Egyptian Knowledge Bank

**_International Journal of Advances in Structural and Geotechnical Engineering_**

https://asge.journals.ekb.eg/

*Print ISSN 2785-9509* *Online ISSN 2812-5142*

***Special Issue for ICASGE'19***

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*ASGE Vol. 03 (03), pp. 34-40, 2019*

# Analysis of Long Span Soil-Steel Culvert

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## ABSTRACT

Soil–steel structures have been constructed as an alternative to short span concrete and steel bridges. 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.

This paper presents a study to investigate the variations of some geometrical 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 for soil–steel culverts adopting the PLAXIS 2-D program were carried out. The position of the loaded truck were also studied. The Mohr–Coulomb constitutive model was considered in this simulation. 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.

***Keywords:*** *Soil–steel culvert, PLAXIS, long span culvert*

## INTRODUCTION

The soil-steel bridge (culvert) structures consist of shells of corrugated steel plates that are surrounded with well-compacted soil and founded with or without pedestal. The design of these structures have been introduced in 1886 in the USA. 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 the engineering backfill; therefore they are called the soil-steel bridges.

Authorities' demand of a better and safer investment in these structures has enthused the engineering research and the industry section into more design and performance investigations [1-10].

The primary objective of the current study is to analyze the performance of soil-steel bridge. The analysis encompasses different culvert profiles taking the effect of culvert span to height ratio, and soil cover thickness. The parametric analysis was carried out through two dimensional finite element analysis adopting PLAXIS 2-D program [11]. According to the Egyptian loads standard 2008 [12], a four wheel 60 ton truck was implemented as the main live load for all the culverts. The goal of the analysis is to achieve the least stresses laying on the bridge.

## NUMERICAL ANALYSIS

Finite element modelling (FEM) were implemented adopting PLAXIS 2-D program. The geometry dimension was determined after several trials to insure taking the effect of surrounding soil. The trials showed that the soil extending up to 1.5 culvert spacing is enough to capture the effect of surrounding soil on the soil steel culvert. The culvert is surrounded with backfill soil that is compacted in layers; each layer was 33 cm height. The backfill material was modelled as 15-node triangular elements. Mohr- Coulomb failure criterion was adapted to model shear failure in the soil and the resulting plasticity. The backfill soil is well graded remolded sand. Table 1 shows the material properties.

**Table1: Soil properties**

| Modulus of elasticity (MPa) | Unit weight $\gamma$ KN/m3 | Poisson's ratio $\nu$ | Angle of $\phi$ (deg) | Dilation angle $\psi$ (deg) | Cohesion C (MPa) |
|---|---|---|---|---|---|
| 60 | 22 | 0.3 | 42 | 12 | 0.001 |

The interface between the soil and the structure was defined as bonded, with no relative movement allowed. Foundation and pedestals was idealized as elastic plates. This was assumed because the initial studies on the behavior of the foundation system demonstrated that, under the conditions for this study, the foundation and pedestals did not exhibit nonlinear behavior. The parameters are shown in Table 2.
Standards fixities are applied at the edges (horizontally fixed edges) and fixed in both ways for the bottom edge.

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

**Table: 2 Element specifications of foundations and pedestals**

**Modeling Corrugated Sheets in FEM**

Corrugated steel plates of type SuperCor S37 was adopted as the steel structure part. Geometry of the corrugated plates forming the structures was constants as shown in Figure 1. Table 3 shows the physical and mechanical properties of the corrugated steel sheet.

**Table 3: Properties of Corrugated Steel Sheet [12]**

| | |
|---|---|
| Profile type | Corrugated steel of type SuperCor S37 |
| Plate thickness | 7 mm |
| Corrugation height | 140 mm |
| Corrugation length | 381 mm |
| Area | 9.81 mm$^2$/mm |
| Yield strength ($f_y$) | 275 MPa |
| Elasticity modulus | 200 GPa |
| Moment of inertia (I) | 24164 mm$^4$/mm |
| Section modulus (W) | 308.2 mm$^3$/mm |

The corrugated sheets can be modelled adopting orthotropic shell theory with an equivalent thickness equal to the depth of corrugation and the modulus of elasticity is reduced to provide the correct EI value [13]. El-Sawy proposed that the corrugated steel plates can be replaced with an equivalent prismatic section applying the following equations.

$$\bar{t} = \sqrt{\frac{12I}{A}} \quad (1)$$

$$\bar{E} = \frac{12EI}{\bar{t}^3} \quad (2)$$

Where:

$\bar{t}$: Equivalent prismatic section,

$\bar{E}$: Equivalent Young's modulus,

I: Moment of inertia,

A: Area per unit length of the corrugated plate, and

E: Young's modulus.

