 2005, Kim and Yoo 2005, Kang *et al*. 2008, Nagy *et al*. 2010, Lawson *et al*. 2010, Sanford 2010, Lees and Richards 2011, Sun *et al*. 2011, Livaoglu 2013, Fatahi *et al*. 2014, Cakir 2014). The structural response of a full-scale culvert is also of interest to researchers (Lawson *et al*. 2009, Acharya 2012, Acharya *et al*. 2014). Analytical and numerical analysis of buried pipes has also been focus of researchers (Bryden *et al*. 2014, Dezfooli *et al*. 2014). Moreover, some researchers have analyzed the culverts under the earthquake loads (Sawamura *et al*. 2014). Culverts exhibit different responses under static and traffic loading. A culvert can be installed under a flexible pavement, a rigid pavement, or an unsurfaced road. Culverts can be made with different materials in different shapes. However, rectangular concrete box culverts have been popular in practice. These culverts are suitable for a wide range of fill depths and are commonly used under a shallow cover condition.

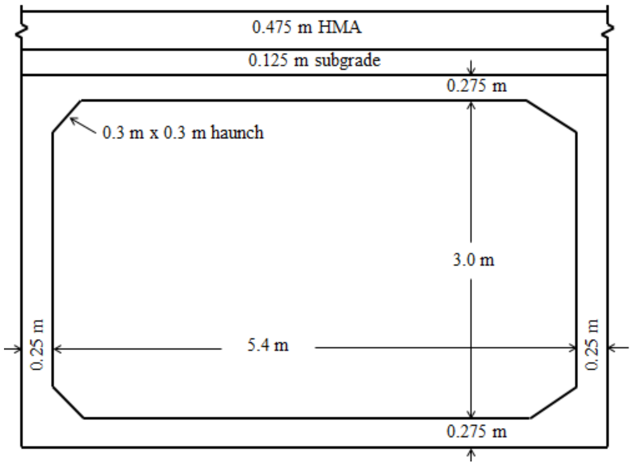
Different factors affect load distribution over a culvert. These include material, geometry, age of the culvert, pavement structure, fill depth, and loading. To investigate some of these factors, a full-scale field test on a box culvert buried under a shallow cover can be conducted under static and traffic loading. The responses of the culvert can be captured under different combinations of loading. The measured responses can be used to verify a numerical model which can be used to carry out a parametric study for the pressure distribution on the culvert. NCHRP (2010) carried out a comprehensive study on the pressure distribution over culverts by numerical modeling of culverts. However, this study did not consider the effect of the pavement. It is necessary to ignore the pavement effect on pressure distribution in culvert design when construction loads are considered. However, a load rating process often involves in-service culverts under pavements. Discounting the effect of the existing pavement on the pressure distribution on the culvert can result in an overly conservative pressure distribution model. This conservative result can prompt the closure of the culvert for heavy trucks or posting of a weight limit unnecessarily.

In practice, the design of a box culvert is often conducted based on a plane strain condition. Such a condition may be valid when uniform soil weight or line load is applied to the fill or pavement surface in the longitudinal direction. As a result, the calculated culvert deflection in the longitudinal direction is uniform. This basic assumption of a uniform culvert deflection in the longitudinal direction has been questioned by researchers (Abdel-Karim *et al*. 1993). It is well known that a traffic load acts more like a concentrated load because of its small contact area as compared with the size of a typical culvert. Unlike a line load, a point load requires a three-dimensional analysis of the problem (Abdel-Karim *et al*. 1993). Therefore, a three dimensional analysis becomes necessary for pressure distribution on a culvert under the traffic load.

Unfortunately, a box culvert with a pavement under a traffic load has not been well investigated three-dimensionally in the past. This paper presents a field study and a three-dimensional numerical analysis of a single-cell low-fill box culvert under a flexible pavement subjected to traffic loading. The numerical results are compared with field test results under the same condition. The verified numerical model can be used for a future parametric study.

