3D Numerical Modeling of Metal Pipe in Enkoping Case Study

I. M. Ezz & H. El Naggar
Department of Civil Engineering – Dalhousie University, Halifax, NS, Canada

ABSTRACT
This paper presents a 3D numerical modeling analysis of a corrugated metal pipe (CMP) consisting of corrugated flexible metal sheets, with backfill layers carefully compacted around and above the pipe. The analysis focuses on a large diameter CMP in a case study in Enkoping, Sweden. The numerical analysis uses the finite element program PLAXIS 3D. Field measurements of the vertical deformations and internal forces are compared with calculations performed according to the Canadian Highway Bridge Design Code (CHBDC) and numerical results estimated from the 3D model. In the model which is developed, the effect of the behavior of the soil surrounding the pipe is represented by utilizing two common constitutive material models, the Mohr-Coulomb (MC) model and the linear elastic (LE) model, with and without compaction effort. This paper presents an initial phase of a larger study that will include additional sophisticated material models.

RÉSUMÉ
Cet article présente une analyse de modélisation numérique 3D d'un tuyau en métal ondulé (CMP) composé de feuilles de métal ondulé flexible, avec des couches de remplissage soigneusement compactées autour et au-dessus du tuyau. L'analyse se concentre sur un CMP de grand diamètre dans une étude de cas à Enkoping, en Suède. L'analyse numérique utilise le programme d'éléments finis PLAXIS 3D. Les mesures sur le terrain des déformations verticales et des forces internes sont comparées aux calculs effectués selon le Code canadien de conception des ponts routiers (CHBDC) et aux résultats numériques estimés à partir du modèle 3D. Dans le modèle qui est développé, l'effet du comportement du sol entourant le tuyau est représenté en utilisant deux modèles de matériaux constitutifs communs, le modèle Mohr-Coulomb (MC) et le modèle linéaire élastique (LE), avec et sans effort de compactage. Ce document présente une phase initiale d'une étude plus vaste qui comprendra d'autres modèles de matériaux sophistiqués.

1 INTRODUCTION

Modern transportation network techniques are needed to facilitate traffic flow in crowded centers. In recent decades, the use of simple, economical, time-saving approaches has become a high priority, due to the rapid expansion of urbanization. Corrugated metal pipes (CMP), which are considered to be a promising technique, are widely used in Europe and North America as soil-steel composite bridges for waterways and roads. In addition, thousands of old, shallow, concrete tunnels in Europe and more than one-third of the over 600 thousand bridges in North America are in need of repair. Such repairs could be costly in comparison to replacement by corrugated metal pipes, which are relatively durable with lower maintenance requirements (Amer, 2012).

Flexible pipes made in factories were first introduced in the 19th century. In 1913, at Iowa State College, buried pipes were tested to measure the weight of the overburden. Then, at the beginning of the 1930s, larger diameter flexible pipes were assembled in field tests to prepare the way for large span culverts. In 1980, preliminary standard charts were used for the first time in CMP design.

A CMP primarily consists of corrugated metal sheets that are flexibly connected to one another with highly stressed bolts to form a metal conduit. Although CMPs are usually closed pipes with various geometries, they can also be formed by using an open arch geometry (open section) that rests on rigid foundations. The spans of these composite structures can currently be as large as 25 m.

Over the years, culverts have been designed by using different bridge codes and international pipe design manuals that follow a variety of standards. These designs estimate the appropriate conduit geometry, the corresponding cover depth, and the expected internal forces. It has been shown by many theories that the soil compaction process enhances the structural capacity due to the confinement produced by compacted backfill layers surrounding the pipe structure. Thus, the highest stresses developed in the metal sheets are due to compaction efforts (Ezz, 2019).

When CMPs are loaded as a result of compaction in addition to static or dynamic loading, arching actions are developed due to the stiffness of the conduit body relative to the adjacent soil medium. The arching phenomenon is attributed to differential deformation, which can result in active arching with a reduction in the applied stresses, or passive arching with an increase in the applied stresses, according to the pipe flexibility relative to the backfill (Tien, 1996).

