FEM SIMULATION OF A STEEL BOX CULVERT TEST
Comparison of numerical results with field data

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February 2006

TRITA-BKN. Master Thesis 232, Structural Design and Bridges 2006
ISSN 1103-4297
ISRN KTH/BKN/EX--232--SE
SUMMARY

This report presents the comparison of the numerical analysis results obtained with a finite element program called Plaxis and the full-scale test measurements of a long-span corrugated steel box culvert in Lidköping, Sweden. This report also presents the analysis of the main characteristics of the backfill soil, as well as predicting the value of the material properties.

Plaxis offers the possibility to analyse the plastic soil behaviour and its interaction with large-span buried flexible structures. Among all the theories available, three different theories were selected that describe the model properly. The theories used and compared are called Mohr Coulomb, hardening soil and linear elastic theory.

Comparisons of the internal forces and stresses are performed at certain parts of the culvert structure. Discrepancies between the data are observed thorough all the analysis, setting the most reasonable explanation according to the judgment of the author of this report.
ACKNOWLEDGEMENTS

At the very beginning, when I started this adventure, I thought it was impossible to make it. I did not know the language, people and customs in Sweden, but after this experience I have to say that I have learnt much more than I expected and I have also enjoyed my time in Stockholm.

I would like to thank Professor Håkan Sundquist, for giving me the opportunity to carry out the Master’s Thesis; Dr Raid Karoumi, for his kind support and motivation; Esra Bayoglu Flener, for her help as well as the attention, sympathy and the good moments on the way to Lidköping; and the research personnel of the Geotechnical division at KTH for teaching me so many interesting things and helping me with any questions I had.

Finally, I would like to thank my parents and my sisters for teaching me everything I know.
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>area</td>
<td>[m²]</td>
</tr>
<tr>
<td>E</td>
<td>elasticity modulus</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>Est</td>
<td>elasticity modulus of the culvert</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>E₅₀₉₀₉₀ ref</td>
<td>secant stiffness in standard drained triaxial test</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>Eₐₚₐₚ ref</td>
<td>tangent stiffness for primary oedometer loading</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>Eₐₜₐₜ ref</td>
<td>unloading/reloading stiffness</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>E₁</td>
<td>initial elastic modulus</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>EA</td>
<td>axial stiffness</td>
<td>[N]</td>
</tr>
<tr>
<td>EI</td>
<td>flexural rigidity</td>
<td>[N mm²]</td>
</tr>
<tr>
<td>HS</td>
<td>Hardening soil theory</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>moment of inertia</td>
<td>[m⁴]</td>
</tr>
<tr>
<td>Ko</td>
<td>Ko-value for normal consolidation.</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>moment</td>
<td>[N m]</td>
</tr>
<tr>
<td>MC</td>
<td>Mohr-Coulomb theory</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>normal stress</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>S</td>
<td>shear stress</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>Tₕ</td>
<td>thrust</td>
<td>[N]</td>
</tr>
<tr>
<td>V</td>
<td>vertical displacement</td>
<td>[m]</td>
</tr>
<tr>
<td>Vₘᵦ</td>
<td>vertical displacement on the culvert with crown rib</td>
<td>[m]</td>
</tr>
<tr>
<td>Vₘᵦₘᵦ</td>
<td>vertical displacement measured at the field</td>
<td>[m]</td>
</tr>
<tr>
<td>W</td>
<td>section modulus</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>c</td>
<td>cohesion</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>k</td>
<td>cohesive shear stress</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>m</td>
<td>experimentally obtained modulus number</td>
<td></td>
</tr>
<tr>
<td>pₚᵉ</td>
<td>reference stress for stiffness</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε₁</td>
<td>axial strain</td>
<td></td>
</tr>
<tr>
<td>εᵥ</td>
<td>volumetric strain</td>
<td></td>
</tr>
<tr>
<td>σₙ</td>
<td>normal stress</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>σ₁</td>
<td>axial stress</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>σ₃</td>
<td>confining pressure</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>σₗₑ₉肸₉肸₉</td>
<td>stresses at the top of the corrugation wave</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>σₗₑ₉肸₉肸₉</td>
<td>stresses at the bottom of the corrugation wave</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>τₖ</td>
<td>shear stress at failure</td>
<td>[N/m²]</td>
</tr>
<tr>
<td>υ</td>
<td>Poisson's ratio</td>
<td></td>
</tr>
<tr>
<td>υₚₑ</td>
<td>Poisson's ratio for unloading-reloading</td>
<td></td>
</tr>
<tr>
<td>φ</td>
<td>dilatancy angle</td>
<td>[degrees]</td>
</tr>
<tr>
<td>φ</td>
<td>friction angle</td>
<td>[degrees]</td>
</tr>
</tbody>
</table>
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Chapter 1  Introduction

1.1 GENERAL

The study of the soil characteristics and behaviour has been a long concern to engineers as it is the most complex construction material and its real behaviour is often based on uncertain assumptions.

To control or optimize a system engineers often have to create a mathematical model based on several hypotheses which try to explain how the system could work or how an unexpected event could affect the structure.

Thus, the engineers must select a soil-structure model which develops an economical and safe design and provides the main guidelines to evaluate the stability of the system. In this particular case, finite element methods are implemented in order to describe the unpredictable response of the soil. However, this tool is not always easily applicable as it requires factors and parameters which are not accurately defined.

Soil-structure interaction of buried flexible steel structures entails that the flexible structure connects with the surrounding soil as a composite structure. The soil in this sort of systems produces earth pressure on the bearing structure and supports much of the load. This interaction is highly non-linear due to the nature of the soil which must be treated as a non-elastic material.

The evaluation of the slender corrugated steel culverts is a tough and arduous task that requires the implementation of finite element methods. This analysis encompasses deep knowledge of structures and soil mechanics, demanding good engineering judgment and relevant experience.

1.2 BACKGROUND

The simplicity of the settlement and the economical advantages increased the interest of this buried flexible structures. Culverts are used intensively as pedestrian paths, road culverts, road underpasses or over small and intermittent waterways under fills. According to {1} the culverts can be classified in the following way:

- Corrugated steel culverts
  - Factory made pipes
  - Structural plate pipes (span range 1.5 to 8 m).
  - Box culvert (span range 8-11m).
  - Long span structures (span range 6 to 12 m).

- Pre-cast concrete pipes: can be circular arch and elliptical in shape and span is up to 4.5 m for circular and up to 12 m for the arched shapes ones.
- Cast-in place concrete culverts: can be rectangular and arched shaped. Most popular one is the concrete box culvert.
• Occasionally aluminium, masonry, timber, cast iron, stainless steel and plastic are also used in making culverts.

The Division of Structural Design at KTH, Sweden was entrusted with the analysis of the behaviour of flexible steel culverts subject to construction and service loads.

Once all the measurements were taken, the data were processed. In parallel, finite element methods in 2 dimensions were carried out, using a user-friendly program called Plaxis. Eventually, the results were compared and evaluated.

1.3 AIMS OF THE REPORT

The first aim of this report is the analysis of the interaction of the culvert-soil by comparing the results obtained by using a finite element method and the field test.

The goal of this work is to give new information to improve our knowledge in the design and construction of the corrugated steel culvert through a better understanding of how the culvert behaves in the presence of the soil.

The first task is to identify the most fundamental material properties to predict the behaviour of the soil. Afterwards, its interaction with the culvert is carried out using three theories which display different responses of the model. Eventually, the theories are compared in order to identify which suits better the results of the field tests.
Chapter 2  Material Properties and Geometry

Material properties of the construction material and some geometric properties are given in Table 2.1, 2.2 and 2.3.

Table 2.1  Metal component properties.

<table>
<thead>
<tr>
<th>Type</th>
<th>Corrugated steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate width</td>
<td>762 mm</td>
</tr>
<tr>
<td>Radius</td>
<td>8820 mm</td>
</tr>
<tr>
<td>Plate thickness</td>
<td>4 mm</td>
</tr>
<tr>
<td>Corrugation height (wave height)</td>
<td>140 mm (from centre to centre)</td>
</tr>
<tr>
<td>Corrugation length (wave length)</td>
<td>381 mm</td>
</tr>
<tr>
<td>Elasticity modulus</td>
<td>200 GPa</td>
</tr>
<tr>
<td>Area $(A)$</td>
<td>$5.59 \text{mm}^2/\text{mm}$</td>
</tr>
<tr>
<td>Moment of inertia $(I_{st})$</td>
<td>$13739 \text{mm}^4/\text{mm}$</td>
</tr>
<tr>
<td>Section modulus $(W)$</td>
<td>$187.7 \text{mm}^3/\text{mm}$</td>
</tr>
</tbody>
</table>

Table 2.2  Geometry of the culvert

<table>
<thead>
<tr>
<th>Parts of the culvert</th>
<th>Linear, haunch and crown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>8820 mm</td>
</tr>
<tr>
<td>Radius of the Haunch</td>
<td>1016 mm</td>
</tr>
<tr>
<td>Span (measured from outer edges)</td>
<td>7945 mm</td>
</tr>
<tr>
<td>Internal height from footing level</td>
<td>2370 mm</td>
</tr>
<tr>
<td>Total angle of the crown</td>
<td>41.91 degrees</td>
</tr>
<tr>
<td>Total angle of the haunch</td>
<td>58.96 degrees</td>
</tr>
<tr>
<td>Length of the linear part</td>
<td>1029 mm</td>
</tr>
</tbody>
</table>

Table 2.3  Backfill soil properties (provided by Skanska).

<table>
<thead>
<tr>
<th>Type</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum density (standard proctor)</td>
<td>$2.15 \text{g/cm}^3$</td>
</tr>
<tr>
<td>Maximum density (modified proctor)</td>
<td>$2.29 \text{g/cm}^3$</td>
</tr>
<tr>
<td>Measured dry density</td>
<td>$1.87 \text{g/cm}^3$</td>
</tr>
<tr>
<td>Bearing Capacity</td>
<td>42 MPa</td>
</tr>
</tbody>
</table>
**Figure 2.1** The culvert geometry and the location of the haunches and the linear parts. The figure shows the inner measures. (Figure is taken from {8}).

**Figure 2.2** The corrugation profile and its geometrical characteristics. (Figure is taken from {8}).
Chapter 3  Field Tests

3.1 INSTRUMENTATION AND TESTING PROCEDURE
This section will briefly describe the field tests that are performed on the culverts in Lidköping, Sweden. The details of the field tests can be found in {8}. 82 strain gauges were installed on the two culverts to carry out the field tests. At each chosen location, two sensors were placed, one at the bottom and one at the top of the corrugation waves.