2. Field test

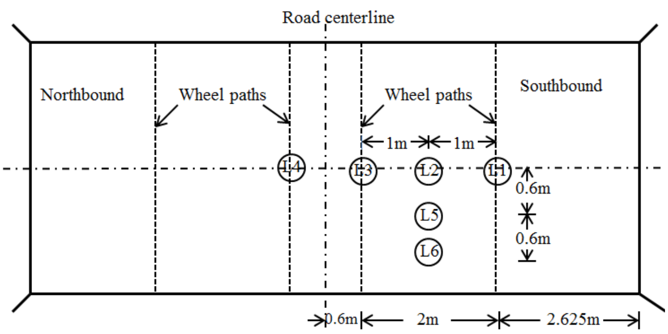
The test culvert was a single span reinforced concrete box culvert located at milepost 68.7 on K-148 highway near Barnes, Kansas. The cross section and the picture of the culvert are shown in Figs. 1(a)-(b), respectively. The culvert aligns perpendicular to the highway. The total fill depth over the culvert including a flexible pavement was 600 mm. The overall length of the culvert was 10.35 m, which included two 3.3 m wide northbound and southbound lanes. The culvert backfill was composed of dark brown low-plasticity clay. The clay had a liquid limit of 43, a plasticity index of 23, and specific gravity of 2.71. The pavement above the box culvert included a 475 mm



(a) Schematic of cross-section

(b) Photograph of the culvert

Fig. 1 Cross section of the test culvert



(a) Schematic of the transducer location

(b) Transducers placed in position

Fig. 2 Locations and installation of the displacement transducers under the culvert roof

thick asphalt concrete layer over a 125 mm thick lime stabilized subgrade.

The response of the culvert under static and traffic loading was monitored using displacement transducers installed under the roof of the culvert. Displacement transducers were used to measure the vertical deflections of the culvert roof slab. Six displacement transducers were used in the test, among which four transducers labeled as L1, L2, L3, and L4 were installed along the box axis as shown in Fig. 2(a). Similarly, transducers L2, L5, and L6 were installed along the culvert span. Due to symmetry, the instrumentation was mainly focused on the southbound lane while only one displacement transducer was installed under the northbound lane. However, loads were applied by a test truck on both lanes in turn. The displacement transducers were laid out by utilizing the symmetry of the culvert about the centerline of the road so that deflection profiles can be drawn along the length of the culvert. Another three transducers were installed perpendicular to the culvert axis to measure deflections in that direction so that deflection profiles along the span for the symmetric load about culvert axis could be obtained. Transducers L1 and L3 were located right under the wheels and L2 was under the middle of the axle during loading. It can be reasonably assumed that, when a load was applied on the northbound lane, transducer L4 would serve as transducer L3 when the southbound lane was loaded. Similarly, the deflections measured by transducers L1 and L2 during the northbound lane loading could be considered as those measured at the symmetric locations under the northbound lane when the load was applied on the southbound lane. Approximately 2.8 m tall metal frames were used to hold the displacement transducers in position as shown in Fig. 2(b). The frames were stabilized by placing sand bags at the base.