Initially, pipe design utilized the ring compression theory, which depends on the thrust developed from surrounding pressures. Subsequently, several empirical methods were introduced to enhance design methodology for corrugated pipes. The soil-culvert interaction (SCI) approach was a promising method based on full-scale tests to simulate the interaction between various metal pipe profiles and the surrounding backfill (Duncan, 1978). In 2007, Pettersson and Sundquist presented the Swedish design method (SDM) as a further development of the SCI theory. However, the race to develop new design methods and to improve old ones has been accelerating, supported by more field tests with different profiles. There is a continuing need to do more research to assess the influence of the geometry, span, corrugated metal sheets, cover depth and compaction efforts on the deformation and internal forces developed in the pipe.

This paper discusses three-dimensional (3D) numerical modeling of corrugated metal pipe in a case study in Enkoping, Sweden. The 3D simulation usually aims to more accurate results due to the three-dimensional effect of surface loading due to backfilling and top service loading. The modeling simulates the orthotropic corrugated steel sheets with associated compaction efforts for each layer of sequenced backfill around and above the metal structure. The Canadian Highway Bridge Design Code (CHBDC) suggests a theoretical approach to obtain the anticipated internal forces. The recorded field measurements of the deflection and internal forces are compared with the results of the theoretical method and the numerical results of the finite element analysis. However, most of the forces in the pipe result from the process of compacting the surrounding layers. The soil medium in the backfill layers is represented by two different constitutive soil models, the Mohr-Coulomb (MC) model and the linear elastic (LE) model, with and without compaction of the surrounding layers. A comparison of these models assesses the accuracy of simulating the interaction between the soil and the steel structure.

2 CORRUGATED METAL PIPES (CMP)

Corrugated metal pipes are defined as flexible structures that consist of separate metal sheets. Depending on the size, they are formed in-situ, or are made in a factory and then transferred to the site. They can be used for waterways or roadways that pass under another roadway.

As shown in Figure 1, loading of a flexible pipe with external loads can cause the crown to sink, while the sides move outward. Compacting the side layers around a pipe generally has the opposite effect, where the pipe sides move inward, with an upward movement of the crown. When the side pressure is large enough, it provides support for greater serviceability loads.

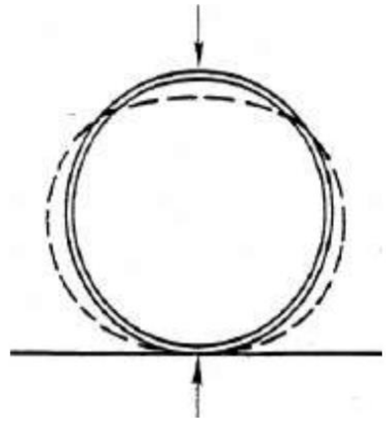

Figure 1. Pipe deformation due to external loads (from ConnDOT Drainage Manual, 2000)

However, CMPs have some cover depth limitations. Using these pipes with closed or open (arch) profiles can save money and construction time. CMPs also usually have a relatively long service life with low maintenance requirements and can be formatted easily.

2.1 Full-Scale Pipe Test in Enkoping, Sweden

Figure 2. Full-scale pipe test in Enkoping, Sweden (Pettersson, 2007)

Enkoping is a town situated about 100 km west of Stockholm in Sweden. This location was remote enough for a full-scale field test to be performed without any disturbance from road traffic. A CMP with a closed arch profile was installed in a gravel pit. The CMP had an inside span of about 6 m, with corrugated steel sheets measuring 200 x 55 x 3 mm. It took about three years, from 1987 to 1990, to complete the pipe test structure with instrumentation (see Figure 2).