Figure 1 demonstrated the concept of the equivalent simulation of corrugated plate.
Section of the corrugated steel plates were replaced with the equivalent plate section using Eqs. (1) and (2). Then:

$$\bar{t} = \sqrt{\frac{12I}{A}} = 172 \text{ mm}$$

$$\bar{E} = \frac{12I}{(\bar{t})^3} = 11804.1 \text{ MPa}$$

Hence, the final parameters are Young's modulus $\bar{E}$= 11804.1 MPa, equivalent plate thickness $\bar{t} = 172$ mm, A = 0.172 $m^2/m$, I = $4.24 \text{X} \, 10^{-4} \, m^4/m$, and ν =0.3

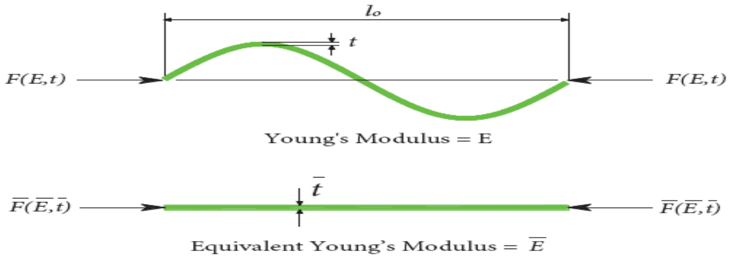



**Fig. 1: Geometry of the corrugated plates forming the structures**

## Loading

According to [12], a four wheel 60 ton truck was considered 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. The axle loads are distributed by the contact axle area 0.4 m 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 load was 306 KN/m over a distance equal to 0.7 m for each loading truck axle. The area around the tuck was loaded with 9 KN/m equal distributed load. Figure 2 shows plan of the tuck with its dimensions and loads.

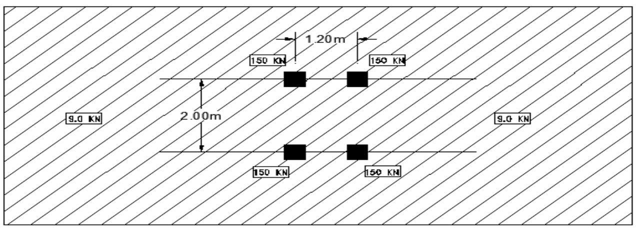



**Fig. 2: Plan view for the loading truck**

## PARAMETRIC VARIABLES

### 1. Culverts Geometry

In order to investigate the behavior of soil steel culverts, three different geometries of soil steel culvert with same span and height were studied, as shown in Figure 3. They are circular arch culvert (profile 1), arch culvert with 1 m vertical concrete pedestals (profile 2), and box culvert (profile 3). The arch culverts with 1 m vertical concrete pedestals were analyzed with different

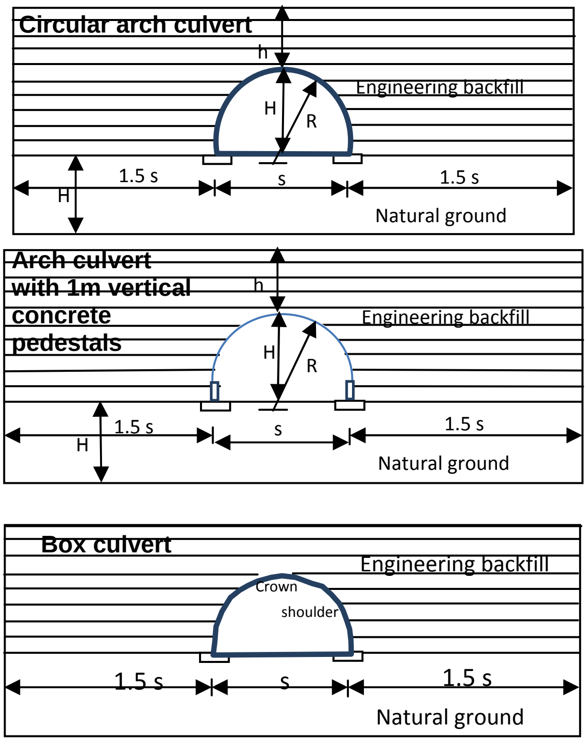
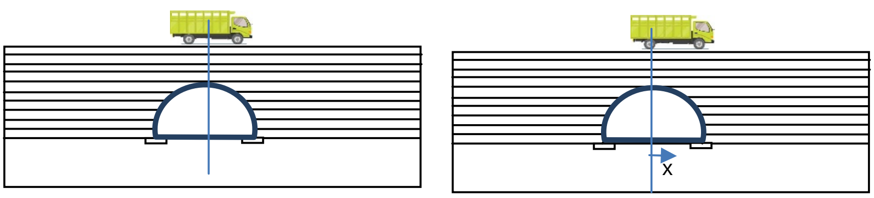



