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TWO-DIMENTIONAL FINITE ELEMENT ANALYSIS FOR DIFFERENT LONG SPAN SOIL-STEEL Culvert GEOMETRY

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الملخص العربي

تعتبر الكباري المكونه من التربـه و الـواح الحديد المعرج و المعروفه بكبـاري التربـه و الحديد بـديل جيد للكباري الخرسانيه و المعدنيه القصيره نتيجه لما تتميز به من سهوله و سرعه التنفيذ و التكلفه الاقتصاديه.لذلك اتجه الباحثون في العديد من الدول لاجراء دراسات حقليه و نظريه لاستكشـاف السلوك الفعلي لهذه المنشـات تحت تـاثير الاحمال الترابيه و احمال المرور اعلي هذه المنشات. في هذه الدراسه تم دراسه تاثير مجموعه من العوامل الخاصه بالشكل النهائي للمنشأ و تغير النسبه بين ابعاد المنشأ (بحر و أرتفاع المنشأ) و تغير سمك الغطاء الترابي فوق المنشأ باستخدام برنامج العناصر المحددة المعروف بالاسم بلاكسز.

ايضا تم دراسه تاثير الاماكن المختلفه لحمل المرور أعلي المنشأ علـي السلوك النهـائي للمنشأ و اظهرت النتائج تاثير كبير للشكل الخارجي و الابعاد لمنشأت التربه و الحديد و ايضا تـاثير كبيـر لتغيـر سمك الغطـاء الترابـي فوق المنشأ

Abstract

Soil–steel structures have been used as an alternative to short span concrete and steel bridges for years because they have some advantages regarding their construction methods, maintenance costs, and construction time. Several researchers have performed experimental and numerical studies about the behavior of these structures under dead loads and crossing live loads.

In this study, in order to investigate the variations of some geometry parameters such as the culvert profile, culvert dimensions, and back fill soil cover thickness on the stability of culverts. A two dimensional finite element analysis simulation for soil–steel culverts using the PLAXIS 2-D program were carried out, the position of the loaded truck were also studied. The Mohr–Coulomb constitutive model was used in this simulation, and as the crossing traffic load, the stage construction method was established. Parametric analyses showed that the culvert profile and dimensions have significant influence on the stability of long span culverts; the backfill soil cover also highly affects the behavior of long span culverts

Key words: Soil–steel culvert, PLAXIS, finite element program

1-INTRODUCTION

The soil-steel bridge (culvert) structures, consisting of shells of corrugated steel plates and surrounding with well-compacted soil, were first used in the USA. Flexible corrugated-plate designs have been used for bridges and culverts since the 19th century. The technology was patented in 1886 in the USA and since that time, steel corrugated plates find increasingly wider application in transport construction in different parts of the world. The main load-carrying element of such structures is an engineering backfill; therefore they are called the soil-steel bridges.

Authorities' demand of a better and safer investment in these structures has stimulated the engineering research and the industry section into more design and performance investigations. The primary objective of the current study is to investigate and improve the performance of soil-steel bridge, by using finite element modeling (FEM) with PLAXIS 2D for different culvert profiles case studies taking the effect of variation culvert span to height ratio and backfilling soil cover thickness to reduce stresses laying on the bridge.

2 PROBLEM AND GEOMETRY DESCRIBTION

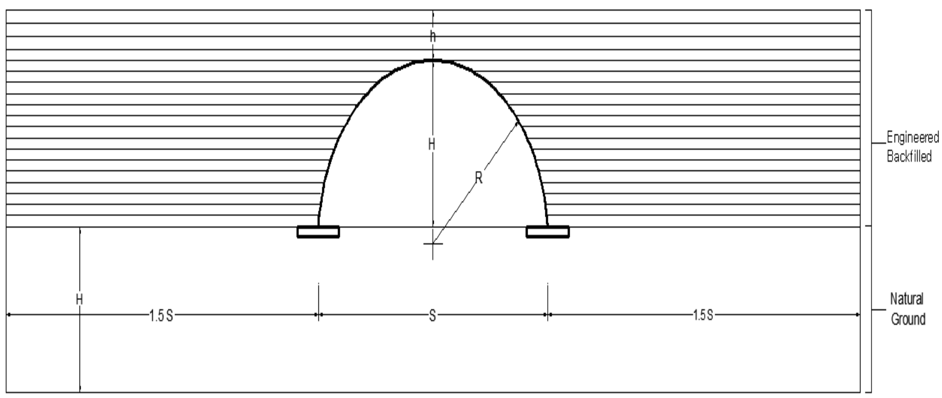
The total model dimension was determined after several calculation trials to insure taking the effect of surrounding soil on the soil steel culvert, the trials showed that the soil extend up to 1.5 culvert spacing is enough to capture the effect of surrounding soil on the soil steel culvert. Compacted soil was used as the backfilled soil surrounding the culvert, the used backfill soil was compacted in layers each layer was 33 cm height, and the natural soil under the culvert was also included in the geometry. According to the Egyptian loads standard 2008, a four wheel 60 ton truck was used as the main live load for all the culverts.

3 PARAMETRIC STUDY

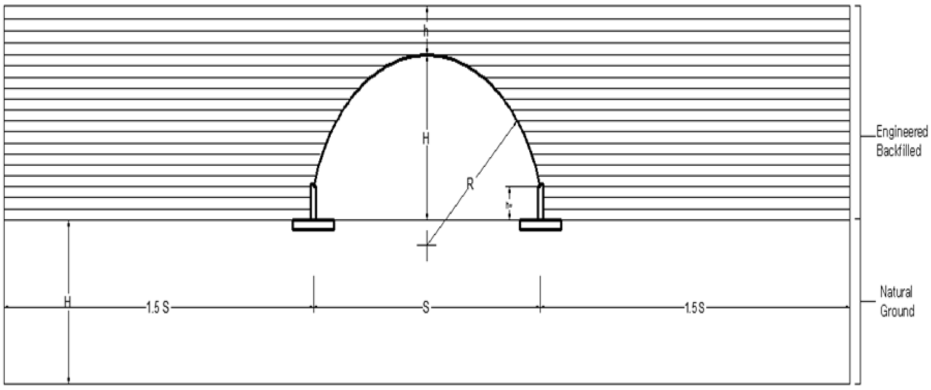
3.1 CULVERTS GEOMETRY

In order to investigate the behavior of soil steel culverts three different geometry of soil steel culvert with same span and height was studied the three geometries as shown in Figure 1 to 3 are circular arch culvert (profile 1), arch culvert with 1m vertical concrete pedestals (profile 2), and box culvert (profile 3) respectively, for the culverts analyzed in the current study. Corrugated steel plates of type SuperCor S37 was used as the steel structure part, geometry of the corrugated plates forming the structures was constants as shown in Figure 5.

