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Determination of Finite Element Modelling Errors for Box Culverts Using Field Load Tests

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ABSTRACT

Buried culverts have been in service more than half a century and their age raises questions about their reliable serviceability for the new standard vehicles. The gross weight and axle spacing of these trucks play an important role on the performance of the buried culverts where the culvert is covered with shallow fill heights. Field live load tests were conducted by driving a loaded truck over some culverts at slow speed while recording data at the critical locations of these culvert. Finite element (FE) models were developed and calibrated using field load test results. Live load distribution formulations were adopted from AASHTO LRFD Bridge Design Specifications for different fill heights. Two- and three-dimensional FE models were modelled and loaded separately to compare the critical section forces. The results showed that the error using two different FE modelling approach yields more than 100% error for the maximum section forces when fill heights is between 60 cm and 120 cm. This study is aimed to highlighting the inherent error in numerical modelling of buried reinforced box culverts for design or rating purposes.

Keywords: Box culvert, field test, fill height, load distribution, finite element modelling.

1. INTRODUCTION

The importance of the load distribution on the buried structures remains an important research topic. Either using classical or alternative filling materials, researchers have studied the accurate load distribution methods of these materials [1–9] with others. These studies showed that the correct live load distribution is an important parameter in FE modelling either using traditional or any material as filler material. Generally, the rapid and alternative construction techniques proposed for an engineering solution to minimize the construction costs. One typical example of catastrophic reconstruction collapse of the I-88 crossing of Carrs Creek in Sydney, New York showed that the correct numerical modelling is an important tool for actual load rating and service life estimation of the existing culverts before dealing with an expensive and extensive construction works [7].

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The age of buried culverts in soil has raised questions about their structural performance for transportation activities. Louisiana State required the Transportation Department of the state to rate their culverts to continue their service or post a tonnage limit if the culvert is low load rated in federal program. Early studies showed that the research was concentrated on the steel culvert performances, mainly their corrosive resistance and durability were investigated for different steel pipe culverts [10,11]. In general, their study highlighted and categorized protective measures for metallic culverts. Similar studies today showed that the performance of these metallic culvert`s and load rating test have been investigated in recent years [12–14].Even though the number of transportation alternatives varies, these culverts continue to carry the increased gross weight of heavy vehicles. In addition to these updated axle loads with varying axle spacing, the old detailing of these culverts raises questions about their strength and serviceability. Different modelling approaches and assumptions have been studied to create an accurate approach for the load rating of the culverts including the experimental field load tests [1–5]. The results showed that these culverts do not show any structural deficiency when they are visually inspected; however, the load rating factors were calculated below the threshold after performing finite element analysis [15]. In one study, the wheel loads over 60 cm to 365 cm fill heights were extracted using pressure cells buried in soil during the field tests to define the wheel load distribution on culverts [1]. In a similar investigation, it was determined that when the fill height is less than 60 cm live load distribution defined in AASHTO LRFD method gives conservative results [2]. Another suggestion was that the section forces due to live load can be neglected when the fill height is above 180 cm after the investigation of relation between the fill depth and culvert performances for different fill heights [6]. In other experimentally tested culverts, flexure dominated failures governed the failure of tested box culverts and their load capacities were obtained either above the calculated capacity [3] or similar to the calculated load capacity [16–18] using AASHTO LRFD load distribution. . The shear failure of the box culverts could not be observed until the applied shear force reached 2 times the designed shear capacity of the tested culverts [19]. Another performance defining parameter is found to be the pavements on road surfaces [20]. The pavement redistributes the wheel load before transferring to the soil; therefore, it helps to increase the performance and load rating of the culverts.

The study here investigates the modelling differences for the reinforced concrete box culverts filled with traditional earth fill. The experimental field tests, culvert details, concrete properties, and surveyed fill heights of the four culverts are provided. All of these culverts cross the traffic perpendicularly. Section forces at the critical locations were collected when the culverts are subjected to the three axle tandem truck loads. This study was repeated with two-dimensional (2D) and three-dimensional (3D) finite element (FE) models. AASHTO LRFD live load distribution method [21] was applied to the culverts having different fill heights. The critical section forces were obtained from the parametric studies of the culvert models, and the modelling errors for different barrel sizes having different fill heights were investigated.

2. INSPECTED CULVERTS

2.1. Loads and FE Modelling

The fill height of each culvert was initially surveyed so that the truck axle load can be distributed following the AASHTO LRFD live load distribution method. The fill heights vary at the centre and the curb of the pavement, so an average fill height was calculated after multiple fill height measurements on the road surfaces. It should be noted that the FE results can vary due to averaging of the fill heights which will overestimates along the center of the pavement path forces and underestimates the pavement edge forces because the load pressure is highly dependent on the AASHTO equations and fill height depth. The tire contact area was given 250 mm x 510 mm according to the AASHTO equations, and the axle pressured area is formulated depending on the fill height as given in Equation (1). After the fill height exceeds 60 cm, a new loaded area can be defined using Equation (2). The axle load pressures at different fill heights can overlap with neighbour axle`s the loaded areas depending on the axle spacing. Load pressure at the overlapped area is normally higher than the non-overlapped areas; which intensify the pressure at those overlapped zones; therefore, when the loaded areas were overlapped, the cumulative load pressure was uniformly redistributed to the total loaded area.

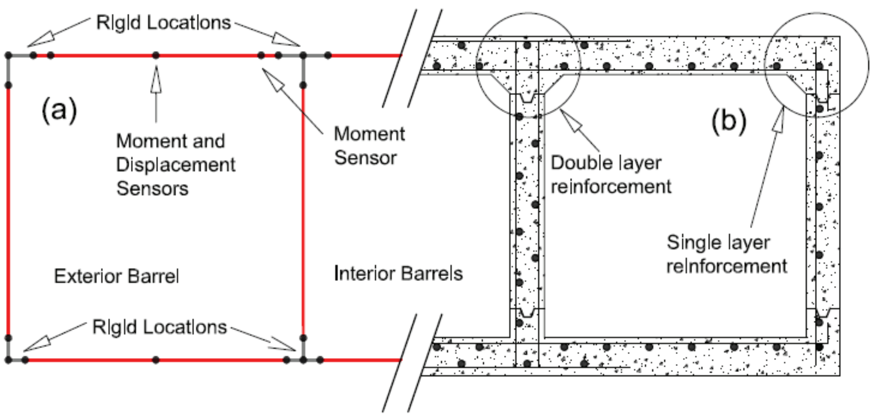
The axle loads were calculated as the uniform axle load pressures for the 3D FE element models where the shell elements were assigned to the culverts` sections. The axle load pressure is converted to uniform line load by multiplying the unit width for the beam elements that the influence lines are defined in 2D and 3D FE models.