**Fig. 3: Geometry of Different Profiles**

spans of 9, 11 and 13 m and constant height of 4 m to investigate the effect of span to height ratio on the behavior of these structures.

2. **Position of truck load**

Most of the design specifications emphasis on positioning 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 behavior of long-span culverts was one of the objectives of this study. After several trials, two main truck positions were included; position 1: the truck was centered over the crown of the culverts. Position2: the wheel truck axle was centered over the crown of the culverts. Figurev4.a and 6.b show the two different truck positions.




**a) Position 1** **b) Position 2**

**Fig. 4: Truck positions**

3. **Depth of soil cover**

The depth of soil 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 of 1.00, 1.25, 1.50, 1.75, 2.00, and 2.30 m.

## RESULTS

**Thickness of soil cover:**

Figures 5 and 6 show the relation between soil cover and bending moment, and normal thrust, respectively. 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.

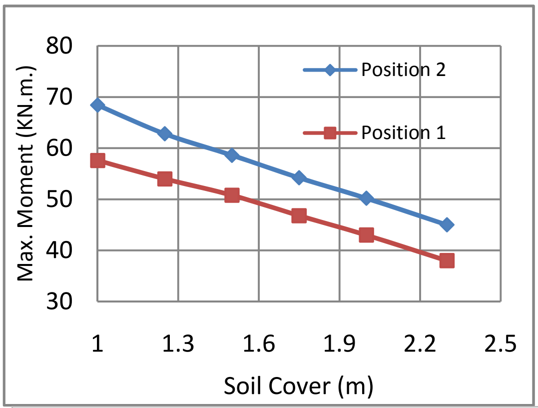



**Fig. 5: Maximum Bending Moments with Different Soil Cover**

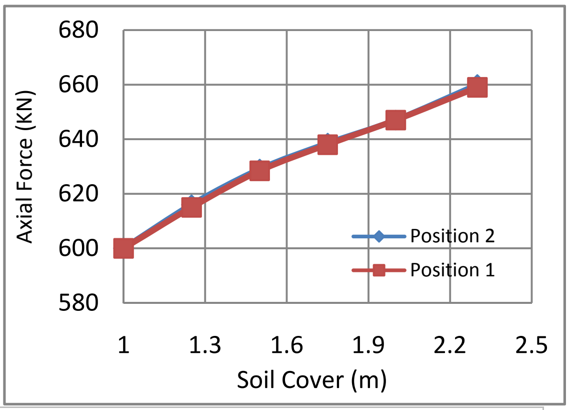



**Fig. 6: Maximum Axial with Different Soil Cover**

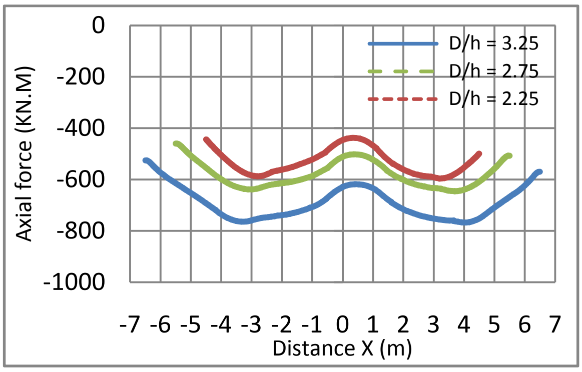
**Truck position**

Two truck positions were considered in the analysis of this study. It was found that the maximum positive moment was calculated under the loading pad at X = 0.0 m measured from the center of the structure, for case position 1; where truck axel was centered over the crown. For truck position 1, the maximum positive moment was under the loading pad at X = 0.7 m measured from the center of the structure. Figure 5 depicts the change of moment with different soil cover for the two positions. Comparing results of the two truck position, the truck position 2 gives higher bending moment. Moreover, the effect of tuck position on the bending moments is greater for low cover thickness 1.00 m and 1.25m than other cover thickness.