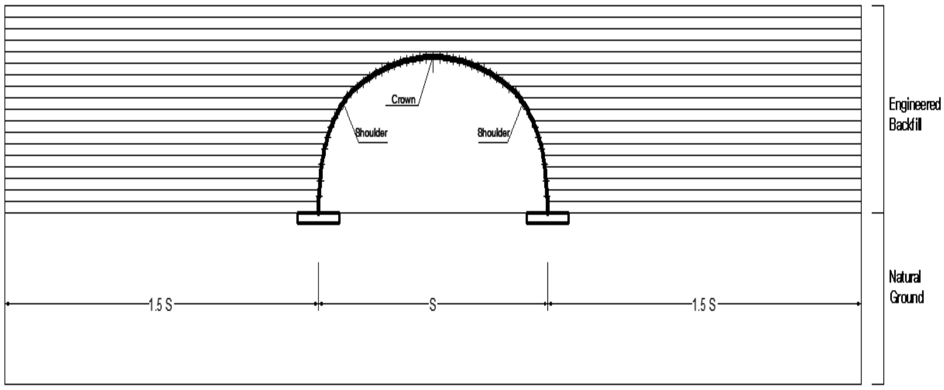
As the stability of this type of structure depends mainly on the equilibrium between the lateral soil earth pressure and the effective vertical stress from backfill soil cover, so the arch culverts with 1m vertical concrete pedestals were analyzed using different spans of 9, 11 and 13 m and constant height of 4 m getting different span to height ratio to investigate the effect of span to height ratio on the behavior of these structures.



Fig(1) Geometry of circular arch culvert



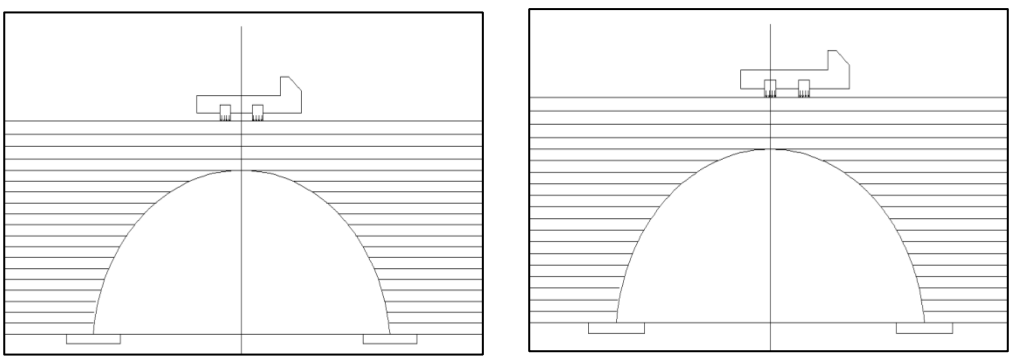
Fig(2) Geometry of arch culvert with 1m vertical concrete pedestals



Fig(3) Geometry of box culvert

3.2Position of truck load

Most of the design specifications mention to position the design truck at the location that produces the maximum moment or thrust without specifying exactly the most critical position. Studying the effect of truck position on the behaviour of long-span culverts was one of the objectives of this thesis, after several trials two main truck position were included; first the truck was centered over the crown of the culverts. This position of the truck was mentioned as position 1; the second position was found when the wheel truck axle was centered over the crown of the culverts. Figure 4.a and 4.b shows the two different truck positions.



Position 1 Position 2

Fig(4) Truck position

3.3 Depth of soil cover

The depth of cover is defined as the distance between the top of the corrugation and the road surface, the depth of cover has a great effect on the stability of the corrugated steel culvert as the live load distributed over the soil cover up to the corrugated steel. The box and arch culverts were analyzed using soil cover depth = 1.5 m and extend the work by changing the depth of soil cover to 1.00, 1.25, 1.75, 2.00, and 2.30 m to investigate the effect of soil cover on the behavior of these structures.

4 Numerical Details

4.1 Finite element meshes and Boundary condition of culvert

Orthotropic shell theory was employed to model all box and arch culverts analyzed using four-noded shell elements. This is denoted the "orthotropic analysis". The specific details on how to calculate the equivalent orthotropic parameters has been detailed by to El-Sawy (2003), the backfill material was modelled using 15-node triangular elements as shown in. While standards fixities are applied at the edges (horizontally fixed edges) and fixed in both ways for the bottom edge.

4.2 Material properties

4.2.1 Soil properties

The backfill soil considered in the current study were considered according to experimental tests performed a well graded remolded sand samples were used .Tables 1 shows the material properties used for two backfill materials considered in the current study. Mohr- Coulomb failure criterion was used to model shear failure in the soil and the resulting plasticity. The interface between the soil and the structure was defined as bonded, with no relative movement allowed.

Table1: Soil Mohr Coulomb mode properties

SOIL	Modulus of elasticity (MPa)	Density ɤ KN/m2	Poisson's ratio ν	Angle of friction φ *(deg)*	Dilation angleψ *(deg)*	Cohesion C (Mpa)
sand	60	22	0.3	42	12	0.001

4.2.2Corrugated steel properties

Table 1 shows the physical and mechanical properties of the corrugation of the structure plate, the dimensions and properties of the (super cor S37) corrugated steel used in this study are also shown in table 1. The orthotropic shell theory which models the corrugation as a solid, prismatic section by using the five-noded shell elements along the neutral surface of the section were used for corrugated steel simulation, Elshimi 2001 mentioned that the orthotropic shell analysis gives the same results of the actual corrugation analysis.