Figure 3.1 Picture showing the location of the sensors throughout the entire culvert structure. (Picture provided by ViaCon).

Notation for the locations of the sensors (See also Appendix A.2)

Sensors on the crown of the culvert [number of sensors]
C1=[11,12]  C2=[13,14]
C3=[15,16]  C4=[17,18]
C5=[19,20]  C6=[21,22]
C2b=[23,24]

Sensors on the foundation level of the culvert [number of sensors]
F1=[1,2]  F1b=[27,28]

Sensors on the haunch of the culvert [number of sensors]
H1=[3,4]  H2=[5,6]
H3=[7,8]  H4=[8,9]
H2b=[25,26]
The culvert is divided into four different parts. Two culvert structures and two side plates located at both ends of the culverts. One of the culvert structures is reinforced with a crown rib placed over it. (See figure 3.2).

![Figure 3.2](image)

**Figure 3.2** Figure showing geometrical characteristics of the culvert and the layers filled over the culvert. (Figures taken from {8}).

Once the culvert was constructed the backfilling is carried out. This test is divided into 12 layers from 0.3 m to 1.2 m over the crown of the culvert. Each layer was compacted several times with 3 paddor 500kg. Readings were taken before and after each compaction.

![Figure 3.3](image)

**Figure 3.3** Picture of the backfilling process for the layer which reaches the crown of the culvert structure. (Picture provided by ViaCon).
Geotechnical tests were also performed during the backfilling. Six points at each side of the culvert were selected. Troxler and dynamics tests were done at each point to determine properties such as the bearing capacity, dry density and water content.

![Image](image1)

**Figure 3.4** Pictures of the geotechnical tests carried out during the backfilling process (Pictures provided by ViaCon).

The next measurements consist of placing a truck on nine different positions over the bridge (See table 3.1). The first test is carried out over the layer 1.2 m. Three more tests were performed removing the soil until 0.9 m, 0.6 m and 0.45 m. Readings for one minute were taken when the truck stopped at the predetermined locations. The specifications of this engine can be seen in Appendix A.2.

![Image](image2)

**Figure 3.5** Picture of the truck test when the truck is located over the layer 1.2 m (picture provided by ViaCon).
Table 3.1 Different locations of the truck

<table>
<thead>
<tr>
<th>Test</th>
<th>Position of the first axle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 m before the centreline of the culvert</td>
</tr>
<tr>
<td>2</td>
<td>3 m before the centreline of the culvert</td>
</tr>
<tr>
<td>3</td>
<td>2 m before the centreline of the culvert</td>
</tr>
<tr>
<td>4</td>
<td>1 m before the centreline of the culvert</td>
</tr>
<tr>
<td>5</td>
<td>0.5 m before the centreline of the culvert</td>
</tr>
<tr>
<td>6</td>
<td>On the centreline of the culvert</td>
</tr>
<tr>
<td>7</td>
<td>0.5 m after the centreline of the culvert</td>
</tr>
<tr>
<td>8</td>
<td>1 m after the centreline of the culvert</td>
</tr>
<tr>
<td>9</td>
<td>0.66 m after the centreline of the culvert</td>
</tr>
</tbody>
</table>

The last test carried out consists of applying load while the layer is 0.45 m thick. This load was increased little by little taking readings at each step. The ultimate load applied was 48.8 t. Figure 3.6 shows the performance of the test.

Figure 3.6 Picture of the performance of the ultimate loading. (Picture provided by ViaCon).
Chapter 4  Results and Calculations

4.1  BASIC KNOWLEDGE OF PLAXIS

Plaxis is a two dimensional finite element computer program used to analyze the stability and the deformations for several types of geotechnical applications. Plaxis offers a sophisticated analysis of the behavior of the soil. Some other programs are largely simplified and do not consider many significant properties of the soil. Due to this, Plaxis was selected as a proper program to model the interaction of the flexible culvert structure and the soil.

Many interesting options are available in Plaxis. The program implements different theories such as the ideal elastic plastic Mohr Coulomb, Hardening Soil model, and soft soil creep soil. Moreover, it is able to simulate soil elements such as geotextiles, tunnel linings and ground anchors. The program has some deficiencies such as the impossibility of performing anisotropic models or handling spatial models.

An outstanding feature of this program is the ability to carry out the analysis when the model is divided into a certain number of phases. This option allows performing the backfilling test in the same way as it is done at site, displaying the possibility to change the material properties, the boundary conditions and the loads at each predetermined phase.

4.2  GEOMETRY OF THE MODEL USED WITH PLAXIS

The first task to start this model is the design of an appropriate geometry which suits with the bridge designed. Viacon provided drafts with the main characteristics of the culvert and the disposition of the soil. The definitive geometry used with Plaxis is showed in Figure 4.1.

Figure 4.1 Design of the geometry of the culvert and disposition of the soil

To carry out a complete analysis a finite element model has to be defined. The mesh can be either 6 or 15 node triangular elements. 15 node triangular element is very accurate that
generates a very high quality stress results however, it consumes high memory which produces slow calculations.

The generation of a model starts with the creation of the geometry. A geometry model consists of points, lines and clusters. Plate elements can be used to simulate the behaviour of walls, plates and shells. These plates are structural objects used to generate slender structures with a high flexural rigidity $E*I$ and the axial stiffness $E*A$.

Plaxis has the possibility to define an interface. An interface evaluates the interaction between the structure and the soil. Each interface has assigned a virtual thickness which is used to define the properties of the interface. This option was ruled out due to the properties of these interfaces are unknown and moreover the results were rather similar when the interface was used.

The culvert is defined as a plate. This is divided into small plates in order to obtain a similar geometry with the real one. To compare all the results the geometry is designed by placing a node at each location of the sensors. In this way all the results can be compared one by one.

A medium mesh and 15 node triangular elements were selected. The boundary conditions along the outline of the soil are obviously free. To define the boundary conditions at the ground all the suitable options offered by plaxis were tested. Vertical and horizontal fixities are the final boundary conditions selected at the ground.

### 4.3 CALCULATIONS WITH FIELD STRAIN DATA.

The in-situ measurements provide the strains at each sensor placed on the culvert. Through the strains, the stresses, moments and thrusts can be calculated using the equations showed below:

- **Stress**
  \[
  \sigma = E*I \cdot \varepsilon
  \]

- **Normal stress**
  \[
  \sigma_N = \frac{\sigma_{\text{top}} + \sigma_{\text{bottom}}}{2}
  \]

- **Thrust**
  \[
  T_N = \sigma_N \cdot A
  \]

- **Moment**
  \[
  M = W \cdot \frac{\sigma_{\text{bottom}} - \sigma_{\text{top}}}{2}
  \]

As an example the moments obtained when the cover height layer is 0.45 m in the truck test can be seen in Figure 4.2.
Figure 4.2 Moments on the culvert when the cover height layer is located 0.45 m over the culvert during the truck test

The following table shows the sign convention used throughout the report.

<table>
<thead>
<tr>
<th>Tension</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>−</td>
</tr>
<tr>
<td>Elongation</td>
<td>+</td>
</tr>
<tr>
<td>Contraction</td>
<td>−</td>
</tr>
<tr>
<td>Displacement upwards</td>
<td>+</td>
</tr>
<tr>
<td>Displacement downwards</td>
<td>−</td>
</tr>
</tbody>
</table>

4.4 MOHR COULOMB THEORY

4.4.1 Basis of the Mohr Coulomb theory

Soils tend to behave in a non-linear way under load. This non-linear response can be analyzed at different levels of sophistication considering the Mohr-Coulomb model as a first approximation of real soil behavior.

This is a perfectly-plastic model which involves five parameters that are difficult to determine with accuracy. Plasticity is associated with the development of irreversible strains. In order to
evaluate whether or not plasticity occurs, a yield function, $f$, is introduced as a function of stress and strain. \{6\}

The failure of a soil mass, particularly cohesion less soil, which develops its strength primarily from solid frictional resistance between the interlocking of grains, appears to be best explained by Mohr’s theory. According to this theory, the shear stress emerges as one of the most important characteristics which may be attributed to three basic components.

- Frictional resistance to sliding between solid particles
- Cohesion and adhesion between soil particles
- Interlocking and bridging of soil particles to resist information

The shear strength of a material is the maximum shear stress it can sustain. When the shear stress $\tau$ is increased, the shear strain $\gamma$ increases; reaching a limiting condition at which the shear strain becomes very large and the material fails; the shear stress $\tau_f$ is then the shear strength of the material. Materials can collapse under different loading conditions. In all cases the failure is associated with the radius of the maximum shear stress.

The predicted behaviour of the soil is obtained from the triaxial tests. Mohr Coulomb theory suggests a similar model to represent the real behaviour of the soil (See figure 4.3).

**Figure 4.3** Results from standard drained triaxial test and elastic-plastic model used by Mohr Coulomb theory

To carry out the Mohr-Coulomb model, five parameters are required that can be obtained from basic tests on soil samples. The relationship between those parameters and the normal and shear stresses can be observed in figure 4.3.
Shear Stress \( S \)

Figure 4.4 Mohr Coulomb relationship in the plane N-S (graphic provided by {10})

1. Elasticity modulus: In solid mechanics, modulus of elasticity is a measure of the stiffness of a given material. It is defined as the limit for small strains of the rate of change of stress with strain. This can be experimentally determined from the slope of a stress-strain curve created during tensile tests conducted on a sample of the material {6}.

The Young's modulus allows us to predict the behavior of a material under load. For many materials, Young's modulus is a constant over a range of strains. Such materials are called linear, and are said to obey Hook’s law. Most metals are isotropic which means their mechanical properties are the same in all directions. Other materials are anisotropic which have different mechanical properties when the load is applied in different directions.

2. Poisson’s ratio: when a sample of material is stretched in one direction, it tends to get thinner in the other two directions. Poisson's ratio is a measure of this tendency. It is defined as the ratio of the contraction strain normal to the applied load divided by the extension strain in the direction of the applied load. For a perfectly incompressible material, the Poisson's ratio would be exactly 0.5. Most practical engineering materials have between 0 and 0.5. A Poisson's ratio greater than 0.5 does not make sense because at a certain strain the material would reach zero volume.

3. Cohesion: The propensity of a single substance to adhere to itself. The cohesive strength has the dimension of stress.

4. Friction angle: angle between the normal force and the resultant force obtained by combining the normal and maximum friction forces which is equal to arc tan of the coefficient of friction.

