Numerical modelling of enhancement of the capacity of buried metal culverts by using geogrids

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Abstract. This paper presents a two-dimensional numerical modelling analysis of a flexible buried corrugated metal arch culvert in Enkoping, Sweden. The numerical results of this study are validated against field measurements of the culvert crown deformation, thrust, and bending moments recorded during backfilling. To model the backfill soil, the hardening soil with small strains (HSs) material model is used because of its efficiency in simulating the soil-structure interaction. Furthermore, in a numerical investigation of the stress distribution at the culvert invert, it is found that weakness of the foundation soil has an insignificant impact, due to stress dissipation resulting from arching actions. The numerical modelling analysis also investigates the use of geogrid layers with dead end bolts in the soil cover above the culvert crown during the application of static surface loads, as an innovative technique to improve the load capacity of the soil-culvert system. The results show a reduction in culvert crown deformation and internal forces when geogrid layers are used. This indicates the efficiency of geogrid layers in improving the load capacity of existing buried culverts or overcoming deficiencies in culvert serviceability by reducing the impact of applied loads.

1 Introduction

Corrugated metal culverts (CMC) have been widely used as a promising system for buried structures, due to their advantages in comparison to conventional reinforced concrete tunnels [6]. Since the 1850s, CMCs have been installed in transportation networks and water supply facilities in Europe and North America to convey stream or storm water flow [7]. The primary reason for the use of such culverts is their corrugated profile that interlocks with surrounding soils, thus providing overall confinement with a higher capacity [17,18]. Their flexible structure allows corrugated culverts to be formed easily into different shapes, such as circular, arch, ellipse, and box geometries.

Buried corrugated culverts were first manufactured as small metal pipes at the end of the 19th century. In 1913, a group of researchers from the University of North Carolina and Iowa State College studied the impact of top backfill loading on buried corrugated culverts. In the same year, Anson Marston [1] introduced a basic theory concerning the mechanism of load transfer between underground culverts and the soil column. This theory was later used to study the impact of load redistribution on flexible pipes and to provide special techniques for reducing the impact of backfilling [2,4]. In 1923, large full-scale tests were performed beneath the Illinois central railroad to study the impact of the interaction between flexible conduits and the surrounding compacted backfill [14]. Buried culverts are subject to two main types of loading: Backfill compaction, and surface top loading. During the compaction of lateral backfill, the culvert sides move inward while the top of the culvert tends to move upward. However, when top loading occurs, the culvert sides tend to move outward while the culvert crown moves downward. Thus, well-compacted backfill soil can limit the deformation of a buried culvert under loading by developing internal forces in the culvert body [17].

Corrugated culvert designs were initially derived based on direct methods of predicting the behaviour of soil-structure interactions [18]. The applied loads on buried culverts can be estimated based on arching actions. Terzaghi (1943) defines arching as the transfer of a load from a yielding mass to an adjacent rigid element, resulting in redistribution of the pressures developed [3]. In 1800, a study of this phenomenon was undertaken by the French army to design large magazine silos. Subsequently, ring compression theory was presented in 1940 as an approach for the design of buried conduits, based on the internal hoop force [3]. In 1978, Duncan introduced the soil-culvert interaction (SCI) theory, based on several field tests of buried corrugated metal conduits [5]. The tests led to the development of empirical formulas that could be used to determine pipe maximum internal forces. The theory was later improved by Pettersson (2007) [8] to enhance the design methodology. Several well-known codes, such as the Canadian Highway Bridge Design Code (CHBDC) [9], the code of the American Association of State Highway and Transportation Officials (AASHTO) [17], and the Swedish Design Manual (SDM) [10] are currently used worldwide as analytical approaches for the design of buried flexible culverts and pipes. Recently, new software technologies have provided extensive automation of finite element analysis computations, which can support numerical modelling to capture the nonlinear coupled behaviour of the soil-structure interaction [11,15,16].

