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NUMERICAL ANALYSIS OF BOX-TYPE SOIL-STEEL STRUCTURE UNDER STATIC SERVICE LOADS

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Abstract

The paper presents the numerical analysis of a long-span deep-corrugated steel box culvert with a span of 14m with soil covers of 0.45m and 1.20m. Current design codes and researchers usually approximate the effect of live loads on such soil-steel culverts, especially for stiffened ones. On the other hand, full-scale field tests are expensive and not always available. Therefore, it is essential to apply accurate numerical analyses with the real material characteristics for soil, steel structure and interface elements. This could be achieved only in lieu to verification of analytical models with experimental results. In this study, three-dimensional finite element analyses (3D FEA) of stiffened and non-stiffened deep corrugated soil-steel culverts are performed and compared with field test results which were obtained in part during experiments. The study shows that owing to precise modelling of the structure, results of 3D FE analyses for the thrust correspond well with the experimentally measured ones. The FE results for bending moments show less agreement with test results, and also show smaller values in the haunches and higher values in the crown in comparison with those obtained from design calculations. This shows that design codes are conservative when estimating moments in haunches, and underestimate bending moments in the crown. The 3D FE model studied in this research was found to be accurate enough to be used in future researche aimed at etimating thrust in box culverts in order to replace design codes, which fail at this task.

Key words: Soil-steel structures, Box culverts, Deep corrugations, Long-span, Three dimensional, Finite element analysis, Field test.

1. INTRODUCTION

Many years of field tests have shown that soil-steel structures under deep cover carry load principally through ring compression. In contrast to structures under deep cover, highway and railway service loads on long-span shallow cover bridges may induce uneven loads that cannot be well established with ring compression theory. Therefore, it is essential to apply accurate numerical analysis in conjunction with field tests to study the actual behaviour of long-span box culverts with deep corrugations and shallow depth of cover under service loads.

In the past, design calculation codes were mostly based on empirical work. The introduction of long-span soil-steel structures, deeper corrugations, structural stiffeners, soil reinforcement, as well as shallow cover depths lead in recent years to efforts to update design procedures. In the United States, AASHTO released a project program for investigating the behaviour of long-span culverts (McGrath et al., 2002). The Canadian Highway and Bridge Design Code (CHBDC) regulations are also under revision (Bakht, 2007). On the other hand, different field tests have been implemented by many researches (McCavour et al., 1998; Webb et al., 1998; Moore and Taleb, 1999; Morrison, 2000; Manko and Beben, 2008; MacDonald, 2010; Bayoglu Flener, 2006, 2007, 2010) to evaluate the effect of different stiffeners, length of span and height of cover on the behaviour of soil-steel bridges.

The study described in this paper is concerned with the effect of soil cover and stiffness of the crown on the performance of a 14m-span box culvert using 3D FE analysis. The results are then compared with the field test results of the same box culvert done by Bayoglu Flener (2010).

2. ANALYTICAL METHOD

The analytical method described in this paper is based on the results of three-dimensional finite element analyses using PLAXIS 3D. This software is mostly used to solve geotechnical engineering problems, and is a practical program to calculate soil-structure interaction.

The 3D FE analyses were performed on 14.11m-span box culvert with 0.45m and 1.20m soil cover under seven different truck positions (Figure 1). The length of the structure with complete plate rings is 9.27m and a half of it is stiffened with reinforcing ribs on the crown. The non-stiffened and stiffened parts of the box culvert are called “Structure 1” and “Structure 2”, respectively (Figure 2).