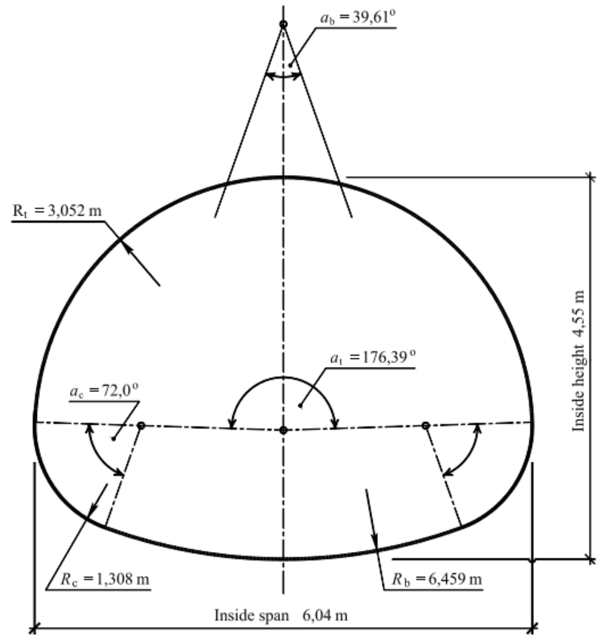

Figure 3. Geometry of pipe in Enkoping case study, with detailed dimensions (Pettersson, 2007)

The pipe length was about 5 m, with instrumentation consisting of deflection gauges, strain gauges and soil pressure cells. To eliminate the end effect with respect to strain gauge readings, the pipe was divided into three parts: the two ends and the middle (5 m), which housed the instrumentation gauges. The geometry and detailed dimensions of the pipe are illustrated in Figure 3.

2.2 Numerical Modeling Analysis

The numerical model of the pipe in Enkoping includes about 19 stages and uses the finite element program PLAXIS 3D. Initially, the pipe rests on very a compacted bedding material comprised of crushed gravel aggregate. Each stage represents the installation of one of the 19 layers of backfill soil that is carefully compacted around and above the pipe. The average height of each layer is about 300 mm, and the layering process starts from a level of about 750 mm above the pipe base. Backfilling continues from the initial stage to a cover depth of 1.5 m above the pipe crown, as shown in Figure 4. Because boundary conditions can affect the model results, the extension of the soil clusters should cover a sufficient length. In the proposed model, the layers extend about 7 m from the pipe side walls to the end of the model. In addition, standard fixities are activated at the boundaries to fix the model in the *x* and *y* directions. The top boundary is set to be free, to allow for vertical movement.

The soil material, with and without compaction efforts, is modeled with two common constitutive models to assess the tendency of the soil-structure interaction. The Mohr-Coulomb (MC) material model represents the soil clusters in a linear elastic-plastic simulation, whereas the linear elastic (LE) model simulates the soil as an elastic material, depending on Hook's law of isotropic elasticity. Table 1 summarizes the backfill soil properties used in the numerical model for the two material models.

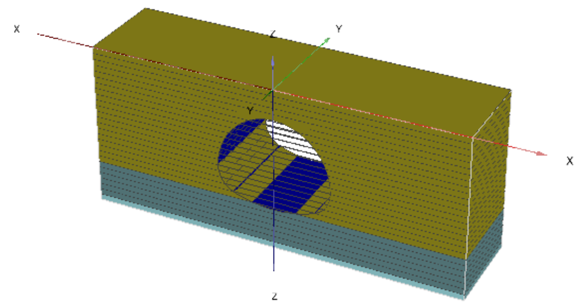

Figure 4. 3D numerical model of the pipe in Enkoping

The pipe is modeled as an orthotropic plate element in two directions, because the pipe cross-section is different in the circumferential and longitudinal directions. Thus, equivalent parameters are used to simulate the properties in both directions (Aagah & Aryannejad, 2014). Table 2 presents the properties of the corrugated metal pipe for both the isotropic and orthotropic cases.