Over the years, most buried underground structures experience deterioration problems due to various factors such as corrosion and aging. Such deterioration can result in damage to structural elements, thus weakening the metal culvert body and reducing the overall load capacity. This structural damage may be characterized by thickness loss and stiffness degradation [21]. As a result, buried culvert system capacity and service life is reduced and must be reassessed to avoid future failure [12]. The rehabilitation of weak systems can improve the operability of corrugated metal culverts in service without having to replace them. The use of geosynthetic materials such as geogrid sheets can be one solution for overcoming such problems and enhancing the overall system capacity.

This paper presents 2D numerical modelling of a flexible buried corrugated metal arch culvert in Enkoping, Sweden. The analysis simulates the soil by using the hardening soil with small strains (HSs) material model. Stress distribution is also investigated to monitor the impact of a weak foundation soil with low stiffness. Furthermore, numerical modelling is employed to investigate the effect of using geogrid layers with dead end bolts in the soil cover above the culvert crown, as an innovative technique to enhance the performance of the soil-structure interaction or to compensate for a deterioration in culvert operability by reducing the impact of applied loads.

2 Enkoping Corrugated Metal Arch Pipe

A flexible corrugated metal arch culvert was constructed in the town of Enkoping, about 100 km west of Stockholm, Sweden, to carry out a set of full-scale field tests [8]. The culvert was installed in a gravel pit to avoid traffic interruptions. The culvert, with a span of about 6.0 m and an internal height of 4.55 m, was formed from corrugated metal sheets with a wavelength of 200 mm, corrugation depth of 55 mm, and sheet thickness of 3 mm. The construction took around three years to complete. To record data during testing, strain gauges were placed around the culvert circumference to measure the deformation and internal forces. Backfilling was performed by using 19 layers of well-graded sand, with an average layer thickness of 300 mm and a soil cover depth of 1.5 m above the culvert crown. Details of the culvert geometry are shown in Figure 1.

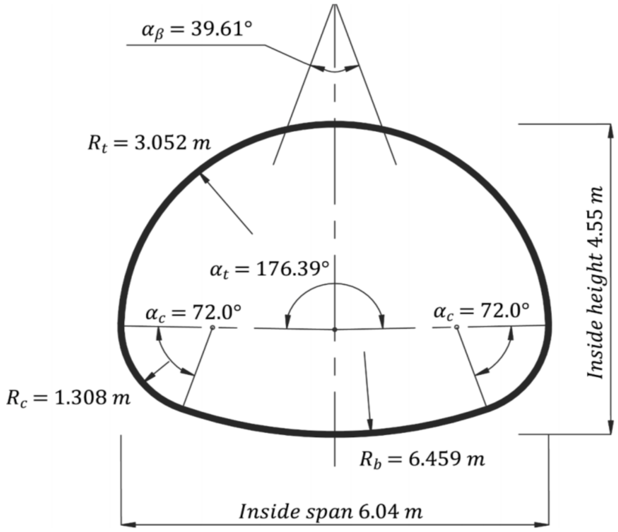


Fig. 1. Geometry of the Enkoping arch culvert, Sweden (after Pettersson, 2007 [8])

3 Numerical Modelling

Modelling of the soil-structure interaction of corrugated metal culverts relies on several factors, including the culvert profile, backfill characteristics, compaction loads, and trench geometry. All these factors need to be incorporated into the numerical model to obtain more accurate estimates of the culvert performance. In the current study, modelling was performed by using the Plaxis 2D finite element software, developed to model geotechnical engineering problems in axisymmetric or plain strain conditions [19]. To capture the nonlinear soil behaviour, the hardening soil with small strains constitutive model was utilized to simulate the stress-dependent behaviour of the soil during backfilling and surface loading [20]. Numerical simulations of field excavation and the installation of culverts with backfill soil can be implemented by activating and deactivating element clusters with loads and/or prescribed displacement. This approach can achieve a more realistic assessment of the stress-displacement performance of buried underground structures. The current research also investigates enhancement of the overall system capacity through the placement of geogrid layers.