$$\begin{aligned} &FH \leq 600mm \\ &W_{perp} = 2440 + 0.12xLS \\ &W_{span} = 250 + 1.15xFH \end{aligned} \tag{1}$$

$$\begin{aligned} &FH > 600mm \\ &W_{perp} = 250 + 1.15xFH \\ &W_{span} = 510 + 1.15xFH \end{aligned} \tag{2}$$

The notations are; FH = Fill height of the culvert (mm), LS = Clear span length (mm), W_{perp} = Equivalent distribution width perpendicular to span (mm), and W_{span} = Equivalent distribution length parallel to span (mm) in Equations (1) and (2)

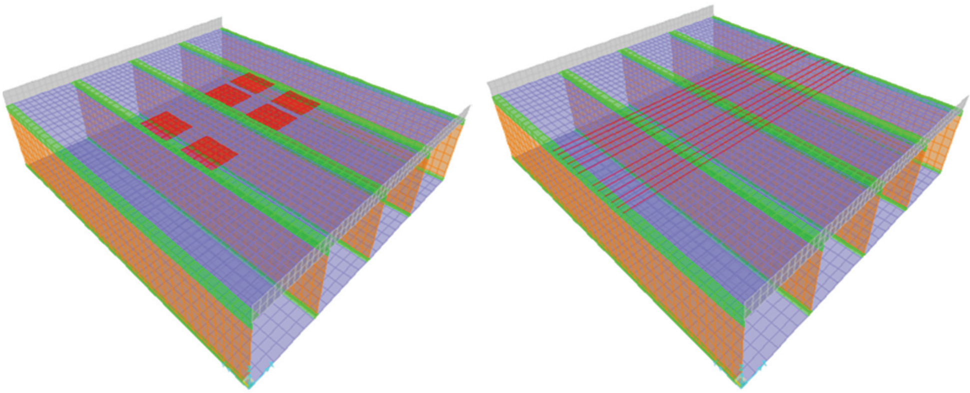
In 3D FE model, thin shell elements are utilized for modelling the slab and wall sections in SAP2000 commercial structural analysis program [22]. The mid-plane geometry of the culvert sections given in Figure 1(b) was drawn for the 2D culvert model as shown in Figure 1(a). Exact clear width and the height of the barrels are redefined with the rigid end offset option in FE models. The foundation soil can be assumed rigid and the variation of the section forces can be neglected where the previous study showed that the soil springs has about 5% effect on the section forces [23]. In 3D FE models, axle load distribution can be defined with two different approaches. The first one can be step by step loading which is the summation of loaded area groups which represents all of the axle loads and positions moving from start to the end of the culvert. For example, a typical loaded area group for single truck position is shown as the shaded rectangular elements in Figure 2(a). Axle positions were moved one element length at every step to obtain a continuous data similar to the field experiment. This approach can simulate every truck position and corresponding sensor data readings on the culvert, and it is the best technique to obtain the accurate field results continuously to compute the section forces [23]. In the second method, multiple influence lines were introduced in 3D FE models as shown in Figure 2(b) to form an influence surface along the travelling path. The load pressured area was divided into about 100 mm element size to define each influence line on the path, then the load pressure was converted to line load on each influence line. This method can provide much faster results then the previous method at the specific locations. The drawback of this method however is that, the results can be obtained as the maxima and minima of that location along the truck path; therefore, sub-step results cannot be saved with the second method. These two methods were validated by using the field test results, and the latter 3D FE model, which utilized the multiple influence lines, then used for the parametric studies.



a) Critical locations in 2D FE Model *b) Typical technical drawing*

Figure 1 - Culvert section through a barrel

On the other hand, two dimensional models are more favourable than three dimensional models in structural analysis due to less detailed model preparation and computational effort. These culvert sections are modelled as unit wide beam elements. Single path is defined on the top slab of the culverts to construct the influence line of the 2D FE models in order to obtain the section forces at the critical locations as shown in Figure 1(a); therefore, the results are obtained as the maxima and minima of the section forces. All the culvert properties and the boundary conditions were adopted from the 3D FE model for the 2D FE culvert model. Loads are applied uniformly distributed line loads using the AASHTO load distribution method. The truck load pressures were applied on a single influence line along the culvert length in 2D FE models. The section forces at critical locations were extracted for different culvert properties and the ratio of these section forces were calculated using 2D and 3D FE model results.



(a) Single truck position for area loading *(b) Multiple influence line method*

Figure 2 - Equivalent soil pressure loads on culvert slabs

2.2. Experimental Load Tests

The load ratings of the culverts modelled with frame elements using 2D FE models showed unrealistic performances [23]. The unexpected load rating of these culverts cannot be attributed to the structural deficiencies of the culverts due to their long service life without major failures. This study addressed the effect of the modelling techniques in multi opening buried box culverts using AAHTO LRFD live load distribution method. The standard details of the aged culverts are shown in Figure 1(b). The most important detail is the reinforcement in the top and bottom slabs. The single layer bars are continuously placed at the bottom layer of top slab. Only the second layer of reinforcing bars are placed for the negative moments on the interior walls. At the corners where the exterior wall joins to slab double layer bars were not placed; therefore, the wall – slab connections at those corner joints can behave like a hinged connection, therefore, the negative moments cannot develop at those corners. The constructed FE models include the hinged joints at both ends of the slabs. This assumption made due to technical details provided in Figure 1(b); however, the cracked sections due to single layer reinforcement cannot be verified by the field inspection due to pavement and earth cover. It should be noted that the haunch at the top wall – slab connections provide partial rigidity to the slab, and this was accounted by adding two thirds of the haunch length to wall thickness in FE models.

Three concrete core specimens from the walls of each tested culverts were obtained and tested under compression to calculate the compressive strength and elastic modulus of those tested culverts following the ASTM standard equations [24]. The field measured properties and calculated elastic modulus of the concrete specimens are given in Table 1.

Tandem three axle dump trucks, one of which is shown in Figure 3(a), were arbitrarily loaded before the test of each culvert. Strain and displacement sensors were placed on the culverts at their critical locations, which are shown in Figure 3(b) inside the opening of the tested culverts. These critical locations are defined as the middle of the exterior opening for displacement and positive strain (moment) and at the ends of the barrel width (30 cm from the wall surfaces) for the negative strain. The loaded truck passed the culverts about 1 or 2 minutes while the data acquisition system was collecting the sensor data continuously. The truck position and corresponding sensor readings were presented based on the truck positions. Finally, each truck was weighed after the test of the culvert, and axle loads were recorded and axle positions were measured on site. The recoded axle weights of these trucks are given in Table 2. The trucks have typically standard axle spacing; 3.70 m and 1.40 m from front to middle and middle to rear axles, respectively. The recorded rear axle loads were not exactly equal, but the total rear axle loads redistributed equally to all four wheels.