5. Dilatancy angle: The increase in volume of a granular substance when its shape is changed. The dilatancy angle, \( \psi \), is specified in degrees. Clay soil tend to show little dilatancy (\( \psi =0 \)).
The dilatancy of sand depends on both the density and on the friction angle. A negative value is only realistic for extremely loose sands.

The first problem of the modeling was the undetermined value of the parameters. The geotechnical experiments were not available and most of the necessary inputs were unknown. The values of the parameters were determined taking into account the bases of the theory and at the end were also checked and improved using the results of the geotechnical experiments.

In order to set the final values the following table was used. These data comprises how the parameters range according to the different geotechnical characteristics of the different soils.

Table 4.2. Values of the parameter for different kind of soils {9}

<table>
<thead>
<tr>
<th>Density</th>
<th>Bearing Capacity (MPa)</th>
<th>Friction Angle (degrees)</th>
<th>Elasticity Modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>0-2.5</td>
<td>29-32</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Low</td>
<td>2.5-5</td>
<td>32-35</td>
<td>10-20</td>
</tr>
<tr>
<td>Medium-high</td>
<td>5-10</td>
<td>35-37</td>
<td>20-30</td>
</tr>
<tr>
<td>High</td>
<td>10-20</td>
<td>37-40</td>
<td>30-60</td>
</tr>
<tr>
<td>Very High</td>
<td>&gt;20</td>
<td>40-42</td>
<td>60-90</td>
</tr>
</tbody>
</table>

For some of the uncertainties in parameters geotechnical experts were consulted. By the time the geotechnical test were available almost all the parameters were already fixed. Nevertheless, it was a help to check that the values make sense and it was also useful to improve and ensure that the values established had a reasonable explanation.

The process to determine the parameters was long and arduous. First of all, the variation of the internal forces and stresses were evaluated using the classical trial and error method that means fixing all the parameters and modifying just one. In order to better understand the interaction of the soil other tests were carried out, varying more than one parameter at the same time. Figure 4.4 to 4.8 show how the displacement and the moments change when the values of the parameters are modified.

Influence of the Elasticity Modulus: Figure 4.5 shows how the vertical displacements and the moments decrease when the elasticity modulus increases.
Figure 4.5 Variation of the vertical displacement of the crown and its moments as the elasticity modulus increases

Influence of the Friction angle: the tendency is the same as the previous one observing a decrease when the value of the friction increases. If the friction angle is smaller than 20 degrees the program does not work.

Figure 4.6 Variation of the displacement and the moments of the culvert as the friction angle increases
Influence of the Cohesion: the same tendency is obtained when the cohesion is increased.

![Graph showing variation of displacement and moments with cohesion](image)

**Figure 4.7** Variation of the displacement and the moments of the culvert as the cohesion increases

Influence of the dilatancy angle: Figure 4.8 shows that the dilatancy does not produce significant changes in the displacements or moments. Although on the graph can not be observed, the displacements and moments decrease when the dilatancy increases.

![Graph showing variation of displacement and moments with dilatancy](image)

**Figure 4.8** Variation of the displacement and the moments of the culvert as the dilatancy increases
Influence of Poisson’s ratio: when the Poisson ratio increases the results obtained show a tendency to increase. This tendency of increasing moments and displacements only appears when this parameter is evaluated.

![Graph showing variation of displacement and moments on the culvert as the Poisson's ratio increases](image)

**Figure 4.9** Variation of the displacement and the moments on the culvert as the Poisson’s ratio increases

The theory says that the most relevant parameters are the elasticity modulus and the friction angle. Both produce decrease in moments and displacements. Also noticeable changes are observed when the cohesion and Poisson’s ratio are altered. The dilatancy is the only one which does not generate relevant alterations.

The table 4.3 shows the final values considered as inputs into the program that give the results more accurate and realistic when compared with the measured results.

| Table 4.3 Value of the parameters used as an input with Mohr Coulomb theory |
|-------------------------------------------------|------------------|
| Elasticity modulus (MPa)                        | 60               |
| Poisson's ratio                                 | 0.2              |
| Cohesion (kN/m²)                                | 5                |
| Friction angle (degrees)                        | 40               |
| Dilatancy angle (degrees)                       | 5                |

These properties can be modified as long as the values remain in a reasonable range. The value of the elasticity modulus was selected considering the granulometric curve, the value of the density and the bearing capacity. The granulometric curve shows that the soil was composed mostly of gravels and also sand.
According to the geotechnical experiments the density is equal to 2.21 g/cm³. This density is considered high, which means that the Elasticity modulus should range from 40 MPa to 60 MPa (See table 4.2). On the other hand, the value of the bearing capacity is greater than 20 Mpa so according to table 4.2 E varies between 60 MP to 90 MPa Many calculations were done in order to obtain the suitable value deciding in the end that E=60 MPa was a compromised solution which generates reasonable and approximate results.

Once the value of the Elasticity modulus is established as 60 MPa, the friction angle is directly equal to 40 degrees according to the same table. Both Elasticity modulus and friction angle are important parameters in Mohr-Coulomb theory. Relevant changes in the results are observed when those values are modified.

A typical value for the cohesion in a gravel soil is c=0 however, that value could generate some calculations which would not perform properly. The manual recommends as the lowest value for the cohesion as 0.2 kPa. Considering that the soil also constitutes with sand, an adequate value for the cohesion is 5 kPa.

To determine the value of the dilatancy angle both Plaxis manual and literature were consulted. The manual shows that a typical value for the dilatancy can be calculated using the following expression (ψ= φ-30), in this case this formula gives a value for the dilatancy that is equal to 10 degrees, nevertheless the literature advises lower values. Geotechnical experts were consulted in order to obtain a realistic value for this particular soil. Due to that this parameter is not a decisive one, and taking into account that they also considered 10 degrees as an unrealistic value, the final value was chosen to be equal to 5 degrees.

The value of Poisson's ratio ranges between 0 and 0.5. According to the literature Poisson's ratio equal to 0.2 is a reasonable value in this particular case.

All these values were consulted with the experts of the department who agreed with all of them, ensuring that the parameters fit into the typical range for the soil given from the geotechnical report and confirming that none of them were unrealistic. Once all the parameters are established the analysis of all the tests were carried out.

4.4.2 Analysis of the backfilling test using Mohr Coulomb.

The backfilling test is the main stage of the culvert construction. This process influences the bearing capacity considerably generating significant deformations of the culvert structure. This test must be carried out with extreme caution due to most of the failures occur as a consequence of an unsuitable compaction and placement of the backfill.

The next sketches show the deformed mesh from the layer 3,7 m to the layer over the crown. There are not significant differences between the layer 3,7 m and the layer 2,85 m. It is
observed that once the soil is located over the culvert the crown goes down pushing that the haunch up. The deformed mesh is scaled up 200 times.

![Figure 4.10 Deformed shape of the culvert and the soil as backfill height of 3.7 m](image)

![Figure 4.11 Deformed shape of the culvert and the soil as backfill height of 3.4 m](image)

![Figure 4.12 Deformed shape of the culvert and the soil as backfill height of 3.1 m](image)

![Figure 4.13 Deformed shape of the culvert and the soil as backfill height of 2.85 m.](image)

Nevertheless, when the backfilling reaches the layer right over the crown the movement of the culvert is different due to the combination of the earth pressure during the layer-by-layer backfilling process and the soil placed over the culvert (See figure 4.14)
Figure 4.14 *Deformed shape of the culvert and the soil as backfill height of 2.5 m.*

To observe the movements of the culvert from the first layer to the layer right over the crown, another geometry is defined because the program does not work if the previous geometry is used. This consists of a symmetrical geometry and it has been used just as an instrument to control the variation of the moments at haunch and to observe the deformed mesh of the culvert. The main tendency is a continuous rise at the crown due to the increasing lateral earth pressure coming from the placement of the compacted layers. However, the culvert moves downward when the first layer is placed. All the deformed mesh can be observed from the following sketches.

Figure 4.15 *Deformed shape of the culvert and the soil as backfill height of 0.3 m.*

Figure 4.16 *Deformed shape of the culvert and the soil as backfill height of 0.6 m.*

Figure 4.17 *Deformed shape of the culvert and the soil as backfill height of 0.9 m.*
Figure 4.18 Deformed shape of the culvert and the soil as backfill height of 1.2 m.

Figure 4.19 Deformed shape of the culvert and the soil as backfill height of 1.5 m.

Figure 4.20 Deformed shape of the culvert and the soil as backfill height of 1.85 m.

Figure 4.21 Deformed shape of the culvert and the soil as backfill height of 2.1 m.

Figure 4.22 Deformed shape of the culvert and the soil as backfill height of 2.5 m.
Through this new geometry the change of the moments at haunch from the first layer to the layer 2.5 m can be analyzed. The moments at haunch change from positive to negative depending on the layer. These moments are too small considering them mostly negligible.

The comparison of the vertical displacement at the middle point of the culvert can be observed from the Figure 4.23.

\[ \text{Verical displacement (m)} \]

\[ \text{Layers (m)} \]

**Figure 4.23** Comparison of the vertical displacement of the culvert for each layer of the backfilling.

When the first layer is located, the numerical displacements show that the crown moves downwards. This response does not look realistic because the layer is exerting lateral earth pressure on both sides of the culvert. Afterwards, both curves display how the culvert moves upwards as a consequence of the mentioned earth pressure. The program predicts that the culvert reverses its movement from upwards to downwards after the layer 2.1 m which is also observed at site. According to the program the culvert reaches its original position after the layer 2.5 m However, the measured displacements change to negative after the layer 3.1 m.

The arching effect is observed in the displacements obtained with Plaxis because from the layer 3.1 m on, there is a tendency of the displacement to maintain the same value. On the contrary, the measured values do not show the same tendency observing a strict downward tendency from that layer 3.1 m on.

Some other tests modifying the representative parameters were done in order to analyze how the results change when the parameters are altered. The results show how the main tendency of the curves remain just observing an increase or decrease of the values. As an example, smaller displacement are displayed when the elasticity modulus and the friction angle increase (see figure 4.24).
Figure 4.24 Variation of the vertical displacement at the middle point of the crown when the elasticity modulus and the friction angle increase.

The distribution of the vertical displacements along the culvert in the layer 3.7 m are showed on the graphic below. The maximum displacement appears at the crown of the culvert just like at site. The vertical displacement maintains the same tendency, changing the distribution in the layer 2.5 m.