In the numerical model, an arch culvert with an inside diameter of 6.1 m, an internal rise of 4.55 m, and a cover depth of 1.5 m above the crown is constructed in a trench with a slope of approximately 1V:1H. To diminish the impact of the boundaries, the distance between the two side boundaries is set to 100 m, and the bottom boundary is set to 15 m below the ground surface and 9 m below the culvert invert. Fixities are assigned to the side boundaries to prevent horizontal deformation, and to the base to prevent any horizontal or vertical movement. The top surface is set to deform freely, to model the soil behaviour under loading. The ground water is set at a deep level, below the culvert base. Figure 2 illustrates the schematic geometry of the numerical model of the arch culvert. The backfill soil is simulated by using the hardening soil with small strains (HSs) material model, which is capable of mimicking higher soil stiffness at small strains [20]. The culvert is modelled as a plate element with an equivalent axial and flexural stiffness to represent the corrugation profile. Table 1 presents the properties of the backfill soil and the arch culvert.

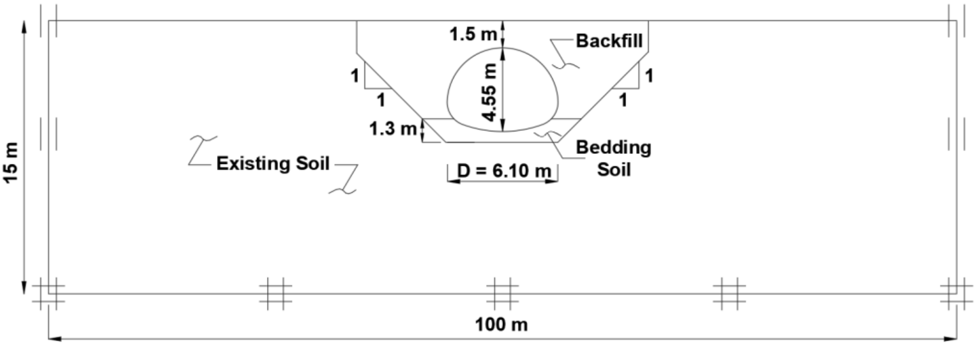


Fig. 2. Schematic geometry of the numerical model of the Enkoping arch culvert

Table 1. Characteristics of the backfill soil and the corrugated metal arch culvert

Backfill Soil Characteristics		**Arch Culvert Characteristics**	
Soil material model	HSs	Plate thickness (t) (mm)	3.00
Soil unit weight (γ) (kN/m^3)	17.8	Plate length (mm)	200.00
Modulus of elasticity (E) = E_{50} (MPa)	16.4	Plate height (mm)	55.00
$E_{oedemeter}$ (MPa)	13.12	Axial stiffness (EA) (MPa/m)	744.20
$E_{unloading\text{-}reloading}$ (MPa)	49.2	Flexural stiffness (EI) (kN.m^2/m)	284.10
Poisson's ratio (υ)	0.2		
Cohesion (c) kPa	1		
Friction angle (φ)	36°		
Dilatancy angle (Ψ)	6°		
Interface coefficient (R_{in})	0.67		
Shear modulus (G_o) (MPa)	150		
Shear strain ($\gamma_{0.7}$)	0.002		

The numerical model comprises more than 21,000 elements and 175,000 nodes, with an average element size of about 150 mm near the culvert body. To allow for slippage and gapping, an interface boundary around the culvert is defined by assigning an interface reduction factor of 0.67 between the culvert and the surrounding soil. The numerical modelling simulation begins with an initial stage, where all the existing soil is activated, while the culvert plate element is deactivated. In the second stage, excavation of the sloped area is simulated by deactivating the existing soil in that region. In the third stage, the culvert body, culvert interface, and bedding soil are activated. In the following sequential stages, compaction loads are applied to simulate the backfilling process. At each stage, a backfill layer is activated with its surface load (representing the compaction impact), and in the following stage that load is deactivated while the subsequent layer and its surface load are activated. This process continues until the end of backfilling, when a total cover depth of 1.5 m is reached. Static surface loads are then simulated by applying line loads to the soil surface across the width of the culvert span. Figure 3 illustrates the meshing distribution of the numerical model, and Figure 4 shows the simulation of the sequential backfilling process with the use of surface compaction loads.