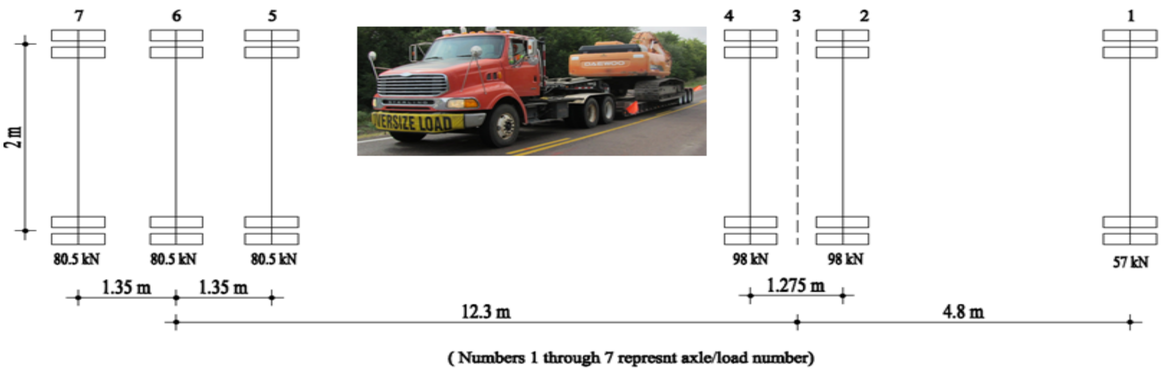


Fig. 3 Axle loads and configuration of the truck used in this study

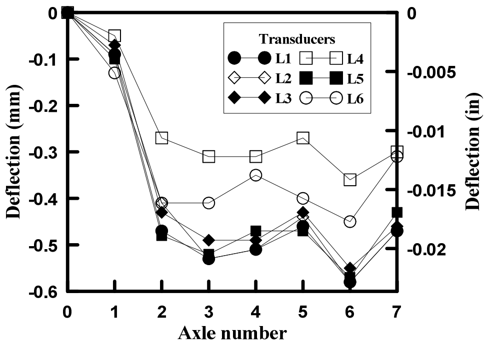
3. Loading procedure

A truck pulling a low-boy trailer loaded with a backhoe was used as the test truck. The truck consisted of six physical axles: a front steering axle, middle tandem axles, and triple axles at the end. However, seven load positions were adopted in this study. The axle configuration and the load on each axle are shown in Fig. 3 (inset shows a photograph of the truck). The load of the front steering axle was 57 kN. The center of the tandem axles was located at 4.8 m from the front axle and had a 98 kN load on each axle. The center of the triple axles was 12.3 m behind the center of the tandem axles. Each of the triple axles had an 80.5 kN load. The center to center distance between wheels on the same axle was 2 m.

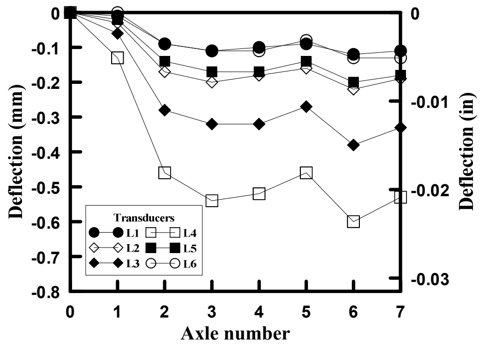
The response of the culvert was measured under static and traffic loading conditions. The axis of the culvert was marked with color sprayer on the surface to determine the position of each axle during static loading. Also the intended lateral positions of the wheels were marked along the same line in both lanes. Seven load combinations (referred here as loads 1 to 7) were obtained through applying static loading at each section by placing six axles of the truck over the marked line in turn. One more combination was obtained by assuming one dummy axle in the middle of the tandem axle. This dummy axle provided one more symmetric load. The numbering of each axle load combination is shown in Fig. 3. Deflection readings were recorded continuously using the data acquisition systems. Traffic loading was also applied on both lanes by moving the truck at six predetermined speeds: 16.1 to 96.6 km/h (10 to 60 mph) at an increment of 16.1 km/h (10 mph).

4. Field test results

The measured deflections of the culvert under static loads at the displacement transducer locations are presented in Fig. 4. Fig. 4(a) shows the deflections during the southbound lane loading. In this case, the deflections observed at transducers L1, L2, L3, and L5 were almost equal. However, transducer L2, which was at the middle of the axle, recorded the maximum deflection. Displacement transducer L4 installed below the northbound lane recorded the minimum deflection. The deflection at the quarter span of the culvert (i.e., at L6) was also considerably lower than the deflections at other locations. Similarly, Fig. 4(b) shows the deflections during the northbound lane loading. In this case, the maximum deflection was observed at transducer L4 and the minimum



(a) Southbound lane loading

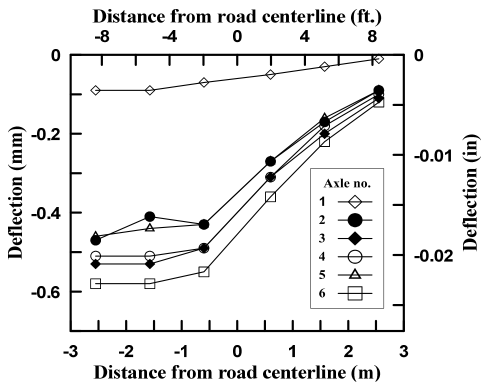


(b) Northbound lane loading

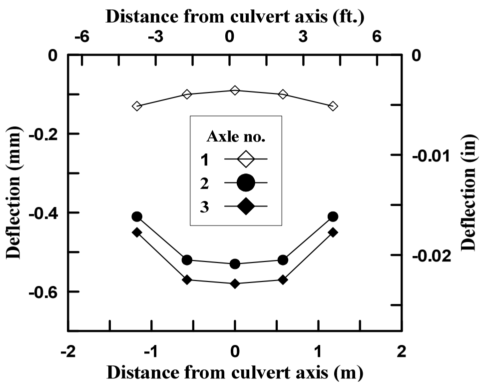
Fig. 4 Deflections during southbound lane static loading

deflections were observed at L6 and L1. The deflections observed at transducers L2 and L5 were almost equal.