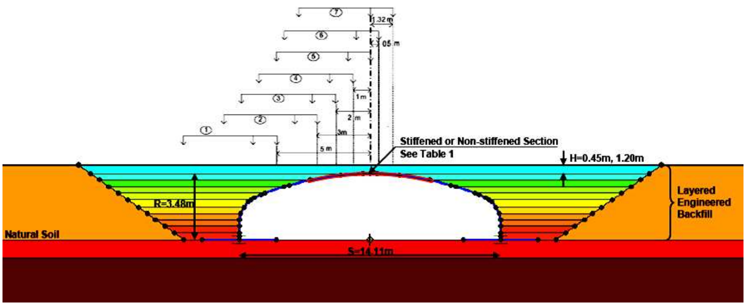

Figure 1. Cross-sectional geometry of the box culvert and the truck positions where the truck approaches the bridge backwards

The computer program (PLAXIS 3D) employed in the analyses models the foundations and the steel culvert as beam elements, and the engineered backfill and natural soil as 15-nodded triangular isotropic elements. After several preliminary analyses to minimize the effect of boundaries on analysis results, the continuum media were extended 60m on both sides of the box centreline and 60m under the foundations of the structure.

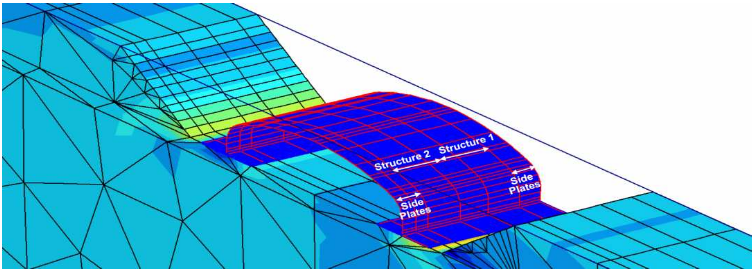

Figure 2. 3D model of the box culvert

2.1. Idealization of the structure

The effect of additional crown stiffness effects on strains, thrusts and bending moments have been examined using non-stiffened and stiffened panels with deep corrugation (Table 1). A full composite behavior cannot be achieved due to some slip between the steel plates, which leads to a reduction of section capacity. The model does not take this slip into account because of the difficulty in determining the amount of this reduction.

The panels have been idealized as elasto-plastic beams. The specifications of beam elements are introduced by axial stiffness *EA* and bending stiffness *EI*, and the equivalent thickness $\bar{t}$ is calculated with:

$$\bar{t} = \sqrt{\frac{12EI}{EA}} \tag{2.1}$$

where *E* is Young's modulus for steel, *I* and *A* are the moment of inertia and area per unit length of corrugated plate, respectively. The summary of implemented parameters for various types of panels is presented in Table 1.

Table 1. Element specifications of non-stiffened and stiffened panels of standard 381*mm*× 140*mm* Corrugation with 7*mm* thickness

	$EA\,(\frac{kN}{m})$	$EI\,(\frac{kN.m^2}{m})$	**Poisson's Ratio**	$M_p\,(\frac{kN.m}{m})$	$P_p\,(\frac{kN}{m})$
Non-stiffened	1.96×10^6	4.83×10^3	0.3	131.35	2646.07
Stiffened	3.92×10^6	30.90×10^3	0.3	331.07	3728.97

In Table 1 plastic moment capacity M_p and the compressive strength P_p are introduced to control the combinations of maximum bending moment and axial force. This combination is also checked in the design of soil-metal structures to avoid buckling (AISI, 2002) with:

$$\alpha = (\frac{P}{P_p})^2 + |\frac{M}{M_p}| \leq 1 \tag{2.2}$$

where M and P are the bending moment and axial force due to live and dead loads.

The backfill zone was idealized with a layered model using the elastic-perfectly plastic Mohr-Coulomb model for each layer, and the soil properties were defined as a function of depth (Abdulrazagh, 2011). The minimum Secant modulus has been defined as E_s=6 Mpa, which corresponds to compaction degree of 88%. Other soil properties are dry density of 18.8 kN/m^3, friction angle 40^o, soil cohesion 7 kN/m^2 and Jaky's K_0- value of 0.357. The values selected for soil parameters represent the equivalent soil around the real structure in the field test (Bayoglu Flener, 2010). During construction of a full-scale soil-steel structure, to achieve the Standard Proctor Density specified by ASTM Standard D 698-91, 10-15% of the material is chosen to be fine particles. This gradation characteristic results in a high friction angle and a relatively small soil cohesion as defined in this paper.