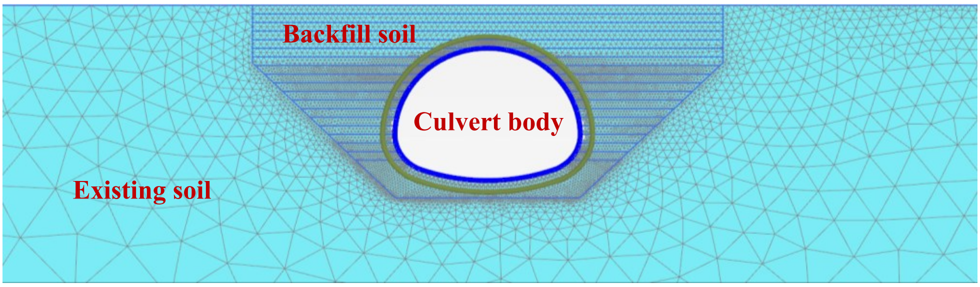


Fig. 3. Meshing distribution of the numerical model of the Enkoping arch culvert

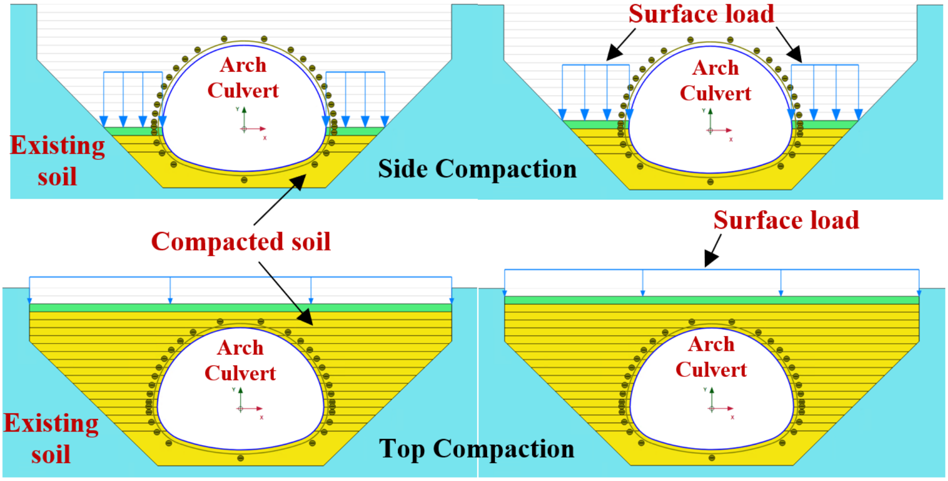
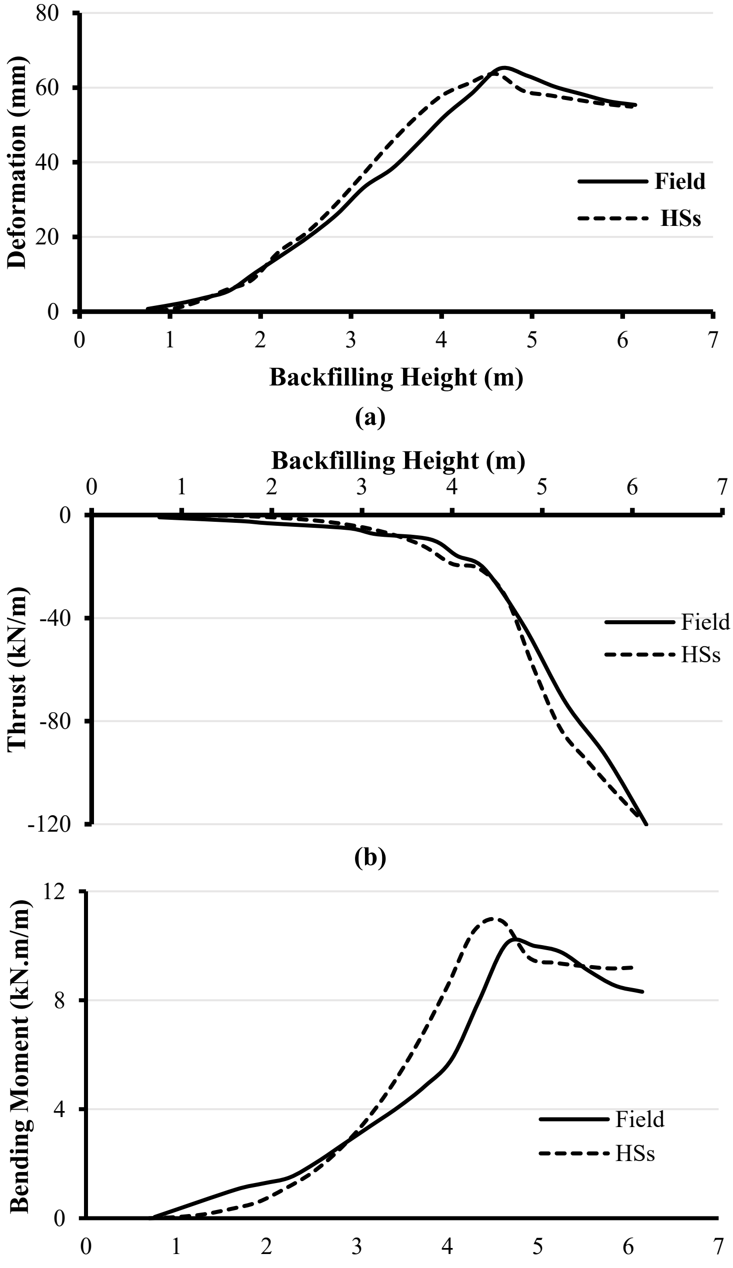