Displacement transducer L4 was at a distance of 1.2 m from the inner wheel of the truck when the load was applied at the southbound lane. Similarly, displacement transducer L3 was at a distance of 1.2 m from the inner wheel of the truck when the load was applied at the northbound lane. Therefore the observed deflections at these locations during southbound and northbound lane loadings were nearly interchangeable. Because of the relative locations of the displacement transducers during southbound and northbound lane loading, it was possible to plot the deflection profile along the culvert axis even under the northbound lane. The resulting deflection profiles under each axle load during the southbound lane loading are shown in Fig. 5(a). While these deflection profiles were drawn, the deflections recorded at L1, and L2 were assumed to be equal to the deflections at the symmetric locations under the northbound lane. Axle 6 produced the maximum deflections at all locations whereas Axle 1 produced the least deflections. The loading was symmetric about the culvert axis when the Axles 1, 3, and 6 were at the marked location. Therefore the deflections observed at L5 and L6 can be assumed to be equal to those at the corresponding locations of the symmetric half of the culvert. Under this assumption the deflection

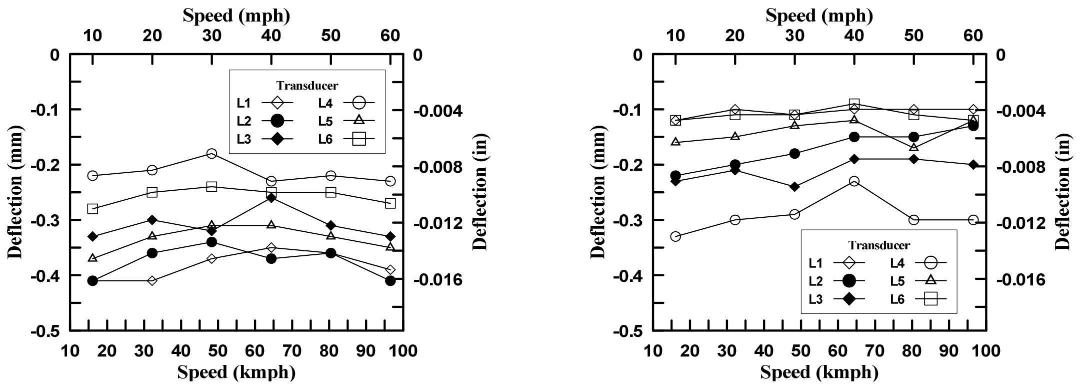


(a) Along culvert axis



(b) Along culvert span

Fig. 5 Deflection profiles along the culvert axis and span during southbound lane loading



(a) Southbound lane loading (b) Northbound lane loading

Fig. 6 Maximum deflections due to traffic load

curve can be plotted as shown in Fig. 5(b). However, the recorded deflections under Axle 1 loading show a curvature in the opposite direction due to anticlastic curvature in a plate. Also, the maximum deflections resulting from moving loads occurring at the transducer locations are shown in Figs. 6(a)-(b) for southbound and northbound lane loading respectively. The general trend of the plot shows that the deflections decreased gradually with an increase in speed from 16.1 to 64.4 km/h (10 to 40 mph). Beyond the speed of 64.4 km/h (40 mph) the deflection remained almost unchanged.

The displacement transducers used in this research were strain gauge-type sensors manufactured by Tokyo Sokki Kenkyujo, Co., Ltd., Japan. They had two displacement ranges: 0 to 100 mm (Model: CDP-100; displacement transducers L2, L3 and L4) and 0 to 50 mm (Model: CDP-50; displacement transducers L1, L5 and L6). The accuracy of the transducers was 0.01 mm. All the deflections discussed in the current study are the deflections of the top slab of the culvert relative to the bottom slab. It should be noted that the total vertical displacement of the culvert could be higher than the recorded relative top slab deflections. However, the experimental program did not incorporate the measurement of the vertical displacement of the entire culvert system.