Interface elements are incorporated between the box culvert and the backfill to permit relative displacements. However for simplicity, full bonded conditions are considered between materials which cause more conservative results due to greater stresses induced in the metal structure. On the other hand, the studies performed by Duncan (1979), MacDonald (2010) and Peterson et al. (2010) demonstrated that, in most cases, the effects of slip between the metal structure and the backfill are negligible.

2.2. Loading condition

Two types of a loading system are defined during 3D FE analyses: The first represents the backfilling loads during the actual sequence of construction; the second one represents a fully loaded truck with a weight of 240kN (front axle=61.5 kN, middle axle=94.5 kN, and rear axle= 84 kN). The distance between the front and the middle axle is 4.2m and the distance between the middle and the rear axle is 1.32m (Bayoglu Flener, 2010). The analyses have been done at seven different load positions that were represented by the position of the rear axle: Position (1) 5m in front of the centreline of the culvert; Position (2) 3m in front of the centreline; Position (3) 2m in front; Position (4) 1m in front; Position (5) on the centreline of the culvert; Position (6) and (7) 0.5m and 1.32m behind the centreline, respectively. These positions are also shown in Figure 1.

3. FIELD TEST

The 3D FE analyses are compared with the field test results of the same idealized box culvert (Bayoglu Flener, 2010). The key to the names and locations of strain gauge couples on the structure are given in Figure 3. Strain gauge couples had the same locations and names for “Structure 1” and “Structure 2”. Side A is the side where the truck approached the bridge backwards. The main measurements in the field were performed directly under one wheel ovehicle the vehicle’s axle.

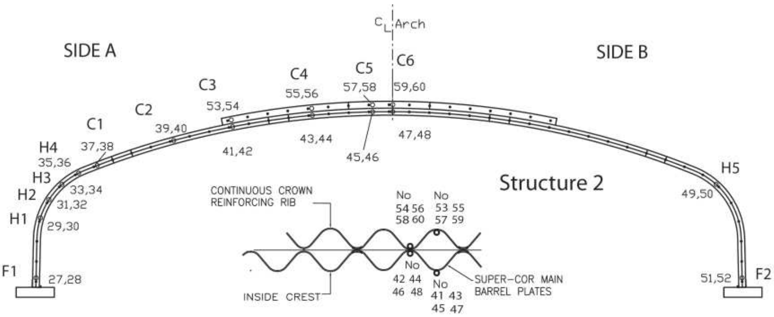

Figure 3. Numbers, locations, and names of the sensors of the 14m-span culvert with crown ribs (Bayoglu Flener, 2010)

4. RESULTS AND DISCUSSIONS

4.1. Strains and displacements

The comparison of FEA results with the measurements from bottom sensors at C6 for both Structures 1 and 2 with cover depth of 0.45m is presented in Figure 4. As can be seen, FEA results are slightly greater than the measured strain values. The strains are very small for the farthest position (1) but as the truck moves near to the culvert centreline, compressive strains increase until they reach their maximum value at position (2), 3m in front of the centreline. The strains change to tensile when the truck is positioned on the crown centreline or behind it. The tensile strain from measurements and numerical results is maximum when the rear axle of the truck is 1.32m behind the centreline (CL) for both structures.

The effect of the stiffened crown in Structure 2, can clearly be seen as a reduction in the strains in Figure 4.

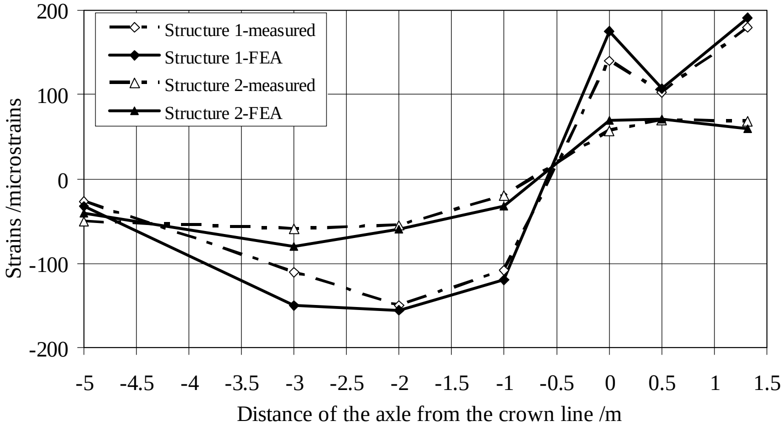

Figure 4. Comparison of the FEA results with bottom sensors measurements at C6 due to different truck positions for 14m-span Structures 1 and 2 with cover depth 0.45 m