Figure 4.25 Distribution of the vertical displacements during the backfilling as backfill height of 3.7 m

When the layer 2.5 m is reached the distribution is different. The maximum displacement appears at the haunch after the middle point. The displacements are not significant, mostly less than 1 mm, which means that the culvert is not subjected to significant movements.
The haunch is considered a critical part of the culvert. Thus, a thorough evaluation of the moments and displacements must be performed. The middle point of the haunch was selected as a representative point of the haunch but the other points of the haunch have been also compared.

The measured moments from tests are small. This might mean that the haunch is not a critical part of the culvert. However, the moments from numerical results can not be considered as negligible. Moments at the end of the backfilling are roughly 8 MPa bigger than at site. The problem might be that the sensor located at H2 did not work properly.

To determine the value of the strains at the haunch two sensors were placed, one at the top and another one at the bottom. The top sensor is located on a flat surface, however, the sensor at the bottom is placed on a cross corrugating surface. The stresses of the haunch are determined using the strains obtained through both sensors.

As both sensors are located on different kind of surfaces, it is possible that the results obtained were not realistic. In this case the numerical analysis results are better approximation of the reality.

If the displacements at the haunch are analyzed, both vertical and horizontal displacements displayed with plaxis are roughly zero, observing an increase when the layer 2,85 meters is reached. From that layer on, the displacements increase up to 0.2 mm and 2 mm respectively. Both at site and with plaxis are small values but the displacements from the numerical analysis are always bigger.

Next the comparison of the moments is carried out. As it was seen on the deformed shape graphs, the crown movement produces positive moments. However, the upwards movement at the haunch generates negative moments. The linear part of the culvert is subjected to positive moments but mostly smaller than the moments at the crown.

From the layer 2,8 m to 3,7 m, the distribution of moments is very similar showing a rise of the moments along the entire culvert. The whole sequence of the moments at each layer is showed in the Appendix B.
Figure 4.27 shows the distribution of the moments when the backfill surface located is 2.85 m. This distribution has apparently a peculiar shape. The program shows the moments generated on each small plate defined in the geometry. To read the values properly we should go from peak to peak.

**Figure 4.27** Distribution of the moments as backfill height of 0.45 m. over the culvert

The maximum negative moment is located at the haunch, starting the negative moments after the linear part of the culvert H1. That means that the whole haunch has a negative distribution which does not happen with the measured moments at site, showing positive moments along the haunch.

From the layer 0.45 m over the crown to 1.2 m, the moments at the middle point of the crown decreases instead of increasing, leaving the maximum positive moments to the points on both sides.

This phenomenon is showed on the following graphs. In the Figure 4.27 where the layer is 3.1 m, the maximum moment appears at the middle point of the culvert. Nevertheless, for the last layer the biggest positive moment does not appear there, it is at the point C5. This decrease might occur due to the generation of a plastic hinge at the middle point of the culvert. The same phenomenon was measured at site, locating the maximum positive moment at both sides of the middle point of the culvert.

**Figure 4.28** Distribution of the moments for cover depth of 0.6 m
Figure 4.29 Distribution of the moments or cover depth of 1.2 m as backfill height of 1.2 m over the crown of the culvert

On the next tables the different values and positions are compared. The maximum numerical positive moment is smaller but the position is the same in both cases. Nevertheless, the maximum numerical negative moment is bigger and the location is different though approximated. The values belong to the layer 3.7 m.

Table 4.4 Maximum numerical and measured positive moments and their positions for the layer 3.7 m

<table>
<thead>
<tr>
<th>Numerical Moment (kNm/m)</th>
<th>Position</th>
<th>Measured Moment (kNm/m)</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.61</td>
<td>C5</td>
<td>17.06</td>
<td>C5</td>
</tr>
</tbody>
</table>

Table 4.5. Maximum numerical and measured negative moments and their positions for the layer 3.7 m

<table>
<thead>
<tr>
<th>Numerical Moment (kNm/m)</th>
<th>Position</th>
<th>Measured Moment (kNm/m)</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.73</td>
<td>H3</td>
<td>3.24</td>
<td>H4</td>
</tr>
</tbody>
</table>

The next table shows how the decrease in crown moment appears after the layer 3.1 m. The values and the positions of the moments can be also observed.

Table 4.6. Maximum numerical positive and negative moments and their positions from the layer 2.5 m to the layer 3.7 m

<table>
<thead>
<tr>
<th>Layer(m)</th>
<th>Positive Moment (kNm/m)</th>
<th>Position (y(m))</th>
<th>Negative Moment (kNm/m)</th>
<th>Position (y(m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>2.3</td>
<td>2.2</td>
<td>1.49</td>
<td>1.6</td>
</tr>
<tr>
<td>2.85</td>
<td>4.08</td>
<td>2.5</td>
<td>1.86</td>
<td>1.6</td>
</tr>
<tr>
<td>3.1</td>
<td>6.26</td>
<td>2.5</td>
<td>8.15</td>
<td>1.8</td>
</tr>
<tr>
<td>3.4</td>
<td>7.25</td>
<td>2.4</td>
<td>9.67</td>
<td>1.827</td>
</tr>
<tr>
<td>3.7</td>
<td>7.73</td>
<td>2.4</td>
<td>10.61</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Another point to emphasize occurs for the layer 2.5 m, in this case the distribution of the moments shows a different shape from the ones showed previously (see figure 4.30).

![Figure 4.30 Distribution of the moments when the layer 2.5 m is reached during the backfilling test](image)

The crown is subjected to negative moments but the maximum negative moment is located at the haunch. The maximum positive moment appears at the beginning of the crown. Even though the graph above looks very different, the moments are much smaller than the moments obtained with increasing layers.

The analysis of the thrusts shows a decrease along the crown while the backfilling is carried out. The maximum axial force is located at the haunch. From the layer 3.1 m to the layer 3.7 m the distribution maintains the same shape, just noticing the mentioned decrease. The next two graphs show the distribution of the thrusts where the decrease of the thrusts can be observed.

![Figure 4.31 Distribution of the thrust along the culvert for the layer 0.45 m over the culvert during the backfilling test](image)
Next, the stresses in the backfilling soil are evaluated. The soil is subjected to compression with the highest stresses at the haunches. The main stresses are produced there because as the soil pushes down the crown a backward movement at the haunches is generated. This movement produces high compression in the soil which surrounds the haunch. The ground is another conflictive area.

The highest stresses remain along the haunch from the layer 2.85 to the layer 3.7m. But on the layer before, the distribution of the stresses changes such that the highest stresses are at the top of the crown. This is the result of an increased lateral earth pressure.
Figure 4.35 *Soil stresses during the backfilling test for the layer 2,5 m in the plane y-y*

The following table shows a brief resume of the extreme values obtained during the backfilling.

**Table 4.7. Maximum internal forces and vertical displacement from the layer 2,5 m to the layer 3,7 m**

<table>
<thead>
<tr>
<th>Layer (m)</th>
<th>Moment (kNm/m)</th>
<th>Axial (kN)</th>
<th>Stresses (kN/m²)</th>
<th>Vertical displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,5</td>
<td>2,3</td>
<td>27,78</td>
<td>39,18</td>
<td>0,4</td>
</tr>
<tr>
<td>2,85</td>
<td>4,08</td>
<td>65,57</td>
<td>61,30</td>
<td>5,17</td>
</tr>
<tr>
<td>3,1</td>
<td>6,26</td>
<td>96,65</td>
<td>94,04</td>
<td>8,15</td>
</tr>
<tr>
<td>3,4</td>
<td>7,25</td>
<td>128,78</td>
<td>117,83</td>
<td>9,94</td>
</tr>
<tr>
<td>3,7</td>
<td>7,73</td>
<td>155,49</td>
<td>134,61</td>
<td>11,04</td>
</tr>
</tbody>
</table>

The complete sequence of the moments, thrust displacement and stresses for each layer is showed in the Appendix.

4.4.3 **Analysis of the truck test using Mohr Coulomb.**

4.4.3.1 **Comparison of the results when the backfill layer is located 60 cm over the culvert.**

When the process of backfilling is concluded the truck test is carried out. Plaxis can not perform the test for the layer 0,45 m. The program warns that the soil body collapses and does not give reasonable results for this test. On the following deformed mesh it can be observed how the loads go into the soil. Plastic points are displayed around the location of the loads.
Thus, the first test carried out is the layer 0.6 m over the crown. The shape of the deformed shape is very similar to the backfilling but obviously the existence of the truck generates bigger displacement and stresses. Figure 4.36 shows the deformed mesh when the truck is located on the position 7.

The comparison of the vertical displacement at C6 is showed in the Figure 4.38.
At the position 1, the truck is still far away from the crown of the culvert. Both displacements are equal to zero that means the truck is far enough from the culvert and there is not noticeable response to it.

When the truck is located at the second position (3 m away from the centerline of the culvert), the measured displacement is still zero. However, the numerical displacement shows how the culvert starts to respond to the truck even though the truck is not yet located close to the crown. Plaxis detects a small response, probably generated for the compression that the truck is exerting on the soil.

The numerical results detect significant response on the culvert when the truck is on the position 3. Nevertheless; the measured one is barely perceptible. After the position 3 the crown moves down due to the compression exerted by truck in the soil. For the next positions the measured displacements present a slope more noticeable. For the last positions of the truck is observed how the values do not show many differences among them. The distance between the last positions, i.e. 7, 8 and 9 are much less than the previous ones. This might explain why the displacements remain practically equal. According to the numerical results, the culvert is weaker, presenting bigger vertical displacements for any position.

Next the distribution of the displacements is presented. The distribution presents almost the same shape increasing the displacement towards to the right, as the truck moves along the bridge. Next Figures how the displacements change for the different positions of the truck. The whole sequence is showed in the Appendix B.

**Figure 4.39** Distribution of the vertical displacement when the truck is located at the position 3
The moments at middle point of the crown are also compared. Figure 4.41 shows the moments for the different positions of the truck. When the truck is located at the first position the moments are approximately zero. From position 0 to position 3, moments are negative on both curves which mean a rise at the crown due to the soil is being compressed by the truck generating that response in the culvert.

Once the truck reaches the position 4 the truck is 1 m from the crown. The culvert moves down appreciating positive moments on both curves. The measured tendency is more noticeable than the numerical one. The moments are almost increased linearly until the position 6.

The measured moments display a noticeable increase on the last position which is less in numerical calculations. The explanation might be that the heaviest load is roughly placed at the middle point of the crown in the eighth position.

The numerical results are smaller for the last layers, this looks incoherent because the displacement were always bigger. The numerical moments are the moments due to the backfilling and the truck test together. To determine the moments generated by the truck the backfill moments are subtracted. Thus, the difference between moments might be a problem of accuracy. Another explanation is that the soil is an isotropic soil and it might be anisotropic.