Table 1 - Experimentally tested culvert properties

Culvert ID / number. of barrels	Fill height. (cm)	Barrel size (m x m)	Wall / slab thickness. (cm/cm)	Elastic modulus (MPa)
C1 / 5	65	1.8x1.8	20/15	31260
C2 / 4	210	2.1x2.1	21/18	32150
C3 / 4	70	2.4x2.4	23/20	37224
C4 / 2	50	3.7x3.7	30/30	33246

Table 2 - Trucks of the field tests

Culvert	Front Axle (kN)	Middle Axle (kN)	Rear Axle (kN)	Gross Weight (kN)
C1	49	83	83	215
C2	56	99	99	254
C3	58	86	86	230
C4	42	73	73	188

(a) Test Turck

(b) Sensor locations

Figure 3 - Typical three axle test truck on a travelling path with sensor locations

2.3. Parametric Load Tests

Three different multi opening culverts (2, 3 and 4 barrels) are considered in this study. Each of these culverts is assigned with 1.50 m, 2.50 m and 3.65 m wide width, and these culverts are called CP1, CP2 and CP3, respectively,. These culverts are considered square box culverts so the height to width ratio was selected as one for all the analysis which correspond to the majority of the culverts in the state. The slab and wall thickness of these culverts are taken from archived technical drawings. Their considered properties are given in Table 3. The average of the experimentally obtained concrete properties was assigned to all tested culverts. Single test truck is redefined for the parametric cases using the average axle loads and spacing of the test trucks given in Table 2; therefore, the results are presented for the three-axle tandem dump truck in this section. However, these results can be used to estimate the modelling errors for the various axle numbers, positions, soil properties, and gross weight of the trucks because the parametric results are presented as the ratio of the two different FE analyses where the influence line of the critical sections is unique for each culvert.

The fill height of the analysed culverts was varied from 0 to 60 cm by using Equation (1), and 60 cm to 210 cm by using Equation (2) for the live load distribution given in the previous section. Typically, about 15 -20 cm fill height intervals were investigated from 0 to 210 cm fill height. Therefore, the analysis was repeated 11 times for one culvert and that led to 99 parametric culverts, each studied with 3D FE model. The culvert properties and load cases were kept identical for 2D FE model analysis and the study repeated independently for another same set of 99 culverts.

The ratio of the critical section forces between FE culvert models was investigated in the first part of this section. The critical locations for the strain readings and displacement during field tests were also considered the critical locations for the parametric studies. Instead of presenting the ratio of the maximum strains at the critical location, the positive moment at the mid span, and negative moment at the wall face of the exterior barrel were used to calculate the positive and negative moment ratios between models.

Table 3 - Parametric properties of the studied culverts

Culvert	Barrel size (mxm)	Number of barrels	Slab & wall thickness (cm)	Elastic modulus (MPa)
CP1	1.50 x 1.50	2 3 4	18.5	33470
CP2	2.50 x 2.50	2 3 4	20.0	
CP3	3.65 x 3.65	2 3 4	30.5	

In the second part of the parametric study, the ratio of the moments obtained in the previous study were used to calculate 3D envelope moments along the culverts. Only the envelope moments of the culvert CP3 with 4 barrels (CP3-4) are presented here for the multi opening culverts. Different sizes of trucks that have varying total gross weights, axle loads and axle positions were crossed the culvert CP3-4, and the variation of the maximum and minimum moments at the critical locations, mid-length and interior wall face of the exterior barrels, were calculated using their influence lines extracted from the 2D dimensional FE models. The simulation of each truck pass was modelled by inputting the influence lines extracted from the SAP2000, axle load coordinates, and axle load pressures to the coded script. Cumulative trapezoidal numerical integration of the influence lines between the predefined two axle load coordinates were calculated and it was repeated for each axle load. Therefore, the section moment variation at the critical location are obtained from the 2D FE models for consecutive load positions. AASHTO HL93 and HL93 tandem design trucks and other standard legal trucks given in Figure 4 are selected to investigate the effect of axle positions on positive and negative moment ratios.

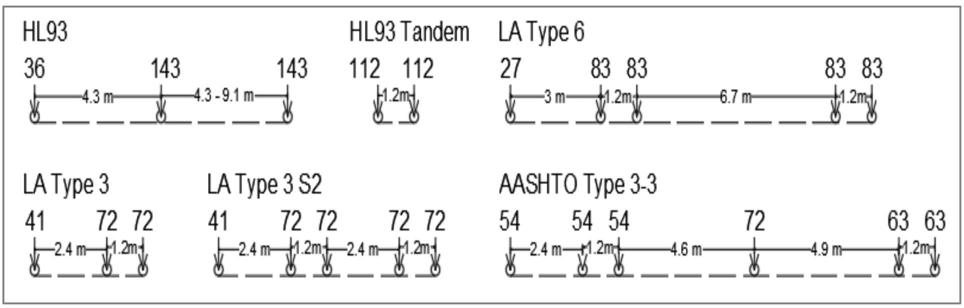


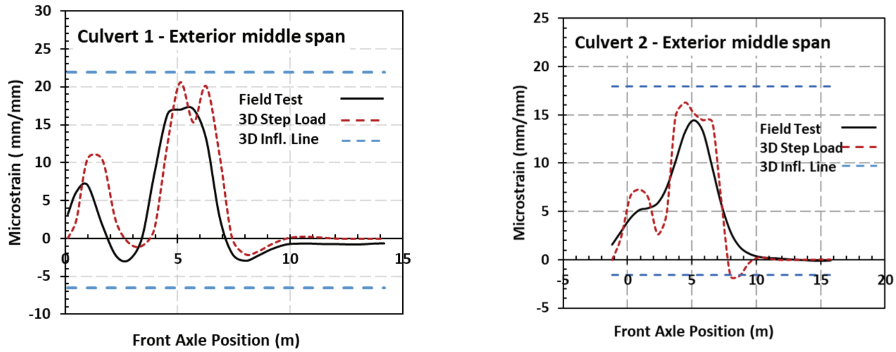
Figure 4 - Selected truck axle positions (m) and loads (kN)