As it can be seen in Figure 4, the maximum compressive and tensile strains were caused by truck positions 3m in front of and 1.32m behind the crown CL. Therefore under these two critical loading positions, FE strain values are compared with values obtained from bottom sensors in Figure 5.

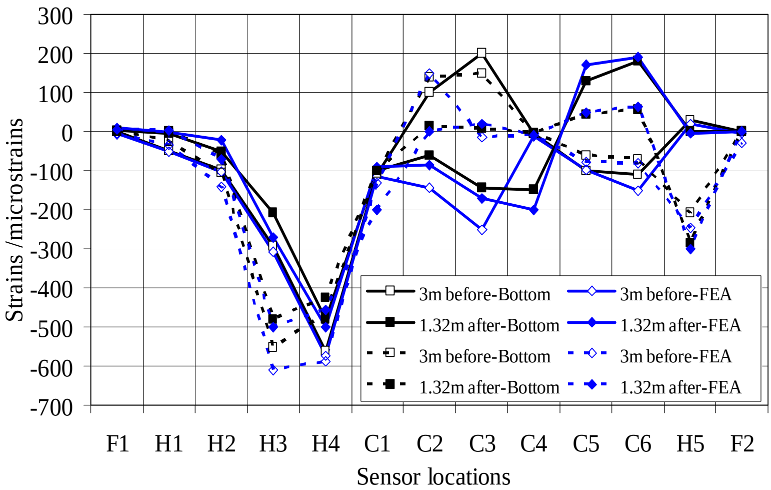

Figure 5. Comparison of the FEA results with top and bottom sensors measurements at different sensor locations for cover depth 0.45 m

Figure 5 shows that compressive strains are maximum at H3 (exactly the midpoint of haunch plate with minimum radius of curvature-see Figure 3) and H4 for FEA and field test results, respectively. On the other hand, the crown maximum strains occur at C6 (exactly at the midpoint of the crown with the maximum radius of curvature-see Figure 3). The strains at the bottom of the crown of Structure 2 are considerably smaller than of Structure 1 under the same truck position.

The comparison of results due to truck position 3 m in fornt of and 1.32 m behind for both FE and field test results shows that maximum strains are mostly from truck position at 1.32 m. Thus, the maximum displacements of both structures caused by this truck position are plotted on Figure 6 and compared to the strains for box culverts with cover depth 1.20 m.

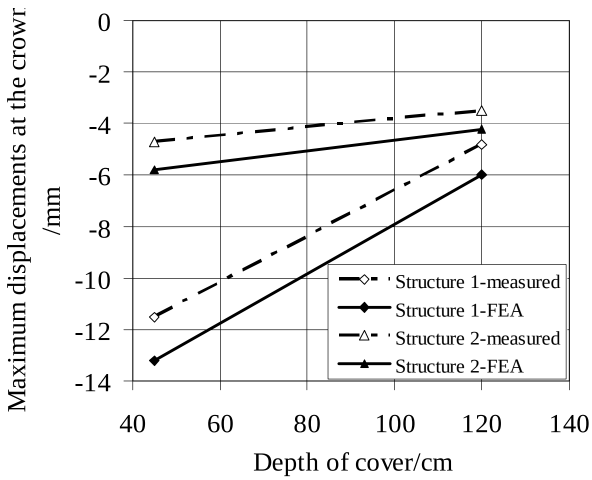

Figure 6. Maximum displacements of the crown during truck loading tests for Structures 1 and 2; negative values indicates downward displacements

As shown in Figure 6, the maximum displacement of Structure 1 is approximately twice of that in Structure 2. The difference in maximum displacement reduces with the increase of cover depth to 1.20 m. FEA values of strains are slightly higher than the test results. The maximum displacements in FEA are 17% and 20 % higher for Structure 1 and Structure 2 respectively.