Table 1: Corrugated steel properties

Steel plate properties	
Profile type	Corrugated steel of type SuperCor S37
Plate thickness	7 mm
Corrugation height	140 mm
Corrugation length	381 mm
Area	9.81 mm2/mm
Yield strength (fyk)	275 MPa
Elasticity modulus	200 GPa
Moment of inertia (I)	24164 mm4/mm
Section modulus (W)	308.2 mm3/mm
Plastic section modulus (Z)	415 mm3/ mm

In the corrugated steel plates, the axial and bending stiffness along both the strong and weak axes are different. According to El-Sawy (2003), these corrugated steel plates can be replaced with an equivalent plate section using Equations (1) and (2).

$$\overline{t} = \sqrt{(12I/A)} = 172 \text{ mm} \quad (1)$$

$$\bar{E} = 12EI/(\overline{t})^3 = 11804.1 \text{ MPa} \quad (2)$$

Here, A, E, and I are the area per unit length of the corrugated plate, Young's modulus, and the moment of inertia per unit length of a corrugated plate, respectively. These equations provide the corrugated steel plate to be replaced with a uniform shell. The properties used in the computer modeling for the metal plates are according to the above-mentioned equations, based on the orthotropic shell theory represented by El-Sawy (2003).

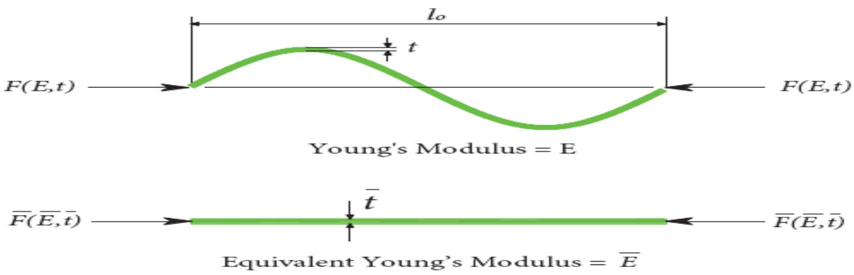


Figure 5 Geometry of the corrugated plates forming the structures

So the final parameters used in PLAXIS model was Young's modulus E= 11804.1 MPa and equivalent plate thickness $\bar{t} = 172$ mm. Other characteristics of the metal shell per unit length of the corrugated plate are:

A = 0.172 m^2/m; $I = 4.24X\,10^{-4}$ m^4/m; W = 0.478 kN/m; υ =0.3

4.2.3 Foundation and pedestals

The behavior of the soil-steel bridge foundation and pedestals was idealized as elastic plates for the 2D FE analyses, which was used to maintain the elastic characteristics under load. This was assumed because the initial studies on the behavior of the foundation system demonstrated that, for the design specifications of the foundation system and under the conditions used for this study, the foundation and pedestals did not exhibit a considerable amount of nonlinear behavior. Therefore, to reduce the computational time, the foundation system was assumed to have an elastic characteristic. The parameters used to idealize this type of material model such as the concrete compressive strength (fc), axial stiffness (EA), flexural rigidity (EI), unit weight of concrete, and Poisson's ratio (ν) per unit length of the foundation system are shown in Table 2

Table 2 Element specifications of foundations and pedestals

Material	Material model	fc KN/m^2	EA KN/m	EI KN.m^2./m	Unit weight KN/m^3	Poisson's ratio
Pedestal	Elastic	35000	2.24x10^6	119,466	25	0.1
foundation	Elastic	35000	1.12x10^6	14.93x10^6	25	0.1

4.4 Loading

According to the Egyptian loads standard 2008, a four wheel 60 ton truck was used as the main live load for all the culverts. The applied force on all culverts was equal to the normal load including the dynamic load factor, according to the Egyptian loads standard the axle loads are distributed by the contact axle area 0.4m x 0.4 m and can be redistributed over asphalt layers with 1:1 distribution slope. In this study the tuck axle loads are distributed by the contact axle area 0.4m x 0.4 m and redistributed over asphalt layer thickness 0.3 m, so the used loads was 306 KN/m over an distance equal to 0.7m for each loading truck axle. The area around the tuck was loaded with 9 KN/m equal distributed load as mentioned in the Egyptian loads standard 2008. Figure 6 shows plan of the used tuck with its dimensions and loads.

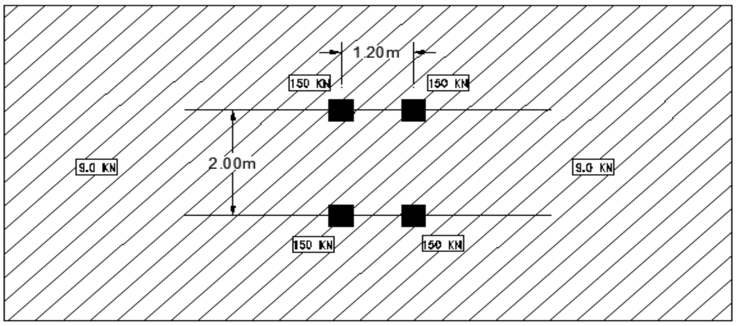


Figure6 plan view for the loading truck

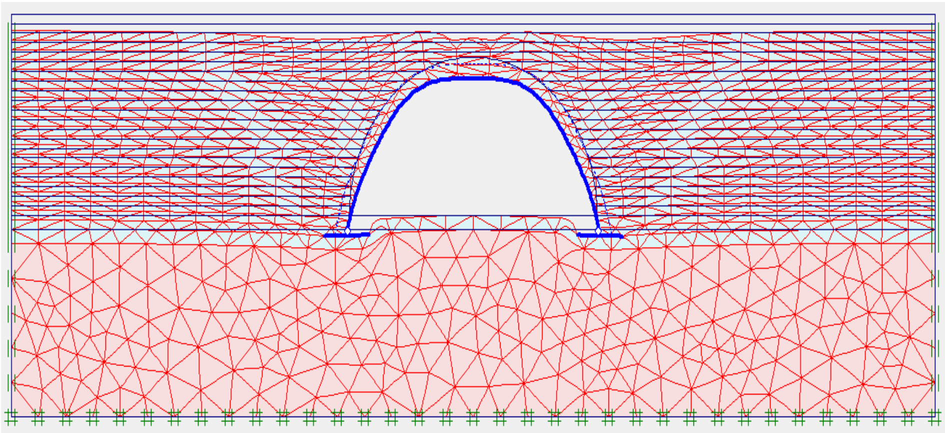
5 Results

5.1 CIRCULAR ARCH CULVERT

For all Arch culverts analyzed in the current study, the deformed shape, bending moments and thrust forces were calculated for earth and live loading. Fig. 7 shows the total deformation after live load for circular arch culvert after backfilling and due to live load at different locations along the X axis. Vertical displacement downward was calculated at the crown and lateral displacement directed away to the center of the culvert was calculated at the shoulder.