5. Laboratory tests of samples

Two asphalt cores and four Shelby tube soil samples were obtained by drilling. The asphalt cores were 475 mm long. The Shelby tubes, which were pushed inside the borehole on the side of the culvert, recovered undisturbed soil samples at four depths (1, 2, 3, and 4 m). The drilling operation found that the box culvert was built on bedrock. The asphalt concrete samples were sawed into a height-to-diameter ratio of 2:1. The height of the samples was 200 mm after sawing and the diameter was 98 mm. The density of the asphalt concrete sample measured before testing was 2138 kg/m^3. A rebound test was conducted to estimate the elastic modulus of the asphalt concrete. Fig. 7 shows the dial gage arrangement and test setup for the rebound test of the asphalt concrete sample. The gage length for the deformation measurement was 150 mm. The compressive load was applied up to 5.33 kN at the rate of 0.5% strain per second. The corresponding maximum compressive stress was 690 kPa, which was nearly equal to the tire contact pressure applied by the test truck. The dial gage measured a total rebound of 0.076 mm. The elastic modulus of the asphalt

Fig. 7 Setup for rebound test of the asphalt concrete cylinder

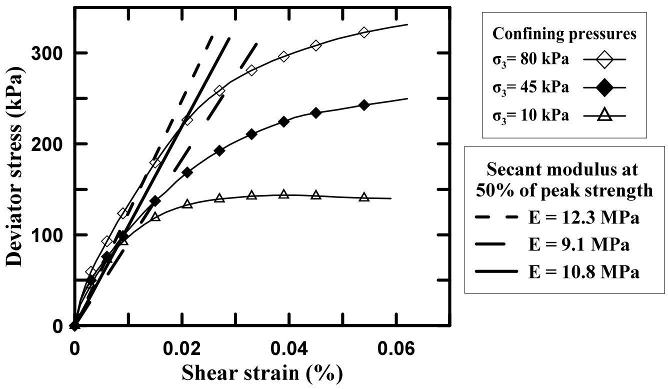


Fig. 8 Triaxial test results of the natural backfill soil

concrete was determined to be 1,827 MPa.

Total strength triaxial tests were performed on the undisturbed soil samples with natural moisture content obtained from the field to determine the elastic modulus, cohesion, and friction angle of the soil. Three triaxial tests were conducted at confining pressures of 10, 45, and 80 kPa respectively. The elastic modulus of the soil was calculated as a secant modulus at 50% of the peak strength. The triaxial test results and corresponding secant moduli of the backfill soil are presented in Fig. 8. The elastic moduli of the soil were found to be 10.8, 9.1 and 12.3 MPa at the confining stresses of 10, 45, and 80 kPa respectively with an average value of 10.7 MPa. Also, the cohesion and the friction angle of the soil were 44 kPa and 22° respectively.

6. Numerical modeling and verification

The culvert was modeled using a finite difference program called Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D). Assuming the stresses developed during the field test are within elastic limit for all the materials involved, including the backfill soil, elastic constitutive models were used for all the materials with their corresponding model parameters. Only half of the culvert was modeled to utilize the symmetry condition as shown in Fig. 9. Unyielding foundation conditions were assumed for the model. Therefore the vertical movement at the bottom of the mesh was restricted by applying a zero vertical displacement boundary condition. Similarly a zero horizontal displacement boundary condition was created along all the vertical boundaries except for the free boundary of the box culvert in the *y* direction.

The elastic modulus of 1827 MPa was used for the asphalt concrete layer as obtained from the rebound test. The AASHTO Guide for Design of Pavement Structures (1993) suggested a typical value of elastic modulus for lime-treated subgrade ranging from 138 to 483 MPa. Therefore, an average value of 310 MPa was adopted for the verification of the numerical model. The average elastic modulus of 10.7 MPa obtained from the triaxial test was used for the backfill soil. It was assumed that the concrete had a typical compressive strength of 31026 kPa. Considering 1% of the steel reinforcement with an elastic modulus of 20 GPa, the elastic modulus of the reinforced concrete was determined to be 27,580 MPa. Poisson's ratio of 0.3 was used for asphalt concrete, lime treated subgrade, and backfill soils and 0.15 was used for the concrete.