4.2. Thrusts

A comparison of the FEA results with the field measurements of the crown for both Structures 1 and 2 with cover depth 0.45m is presented in Figure 7. As can be seen FEA results are slightly greater than the measured values at C6 but correspond well with field test results at C5. Same as strain values, the thrust is minimum for the farthest position (1) but reaches its maximum value as rear axle is positioned on 0.5 m behind the crown CL.

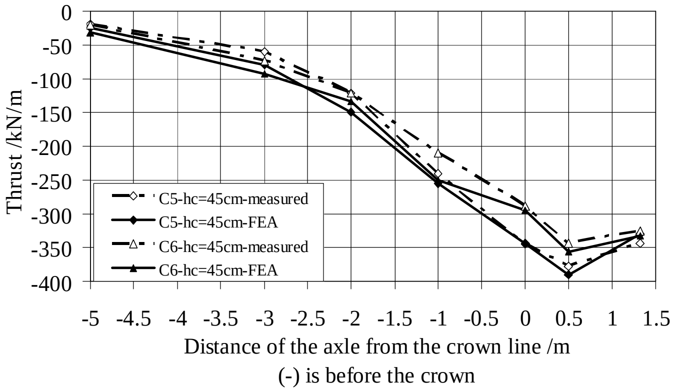

Figure 7. Comparison of the FEA results with measurements at C5 and C6 due to different truck positions for 14m-span Structures 1 and 2 with cover depth 0.45m

Figure 8 demonstrates that the maximum thrust values were caused by the truck position at 0.5m behind the crown CL. Therefore for this case, the results were plotted versus different sensor locations. This Figure shows that for the haunches and the crown, thrust reaches the maximum values at H4 and C5, respectively. There is good agreement between the results.

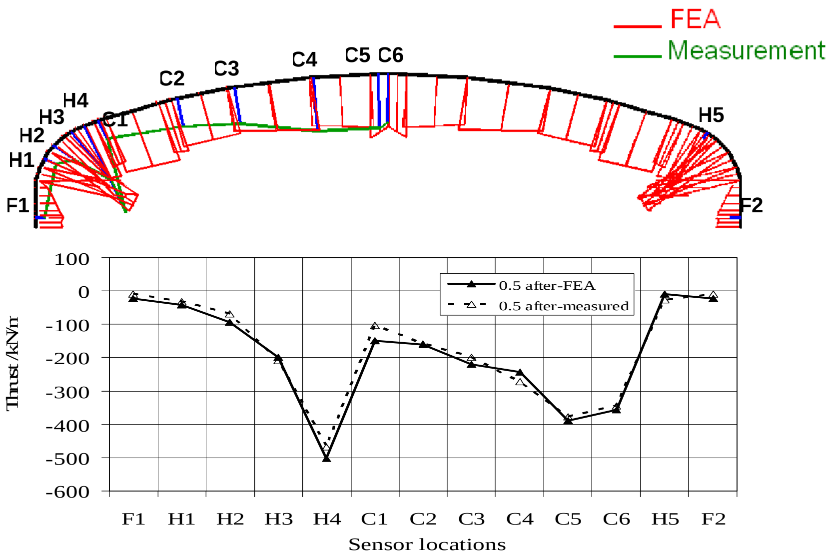

Figure 8. Comparison of the thrust results at different sensor locations for Structure 1 with cover depth 0.45m; not to scale (measurement values from Bayoglu Flener, 2010)

Figure 9 illustrates that thrust values are greater for truck position on the crown. It also shows that the structure is more sensitive to the change of truck position when the depth of cover is smaller. Thrust values for cover depth 0.45m are 3 to 3.5 times greater than those obtained for a structure with 1.20 m of cover. This indicates the contribution of the height of soil cover on the reduction of live load effects.