3. RESULTS AND DISCUSSIONS

3.1. Experimental Test Results

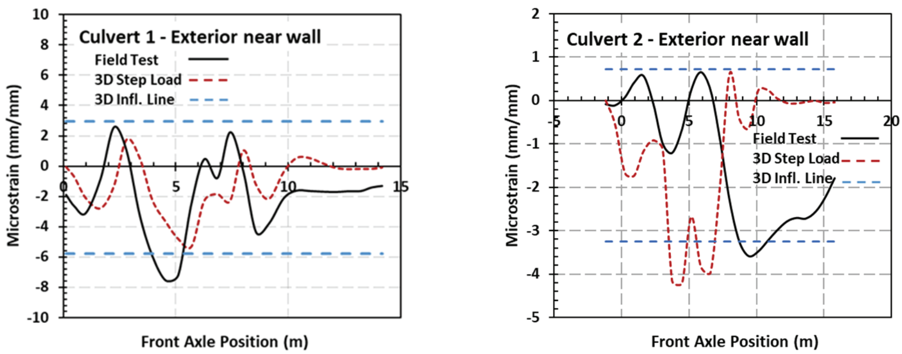
The field test results were investigated for four different culverts, and their 3D FE modelling results are verified in this study, but only first two of them, Culvert 1 and Culvert 2 are presented graphically in this section. Typical results of the 3D FE modelling approaches using step by step area loading and multiple influence line methods results are plotted from Figure 5 to 7. The solid black line represents the field test results, the continuous red dashed line represents the step-by-step area loading results, and constant blue dashed line shows the maximum and minimum peak strain results at the critical location using the multiple influence line method for Culverts 1 and 2 from Figure 5 to7. Positive strain changes are calculated from the moment forces at the critical location and they are plotted in Figure 5(a) and 5(b). The first positive peak strain recorded when the front axle loads positioned at the middle of the exterior opening, and the trailing rear axle loads caused the maximum strain in the culverts. When the multiple influence line method was used, sensor data at any specific load position diminished and only positive and negative minimum peaks can be obtained; therefore, the second approach concludes an upper and a lower bound of maximum peaks. It can be said the second approach over estimates the positive maximum peaks. The average error in Figure 5(a) and 5(b) is about 15% and 24% for the positive moments using the area and influence line loading methods, respectively.

The second sensor location was selected near the wall face to capture negative moments at the slab section. All the negative maximum peaks are plotted in Figure 6(a) and 6(b) for Culverts 1 and 2, respectively. It can be concluded that the multiple influence line method predicted the negative maximum peaks moment less than the maximum peaks of the field and step-by-step area loading results. It should be noted that the absolute intensity of the straining action near wall face is smaller when compared to the positive strain results. The area loading and influence line loading methods predict the negative peak strains by 21 % and 15% error, respectively.



(a) Culvert 1 – Fill height = 65 cm *(b) Culvert 2 – Fill height = 210 cm*

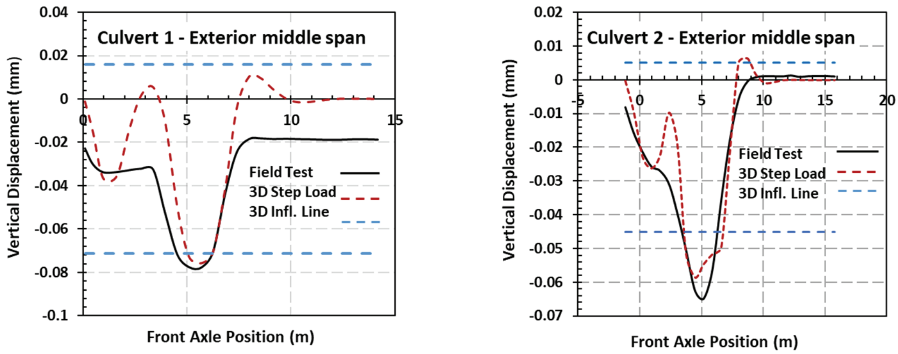
Figure 5 - Positive strains at the mid-span of the exterior opening



(a) Culvert 1 – Fill height = 65 cm *(b) Culvert 2 – Fill height = 210 cm*

Figure 6 - Negative strains at the wall face of the exterior opening

Finally, the peak positive moment and the peak vertical displacement were obtained at the same location during the field tests, and the displacement readings are shown in Figure 7(a) and 7(b). The area loading and multiple influence line methods predicted the displacements by 7.5% and 19% error, respectively. These results showed that the average overall error is about 17% for both culverts. The relative error between the two loading methods is about 5% and 12% for Culvert 1 and 2 respectively. It can be concluded that the influence line method provided an average of about 10% error for all four culvert. Considering computational cost of area loading method, the expected error due to use of multiple influence line method can be disregarded in culvert design or load ratings.



(a) Culvert 1 – Fill height = 65 cm *(b) Culvert 2 – Fill height = 210 cm*

Figure 7 - Maximum displacement at the mid-span of the exterior opening

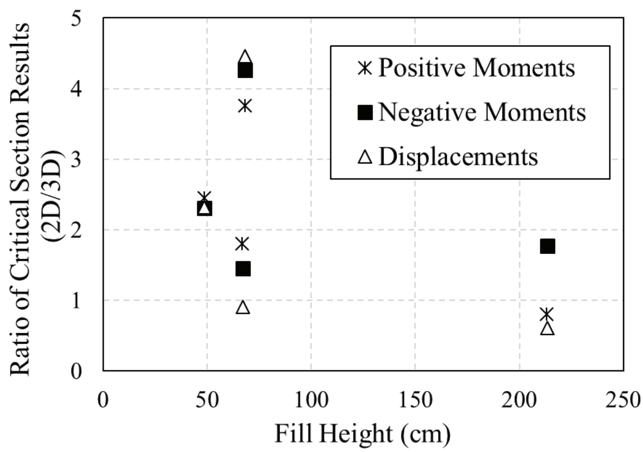


Figure 8 - FE model ratios for the experimentally tested culverts

All four culverts were then modelled using 2D frame elements and they were similarly loaded with the test trucks using single influence line method. The section forces were obtained and compared to the section results of the 3D FE, and the ratio of the section forces are plotted in Figure 8. It was found that the section forces from the 2D FE models can yield up to four times the validated section forces of the 3D FE models. This preliminary study showed that the modelling approach is an important design consideration specifically for the shallow fill heights when the AASHTO LRFD live load distribution is used. The results in Figure 8 did not show a good correlation for the ratios of the shallow fill height culverts. This implies that the other factors are still effective in the calculation of the section forces, which is not in the scope of this study. Nevertheless, the use of single influence line method using the 2D FE modelling approach cannot accurately represent any of the 3D FE modelling accuracy.