Axles 1, 3, and 6 provided symmetric loads with respect to the culvert axis. Therefore, loads from these axles were applied on the model. The resulting deflections calculated from the numerical model were compared with the deflections measured from the field test. The length,

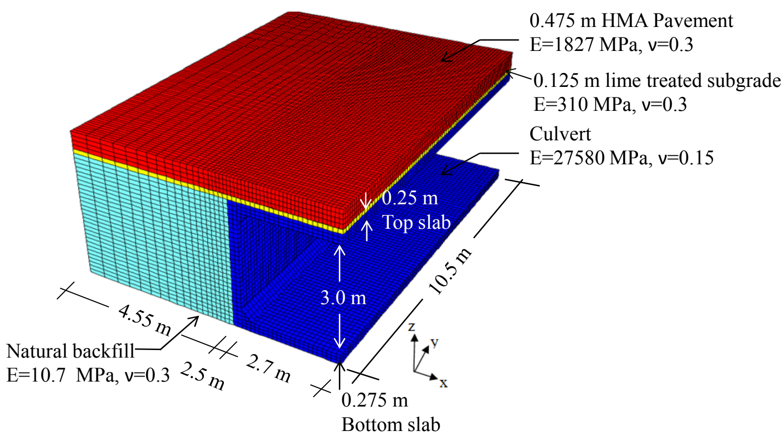
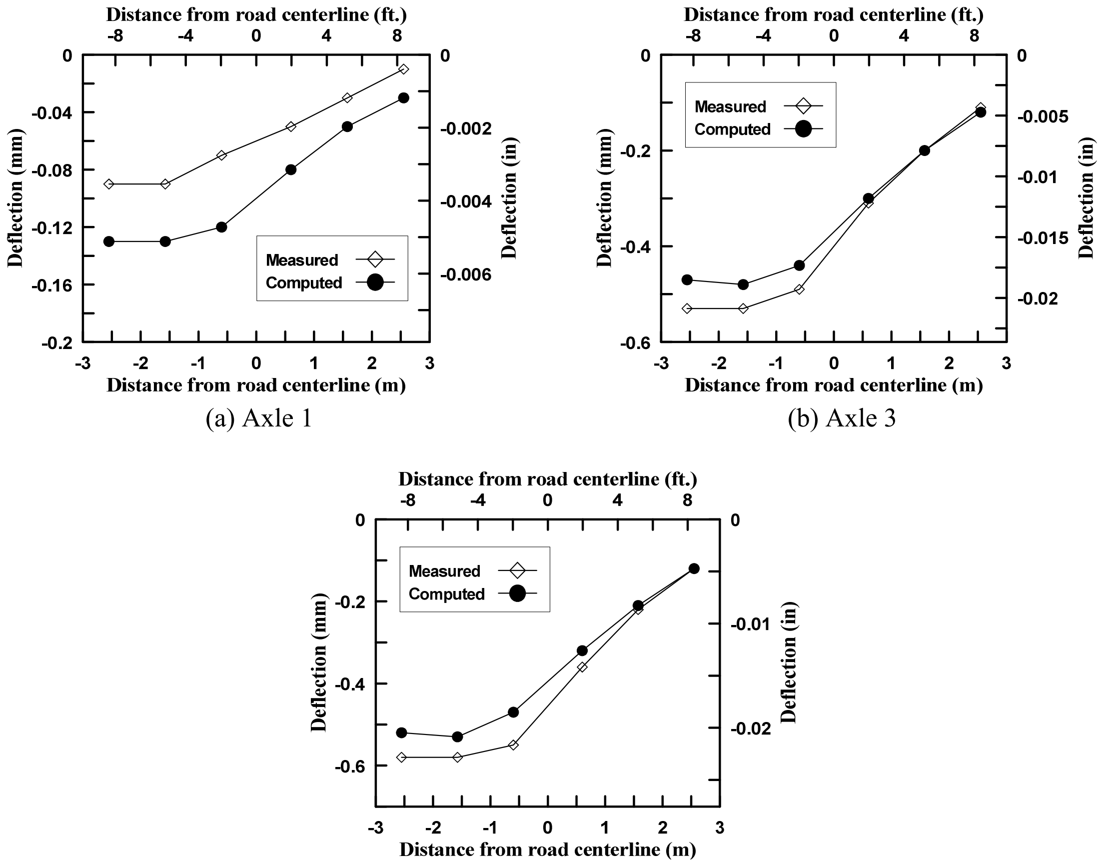