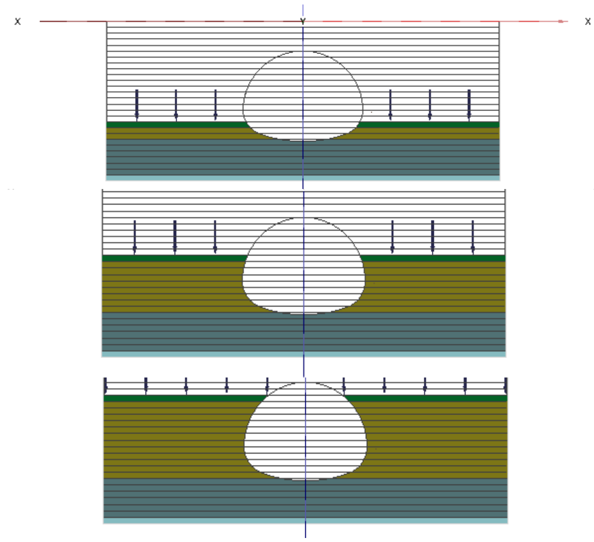

Figure 5. Selected stages of simulating the compaction effort in the backfill layers

In the compaction simulation, the main focus is the compaction of the soil layers to attain a compacted soil with higher density. The metal structure comprised of flexible sheets has a relatively low stiffness when used separately; however, compacting the soil layers surrounding the corrugated steel structure enhances the capacity of the structure to withstand higher applied stresses. Because the steel pipe response is influenced by the degree of compaction during the backfilling process, the strains developed are significantly affected by the compaction of each layer.

The compaction effort is simulated in PLAXIS 3D by using a surface load. In each stage, the corresponding soil layer is activated with its compaction load. Subsequently, the load of the next layer is activated, and the load of the preceding layer is deactivated. This sequence is followed until the soil reaches the required cover depth. Furthermore, the top layers at crown level should be carefully compacted with less surface loads to avoid any damages in the pipe body. Figure 5 presents selected stages of the sequential compaction process.

Table 1. Characteristics of the backfill soil for the Mohr-Coulomb (MC) and linear elastic (LE) material models

Characteristic	MC	LE
Soil density (ɣ) (kN/m^3)	17.80	17.80
Modulus of elasticity (E) =E_{50} (Mpa)	16.40	16.40
Poisson's ratio (υ)	0.20	0.20
Cohesion (c) kPa	1	–
Friction angle (φ)	36°	–
Dilatancy angle (Ψ)	6°	–
R_{in}	0.67	0.67

Table 2. Isotropic and orthotropic characteristics of the corrugated metal pipe used in the numerical model

Characteristic	CMP in Enkoping
Profile type	Arch pipe
Plate thickness (t) (mm)	3
Plate length (mm)	200
Plate height (mm)	55
Isotropic area (A) (mm^2/mm)	3.54
Isotropic moment of inertia (I) (mm^4/mm)	1353
Isotropic elasticity modulus (E_s) (GPa)	210
Isotropic Poisson's ratio (υ)	0.3
Isotropic unit weight (ɣ) (kN/m^3)	78
Orthotropic plate thickness (t') (mm)	67.69
Orthotropic area (A') (mm^2/mm)	67.69
Orthotropic moment of inertia (I') (mm^4/mm)	25843.40
Circumferential orthotropic elasticity modulus (E_Θ) (MPa)	10994.30
Longitudinal orthotropic elasticity modulus (E_L) (MPa)	18.28
Circumferential orthotropic out-of-plane shear modulus ($G_{\Theta R}$) (MPa)	4228.58
Longitudinal orthotropic out-of-plane shear modulus (G_{LR}) (MPa)	7.03
Orthotropic in-plane shear modulus ($G_{\Theta L}$) (MPa)	1.28
Orthotropic Poisson's ratio (υ')	0.00
Orthotropic unit weight (ɣ') (kN/m^3)	4.08

Tables 1 and 2 present the backfill soil and corrugated metal sheet parameters used in the 3D numerical model.