3.2. Parametric Test Results

The parametric test results are presented as the ratio of the maximum peak moments and displacement at the critical locations. It should be noted that the critical location of these parametric results can be slightly different from the critical locations shown in Figure 1(a). Therefore, the ratio between two FE models was calculated for their peak results, not the results of one specific location. Fill heights of these culverts was varied from 0 to 210 cm (0, 15, 30, 45, 60, 61, 75, 90, 105, 120, and 210 cm), where the live load pressure is negligible after 240 cm according to AASHTO design manual [25]. The axle load pressures were calculated using the Equations (1) and (2) depending on the selected fill heights. The number of barrels in this study was limited with 2, 3 and 4 for each culvert, and parametric culverts will be called as CP1, CP2 and CP3 as described earlier. The detailed graphic presentation of the calculated ratios for all the culverts are provided from Figure 9 to 10 as the fill height increased from 0 to 210 cm and discussed in details next.

The modelling error in these culverts increased parallel to the culvert sizes, meaning that the flexure dominant culvert, CP3, produced larger model errors. When the fill height is less than 60 cm as shown in Figure 9, for example, the error ratio is about 1.10 and 1.48 for the CP1 and CP3, respectively. The error ratio showed sharp jump at around 60 for the positive moments when the load distribution equation changed from Equations (1) to (2). It was found that the modelling error can reach a ratio of about 2 for CP3 culvert after 60 cm fill height has been exceeded, then that ratio gradually reduces to 1.22 for the CP3 with 210 cm fill height. Therefore, the variation of the ratios at different fill heights can be attributed to the error of the load distribution method. The critical fill height for the load distribution method is found between the 60 cm and 120 cm using the Equation (2) for all the culverts. The span length effect is clearly seen in Figure 9 where the longer span, CP3, produces the larger error for all the fill heights. Therefore, the span length effect should be included in the considered live load distribution formulations when the fill height exceeds 60 cm. Another important result in Figure 9 is that when the culverts have multi openings, CP1-2-3-4, CP2-2-3-4, or CP3-2-3-4, the error ratio between the 2D and 3D FE models does not change much, and it is well correlated when the fill height exceeds 60 cm. The variation of the error ratio is negligible when the fill height exceeds 60 cm which produces maximum 1.73% standard deviation of the mean value of positive moment ratios between the CP1 culverts. The standard variation is slightly larger when the fill height is less than 60 cm, 6.83%, between the CP1 culverts. The other culvert groups, CP2 and CP3, correlated well when compared to the CP1 culverts. Therefore, the variation of the positive moments between the multi opening culverts did not cause a major modelling errors.

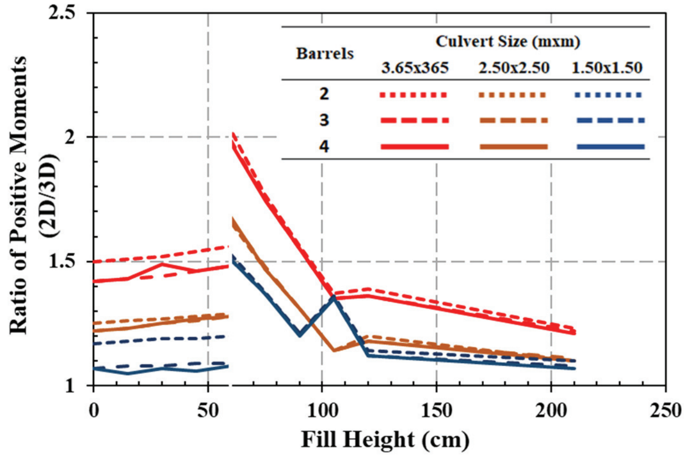


Figure 9 - *Positive moment ratios between 2D and 3D FE model analysis*

The maximum negative moments are recorded at the interior wall face of the exterior barrels as the minimum peak readings in FE models, and their ratios are shown in Figure 10. Similar to the ratio of positive moments shown in Figure 9, the critical fill height can be located between 60 cm and 120 cm fill heights. The modelling error in this region reaches the average of 1.39 and 1.74 for the CP1 and CP3 culverts, respectively. These ratios between critical fill heights are below the ratio of positive moments, so the modelling error becomes smaller for the calculated negative moments. After the fill height exceeds 120 cm, the average error gradually drops to 1.03 and 1.12 for the CP1 and CP3 culverts, respectively. Some of the ratios of the negative moments on the other hand is calculated less than 1 when the fill height is below 60 cm for culverts CP1-2 and CP1-3. This showed that the FE modelling error is also depend on the location and section forces. The increased barrel width increases the modelling error for the negative moments as well. The number of barrels in a multi opening culvert has similarly negligible effect on the ratios, and error between the culvert groups is strongly correlated. The maximum standard deviation of the mean negative moments can be calculated as 4.04% between the culvert group of CP1.

The maximum span displacement at the mid span of the exterior barrel is recorded in both FE models. The calculated displacement ratios of culvert models are plotted in Figure 11. The adopted load distribution method increased the modelling error between 60 cm and 120 cm fill heights significantly for the maximum displacements. The modelling error between these fill height reaches the average ratio of 1.71 and 2.27 for the CP1 and CP3 culverts, respectively. The variation of the errors between the section forces and displacements on the same culvert showed that one type of live load distribution method cannot represent a valid load distribution for the section forces. The load distribution for the positive moment for example can be different than the load distribution for the negative moments. The same can be said for the maximum displacement.