The moments on the position one present the same shape as the distribution obtained for the backfilling. This is due to the truck is located far away from the culvert. As the truck moves to the crown the moments increase but once the position 6 is reached the moments present a constant tendency. The whole sequence of each position is displayed in the Appendix B.
Figure 4.41 Moments for different positions of the truck at the middle point of the culvert

Figure 4.42 Distribution of the moment when the truck is located on the first position

Figure 4.43 Distribution of the moments when the truck is located on the fourth position
If the haunch is analyzed, the numerical moments differ considerably. The difference between moments is up to 8 Mpa for the position more unfavorable that is the position 8. This fact steps up the possibility of the imprecise results obtained with the sensors located at the haunch.

4.4.3.2 Comparison of the results when the backfill layer is located 90 cm over the culvert.

The results obtained for the next layer show smaller displacements and moments compared to the previous layer. Figure 4.45 shows the comparison of the displacement at the middle point of the crown.

According to Plaxis the crown moves upward when the truck is located on the positions 1 and 2. As before the measured results do not detect response in the culvert when the truck is located on those positions.

The measured displacements decrease in average much more than the numerical ones, (roughly 5 mm between the layers 0,6 m and 0,9 m, whereas the numerical displacements only decrease 2 mm).This means that the culvert in reality is more sensitive to the truck test than the program predicts. However, the numerical displacements remain always bigger which means that the culvert is safer because according to the in-situ measurements the movements are much smaller.
Figure 4.45 *Distribution of the vertical displacement of the crown when the truck is located on different predetermined positions*

Next, the comparison of the in situ moments and numerical moments for the layer 0.6 m and 0.9 m is presented. The in-situ moments show such a significant difference from one layer to the next one. For the layer located far from the culvert the moments are obviously smaller and the slopes less marked. The numerical moments hardly decrease. The tendency of both numerical curves remain invariable. This fact reinforces the idea of the culvert being more sensitive to the truck test.

Figure 4.46 *The measured moments at the middle point of the culvert during the truck test done on 60 and 90 cm depth of covert.*
**Figure 4.47** The numerical analysis moments at the middle point of the culvert during the truck test on 60 and 90 cm depth of cover.

Figure 4.48 presents the comparison of the moments when the truck is over the layer 0.9 m.

**Figure 4.48** Comparison of the moments at the middle point of the culvert during the truck test over the layer 0.9 m

Figure 4.49 shows the difference between the moments at both haunches
The behavior of the haunches during the truck test is different. On the first position the truck does not affect the right haunch. Nevertheless, the left haunch responds by moving upwards. There are not significant differences between the three first positions, remaining the moments always bigger at the left haunch. From the position 3 on, the truck is located on the haunch, being observed how the moments increase. The rise of the moments at the right haunch is smaller but the tendency is more linear. Just for the last position the moments at the right haunch are bigger than the moments at the left. The truck is pushing the right part of the crown causing right haunch to move up more than the left one.

The results in the layer 1,2 m do not show significant differences. The display the same tendency as the previous layer (0.9 m).

Next, the distribution of the moments is analyzed. The fact that displacements and the moments decrease from the layer 0.6 to 1.2 m could not agree with the apparition of the plastic hinge. However, the graphic below shows the influence of both backfilling and truck together which means that the moments increase from a backfill layer to the next one. The whole sequence of the moments is displayed in the Appendix B.
There is another point to emphasize in this analysis. Previous results have shown that the biggest moments are always at both haunches. In the truck test and after the position 4 the moment around the crown is bigger than the moment at haunch. Therefore, this test helps us to conclude that both haunch and crown are sensitive parts and an intense study of both of them must be carried out.

According to Figure 4.51 and 4.52, high soil stresses appear at both haunches and on the location of the loads.

![Figure 4.51 Soil stresses in the soil when the truck is located on the position 6 (plane x-x)](image)

![Figure 4.52 Soil stresses in the soil when the truck is located on the position 6 (plane y-y)](image)

4.4.3.3 Analysis of the results with hyperbolic stress-strain \{1\} relationship.

Once all the calculations have been finished the new goal is to improve the results using some other theories or properties which can help to have a better understanding of the effects on the culvert structure.

Due to the process of compaction during the construction of the culvert, the elasticity modulus and other parameters might increase with the depth. To calculate how the E might increase a theory developed by Konder et al was performed. This theory suggests that the stress-strain curves could be approximated by a hyperbole. \{1\}

The first test consists of assigning different values for E and c for each layer increasing value of E according to the mentioned theory. Those values are assigned as an input into the each
layer defined in the geometry. The truck test was also carried out. Figure 4.53 shows the different properties for each layer.

![Figure 4.53 Modelling of the system with different values of the material properties in all the compacted layers](image)

The numerical results do not show relevant differences. The reason might be that the likelihood of an increase of the elasticity modulus and of the other parameters could be not realistic because the depth from the top to the foundation level is only 3.7 meters.

### 4.4.3.4 Analysis of the results with advanced parameters displayed in Plaxis.

Plaxis offers another possibility that allows us to introduce some additional advanced parameters. The advanced features comprise the increase of stiffness and cohesive strength with depth and the use of a tension cut-off analysis. In some areas tensile stresses and tensile cracks may appear. This indicates that the soil might fail in tension instead of in shear. This analysis is more accurate for the tension failure.

The stiffness depends on the stress level, which means that the stiffness increases with the depth. In order to take into account this phenomenon, the value of the elasticity modulus can be increased per unit of depth. The cohesion can also be raised per unit of depth. \( \{6\} \)

The increase of the E ranges from 30 MPa at the top to 60.7 MPa at the ground that is an increase of 10 MPa per unit of depth. The value of the cohesion increases by 1 kpa per unit of depth which is 4.7 kPa at the foundation level.

Also in this case the results did not show differences. This test also fulfils the theory because after the layer 3.1 m the displacement hardly increases tending to stabilize.
Figure 4.54 Comparison of the vertical displacements of the basic and advanced parameters and the measured displacements at the middle point of the crown

Considering that the range of $E$ and cohesion do not follow any rule or theory and it was evaluated just using the classical method trial and error, the use of the basic parameters seem more precise. On the next graphic can be observed the difference between both alternatives, realizing that the differences are not very significant.

### 4.5 HARDENING SOIL MODEL

#### 4.5.1 Basics of the hardening soil theory

The hardening soil model is an advanced model to simulate the behaviour of both soft soils and stiff soils. This is an elastoplastic type of hyperbolic model, which involves compression to simulate the irreversible compaction of soil under primary compression. This model represents the behaviour of sands and gravel as well as softer kinds of soils such as clays and silts. {6}

The advantage of the hardening soil model over the Mohr-Coulomb model is not only making use of a hyperbolic stress-strain curve instead of a bi-linear curve. It is also that the control of the stress level is more accurate. The model involves 13 parameters; failure, basic and advanced parameters. The failure parameters are the same as the ones used with Mohr-Coulomb.

Failure parameters in Mohr Coulomb model and basic parameters for the soil stiffness are:

- $c$: cohesion.
- $\Phi$: Angle of internal friction.
- $\Psi$: Angle of dilatancy.
- $E_{50}^{\text{ref}}$: secant stiffness in standard drained triaxial test.
- $E_{\text{oe}}^{\text{ref}}$: tangent stiffness for primary oedometer loading.
- $m$: power for stress-level dependency of stiffness.
Advanced parameters are:

\[ E_{ur}^{ref} \]: Unloading/reloading stiffness \\
\[ \nu_{ur} \]: Poisson's ratio for unloading-reloading. \\
\[ p_{ref} \]: reference stress for stiffness \\
\[ K_0^{nc} \]: K_0-value for normal consolidation.

The Plaxis manual offers tables with the value of all these parameters for loose, medium and dense sands. These values have to be extrapolated because the soil is mostly composed of gravels and not of sands. Table 4.8 shows the value of the parameters used with Plaxis.

**Table 4.8. Hardening soil parameters for gravel and sand**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{50}^{ref} ) (kN/m²)</td>
<td>60000</td>
</tr>
<tr>
<td>( E_{oed}^{ref} ) (kN/m²)</td>
<td>60000</td>
</tr>
<tr>
<td>( E_{ur}^{ref} ) (kN/m²)</td>
<td>180000</td>
</tr>
<tr>
<td>Cohesion. (kN/m²)</td>
<td>5</td>
</tr>
<tr>
<td>Angle of internal friction ( \Phi ) (degrees)</td>
<td>40</td>
</tr>
<tr>
<td>Angle of dilatancy ( \Psi ) (degrees)</td>
<td>5</td>
</tr>
<tr>
<td>Power m</td>
<td>0,5</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0,2</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>-</td>
</tr>
<tr>
<td>Failure ratio</td>
<td>0,9</td>
</tr>
</tbody>
</table>

**4.5.2 Analysis of the Backfilling Test using hardening soil**

If both theories Mohr Coulomb and hardening soil are compared the same shape in the deformed mesh is observed. The graphics below shows a different deformed mesh when the layer 2,5 m is reached. Both sketches are scaled 1000 times.

**Figure 4.55** Hardening soil deformed shape of the culvert and the soil when the layer 2,5 m is placed
The Figure 4.57 shows the comparison of the vertical displacement at middle point of the culvert.

Figure 4.57 Comparison of the vertical displacements during the backfilling test at the middle point of the culvert using hardening soil theory

The results of the backfilling with this theory show an interesting point when compared with Mohr Coulomb. According to Hardening Soil theory the culvert is not sensitive to the backfilling until the layer 2.1 m. Displacements are roughly equal to zero. Even though the compacted layers are exerting lateral earth pressure the culvert keeps imperturbable. This behaviour does not look reasonable because even Mohr Coulomb theory, which is considered just an approximate theory, displayed small alterations during the placement of the mentioned layers. The tendency of arching is also showed with this theory.

The distribution of the displacements presents the same shape as the Mohr Coulomb, with differences in the values. The comparison of the displacements for the layer 2.5 m shows how the reduction of the displacement around the crown is bigger using Mohr’s Coulomb theory. Hardening Soil theory also presents the same tendency around the crown but the decrease is hardly noticeable. Both graphics are scaled up 1000 times in order to appreciate better the differences between them.
The next step is the comparison of the moments. The moments do not keep the same position moving forward along the crown as the backfilling process makes progress.

The maximum negative moment is always located around the haunch remaining at the same point from the layer 2.85 m to 3.7m. In Table 4.9 the position and the value of the moments are displayed.