2.3 The CHBDC Theoretical Approach to CMP Design

The CHBDC provides a theoretical approach to estimate the internal forces in steel plates with shallow, deep, and deeper corrugations (CHBDC, 2014). The maximum thrust developed from the engineered backfill can be estimated by using Equation 1, and the bending moment can be calculated by using Equations 2 and 3 for the side backfill and the topsoil cover, respectively.

$$T_D = 0.5(1 - 0.1C_s)A_f\ W \quad [1]$$

$$M_1 = K_{M1} \,.\, R_B \,.\, \gamma \,.\, D_h^3 \quad [2]$$

$$M_B = -K_{M2} \,.\, R_B \,.\, \gamma \,.\, D_h^2 \,.\, H_c \quad [3]$$

where:
T_D= maximum thrust due to the unfactored dead load.
C_s= axial stiffness parameter for the steel plates.
A_f= dead load coefficient for calculating the thrust.
W= column weight of backfill soil above the pipe.
M_I= maximum bending moment in the steel pipe due to the side backfill up to the crown level.
M_B= additional bending moment in the steel pipe due to the soil cover above the crown level.
K_{M1}, K_{M2}, R_B = factors for calculating the moment due to the engineered backfill.
ɣ= backfill soil density.
D_h= horizontal diameter (span) of the pipe.
H_c= height of soil cover above the crown.

3 ASSESSMENT OF THE RESULTS OF THE NUMERICAL MODEL AND THE CHDBC THEORETICAL APPROACH IN RELATION TO THE RECORDED FIELD MEASUREMENTS

The pipe in Enkoping was tested during the backfilling process to capture changes in the pipe deflection and internal forces, since the compaction exerts a major influence on these values. The monitored data were obtained at the crown of the conduit body at section C, which was located at the pipe cross-section 1.50 m from the pipe entrance. In general, the highest deflection and bending moment values can be expected to be found at the crown, but the maximum value for the thrust can be expected to be found at the pipe support or spring line.

In the case of vertical deflection, with and without compaction of the backfill layers, an upward deformation at the crown is expected during addition of the side layers until a maximum value is attained when the backfill reaches the crown level. Then a slight downward movement of the crown is expected when backfill is placed above the pipe. Figure 6 shows the deflection behavior in relation to the height of the backfill. It can be seen that the field data indicate a maximum deflection of 65 mm when the backfill reaches the crown level followed by a lower value of 55 mm at the end of backfilling, with a cover depth of 1.50 m. With regard to the two material models used in the analysis, with and without compaction, it can be seen that the MC model with compaction effort shows good agreement with the field data deflection curve; the model yields crown deflections of 57 mm and 39 mm when the backfill reaches the crown level and the maximum cover depth, respectively. The MC model without compaction yields a maximum crown deflection of 26 mm. In contrast, the LE model with compaction yields a maximum deformation of about 12 mm, and the LE model without compaction is the only model to yield a downward deformation.

For the thrust, maximum values are to be expected at the pipe spring line; however, the field data were obtained at the crown. Strain gauges A and B were installed at the crown of the steel sheets. The internal forces values were obtained from the strain gauge readings via the following equations:

$$N = 0.333 \,.\, \epsilon_A + 0.370 \,.\, \epsilon_B \quad [4]$$

$$M = 4.92 \,.\, 10^{-6} . (\epsilon_A - \epsilon_B) \quad [5]$$

Figure 7 shows the readings of the two strain gauges. With the aid of Equations 4 and 5, these readings were used to compute the field thrust and bending moment values at the crown, as shown in Figures 8 and 9, respectively. The field data thrust curve gives a maximum value of -120 kN/m at the end of backfilling. In comparison, the MC model with compaction yields a value of -101.6 kN/m, whereas the MC model without compaction yields a value of -73 kN/m. The LE model with compaction indicates a maximum crown thrust of -91 kN/m, while the LE model without compaction yields a value of -63 kN/m. The CHBDC approach estimates a maximum thrust value of -147.7 kN/m at the pipe spring line. The numerical analyses yield maximum thrust values at the spring line of -157.5 kN/m, -136 kN/m, -193 kN/m, and -162.7 kN/m for the MC model with and without compaction, and the LE model with and without compaction, respectively