5.1.1 Truck position

As mentioned before two truck positions were used in the model. Figure 8 shows the bending moment calculated at different locations along the X axis for case position 1 where truck axel was centered over the crown. The maximum positive moment was calculated under the loading pad at X = 0.0 m measured from the center of the structure. The effect of live load on the bending moment was more significant at the crown. The live load moment at the crown was about 80% of the total moment, while it was only 30% at the shoulder. Figure 9 shows the calculated thrust forces at different locations along x-axis. The maximum thrust load was calculated at X = 3.40 m. The effect of live load was more significant at the crown. It should be noted the footings of all culverts were modelled with vertical movement allowed. The maximum bending moment was 11.5 m.ton / m.



Figs 7 Deformation shape after live load for truck position 1

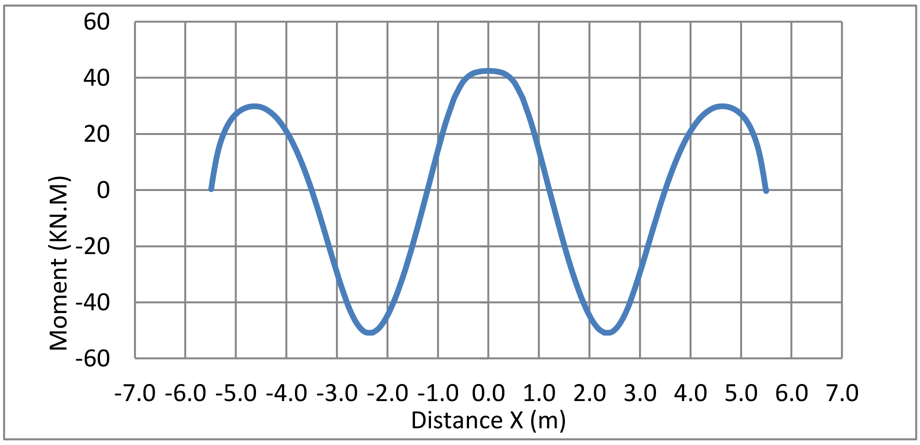


Fig 8 Bending moments after live load for truck position 1

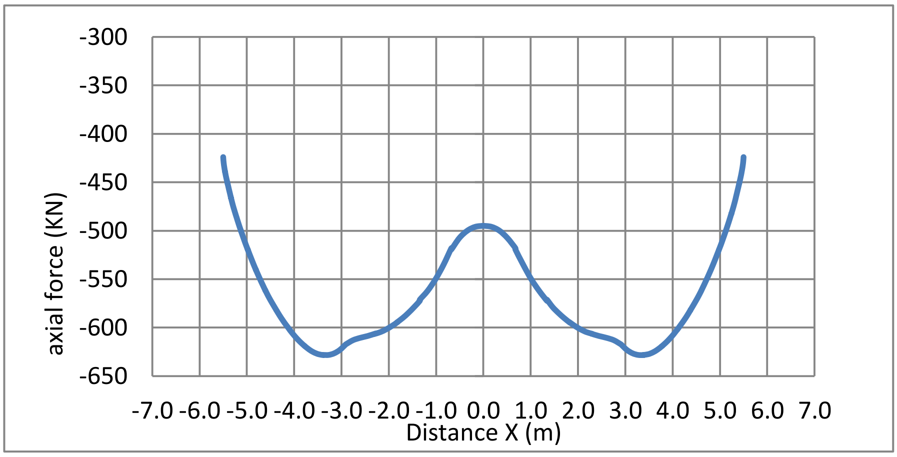


Fig9 Axial force after live load for truck position 1

Figure 10 shows the maximum deformation after live load for circular arch culvert and due to live load position 2 at different locations along the X axis. Vertical displacement downward was calculated at the crown and lateral displacement directed away to the center of the culvert was calculated at the shoulder. Figure 11 shows the bending moment calculated at different locations along the X axis. The maximum positive moment was calculated under the loading pad at X = 0.7 m measured` from the center of the structure, the maximum negative moment increased with 15% than the maximum negative moment for position 1. The effect of live load on the bending moment was more significant at the crown. Figure 12 shows the calculated thrust forces at different locations along X axis. The maximum thrust load was calculated at X = 3.70 m. As mentioned before the culvert footings were modelled with vertical movement allowed. The maximum bending moment was 12.2 m.ton / m. Comparing results of the two truck position, the truck position 2 gives higher bending moment and the thrust force is almost the same in the two cases. Figures 13 and 14 also show the relation between the maximum bending moment and the maximum axial force respectively for the two truck position with different soil cover. The effect of tuck position on the bending moments is grater for low cover thickness 1.00 m and 1.25m than other cover thickness over that.