**Table 4.9** Maximum numerical positive and negative moments and their positions from the layer 2.5 m to the layer 3.7 m over the culvert structure.

<table>
<thead>
<tr>
<th>Layer(m)</th>
<th>Negative Moment(kNm/m)</th>
<th>Position (y))</th>
<th>Positive Moment(kNm/m)</th>
<th>Position (y))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>3.47</td>
<td>1.64</td>
<td>2.77</td>
<td>2.25</td>
</tr>
<tr>
<td>2.85</td>
<td>6.74</td>
<td>1.82</td>
<td>4.64</td>
<td>2.40</td>
</tr>
<tr>
<td>3.1</td>
<td>9.12</td>
<td>1.82</td>
<td>5.82</td>
<td>2.49</td>
</tr>
<tr>
<td>3.4</td>
<td>10.76</td>
<td>1.82</td>
<td>7.24</td>
<td>2.49</td>
</tr>
<tr>
<td>3.7</td>
<td>11.97</td>
<td>1.82</td>
<td>7.89</td>
<td>2.49</td>
</tr>
</tbody>
</table>
This theory presents bigger moments than the moments obtained with Mohr Coulomb’s theory. The distribution of the moments is alike in both theories showing only a different distribution for the layer 2.5 m. Smaller moments around the middle of the culvert are displayed when HS is used. The figures below represent the distribution of the moments at the layer 2.5 m.

**Figure 4.60** Distribution of the moments during the backfilling test for the layer 2.5 m using hardening soil theory

As it was said before Mohr Coulomb shows the highest negative moments around the haunch and the highest positive moment at the crown. However, Hardening Soil theory shows that another area to consider as a relevant one is the area around the foot of the culvert. Even though the biggest moments appear around the crown the positive moments at the foundation of the culvert are not negligible.

There are not significant differences between among the thrusts when both theories are compared. However, the same tendency as the one obtained for the moments is observed for the thrusts when the layer 2.5 m is reached. According to Hardening Soil theory when the backfilling reaches the layer over the crown the biggest thrust is located at the foot of the culvert. Mohr Coulomb’s theory don not show that increase at the foundation noticing the highest value at the crown.

The following table shows how the biggest thrust change the position as the backfilling makes progress.
Table 4.10 Maximum numerical thrust and its position from the layer 2.5 m to the layer 3.7 m over the culvert structure.

<table>
<thead>
<tr>
<th>Layer(m)</th>
<th>Haunch(kN)</th>
<th>Crown(kN)</th>
<th>Foundation(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>163.17</td>
<td>111.04</td>
<td>131.64</td>
</tr>
<tr>
<td>3.4</td>
<td>133.08</td>
<td>102.49</td>
<td>102.97</td>
</tr>
<tr>
<td>3.1</td>
<td>97.59</td>
<td>88.02</td>
<td>63.24</td>
</tr>
<tr>
<td>2.85</td>
<td>56.195</td>
<td>62.83</td>
<td>44.37</td>
</tr>
<tr>
<td>2.5</td>
<td>16.85</td>
<td>23.73</td>
<td>33.72</td>
</tr>
</tbody>
</table>

The figures below show how the thrusts are bigger around the crown when MC is used and the high thrusts at the foundation when HS is used.

Figure 4.62 Distribution of the thrusts during the backfilling test for the layer 2.5 m using hardening soil theory

Figure 4.63 Distribution of the thrusts during the backfilling test for the layer 2.5 m using Mohr Coulomb theory

According to the results obtained with Hardening Soil Theory the foundation level is an important part of the culvert which should be taken into account. The evaluation of the stresses confirms that the main stresses are located at the haunch and also around the foot. Mohr Coulomb disagrees with this, showing the most conflictive part the area around the haunch.
4.5.3 Analysis of the Truck test

4.5.3.1 Comparison of the results when the layer is located 60 cm over the culvert.

First of all, the vertical displacement at the middle point of the crown is compared.

Both curves are similar but the numerical results show a steep linear slope from the third to the fourth position. When the load is located at the position 3 the truck is mainly over the
haunch, however, on the position 4 the highest loads of the truck are located over the crown. This might be the reason of that steep slope. Afterwards the curves present the same tendency to increase the displacement gradually.

The analysis of the moments shows very similar values. The main discrepancy appears for the middle positions, i.e. 3, 4 and 5. First of all, the measured results for the position 3 show how the middle point moves upwards with a negative moments on it. Afterwards, on both curves, an increase of the positive moments as the truck moves towards the crown is observed. FEM results are in good agreement with full-scale test results. This graphic show a good approximation to the measured moments observing that with both tests the culvert responds in the same way.

![Figure 4.67](image1.png)

**Figure 4.67** Comparison of the moments at the middle point of the culvert when the truck is placed on the layer 0.6 m over the culvert using Hardening Soil theory

![Figure 4.68](image2.png)

**Figure 4.68** Comparison of the vertical displacement at the middle point of the culvert when the truck is placed on the layer 0.9 m over the culvert using hardening soil theory.
Figure 4.69 Comparison of the moments at the middle point of the culvert when the truck is placed on the layer 0,6 m over the culvert using hardening soil theory

Figure 4.68 and Figure 4.69 show the comparison of the results when the layer is located 90 cm over the culvert. The same conclusions as the ones obtained for Mohr Coulomb Theory can be given.

4.6 LINEAR ELASTIC THEORY

4.6.1 Basis of the linear elastic theory.

Linear elastic model is the simplest theory used to simulate the behaviour of the stiff structures in the soil. This theory represents Hook’s law of isotropic linear elasticity. The theory requires a total of two parameters, namely Young's modulus $E$ and Poisson's ratio $v$. Even though this model gives fast calculations and it does not generate problems during the running process such as plastic points and tension cut-off is very limited and the accuracy is low. As it was expected the linear theory is more similar to the Mohr’s Coulomb theory. The deformed mesh has similar shape. Stresses, moments, thrust and displacements present slightly smaller distributions. There are some interesting details when the linear theory is compared with the others theories.

4.6.2 Analysis of the backfilling test.

The analysis of the displacements shows how the middle point tends to keep constant until the layer 2,5 m. The culvert hardly responds during the test. All the displacements observed are too small and the culvert does not suffer any significant movement. As it was said, this theory is too simple and it can be used as an approximation of the real results.
Figure 4.70 Comparison of the vertical displacements during the backfilling test at the middle point of the culvert using linear elastic theory

The following table shows the maximum positive and negative moments for each layer.

**Table 4.11 Maximum numerical positive and negative moments from the layer 2,5 m to the layer 3,7 m over the culvert structure.**

<table>
<thead>
<tr>
<th>Layer (m)</th>
<th>Negative Moment (kNm/m)</th>
<th>Positive Moment (kNm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,7</td>
<td>7,46</td>
<td>4,88</td>
</tr>
<tr>
<td>3,4</td>
<td>6,55</td>
<td>4,32</td>
</tr>
<tr>
<td>3,1</td>
<td>5,35</td>
<td>4,19</td>
</tr>
<tr>
<td>2,85</td>
<td>3,63</td>
<td>2,58</td>
</tr>
<tr>
<td>2,5</td>
<td>1,28</td>
<td>1,48</td>
</tr>
</tbody>
</table>

The distribution of the thrust is closer to the Mohr’s Coulomb. Smaller thrusts are displayed with the linear theory but the location of the maximum value is roughly the same. The stresses are also smaller.

**Table 4.12 Comparison of maximum numerical thrust from the layer 2,5 m to the layer 3,7 m over the culvert structure between linear and Mohr-Coulomb theories.**

<table>
<thead>
<tr>
<th>Layer (m)</th>
<th>Thrust linear (kN)</th>
<th>Thrust MC (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,7</td>
<td>132,5</td>
<td>155,49</td>
</tr>
<tr>
<td>3,4</td>
<td>118,28</td>
<td>128,78</td>
</tr>
<tr>
<td>3,1</td>
<td>92,73</td>
<td>96,95</td>
</tr>
<tr>
<td>2,85</td>
<td>60,50</td>
<td>65,57</td>
</tr>
<tr>
<td>2,5</td>
<td>21,98</td>
<td>27,78</td>
</tr>
</tbody>
</table>
Table 4.13 Comparison of the maximum soil stresses from the layer 2.5 m to the layer 3.7 m over the culvert structure between linear and Mohr-Coulomb theories.

<table>
<thead>
<tr>
<th>Layer (m)</th>
<th>Stresses linear (kN/m²)</th>
<th>Stresses MC (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>102.04</td>
<td>134.61</td>
</tr>
<tr>
<td>3.4</td>
<td>92.7</td>
<td>117.83</td>
</tr>
<tr>
<td>3.1</td>
<td>78.69</td>
<td>94.04</td>
</tr>
<tr>
<td>2.85</td>
<td>55.70</td>
<td>61.30</td>
</tr>
<tr>
<td>2.5</td>
<td>24.41</td>
<td>39.18</td>
</tr>
</tbody>
</table>

4.6.3 Analysis of the Truck test

4.6.3.1 Comparison of the results when the layer is located 60 cm over the culvert.

The linear theory is the only one which offers smaller displacement than the in-situ displacements. Throughout the test the middle point of the crown hardly responds confirming the low precision of this theory.

![Figure 4.71](image_url)  

**Figure 4.71** Comparison of the vertical displacement at the middle point of the culvert when the truck is placed on the layer 0.6 m over the culvert using linear elastic theory

Also the numerical moments are mostly smaller than the measured moments. Another point to emphasize is that there is not rise in the moments when the truck is located right over it. This distribution of the moments gives another example of the low accuracy of this theory.
4.6.3.2 Comparison of the results when the layer is located 90 cm over the culvert.

The results for the next layer are also analyzed. As it was said before, the numerical displacements do not decrease as much as the measured displacements. Therefore, the comparison of the displacement on the next graph looks better than on previous graphics. This resemblance does not mean this theory is the most suitable.

Figure 4.73 Comparison of the vertical displacements at the middle point of the culvert when the truck is placed on the layer 0,9 m over the culvert using linear elastic theory.

Comparing with the other theories the middle point does not show the decrease at the middle point of the crown. This fact reinforces that this theory should be used just as an approximation of the final results.

Figure 4.74 is very similar to the one measured for 60 cm. The same characteristics and discrepancies as before are observed below.
Figure 4.74 Comparison of the moments at the middle point of the culvert when the truck is placed on the layer 0.9 m over the culvert using linear elastic theory.

4.7 ULTIMATE TEST

The last test carried out was the ultimate test. Through Mohr Coulomb’s theory and Hardening Soil theory the whole test can not be performed. Thus, this test will be analyzed with the linear theory.