For the bending moment, as in the case of the vertical deflection, the maximum moment value is expected to develop at the crown when the backfill reaches the crown level, and the value is then expected to decrease when the top backfill layers are added. Figure 9 shows the bending moment curve from the field measurements, with a maximum value of 10.3 kN.m/m, followed by a lower value of 8.3 kN.m/m at the end of backfilling. Figure 9 also compares the field data bending moments with the numerical results. The MC model with and without compaction yields maximum bending moments of 10.0 kN.m/m and 4.5 kN.m/m, respectively, while the LE model with and without compaction gives maximum moments of 4.3 kN.m/m and 0.7 kN.m/m, respectively. The CHBDC approach estimates a maximum bending moment of 3.6 kN.m/m since the side backfill is underestimated in comparison with the field data and the numerical modeling results.

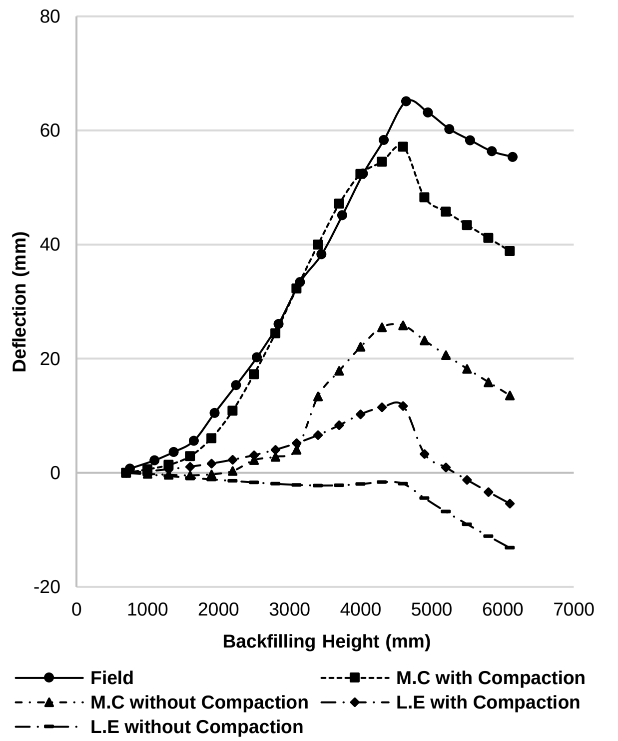

Figure 6. Crown deflection versus backfill height: Comparison of field data and numerical analyses

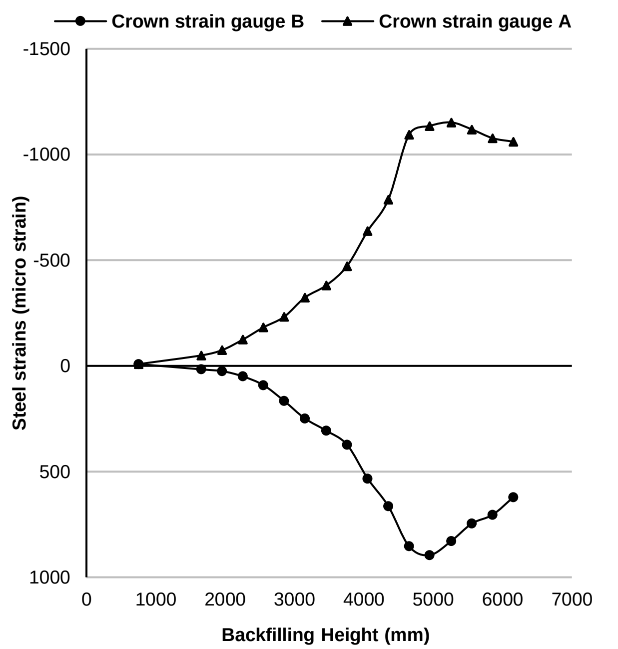

Figure 7. Plot of readings of crown strain gauges A and B for different backfill heights