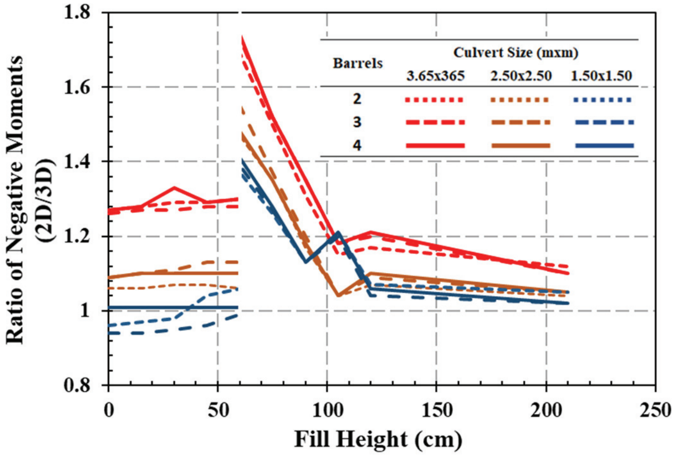


Figure 10 - Negative moment ratios between 2D and 3D FE model analysis

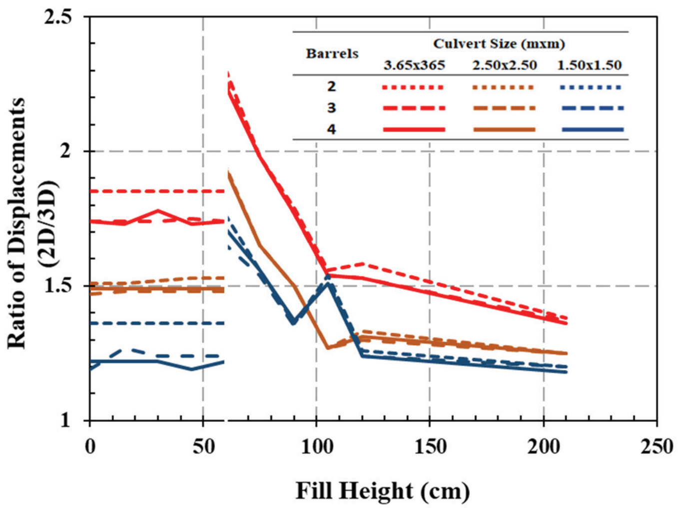


Figure 11 - Displacement ratios between 2D and 3D FE model analysis

The maximum and minimum design or load rating moment envelopes can be created for any culvert properties simply by creating the culvert`s corresponding influence line and actual fill height. The resultant moment envelopes will not fit this paper, therefore, only one selected culvert with three different fill heights, 0, 60 cm and 210 cm, are presented in this section. The design envelopes are actually produced from the 2D FE analysis and then multiplied by their corresponding moment ratios described in the aforementioned paragraphs. The positive and negative moments are plotted in the same figure by following the sign conventions from Figure 12 to 14. HL93 with varied axle spacing and HL93 Tandem trucks are the design trucks and dominating the peak maximum and minimum moments for both fill heights. In

Figure 12, the positive and negative moment ratios are 1.42 and 1.26, respectively when there ıs no fıll height was considered. The maximum and minimum moments are divided by their calculated positive and negative moment ratios, 1.48 and 1.30, respectively, which can be found in Figure 9 and 10 when the fill height is at 60 cm. In Figure 14, the positive and the negative moment ratios are 1.22 and 1.10, respectively when the fill height is 210 cm. These three figures show that the maximum envelope depends to the axle weights and positions. Fill height distributes the load more uniformly along the culvert length and section force intensities are also reduces when the fill height is increased due to distribution of the truck loads according to the AASHTO live load distributions. Finally, the section moments depend highly on the axle number and positions instead of the gross weight of the trucks. For example, LA Type 3 has 185 kN gross weight, which is less than AASHTO Type 3 truck at 297 kN; however, they produce almost identical positive and negative moments at the critical sections. Therefore, the variation of the trucks and their axle positions and axle loads needs to be studied independently.

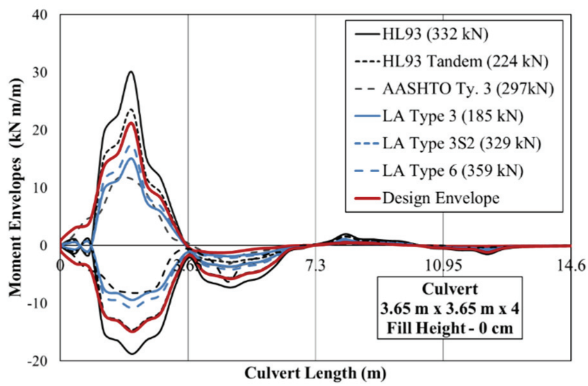


Figure 12 - Moment envelopes for 0 fill height

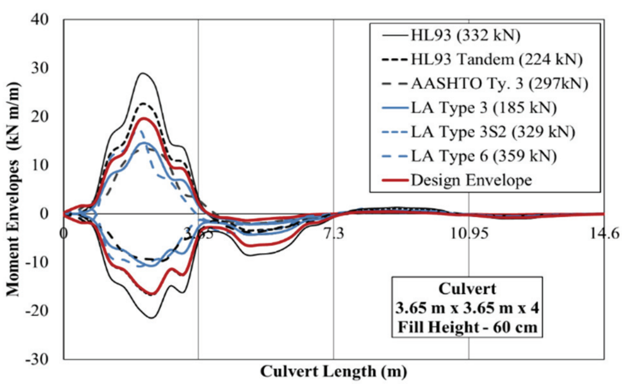


Figure 13 - Moment envelopes for 60 cm fill height

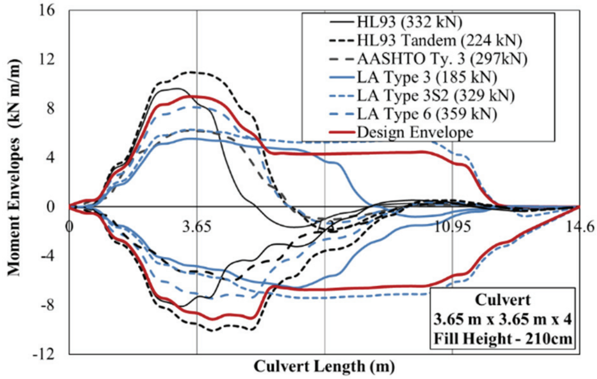


Figure 14 - Moment envelopes for 210 cm fill height

Table 4 - Ratio between 2D and 3D FE Model Results for Culvert CP1

Culvert x Barrel	Fill Height (FH), cm											Location
	0	**15**	**30**	**45**	**60**	**60**	**75**	**90**	**105**	**120**	**210**	
CP1 x2	1.17	1.18	1.19	1.19	1.2	1.53	1.38	1.21	1.36	1.14	1.1	M+
	0.96	0.97	0.98	1.04	1.06	1.37	1.26	1.13	1.21	1.07	1.05	M-
	1.36	1.36	1.36	1.36	1.36	1.76	1.56	1.36	1.54	1.26	1.2	D
CP1 x3	1.07	1.08	1.08	1.09	1.09	1.51	1.37	1.21	1.35	1.12	1.08	M+
	0.94	0.94	0.95	0.96	0.99	1.39	1.27	1.13	1.2	1.04	1.02	M-
	1.19	1.27	1.24	1.24	1.24	1.65	1.54	1.35	1.52	1.24	1.2	D
CP1 x4	1.07	1.05	1.07	1.06	1.08	1.51	1.37	1.2	1.35	1.12	1.07	M+
	1.01	1.01	1.01	1.01	1.01	1.41	1.28	1.13	1.21	1.06	1.02	M-
	1.22	1.22	1.22	1.19	1.22	1.71	1.56	1.37	1.51	1.24	1.18	D
μ	1.1	1.1	1.11	1.11	1.12	1.52	1.37	1.21	1.35	1.13	1.08	M+
σ (%)	5.77	6.81	6.66	6.81	6.66	1.15	0.58	0.58	0.58	1.15	1.53	
μ	0.97	0.97	0.98	1	1.02	1.39	1.27	1.13	1.21	1.06	1.03	M-
σ (%)	3.61	3.51	3	4.04	3.61	2	1	0	0.58	1.53	1.73	
μ	1.26	1.28	1.27	1.26	1.27	1.71	1.55	1.36	1.52	1.25	1.19	D
σ (%)	9.07	7.09	7.57	8.74	7.57	5.51	1.15	1	1.53	1.15	1.15	