The linear theory might not be a proper theory to evaluate this test. Nevertheless, the previous experiments have shown that the main tendency can be also observed with this theory. All the results are smaller but mostly are approximated to the results obtained with the other theories. First of all, the results obtained with Mohr Coulomb theory are analyzed. The model studied and the deformed mesh is shown on the sketches below.

Figure 4.75 Sketch of the model used with plaxis for the ultimate test.

Figure 4.76 Deformed mesh displayed with plaxis when the load applied is $q = 20kN/m$. 
According to Plaxis the last load \((q^*)\) borne by the culvert is equal to 35.8 t however, the ultimate load applied \((q)\) at site was 48.8 t. Plaxis warns that the soil body has collapsed showing plastic points on the location of the load and around the crown, if the load applied is bigger than \(q^*\). The following picture shows how the load goes into the soil generating the impossibility of the performance of the test.

![Intrusion of the load into the soil when the load applied is 60.09 kN/m.](image1)

**Figure 4.77** Intrusion of the load into the soil when the load applied is 60.09 kN/m.

During the in-situ test, it was also seen how the soil went down gradually as the load was applied, the vertical displacement measured was equal to 4 mm. This does not entail a significant effect in the culvert or into the soil, still working properly.

![Picture of the intrusion of the load into the soil during the ultimate test.](image2)

**Figure 4.78.** Picture of the intrusion of the load into the soil during the ultimate test.

The numerical displacements are similar to the measured ones, remaining always smaller. The displacement raises little by little in both cases.
Figure 4.79 Comparison of the vertical displacement at the middle of the culvert during the ultimate test using Mohr Coulomb theory.

On the next graphs the comparison of the moments and their distribution along the entire culvert can be observed.

Figure 4.80 Comparison of the vertical displacement at the middle of the culvert during the ultimate test using Mohr Coulomb theory.

The comparison of the curves shows how the predicted behaviour of the culvert is less sensitive to the increasing loads, rising the moments gradually. However, measured moments have a slope more noticeable. The distribution of the moments shows a symmetrical shape with significant moments at the crown and at the haunch.
Figure 4.81  Distribution of the moments along the entire culvert when a load equal to 21.07 kN/m is applied.

The tendency of the moments at the haunch is also the same; the numerical moments tend to be more negative due to the load is pushing down the crown producing an upward displacement along the haunch. However, the moments at site entail an increasing positive tendency. The negative moments according to the in-situ measurements always appear after the middle point of the haunch.

The results obtained with the Linear Elastic theory can be observed from the Figures 4.82 and Figure 4.83. The field tests show how both moments and vertical displacement raise their value for the last loads applied. However, the linear theory displays a gradual increase. If the load is increased much more than the ultimate load applied at the construction test, the rise of the values can be observed which means that according to the prediction of this theory the culvert is stronger and can bear higher loads.

Figure 4.82  Comparison of the moments at the middle point of the crown during the ultimate test using linear elastic theory.
4.8 ANALYSIS OF THE CULVERT WITH CROWN RIB.

The next graphic shows the comparison of the vertical displacements at the middle point of the culvert between the culvert with rib and without. The expected effect in this point of the culvert from the first layer to the layer right over the crow is a rise as a consequence of the lateral earth pressure. However; both present a downward forward for the first layer of the backfilling being more noticeable in the culvert with rib.
The numerical displacements displayed in the culvert with rib always remain smaller, mainly along the crown, confirming that the rib reinforces the crown. The graphic below shows the comparison of the vertical displacement between the culvert with rib and without, displaying how the reduction measured during the field test is more noticeable.

![Comparison of vertical displacement](image)

**Figure 4.85** Comparison of the vertical displacement obtained in-situ at the middle point of the crown for the culvert with rib and the culvert without.

The comparison of the vertical displacements during the whole process of backfilling in the culvert with rib presents the same tendency as the one obtained for the previous culvert. The arching effect is also appreciated in this case.

![Comparison of vertical displacement during backfilling](image)

**Figure 4.86** Comparison of the vertical displacement at the middle point of the crown during the backfilling in the culvert with rib using Mohr Coulomb theory.

Even though, the comparison of the backfilling showed a reduction of the displacement not very significant the truck test confirms that the rib produces a favourable effect in the culvert response. The displacements are rather reduced when the truck is located over the crown.
Figure 4.87 Comparison of the vertical displacement at the middle point of the crown during the truck test between the culvert with rib and using Mohr Coulomb theory.
Chapter 5  Comparisons and Conclusions

5.1  COMPARISON OF THE BACKFILLING TEST

The comparison of the three theories is carried out in order to decide the most appropriate theory which suits better with the measured results and offers a better explanation of the effects observed during the field tests.

The next graph shows the comparison of the vertical displacements during the backfilling at the middle point of the culvert.

![Graph comparing Mohr Coulomb, hardening soil, and linear elastic theories](image)

Figure 5.1  Comparison of Mohr Coulomb, hardening soil and linear elastic theories by displaying the vertical displacements at the middle point of the culvert during the backfilling test.

The main difference between Mohr Coulomb and Hardening Soil appears in the beginning of the process. According to the Hardening Soil the culvert does not move when the compacting process is carried out, ignoring the lateral earth pressure exerted by the layers. This might mean that the compacting process is unnecessary whereas this process is essential and must be executed with care. The linear theory results are similar to the MC but the displacements predicted are on the whole too small.

As a conclusion, the theory which suits better to the field test results is Mohr Coulomb’s theory. The lateral effect produced by earth pressure is predicted and the downward displacements when the layers are placed over the culvert are also observed. Moreover, Mohr Coulomb fulfills the theory displaying the arching effect.
5.2 COMPARISON OF THE TRUCK TEST

The results of the truck test are compared in the following figure.

![Figure 5.2](image_url)

**Figure 5.2** Comparison of the moments at the left haunch during the truck test using Mohr Coulomb, hardening soil and linear elastic theories

The comparison at the left haunch of the culvert shows that the most unfavourable position for the haunch is the position four. The load 2 and 3 that are the highest ones are pushing the crown down causing the haunch move upwards.

The next two graphs show the comparison of the displacements and the moments for all the theories.

![Figure 5.3](image_url)

**Figure 5.3** Comparison of the vertical displacement at the middle point of the culvert displayed with Mohr Coulomb, hardening soil and linear elastic theories during the truck test
Figure 5.4 Comparison of the moments at the middle point of the culvert displayed with Mohr Coulomb, hardening soil and linear elastic theories during the truck test

The most similar displacements, both value and tendency is obtained with Mohr Coulomb. However, the moments are smaller than the measured ones whereas the displacements are always bigger. The reason might be just a problem of accuracy as it was explained before. Hardening Soil displacements are also very similar to the measured and the displayed moments are more reasonable suiting the measured moments better

Through the truck test, the best theory is the Hardening soil however; the backfilling test presents significant discrepancies which help us to discard this theory as a good approximation.

As a conclusion the theory selected as the best one is Mohr Coulomb. This theory seems to represent better the reality offering reasonable results which suit with the main phenomenon detected in the field tests.

5.3 RESULTS AND CONCLUSIONS

The critical part of the construction process is the backfilling. The earth pressure causes in the culvert significant stresses and internal forces mainly at both haunches and at the middle point of the culvert. This entails that a deep analysis at both parts must be carried out, considering the haunch as the most critical part according to the numerical results

Due to the soil data were not available, the material properties were predicted. Under the assumed values, the culvert is safer than the prediction offered with Plaxis.

The linear theory does not represent the real behaviour of the soil. The accuracy of this theory is not good enough and it has to be drop as a good theory for the tests carried out. Hardening soil theory was also dropped due to the unrealistic behaviour of the culvert during the backfilling test. The most suitable theory is Mohr Coulomb theory which seems to represent the reality better. This theory adjusts to the in-situ measurements by showing the main effects of the culvert detected at the field tests.

It is advisable and desirable to perform a spatial analysis with other finite element program, such as Ansys or Abacus.
### References

<table>
<thead>
<tr>
<th></th>
<th>Author</th>
<th>Title</th>
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<tr>
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<td>American Society of Civil Engineers (2000)</td>
<td>“Numerical Methods in Geotechnical Engineering”. Sponsored by the Computer Applications Committee of the Geo-Institutes Asce American Society of Civil Engineers (August 5-8-2000)</td>
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<tr>
<td>{8}</td>
<td>Bayoglu Flener E. (2006)</td>
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<td>{9}</td>
<td>Researchers at KTH (2005)</td>
<td>Personal consulting with experts from Geotechnical division at KTH</td>
</tr>
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<td>{10}</td>
<td>Dartevelleand, Sebastian</td>
<td>Granular-Vulcano Group</td>
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Appendix A.1 – Material properties and geometry characteristics of the Mohr Coulomb, hardening soil and linear elastic theories

### Material properties used for Mohr Coulomb theory

<table>
<thead>
<tr>
<th>Identification</th>
<th>Gravel</th>
</tr>
</thead>
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<td>Material Model</td>
<td>Mohr Coulomb</td>
</tr>
<tr>
<td>Material Type</td>
<td>Drained</td>
</tr>
<tr>
<td>$\gamma_{\text{saturated}}$</td>
<td>18.4 kN/m$^3$</td>
</tr>
<tr>
<td>$\gamma_{\text{unsaturated}}$</td>
<td>25.29 kN/m$^3$</td>
</tr>
<tr>
<td>Permeability($k_x$ and $k_y$)</td>
<td>1.15E-08</td>
</tr>
<tr>
<td>Elasticity Modulus</td>
<td>60 MPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>Cohesion</td>
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<tr>
<td>Friction angle</td>
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<td>Dilatancy</td>
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### Properties of the culvert and the haunch

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<th>E</th>
<th>200 GPa</th>
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<tr>
<td>A</td>
<td>5.59 mm$^2$/mm</td>
</tr>
<tr>
<td>I</td>
<td>13739 mm$^4$/mm</td>
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<tr>
<td>I$_{\text{haunch}}$</td>
<td>7381 mm$^4$/mm</td>
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<tr>
<td>Weight steel</td>
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### Material properties used for linear elastic theory

<table>
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<th>Identification</th>
<th>Gravel</th>
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<tr>
<td>Material Model</td>
<td>Mohr Coulomb</td>
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<tr>
<td>Material Type</td>
<td>Drained</td>
</tr>
<tr>
<td>$\gamma_{\text{saturated}}$</td>
<td>18.4 kN/m$^3$</td>
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<td>$\gamma_{\text{unsaturated}}$</td>
<td>25.29 kN/m$^3$</td>
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<td>Poisson’s ratio</td>
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<td>Material properties used for Hardening Soil theory</td>
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<td>-----------------------------------------------</td>
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<tr>
<td>Identification</td>
<td>Gravel</td>
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<tr>
<td>Material Model</td>
<td>Hardening Soil</td>
</tr>
<tr>
<td>Material Type</td>
<td>Drained</td>
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<td>$\gamma_{\text{saturated}}$</td>
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<td>60000 kN/m$^2$</td>
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<td>$E_{oed}^{\text{ref}}$</td>
<td>60000 kN/m$^2$</td>
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<tr>
<td>$E_{ur}^{\text{ref}}$</td>
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<tr>
<td>Cohesion.</td>
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<tr>
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<td>Angle of dilatancy $\Psi$</td>
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<td>Power m</td>
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<td>Poisson's ratio</td>
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<td>Failure ratio</td>
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Appendix A.2 –Properties of the truck used during the truck test and location of the sensors on the culvert.