Fig. 4. Numerical modelling simulation of two sequential compaction stages for side compaction (upper diagram) and top compaction (lower diagram) of the 2D arch culvert

4 Results and Discussion

To capture the culvert deformations and internal forces, field measurements were recorded during backfilling via a set of strain gauges attached to the circumference of the middle section of the culvert. As can be seen in Figure 5, the numerical modelling results with the HSs material model exhibit close agreement with the field measurements for the crown deformation, thrust, and bending moment of the corrugated metal culvert. For the crown deformation, the numerical model gives a maximum upward movement of around 63.5 mm when backfilling is near the crown level, as compared to the field measurement of 65 mm. At the end of backfilling, the numeral modelling maximum thrust result of -118 kN/m is close to the field measurement of -120 kN/m. Likewise, the maximum bending moment developed with backfilling at the crown level is given as approximately 11 kN.m/m by the numerical model, in comparison to 10.2 kN.m/m measured in the field. Thus, it can be concluded that the numerical model efficiently simulates the observed field results.



(a)

(b)

(c)

Fig. 5. Comparison of field measurements and HSs numerical modelling results for the (a) crown deformation, (b) thrust, and (c) bending moment of the arch CMC

5 Enhancement of the Capacity of Buried CMCs

Buried culverts are generally subject to two types of loading: Compaction loads due to side and top backfilling, and surface loads due to traffic and serviceability loading. In the numerical model, after the completion of backfilling, static loads with incremental increases (i.e., 50, 100, 150, 200, 250, 300, 350, and 400 kPa) are applied at the soil surface to investigate their impact on the buried arch culvert. As shown in Figure 6. under a 400 kPa surface load, at the arch culvert invert most stresses are diverted due to arching actions and stress redistribution around the culvert body. Thus, the numerical modelling indicates that the impact of a weak foundation soil with lower stiffness is insignificant because most of the applied loads are transferred to the adjacent medium.

To improve the soil-structure interaction mechanism for buried metal culverts, the use of geogrid layers with an axial stiffness of 1000 kN/m and dead-end steel bolts 10 mm in diameter is suggested, to enhance the system capacity during the application of static surface loads. As shown in Figure 7, geogrid layers with steel bolts at the ends are positioned between the backfill layers in the soil cover above the culvert crown, to mobilize passive resistance to applied loads. Figure 8 illustrates the efficiency of the geogrid layers in reducing the culvert crown deformation, thrust, and bending moment. Under a 400 kPa static load, with the use of geogrid layers, the numerical modelling results indicate a reduction of approximately 9.7% in the culvert crown deformation, with a 6.7% and 24% reduction in the thrust and bending moment, respectively. Thus, it can be concluded that the use of geogrid layers may be recommended as a way of enhancing the load capacity of buried corrugated metal culverts.