Fig. 9 FLAC3D numerical mesh of the culvert

Table 1 Calculation of pressure and number of zones for pressure

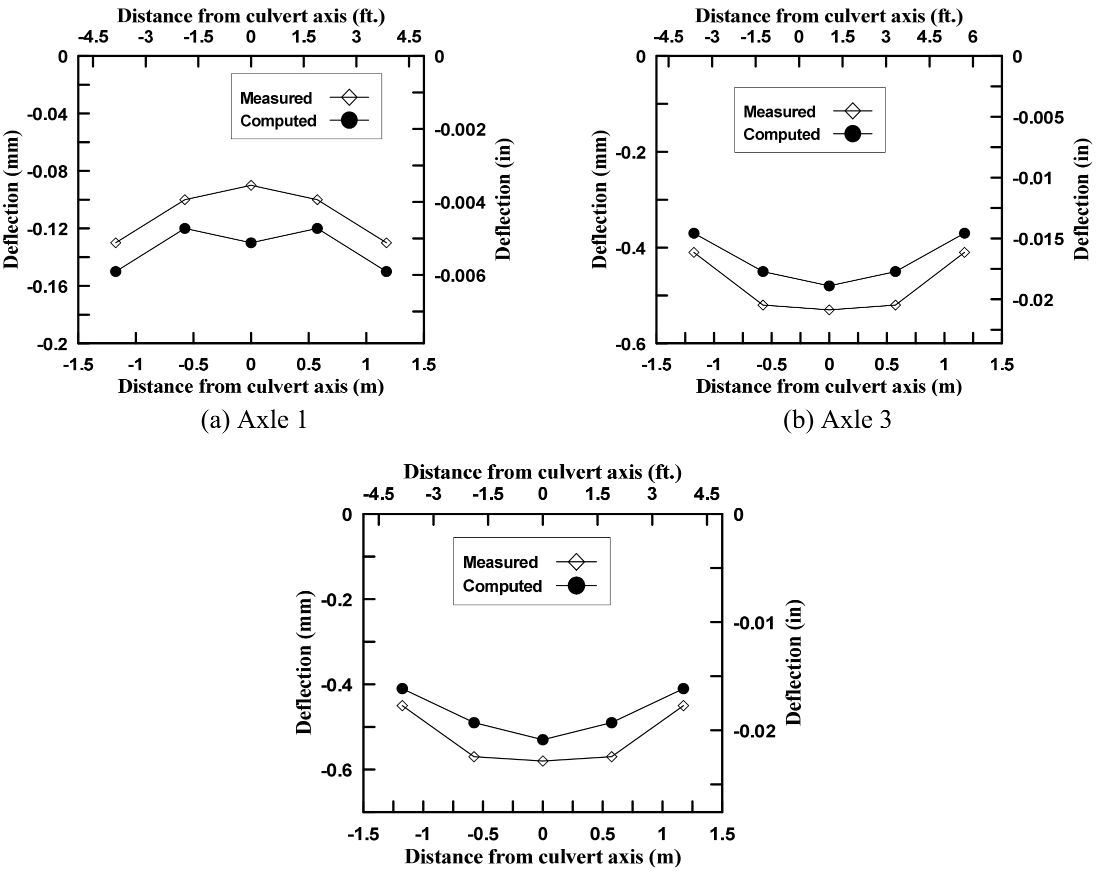
Axle No.	Single wheel load (kN)	Actual tire pressure (kPa)	Contact area (m^2)	Area of each zone (m^2)	Number of zones	Applied pressure (kPa)
1	28.5	760	0.038	0.01	4	700
2	49	760	0.064	0.016	4	784
3	0	0	0	0	0	0
4	49	760	0.064	0.016	4	784
5	40.25	760	0.052	0.013	4	805
6	40.25	760	0.052	0.013	4	805
7	40.25	760	0.052	0.013	4	805