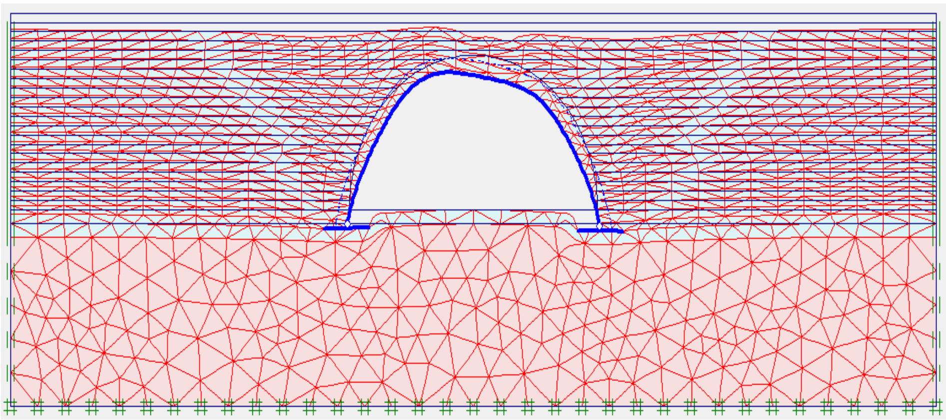
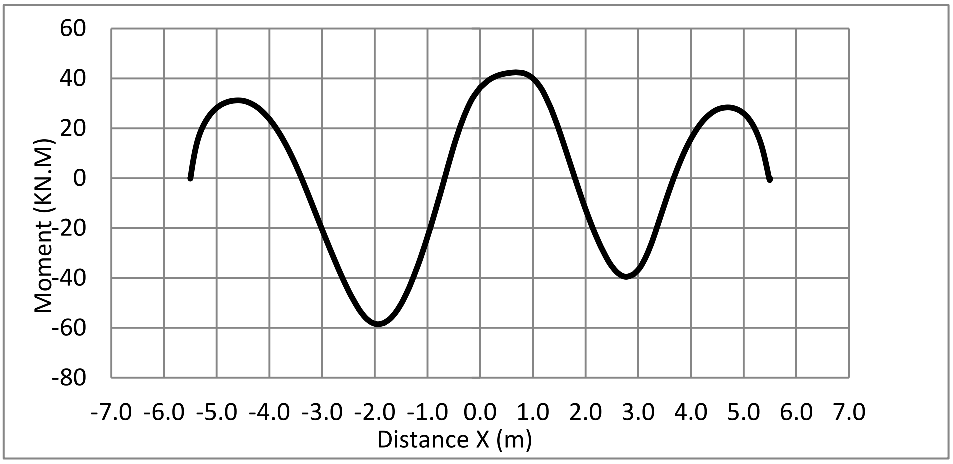


Fig 10 Deformation shape after live load for truck position 2



Figs 11 Bending moments after live load for truck position 2

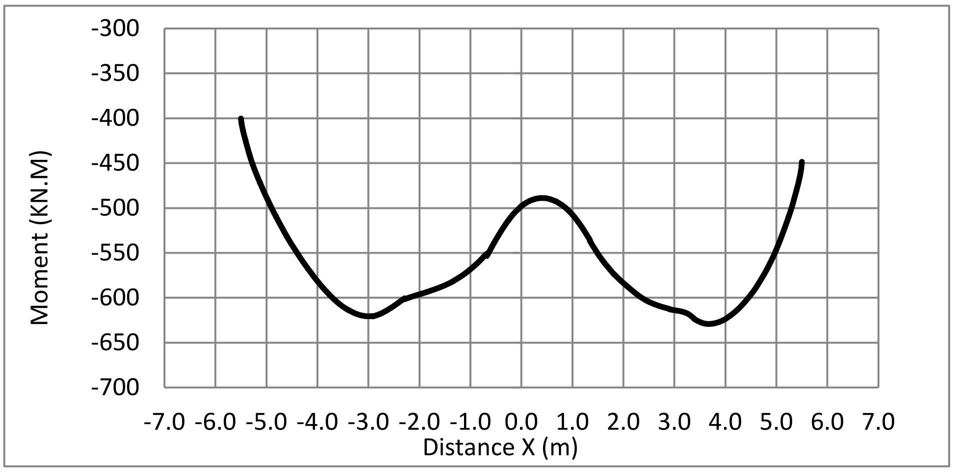


Fig 12 Axial force after live load for truck position 2

5.1.2 Thickness of soil cover

Figure 13 and 14 clearly shows the relation between soil cover and bending moment in the structure, it can be seen that increasing soil cover leads to more load dissipation and so the bending moments become less, but also increasing soil cover increases the total weight over the structure giving higher thrust force in the structure.