**Span to Height Ratio**

Figure 7 shows distribution of the maximum total bending moment calculated for the three arch culverts having different spans (different span to height ratios). The total moment in Figure 7 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 8 show the distribution of total thrust force for the three arch culverts having different spans (different span to height ratios). The maximum thrust values 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.



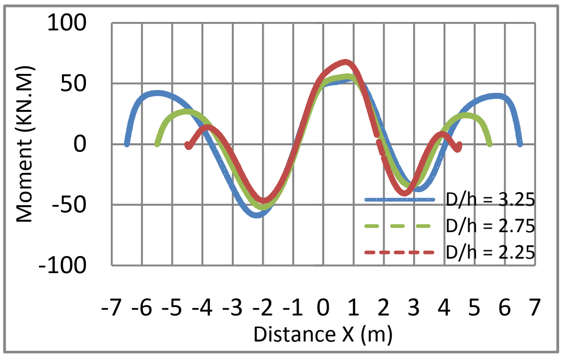
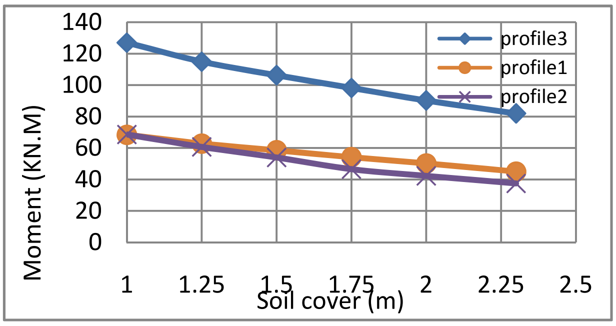




**Fig.7: Bending moment distribution for different span to height ratio-culvert profile (2)**

**Fig. 8: Axial force distribution different span to height ratio-culvert profile (2)**

**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 8 depicts the results of bending moments for the three culvert profiles with different soil cover. From the Figure, it can be seen 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 the maximum. Figure 9 illustrates the results of thrust force for the three culvert profiles with different soil cover. From figures 8 and 9, its clearly shows that the arch profile with 1 m vertical concrete pedestals gives good results for bending moments and thrust force. So, this profile exhibits good behavior; it is particularly useful in meeting needs for structures with limited vertical clearance. It also provides large cross-sectional area for water conveyance.



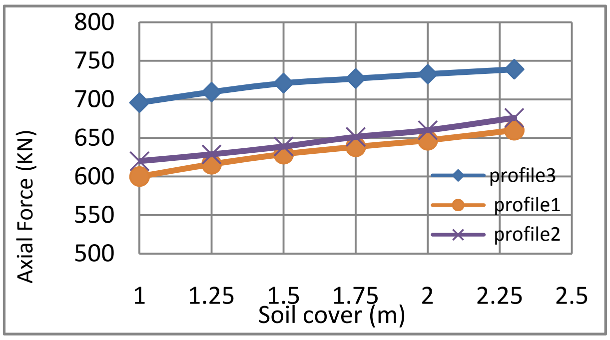




Fig.8: Bending Moment Distribution for Different Culvert Profile

Fig. 9: Axial Force Distribution for Different Culvert Profile

## 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. Several factors including culvert profile, culvert span to height ratio, and the traffic load position were considered 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 bending moment and thrust force were obtained for each culvert, and the effects of different parameters were examined. Within the limit of this study, the following conclusion can be derived.

- Increasing soil cover reduces the total bending moments in the box and arch culverts, but also increasing soil cover increases the total weight over the structure giving higher thrust force in the structure.
- 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 height
- . It was found that placement of the wheel axle of the trucks at the crown of the culverts produces the maximum moment.
- 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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