width, and height of the model were 10.5, 7.5, and 4.225 m respectively. Each component of the culvert and pavement layers were divided into several small elements called zones in FLAC3D. It is similar to the mesh generation in finite element application. The numbers of zones in the numerical mesh were 87864, 80304, and 84924 when Axles 1, 3, and 6 were applied in the model respectively. The reason for the difference in the number of zones for different axles is that each axle had a different contact area of the load, which required changing the size of the mesh on the surface where the load was applied. Finer zones were used near the culvert and the zone density gradually decreased away from the culvert. The load was applied in the form of pressure on the surface of the pavement. The number and size of zones required to apply the pressure were calculated and are shown in Table 1 so that the total wheel load was equal to that in the field test while the contact pressure was close to that in the field test. When Axle 1 was applied in the model, each wheel only had two zones due to the symmetry condition. Axle 3 did not have its own load. However, when Axle 3 was in place, the wheel load used for Axle 2 or 4 was applied on the model due to the symmetry. Similarly, when Axle 6 was in place, the wheel loads for Axles 5 and 7 were also applied on the culvert. However, only half of the load from Axle 6 and a full load from Axle 5 or 7 were applied on the model.



(c) Axle 6

Fig. 10 Measured and computed deflections along the culvert axis



(a) Axle 1

(b) Axle 3

(c) Axle 6

Fig. 11 Measured and computed deflections along culvert span

7. Deflections of culvert top slab

The measured deflections at Locations L1 through L6 are compared with those from FLAC3D. Figs.10 and 11 show the measured deflections as compared with the computed ones from FLAC3D when Axles 1, 3 and 6 were applied on the pavement. Figs. 10(a) and 11(a) show that the measured deflections at all the locations reasonably match with the computed ones from FLAC3D when Axle 1 was applied on the pavement. The difference in their deflections was more significant near the point of the load application and gradually decreased with an increase of the distance. Similarly, Figs. 10(b) and 11(b) show a reasonable comparison of the measured and computed deflections when Axle 3 was applied on the pavement. Figs 10(c) and 11(c) show a better comparison of the measured and computed deflections when Axle 6 was applied on the pavement. Overall, the computed deflection profiles had similar shapes to the measured ones but the measured deflections were larger or smaller than the computed ones depending on the axles. Their differences were most obvious when Axle 1 was applied on the pavement and were smallest when Axle 6 was applied. The observed differences in measured and computed deflections at some of the locations may be due to the following reasons: (1) assumption of an unyielding culvert foundation; (2) lack of interface elements to precisely simulate the soil-culvert interaction; (3) simplification of the numerical model with elastic constitutive relationships for all materials, and (4) difference in the actual tire pressure during loading and the pressure applied to the culvert during numerical simulation.

7. Conclusions

A low-fill reinforced concrete box culvert was instrumented and tested under static and traffic loading under a flexible pavement. Displacement transducers were mainly used to monitor the structural response. A finite difference model of the culvert was developed and subjected to similar loading as applied in the field. Linear elastic models were used for all the materials of the culvert because the stress levels of the load rating as compared with the strengths of the materials are usually low. The numerical model created using the finite difference program FLAC3D were validated using the data from field tests. The following conclusions can be drawn from this study:

- The deflections of the culvert under static loading varied with the magnitude and position of the axle load. A larger load produced larger deflections of the culvert. The maximum deflection happened in the mid-span of the culvert. The deflections decreased in both longitudinal and transverse directions with distance. This result implies a two way slab action. In general, the observed deflections were smaller under moving loads than static loads.
- Elastic models were used for all the materials. The field deflection data supported the assumption that use of linear elastic models for all the materials is valid for the culvert under the pavement. The elastic moduli of the reinforced concrete culvert, asphalt concrete pavement, and lime-treated subgrade used in the numerical modeling were 27,580, 1,830, and 310 MPa, respectively. The analyses showed that the selected modulus values were appropriate for respective materials.
- The deflection profiles obtained from the field test and numerical simulation suggest that the traffic load acted more like a concentrated load than a uniform load distributed over the culvert. Therefore a three dimensional analysis of pressure distribution on the culvert is necessary.
- The deflections computed by the numerical method were in good agreement with those observed in the field test. These comparisons demonstrate that the numerical model reasonably simulated the behavior of the box culvert when an axle load was applied on the pavement. Also, the pressure applied on the specified contact area of the tire simulated the wheel load well.

The numerical model generated as a result of this study will be used for future research to investigate several key influence factors on load distribution through different pavement structures, which will be useful for load rating of culverts under flexible pavements.

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