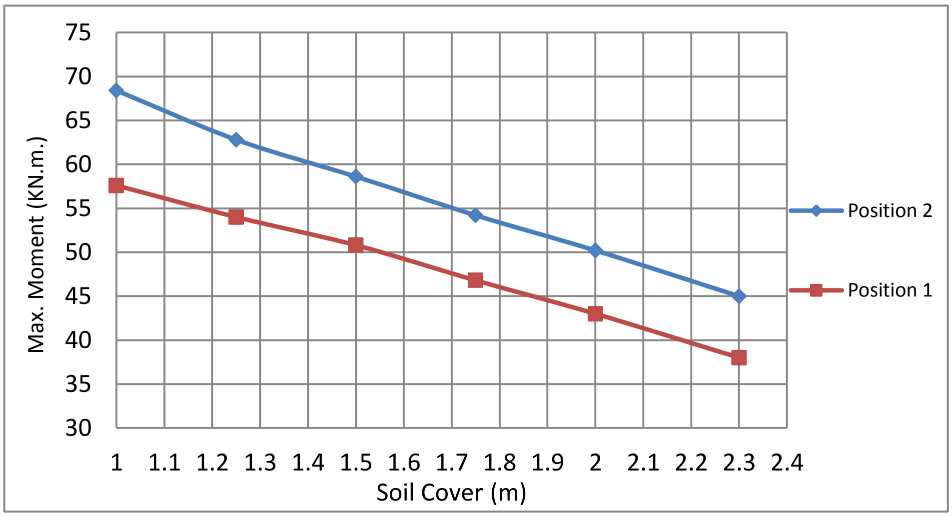


Fig13 Maximum bending moments after live load with different soil cover

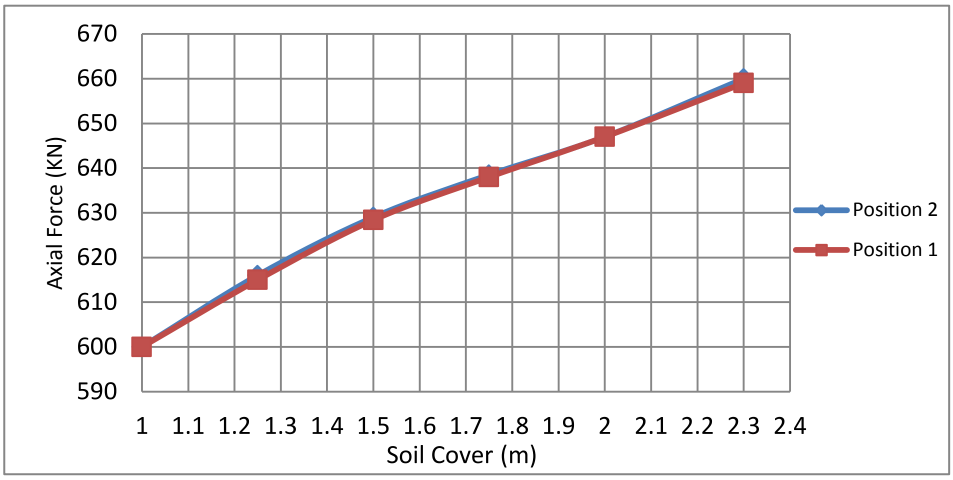


Fig14 Maximum axial force after live load with different soil cover

5.2 Arch culvert with 1m vertical concrete pedestals

Figure 15 clearly shows the relation between soil cover and bending moment in the structure, it can be seen that increasing soil cover leads to more load dissipation and so the bending moments become less, but also increasing soil cover increases the total weight over the structure giving higher thrust force in the structure. The effect soil cover on the bending moment of the structure is grate for low cover thickness up to 1.50 m and becomes less over this thickness

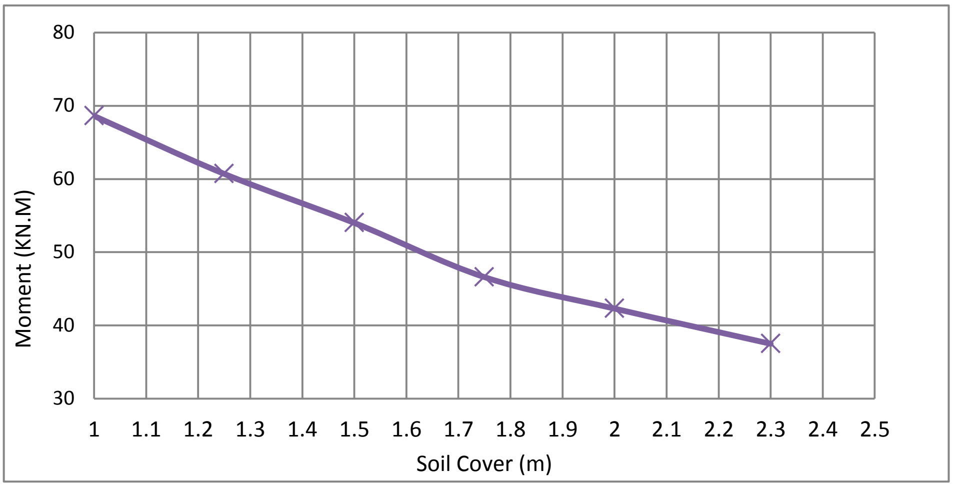


Fig 15 Maximum bending moments after live load with different soil cover

Figure 16 shows distribution of the maximum total bending moment after earth load and live load calculated for the three arch culverts having different spans (different span to height ratios). The total moment in Figure 16 summaries that decreasing the culvert span increases the bending moments at the crown and decreasing bending moments at the shoulders. The culvert with span to height ratio equal to 2.25 gives the maximum bending moment at crown with value equal to 68 KN/m, culvert with span to height ratio equal to 3.25 gives maximum bending moment at shoulder with value equal to 57 KN/m the culvert span to height ratio of 2.75 gives maximum bending moment lower than the other ratios of 2.25 and 3.25 about 26 KN/m at the crown, this is due to the good distribution of moments between crown and shoulder

Figure 17 show the distribution of total thrust force, live load and earth load thrust calculated for the three arch culverts having different spans (different span to height ratios). The maximum thrust values calculated for all arch culverts were small compared to the thrust capacity of the deep-corrugated section (2200 kN/m).The thrust forces increases with span increase as the total earth weight on the structure increases with span increase. The increase in the thrust forces with the span of the culvert was not linear, the increase for span to height ratio from 2.75 to 3.25 was almost twice the increase of thrust force for span to height ratio from 2.25 to 2.75. The increase in span had significantly more effect on earth load thrust than on live load thrust.

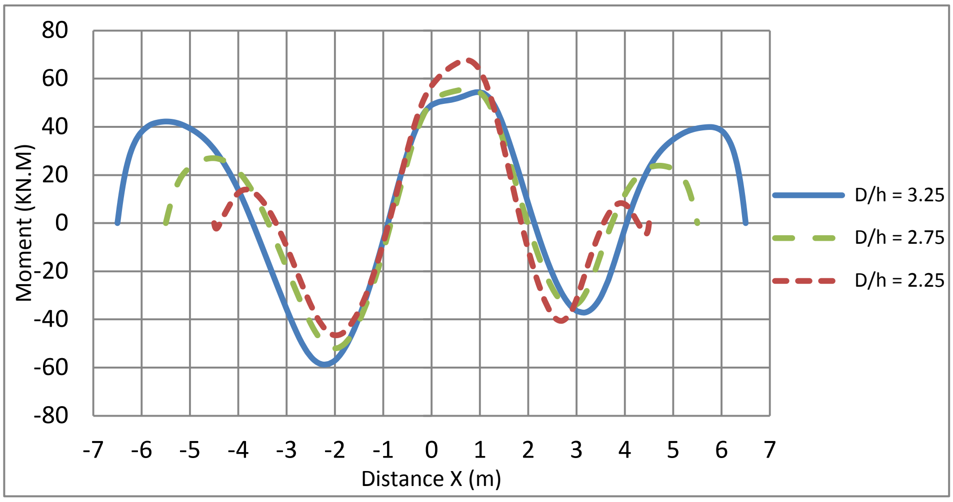


Fig16 Bending moment distribution after live load for different span to height ratio-culvert profile (2)