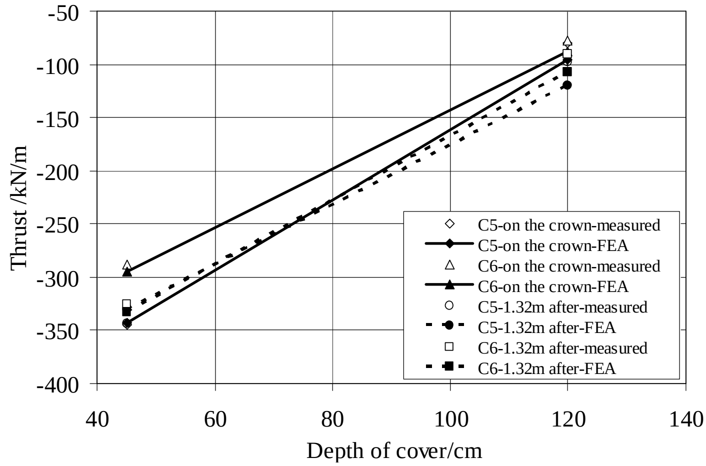

Figure 9. Thrusts at C5 and C6 for Structure 1 with cover depth 0.45m and 1.20m; for truck positions on the crown and 1.32m after crown CL

4.3. Moments

In comparison with thrust, Figure 10 shows that FEA bending moments show less agreement with the measured bending moments, which demonstrates that bending moments are more suited to accurate modeling. The diagram follows approximately the strain pattern versus different positions of the rear truck axle. The moments are near to zero which confirms the hinge supports at conjunction of plate walls and the concrete foundations in the FE idealization.

For both measured and calculated results, the negative bending moments at center of the crown (C6) are maximum where the rear axle is 2m before the crown CL. The maximum positive bending moments occur at the crown and 0.5 behind the crown CL for FE model and the full-scale structure, respectively. Therefore for the truck position on the crown, the bending moments resulted from FE analyses, field tests and Canadian Highway Bridge Design Code (CHBDC) calculations are compared in Figure 11 at different sensor locations.

Figure 11 shows that the negative and positive bending moments are maximum at H1 and C6 (C5 for field test results). The comparison of both measurements and FEA values with CHBDC calculations demonstrates that the Canadian design Code overestimates bending moments at the haunches and underestimates them at the crown. It is important to note that the CHBDC calculations are limited to the design of box culverts equal or less than 8m span.

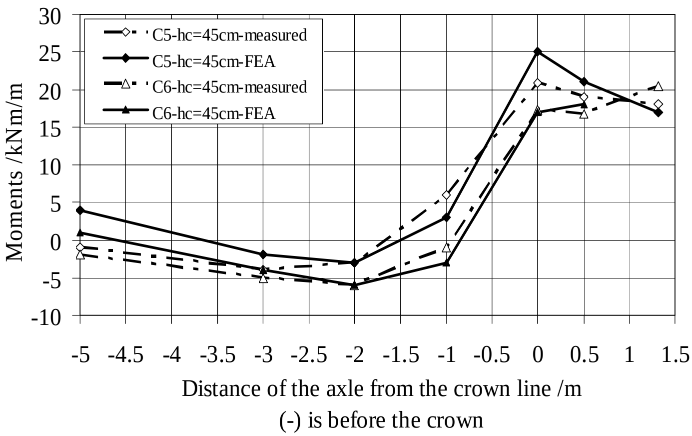

Figure 10. Comparison of the bending moments obtained from FE analyses with measurements at C5 and C6 caused by various truck positions for the depth of 0.45m