Table 5 - Ratio between 2D and 3D FE Model Results for Culvert CP2

Culvert x Barrel	Fill Height (FH), cm											Location
	0	**15**	**30**	**45**	**60**	**60**	**75**	**90**	**105**	**120**	**210**	
CP2 x2	1.25	1.26	1.27	1.28	1.29	1.66	1.47	1.31	1.14	1.2	1.1	M+
	1.06	1.06	1.07	1.07	1.06	1.47	1.35	1.17	1.04	1.07	1.04	M-
	1.51	1.51	1.52	1.53	1.53	1.94	1.65	1.5	1.27	1.33	1.25	D

Table 5 - Ratio between 2D and 3D FE Model Results for Culvert CP2 (continue)

Culvert x Barrel	Fill Height (FH), cm											Location
	0	**15**	**30**	**45**	**60**	**60**	**75**	**90**	**105**	**120**	**210**	
CP2 x3	1.22	1.23	1.25	1.26	1.28	1.67	1.48	1.31	1.14	1.18	1.11	M+
	1.09	1.1	1.11	1.13	1.13	1.55	1.37	1.2	1.04	1.09	1.05	M-
	1.47	1.48	1.48	1.48	1.48	1.93	1.65	1.5	1.27	1.3	1.25	D
CP2 x4	1.22	1.23	1.25	1.27	1.28	1.68	1.47	1.31	1.14	1.18	1.1	M+
	1.09	1.1	1.1	1.1	1.1	1.48	1.35	1.18	1.04	1.1	1.05	M-
	1.49	1.49	1.49	1.49	1.49	1.93	1.65	1.5	1.27	1.31	1.25	D
μ	1.23	1.24	1.26	1.27	1.28	1.67	1.47	1.31	1.14	1.19	1.1	M+
σ (%)	1.73	1.73	1.15	1	0.58	1	0.58	0	0	1.15	0.58	
μ	1.08	1.09	1.09	1.1	1.1	1.5	1.36	1.18	1.04	1.09	1.05	M-
σ (%)	1.73	2.31	2.08	3	3.51	4.36	1.15	1.53	0	1.53	0.58	
μ	1.49	1.49	1.5	1.5	1.5	1.93	1.65	1.5	1.27	1.31	1.25	D
σ (%)	2	1.53	2.08	2.65	2.65	0.58	0	0	0	1.53	0	

Table 6 - Ratio between 2D and 3D FE Model Results for Culvert CP3

Culvert x Barrel	Fill Height (FH), cm											Location
	0	**15**	**30**	**45**	**60**	**60**	**75**	**90**	**105**	**120**	**210**	
CP3 x2	1.50	1.51	1.52	1.54	1.56	2.03	1.77	1.56	1.37	1.39	1.23	M+
	1.27	1.28	1.29	1.29	1.30	1.69	1.50	1.31	1.15	1.17	1.20	M-
	1.85	1.85	1.85	1.85	1.85	2.30	1.98	1.79	1.56	1.58	1.38	D
CP3 x3	1.42	1.43	1.44	1.46	1.48	1.99	1.75	1.55	1.35	1.36	1.22	M+
	1.26	1.27	1.27	1.28	1.28	1.73	1.52	1.35	1.18	1.20	1.10	M-
	1.74	1.74	1.74	1.75	1.74	2.26	1.98	1.77	1.54	1.53	1.37	D
CP3 x4	1.42	1.43	1.49	1.46	1.48	1.98	1.75	1.55	1.35	1.36	1.21	M+
	1.27	1.28	1.33	1.29	1.30	1.74	1.52	1.35	1.18	1.21	1.10	M-
	1.74	1.73	1.78	1.73	1.74	2.24	1.98	1.77	1.54	1.53	1.36	D
μ	1.45	1.46	1.48	1.49	1.51	2.00	1.76	1.55	1.36	1.37	1.22	M+
σ (%)	4.62	4.62	4.04	4.62	4.62	2.65	1.15	0.58	1.15	1.73	1.00	
μ	1.27	1.28	1.30	1.29	1.29	1.72	1.51	1.34	1.17	1.19	1.13	M-
σ (%)	0.58	0.58	3.06	0.58	1.15	2.65	1.15	2.31	1.73	2.08	5.77	
μ	1.78	1.77	1.79	1.78	1.78	2.27	1.98	1.78	1.55	1.55	1.37	D
σ (%)	6.35	6.66	5.57	6.43	6.35	3.06	0.00	1.15	1.15	2.89	1.00	

M+: Positive moment, M-: Negative moment, D: Displacement,
μ: Mean, σ: Standard deviation

4. CONCLUSIONS

The experimental field tests on the selected four culverts were conducted and the critical section forces were extracted using the data acquisition system. The cored concrete specimens were tested to obtain the material properties of the tested culverts. Two different 3D FE modelling approaches, namely area loading method, and multiple influence line method were utilized to apply the soil pressure on the culverts using AASHTO live load distribution method. Computationally the least time consuming procedure, multiple influence line method, was verified and adopted for the parametric studies. 2D FE model using frame elements which share identical geometrical, material, load properties of the experimentally tested culverts were developed to obtain the section forces at the critical locations using the influence line method. Maximum positive and negative moments, and displacements were extracted, and the ratio of the 2D to 3D FE mode results were investigated as the modelling error. Finally, the study concluded that;

- The construction of 3D FE model with area loading is more cumbersome than the multiple influence line loading method. However, the data is only available for each load position with area loading method. Multiple influence line method only provides envelope of the maximum and minimum results.
- The field tests showed that the exterior barrel of the multi opening box culverts is typically the controlling section for the peak section forces. The maximum positive moments and displacements were recorded at around the mid span of this barrel, and the maximum negative moments on the other hand could be obtained near the wall face of the interior wall of this barrels.
- The difference between the 2D and 3D FE model results are presented as the ratio of peak moments and displacements and the modelling error can reach 2.00 and 2.27 for the peak moments and displacements, respectively.
- AASHTO live load distribution method increases the modelling error when the fill height is between 60 cm and 120 cm. Therefore, it is important to validate FE models when AASHTO live load distribution method is used between these fill heights. Different modelling approaches including the soil properties and load distribution behaviour in FE analysis can be further studied using 3D full section properties.
- The modelling errors show sharp jump at 60 cm fill height for all the culverts. Then the error decreases linearly with a sharp slope until 120 cm fill height. After the fill height exceeds 120 cm, the modelling errors remain constant for narrow barrel widths or gradually reduce for wider barrel widths up to the 240 cm fill height.
- The modelling error is dependent on the barrel width. The increase in barrel width increases the modelling error ratio between the FE models. The modelling error is more dominant for the shallow fill heights. Multi-opening culverts having either 2 or 4 barrels produced similar modelling errors.
- The modelling error and filed calibration of 3D FE results showed that one typical load distribution method cannot represent the actual axle loads and its effects on the different section forces. Therefore, different live load distribution method should be considered for the calculation of the critical section forces.