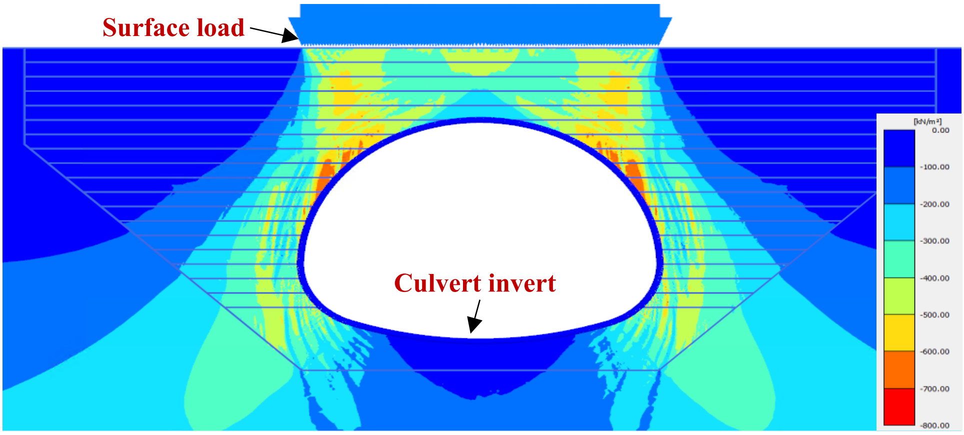


Fig. 6. Vertical stress distribution under a 400 kPa surface load

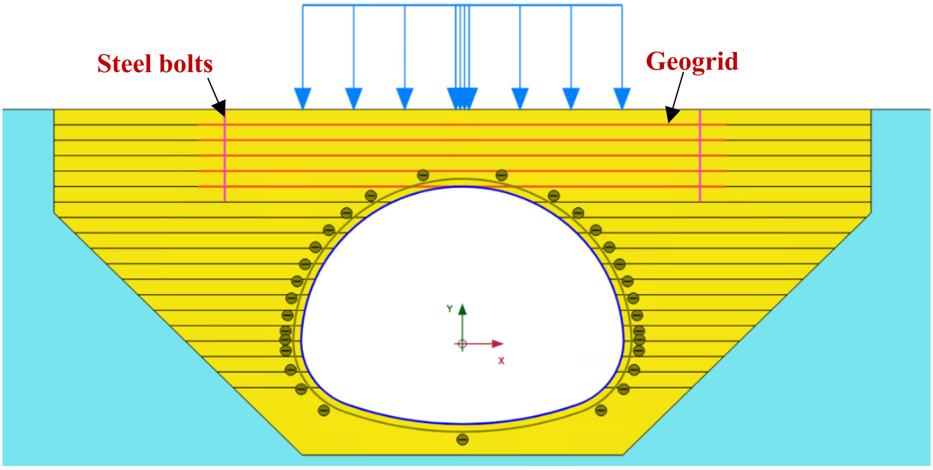
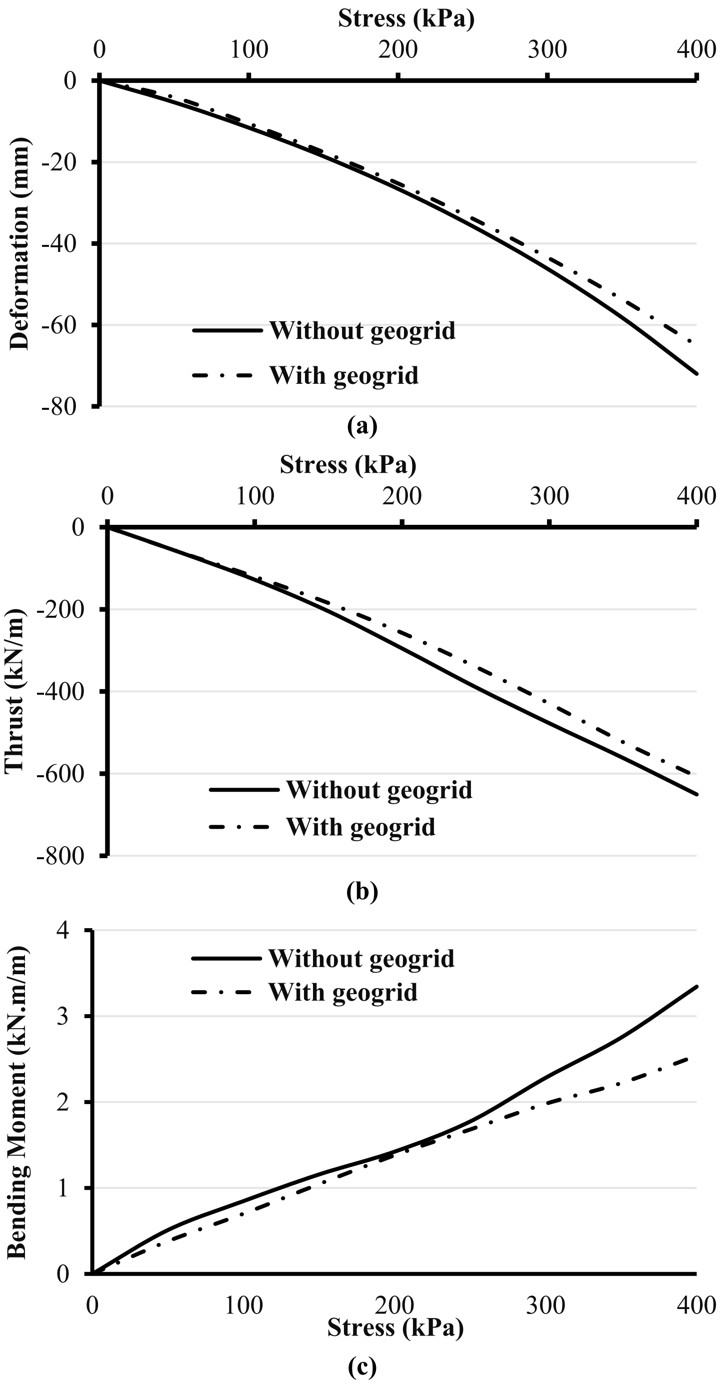


Fig. 7. Placement of geogrid layers with dead end steel bolts



(a)

(b)

(c)

Fig. 8. Numerical modelling results for the (a) crown deformation, (b) thrust, and (c) bending moment of the arch CMC, with and without the use of geogrid layers

6 Conclusions

This paper presents the simulation of a buried corrugated metal arch culvert with two-dimensional modelling, under backfill compaction and static surface loading. The numerical analysis demonstrates the efficiency of using the HSs material model to capture the interaction between the culvert and the surrounding soil. The numerical model was validated against field measurements of culvert crown deformation, thrust, and bending moment data during compaction. Numerical modelling results showed the stress distribution in deep soil layers, where minimal internal forces developed at the culvert invert due to soil stress redistribution resulting from arching actions. Thus, the presence of a weak foundation soil was found to have an insignificant impact on culvert serviceability and the development of internal forces.

Improvement of the buried culvert soil-structure interaction system can be achieved by mobilizing new techniques. The current study suggests using geogrid layers with dead end bolts to provide passive resistance to applied loads. Under static service loading of up to 400 kPa, geogrid layers placed in the soil cover above the culvert crown were found to contribute to the reduction of culvert crown deformation and internal forces. The numerical modelling results indicated reductions of around 9.7%, 6.7%, and 24% in the crown deformation, thrust, and bending moment values, respectively. In conclusion, the geogrid layers showed the potential of being applied as an effective technique to enhance the capacity of buried corrugated metal culverts or to compensate for deficiencies resulting from deterioration.

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