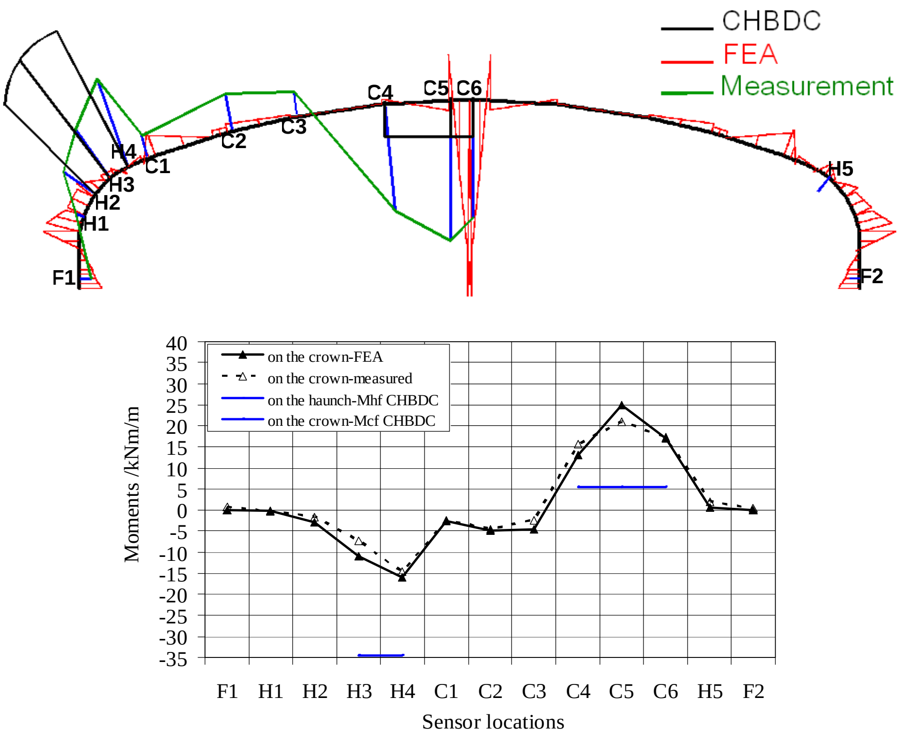

Figure 11. Comparison of bending moments at different sensor locations for Structure 1 with cover depth of 0.45m; not to scale (measurement values from Bayoglu Flener, 2010)

Figure 12 illustrates that the bending moments are greater for truck positioned on the crown. It also shows that the structure is more sensitive to the change of truck position when the depth of cover is smaller. Thus, the values for cover depth of 0.45 m are 3.5 times greater than those obtained for structure with 1.20 mof cover. The FE results have good agreement with experimental results for 0.45m depth of cover, but about 55% higher than field measurements for soil cover depth of 1.20m.

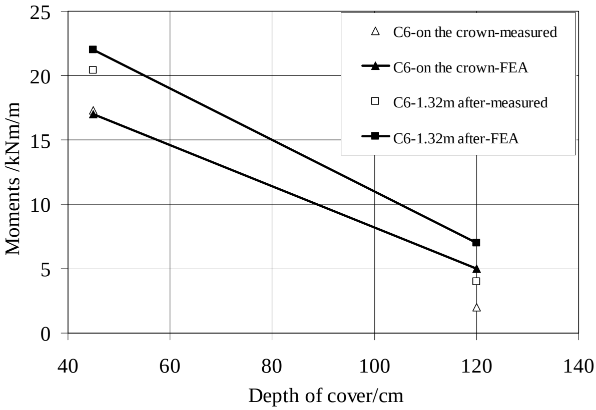

Figure 12. Moments at C6 for Structure 1 with cover depth 0.45 m and 1.20 m; for truck positions on the crown and 1.32 m after crown CL

4.4. Thrusts and Moments in Longitudinal Section

Thrusts and moments along the longitudinal axis of the Stucture 1 with cover depth 0.45m are summarized in Table 2.

Table 2. Thrusts and moments at C6 for Structure 1 with cover depth 0.45 m for truck positions on the crown

Plane	Z-coordinate/m	Thrust/kN/m	Moment/kNm/m
Rear Plane	0.000	-295.01	17.07
Plane G	1.238	-294.85	17.47
Plane F	1.239	-295.00	17.56
Plane E	3.037	-294.80	17.43
Plane D	3.038	-294.91	17.62
Plane C	4.636	-294.83	19.86
Plane B	6.523	-294.38	23.78
Plane A	7.198	-293.15	27.29

Sections between Planes G and F, and Plane E and D are exactly under the front wheel loads. Sections between Plane B and the Front Plane are related to side plates (see Figure 2), where the slope of embankment exists. As can be seen in Table 2, the value of thrust does not change significantly along the longitudinal axis of the structure, but the moment increases towards side plates due to a smaller soil cover over the structure. The relatively steady values of internal forces show that effect of longitudinal arching can be neglected.