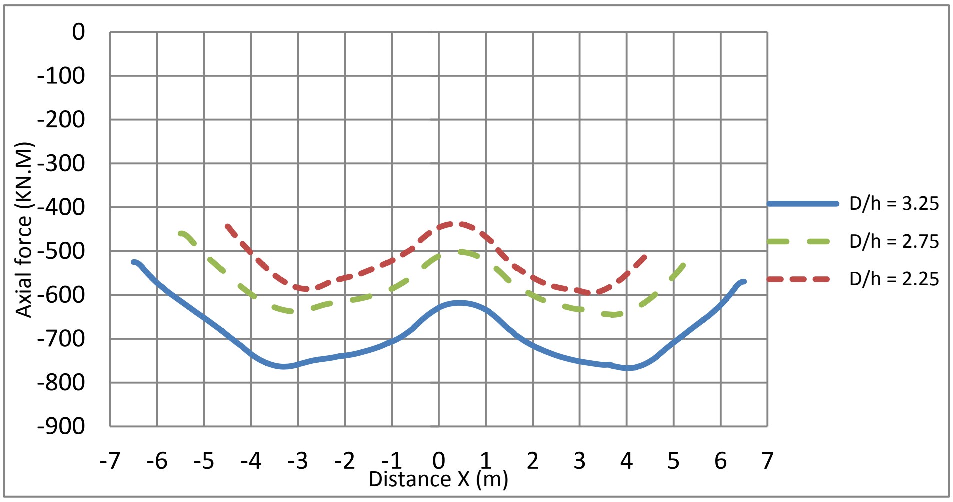


Fig17 Axial force distribution after live load for different span to height ratio-culvert profile (2)

5.3 Box culvert

For all box culverts analyzed in the current study, the deformed shape, bending moments and thrust forces were calculated for earth and live loading. Figure18 shows the deformation after live load for box culvert after backfilling and due to live load at different locations along the X axis. Vertical displacement downward was calculated at the crown, while displacement upward and lateral displacement directed away from the center of the culvert was calculated at the shoulder. Figure 19 shows the bending moment distribution along the structure for box culvert after backfill soil and live load was at the crown

5.3.1 Thickness of soil cover

Figure 20 shows the relation between soil cover and bending moment for the studied box culvert, again increasing soil cover leads to more load dissipation and so the bending moments become less, but also increasing soil cover increases the total weight over the structure giving higher thrust force in the structure. The effect soil cover on the bending moment of the structure is grate for low cover thickness up to 1.25 m and becomes less over this thickness

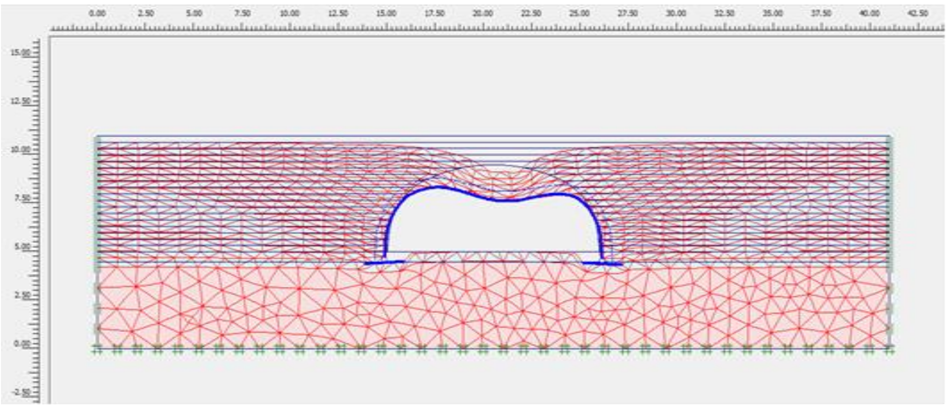


Fig18 Deformation shape after live load for box culvert

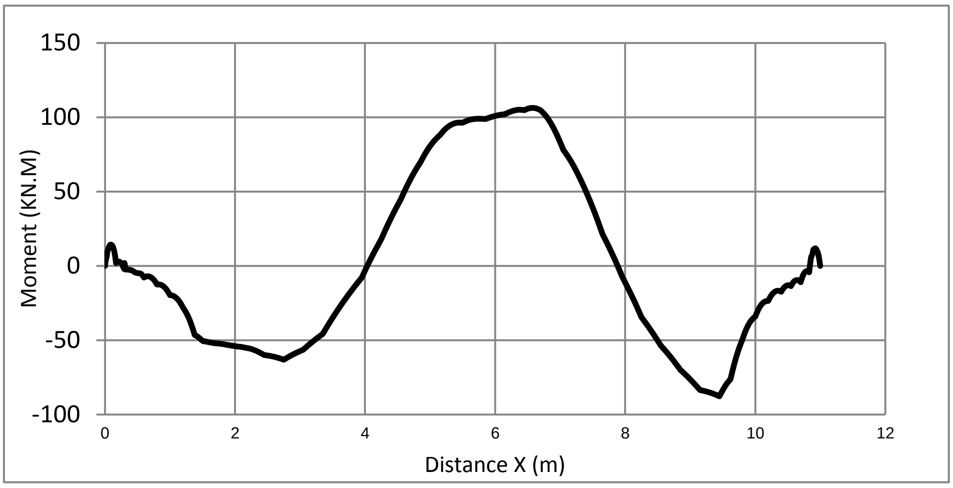


Fig19 Bending moment distribution after live load for box culvert

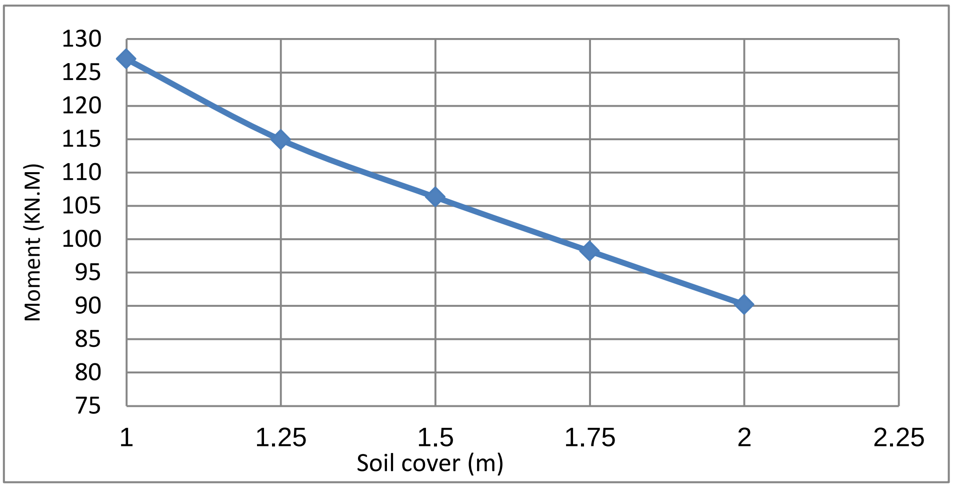


Fig20 Maximum bending moments after live load for different soil cover for box culvert