- The study here showed that the modelling approach with 2D FE modelling did not reflect the field performance of the buried box culverts. The validated 3D FE modelling approach showed that simple 2D FE frame models produce very conservative results without considering any load factors. One should remember that the inherent error in 3D FE models adds to the error of 2D FE models without verification of the results. Therefore, the modelling error can be eliminated by validated 2D FE models otherwise inherent errors produce incorrect results and predictions for the design and load rating of the reinforced box culverts.
- The axle loads and positions are important parameters to construct the moment envelopes for the design or load rating purposes. The modelling error ratios can be used for the construction of the corrected section forces.

Notations

μ: Mean value

σ: Standard deviation

D: Displacement

FH: Fill height of the culvert (mm)

LS: Clear span length (mm)

M+: Positive moment

M -: Negative moment

W_{perp} : Equivalent distribution width perpendicular to span (mm)

W_{span} : Equivalent distribution length parallel to span (mm)

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References

[1] Abdel-Karim, A.M., Tadros, M.K. and Benak, J.V., Live Load Distribution on Concrete Box Culverts, Record No.1288; Transportation Research Board of the National Academy of Sciences, Washington, D.C., USA, 1990.

[2] McGrath, T., Liepins, A. and Beaver, J., Live load distribution widths for reinforced concrete box sections, 6th International Bridge Engineering Conference: Reliability, Security, and Sustainability in Bridge Engineering, Boston, MA, USA, July, 2005.

[3] Abolmaali, A., and Garg, A.K., Effect of wheel live load on shear behavior of precast reinforced concrete box culverts, Journal of Bridge Engineering, 13(1), 93–99, 2008.

[4] Wood, T.A., Lawson, W.D., Jayawickrama, P.W. and Newhouse, C., Evaluation of production models for load rating reinforced concrete box culverts, Journal of Bridge Engineering, 20(1), 4014057, 2015.

[5] Wood, T.A., Lawson, W.D., Surles, J.G., Jayawickrama, P.W. and Seo, H., Improved load rating of reinforced-concrete box culverts using depth-calibrated live-load attenuation", Journal of Bridge Engineering, 21(12), 4016095, 2016.

[6] Orton, S.L., Loehr, J.E., Boeckmann, A. and Havens, G., Live-load effect in reinforced concrete box culverts under soil fill, Journal of Bridge Engineering, 20(11), 04015003, 2015.

[7] Negussey, D., Andrews, L., Singh, S. and Liu, C., Forensic investigation of a wide culvert reconstruction failure, Journal of Pipeline Systems Engineering and Practice, 10(3), 2019.

[8] Puppala, A.J., Ruttanaporamakul, P. and Congress, S.S.C., Design and construction of lightweight EPS geofoam embedded geomaterial embankment system for control of settlements, Geotextiles and Geomembranes, 47(3), 295–305, 2019.

[9] Wysokowski, A. (2021), Influence of single-layer geotextile reinforcement on load capacity of buried steel box structure based on laboratory full-scale tests, Thin-Walled Structures, 159, 107312, 2021.

[10] Kinchen, R.W., Temple, W.H., Lacinak, H.W. and Gueho, B.J., Evaluation of drainage pipe by field experimentation and supplemental laboratory experimentation, Report No. FHWA/LA-78/115; Louisiana Department of Transportation & Development, 1978.

[11] Garber, J.D., Lin, J.H. and Smith, L.G., Feasibility of Applying Cathodic Protection to Underground Culverts, Report No. FWWA/LA-91; Louisiana Department of Transportation & Development, Baton Rouge, LA, USA, 1991.

[12] Wadi, A., Pettersson, L. and Karoumi, R., FEM simulation of a full-scale loading-to-failure test of a corrugated steel culvert, Steel and Composite Structures, 27(2), 217–27, 2018.

[13] Xu, C., Peiris, A. and Harik, I. (2019), Analysis and load rating of corrugated steel arch culverts", Ce/Papers, 3(3-4), 85–90, 2019.

[14] Liu, Y., Hoult, N.A. and Moore, I.D., Structural performance of in-service corrugated steel culvert under vehicle loading, Journal of Bridge Engineering, 25(3), 4019142, 2020.

[15] Okeil, A., Ulger, T. and Elshoura, A., Live Load Rating of Cast-in-Place Concrete Box Culverts, Report No. FHWA/LA.17/593; Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA, USA, 2018.

[16] Acharya, R., Han, J., Parsons, R.L. and Brennan, J., Field testing and numerical modeling of a low-fill box culvert under a flexible pavement subjected to traffic loading, Geomechanics and Engineering, 11(5), 625–38, 2016.

[17] Beben, D., and Wrzeciono, M., Numerical analysis of steel-soil composite (SSC) culvert under static loads, Steel and Composite Structures, 23(6), 715–26, 2017.

[18] Sun, Q., Peng, D. and Dias, D., Seismic performances of three- and four-sided box culverts: a comparative study, Geomechanics and Engineering, 22(1), 49–63, 2020.

[19] Garg, A. and Abolmaali, A., Finite-element modeling and analysis of reinforced concrete box culverts", Journal of Transportation Engineering, 135(3), 121–28, 2009.

[20] Acharya, R., Han, J. and Parsons, R.L., Numerical analysis of low-fill box culvert under rigid pavement subjected to static traffic loading, International Journal of Geomechanics 16(5), 4016016, 2016.

[21] AASHTO LRFD Bridge Design Specifications 8th. Ed., American Association of State Highway and Transportation Officials; Washington, DC, USA, 2017.

[22] SAP2000, Integrated Software for Structural Analysis and Design, Berkeley, California: Computers and Structures Inc, 2014.

[23] Ulger, T., Okeil, A.M. and Elshoura, A., Load testing and rating of cast-in-place concrete box culverts, Journal of Performance of Constructed Facilities, 34(2), 4020008, 2020.

[24] ASTM C42, Standard method of test for obtaining and testing drilled cores and sawed beams of concrete, ASTM International, West Conshohocken, PA, USA, 2013.

[25] AASHTO The Manual for Bridge Evaluation 2nd. Ed., American Association of State Highway and Transportation Officials; Washington, DC, USA, 2011.