5. CONCLUSIONS

3D FE analyses have been performed on a 14m-span box culvert with a non-stiffened and stiffened crown, and soil cover depth 0.45m and 1.20m under the effect of static truck loads. Corrugated steel plates have been idealized with isotropic beams, and the layered model was considered to account for soil properties as a function of depth. FE results then have been compared with experimental measurements of Bayoglu Flener (2010). Regarding the assumptions used in the FE models, the numerical results, in general, show good agreement with experimental results; maximum 5 kNm/m difference (25% overestimating) for bending moments.

Both results for thrusts and bending moments show that the truck position on the crown has the maximum effect on the 14m-span box culvert with 0.45m and 1.20m covers. This is an important result which will allow for the reduction of amount and time of calculations, especially when the effect of various parameters of a steel structure or soil is going to be studied.

Regarding the verification of numerical results with field test measurements, the 3D FE model studied in this research is accurate enough to be used in future researche to propose calculation formulas for thrust in box culverts with limited length and unyielding foundation.

In addition to underestimation by the Canadian design code of crown bending moments, same values for non-stiffened and stiffened crown have been obtained, which suggests that the design calculated moments require adjustment.

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Streszczenie

Praca przedstawia analizę numeryczną przepustu skrzynkowego o rozpiętości 14 m wykonanego ze stalowej blachy falistej o głębokiej fali z naziomem gruntowym o wysokości 0,45 m i 1,20 m. W aktualnie stosowanych przepisach projektowych oraz badaniach zwykle przedstawia się przybliżone wartości obciążeń zmiennych działających na przepusty gruntowo-stalowe tego typu, szczególnie w wersji usztywnionej. Z drugiej strony, próby terenowe w pełnej skali są kosztowne i nie zawsze dostępne. Z tej przyczyny kluczowe znacznie ma stosowanie dokładnych analiz numerycznych z wykorzystaniem rzeczywistych własności materiałowych dla gruntu, konstrukcji stalowej oraz elementów łączących. Można to uzyskać jedynie dzięki weryfikacji modeli analitycznych, jaką umożliwiają rezultaty eksperymentów. W tym badaniu wykorzystano trójwymiarową analizę elementów skończonych (3D FEA) usztywnionych i nieusztywnionych przepustów gruntowo-stalowych z blachy o głębokiej fali, której wyniki porównano z rezultatami prób terenowych, uzyskanych częściowo podczas eksperymentów. Badanie pokazuje, że dzięki dokładnemu modelowaniu konstrukcji, rezultaty analizy 3D FE dla sił osiowych charakteryzuje dobra zgodność z wartościami zmierzonymi eksperymentalnie. Rezultaty analizy elementów skończonych dla momentów zginających wykazują mniejszą zgodność z rezultatami prób, a także wskazują na występowanie mniejszych wartości w pachwinie i wyższych wartości w koronie, w porównaniu do wartości uzyskanych podczas obliczeń projektowych. Te rezultaty pokazują, że przepisy projektowe przeszacowują momenty w pachwinach, a jednocześnie prowadzą do niedoszacowania momentów zginających w koronie. Badany model 3D FE okazał się wystarczająco dokładny do użycia w przyszłych badaniach nakierowanych na szacowanie sił osiowych w przepustach skrzynkowych, co pozwoli na zastąpienie przepisów projektowych, które nie radzą sobie z tym zadaniem.

Słowa kluczowe: konstrukcje gruntowo-stalowe, przepusty skrzynkowe, głęboka fala, duża rozpiętość, trójwymiarowe, analiza elementów skończonych, próby terenowe.