5.4 Geometry of culvert

The effect of culvert geometry was studied for three different geometries of circular arch culvert, arch culvert with 1m vertical concrete pedestals, and box culvert. Figure 21 compares the results of bending moments for the three culvert profiles with different soil cover, its clearly show that the arch profile with 1m vertical concrete pedestals gives the minimum values for the bending moments specially for large soil cover, while the box culverts gives maximum. Figure 22 compares the results of thrust force for the three culvert profiles with different soil cover, from figure 21 and 22 its clearly shows that the arch profile with 1m vertical concrete pedestals gives good results for bending moments and thrust force, so this profile exhibits good behavior and particularly useful in meeting a need for structures with limited vertical clearance that also provide large cross-sectional area for water conveyance.

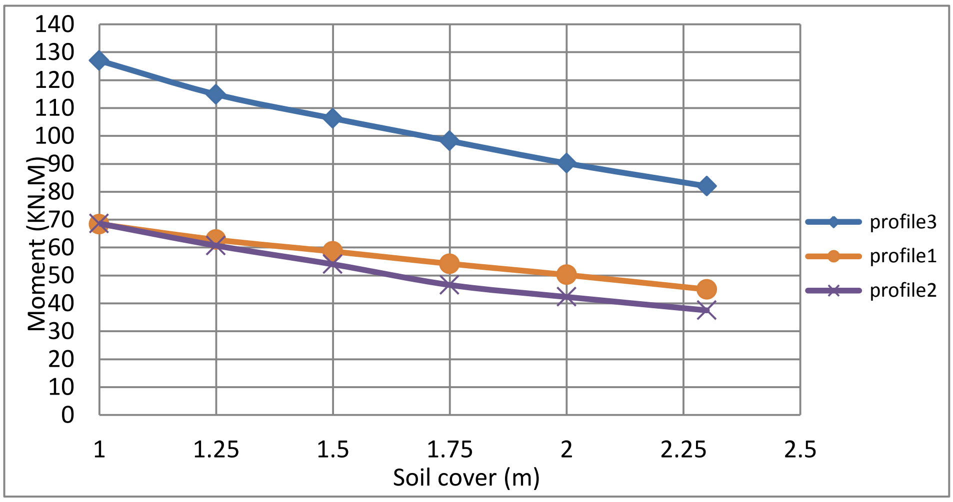


Fig21 Maximum bending moments after live load for different culvert profiles

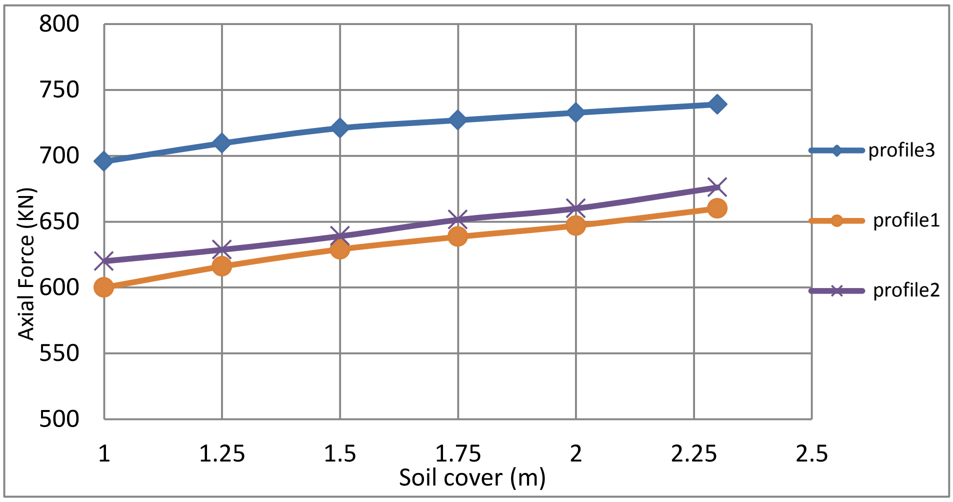


Fig22 Maximum axial force after live load for different culvert profiles

6 CONCLUSION

A parametric study was performed using finite element analysis for long-span, deep-corrugated metal circular arch culvert, arch culvert with 1m vertical concrete pedestals, and box culvert. Thirty case studies were examined during the study. Several factors including culvert profile, culvert span to height ratio, and the traffic load position were changed during this study to investigate their effects on the behavior of long-span metal culverts. Two-dimensional finite element analysis was performed in the study employing orthotropic shell theory to model the culvert and Mohr-Coulomb constitutive model for soil modeling. The maximum values of displacement, bending moment and thrust force were obtained for each culvert, and the effects of different parameters were examined in detail

- The use of 1m vertical concrete pedestals with arch culverts reduces the bending moments with 10% and reduces the bending moments with 40% than using culvert profile for the same span and higth
- Increasing soil cover reduces the total bending moments in the box and arch culverts , as well as increasing soil cover increases the total weight over the structure giving higher thrust force in the structure
- The finite element model successfully predicted the behaviour of the culvert under truck loading for different truck positions
- . It was found that placement of the wheel axle of the trucks at the crown of the culverts produces the maximum moment and thrust force
- For arch culvert with low span to height ratio = 2.25 the maximum moment appears in the culvert crown while the maximum moment appears in the culvert shoulder for arch culvert with low span to height ratio arch culvert with high span to height ratio=3.25
- The arch culvert with span to height ratio of 2.75 gives maximum bending moment lower than the other ratios of 2.25 and 3.25.

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