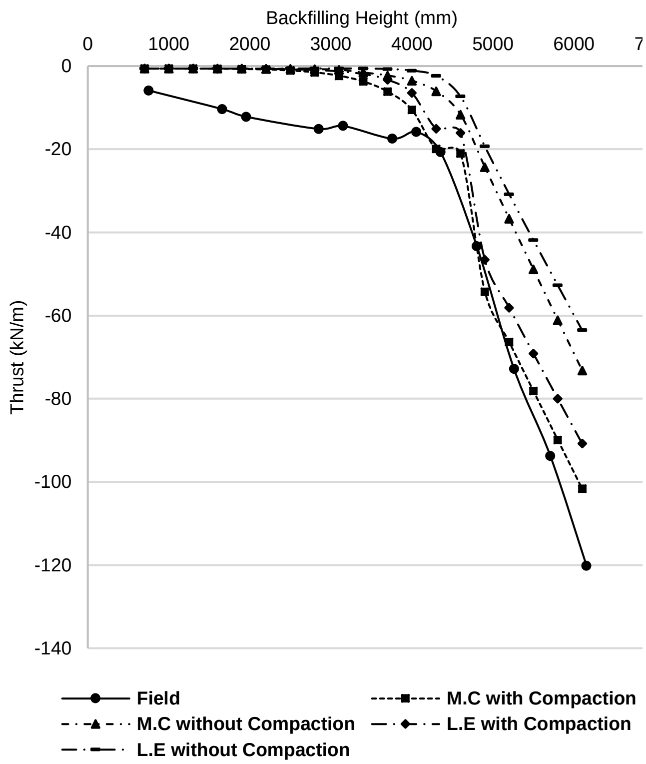

Figure 8. Crown thrust versus backfill height: Comparison of field data and numerical analyses

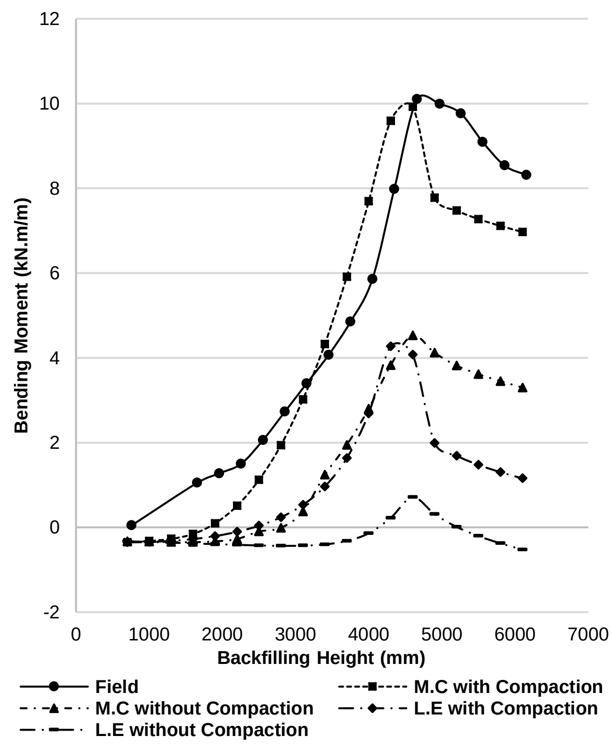

Figure 9. Bending moment versus backfill height: Comparison of field data and numerical analyses

These results show that the choice of soil model and consideration of the compaction effort make an important contribution to the effectiveness of the numerical modeling. The use of more accurate constitutive models that capture smaller strains and consider compaction of the backfill leads to results that more closely approximate those obtained from field measurements. Thus, the MC model with compaction simulates the soil-structure interaction more efficiently than is the case with the LE models.

Arching is the transfer of loads from a more flexible medium to an adjacent stiffer element due to side shear stresses developed from differential movements (Terzaghi, 1943). The numerical analysis shows an arching mechanism which is common in underground structures. This arching depends on the relative stiffness of the two different media. An increase in the maximum pipe thrust at the spring line can be captured when the soil column weight above the pipe which is about -117 kN/m is compared with the closest numerical thrust from the MC compacted model which is about -157.5 kN/m. Figure 10 illustrates arching actions associated with the pipe in Enkoping. This is considered to be passive arching, since due to compaction the soil is more deformable than the conduit steel body. Thus, an increase in pipe stresses is activated, corresponding to a reduction in the stresses of the side backfill soil.

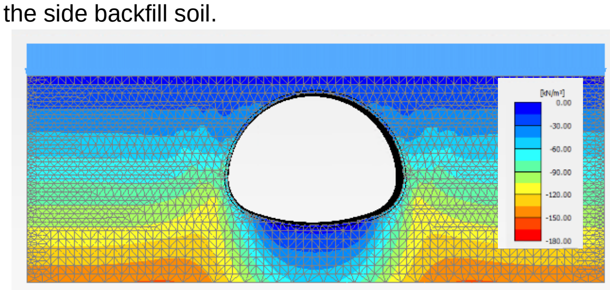

Figure 10. Vertical stress distribution in the sequential numerical model, showing arching actions with reduced stresses in the side backfill

Many alternatives are being investigated to improve CMP design by using more deformable materials in the top backfill layers. The aim is to develop active arching, to transfer the forces away from the buried structures to the side soils. The use of tire-derived aggregate (TDA) is a promising technique that could contribute to the development of more efficient design methodology (Mahgoub and El Naggar, 2019, 2020a & 2020b). Moreover, research is also being done on the use of more accurate constitutive models, to obtain results closer to the measured field data

4 CONCLUSION

This paper introduces a technical approach used to simulate corrugated metal pipe while considering the effect of compacting the surrounding backfill layers. A 3D numerical analysis is performed by using the finite element software PLAXIS 3D to model the soil-structure interaction. The results for the MC model show good agreement with the deformations and internal forces determined in the field study. Basically, the model demonstrates that most of the internal forces are due to the weight of the backfill subjected to compaction efforts. Moreover, the numerical model can capture the arching actions that lead to an increase or decrease in the internal stresses of the structure, depending on its stiffness relative to the side media.

The numerical model simulating the case study in Enkoping uses the two common constitutive models MC and LE. In comparison with the maximum pipe crown deformation of 65 mm measured in the field, the MC and LE models that consider compaction of the surrounding soil layers yield corresponding values of 57 mm and 12 mm, respectively. These results are better than those provided by the MC and LE tests that do not consider compaction. For the internal thrust forces and bending moment, the field measurements captured a thrust of about -120 kN/m at the crown at the end of backfilling, as compared with values of -102 kN/m and -91 kN/m yielded by the MC and LE models with compaction, respectively. For the maximum thrust, the theoretical CHBDC approach estimates a value of -148 kN/m at the spring line of the pipe arch, as compared to corresponding values of around -157.5 kN/m and -193 kN/m yielded by the MC and LE models with compaction. Finally, field measurements showed a bending moment at the crown with a maximum value of 10.30 kN.m/m, as compared to values of about 10.0 kN.m/m and 4.30 kN.m/m obtained by the MC and LE models with compaction, respectively. The theoretical CHBDC approach gives an underestimated maximum bending moment value of 3.6 kN.m/m for the same stage of construction.

In conclusion, the 3D modeling of CMPs can be regarded as an efficient way to obtain close estimates of the deformation and internal forces in the pipe structure. Different constitutive material models can be used to enhance the simulation process by achieving the best fit to the field behavior. This study represents an initial approach to utilizing more accurate material models to consider small deformations in the simulation process. In this paper, the MC model yields more accurate results than the LE model, which yields values that differ considerably from the field data. It is shown that most of the internal forces developed in the structure are generated due to compaction loads. Thus, the consideration of compaction results in better modeling of the soil-structure interaction. Finally, the use of numerical modeling results can contribute to the design process by assessing the capacity of the selected cross-section of the corrugated steel sheets, where it is anticipated that internal stresses will be developed.

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