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<td>Total weight</td>
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<td>First axis</td>
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<tr>
<td>Second Axis</td>
<td>130.9 kN</td>
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<tr>
<td>Third Axis</td>
<td>115.7 kN</td>
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</tbody>
</table>
Appendix B Mohr Coulomb results in the backfilling test

B.1 Distribution of the vertical displacements

B.2 Distribution of the moments

B.3 Distribution of the thrusts

B.4 Soil Stresses
Appendix B.1. Distribution of the vertical displacements in the backfilling test using Mohr-Coulomb theory

Figure B1 Distribution of the vertical displacements of the culvert for the layer 2.5 m using Mohr-Coulomb theory

Figure B2 Distribution of the vertical displacements of the culvert for the layer 2.85 m using Mohr-Coulomb theory.

Figure B3 Distribution of the vertical displacements of the culvert for the layer 3.1 m using Mohr-Coulomb theory
**Figure B4** Distribution of the vertical displacements of the culvert for the layer 3.4 m using Mohr Coulomb theory

**Figure B5** Distribution of the vertical displacements of the culvert for the layer 3.7 m using Mohr Coulomb theory
Appendix B.2. Distribution of the moments in the backfilling test using Mohr-Coulomb theory

Figure B6  Distribution of the moments of the culvert for the layer 2.5 m using Mohr Coulomb theory

Figure B7  Distribution of the moments of the culvert for the layer 2.85 m using Mohr Coulomb theory

Figure B8  Distribution of the moments of the culvert for the layer 3.1 m. using Mohr Coulomb theory
Figure B9 Distribution of the moments of the culvert for the layer 3.4 m using Mohr Coulomb theory

Figure B10 Distribution of the moments of the culvert for the layer 3.7 m using Mohr Coulomb theory
Appendix B.3. Distribution of the thrusts in the backfilling test using Mohr-Coulomb theory

**Figure B11** Distribution of the thrusts of the culvert for the layer 2.5 m using Mohr Coulomb theory

**Figure B12** Distribution of the thrusts of the culvert for the layer 2.85 m using Mohr Coulomb theory
Figure B13  Distribution of the thrusts of the culvert for the layer 3.1 m using Mohr Coulomb theory

Figure B14  Distribution of the thrusts of the culvert for the layer 3.4 m using Mohr Coulomb theory

Figure B15  Distribution of the thrusts of the culvert for the layer 3.7 m using Mohr Coulomb theory
Appendix B.4. Soil stresses in the backfilling test using Mohr-Coulomb theory

Figure B16 Stresses of the soil for the layer 2.5 m using Mohr Coulomb theory in the plane x y

Figure B17 Stresses of the soil for the layer 2.85 m using Mohr Coulomb theory in the plane x y

Figure B18 Stresses of the soil for the layer 3.1 m using Mohr Coulomb theory in the plane x y
Figure B19 Stresses of the soil for the layer 3.4 m using Mohr Coulomb theory in the plane x y

Figure B20 Stresses of the soil for the layer 3.7 m using Mohr Coulomb theory in the plane x y
Appendix C Hardening Soil results in the Backfilling Test

C.1 Distribution of the moments

C.2 Distribution of the thrusts

C.3 Soil stresses
Appendix C.1 Distribution of the moments in the backfilling test using hardening soil theory

Figure C1 Distribution of the moments of the culvert for the layer 2.5 m using hardening soil theory.

Figure C2 Distribution of the moments of the culvert for the layer 2.85 m using hardening soil theory.

Figure C3 Distribution of the moments of the culvert for the layer 3.1 m using hardening soil theory.
Figure C4 Distribution of the moments of the culvert for the layer 3.4 m using hardening soil theory.

Figure C5 Distribution of the moments of the culvert for the layer 3.7 m using hardening soil theory.
Appendix C.2 Distribution of the thrust in the backfilling test using hardening soil theory

Figure C6 Distribution of the thrusts of the culvert for the layer 2.5 m using hardening soil theory.

Figure C7 Distribution of the thrusts of the culvert for the layer 2.85 m using hardening soil theory.

Figure C8 Distribution of the thrusts of the culvert for the layer 3.1 m using hardening soil theory.
Figure C9 Distribution of the thrusts of the culvert for the layer 3.4 m using hardening soil theory.

Figure C10 Distribution of the thrusts of the culvert for the layer 3.7 m using hardening soil theory.
Appendix C.3 Stresses in the backfilling test using hardening soil theory.

Figure C11 Stresses of the soil for the layer 2.5 m using hardening soil theory.

Figure C12 Stresses of the soil for the layer 2.85 m using hardening soil theory.

Figure C13 Stresses of the soil for the layer 3.1 m using hardening soil theory.
Figure C14 *Stresses of the soil for the layer 3,4 m using hardening soil theory.*

Figure C15 *Stresses of the soil for the layer 3,7 m using hardening soil theory.*
Appendix D Distribution of the moments in the backfilling test using linear elastic theory

**Figure D1** Distribution of the moments of the culvert for the layer 2.5 m using linear elastic theory.

**Figure D2** Distribution of the moments of the culvert for the layer 2.85 m using linear elastic theory.

**Figure D3** Distribution of the moments of the culvert for the layer 3.1 m using linear elastic theory.
Figure D4 Distribution of the moments of the culvert for the layer 3.4 m using linear elastic theory.

Figure D5 Distribution of the moments of the culvert for the layer 3.7 m using linear elastic theory.
Appendix E Mohr Coulomb theory results of the truck test (60 cm cover)

E.1 Vertical Displacements

E.2 Distribution of the Moments

E.3 Distribution of the Thusts

E.4 Soil Stresses
Appendix E.1 Vertical displacement in the truck test using Mohr-Coulomb

Figure E1 Vertical displacement of the culvert when the loads are located on the position 1 using Mohr Coulomb theory.

Figure E2 Vertical displacement of the culvert when the loads are located on the position 2 using Mohr Coulomb theory.

Figure E3 Vertical displacement of the culvert when the loads are located on the position 3 using Mohr Coulomb theory.
Figure E4 Vertical displacement of the culvert when the loads are located on the position 4 using Mohr Coulomb theory.

Figure E5 Vertical displacement of the culvert when the loads are located on the position 5 using Mohr Coulomb theory.

Figure E6 Vertical displacement of the culvert when the loads are located on the position 6 using Mohr Coulomb theory.
Figure E7 Vertical displacement of the culvert when the loads are located on the position 7 using Mohr Coulomb theory.

Figure E8 Vertical displacement of the culvert when the loads are located on the position 8 using Mohr Coulomb theory.

Figure E9 Vertical displacement of the culvert when the loads are located on the position 9 using Mohr Coulomb theory.
Appendix E.2 Distribution of the moments in the truck test

Figure E10 Distribution of the moments of the culvert when the loads are located at the position 1 using Mohr Coulomb theory.

Figure E11 Distribution of the moments of the culvert when the loads are located at the position 2 using Mohr Coulomb theory.

Figure E12 Distribution of the moments of the culvert when the loads are located at the position 3 using Mohr Coulomb theory.
Figure E13 Distribution of the moments of the culvert when the loads are located at the position 4 using Mohr Coulomb theory.

Figure E14 Distribution of the moments of the culvert when the loads are located at the position 5 using Mohr Coulomb theory.

Figure E15 Distribution of the moments of the culvert when the loads are located at the position 6 using Mohr Coulomb theory.
Figure E16 Distribution of the moments of the culvert when the loads are located at the position 7 using Mohr Coulomb theory.

Figure E17 Distribution of the moments of the culvert when the loads are located at the position 8 using Mohr Coulomb theory.

Figure E18 Distribution of the moments of the culvert when the loads are located at the position 9 using Mohr Coulomb theory.
Appendix E.3 Distribution of the thrust in the truck test

**Figure E19** Vertical displacement of the culvert when the loads are located at the position 1 using Mohr Coulomb theory.

**Figure E20** Vertical displacement of the culvert when the loads are located at the position 2 using Mohr Coulomb theory.

**Figure E21** Vertical displacement of the culvert when the loads are located at the position 3 using Mohr Coulomb theory.
Figure E22 *Vertical displacement of the culvert when the loads are located on the position 4 using Mohr Coulomb theory.*

Figure E23 *Vertical displacement of the culvert when the loads are located at the position 5 using Mohr Coulomb theory.*

Figure E24 *Vertical displacement of the culvert when the loads are located at the position 6 using Mohr Coulomb theory.*
Figure E25 *Vertical displacement of the culvert when the loads are located at the position 7 using Mohr Coulomb theory.*

Figure E26 *Vertical displacement of the culvert when the loads are located at the position 8 using Mohr Coulomb theory.*

Figure E27 *Vertical displacement of the culvert when the loads are located at the position 9 using Mohr Coulomb theory.*
Appendix F. Distribution of the moments in the truck test using hardening soil theory

Figure F1 Distribution of the moments of the culvert when the loads are located at the position 1 using hardening soil theory.

Figure F2 Distribution of the moments of the culvert when the loads are located at the position 2 using hardening soil theory.

Figure F3 Distribution of the moments of the culvert when the loads are located at the position 3 using hardening soil theory.
Figure F4 Distribution of the moments of the culvert when the loads are located at the position 4 using hardening soil theory.

Figure F5 Distribution of the moments of the culvert when the loads are located at the position 5 using Hardening Soil theory.

Figure F6 Distribution of the moments of the culvert when the loads are located at the position 6 using hardening soil theory.
Figure F7 Distribution of the moments of the culvert when the loads are located at the position 7 using hardening soil theory.

Figure F8 Distribution of the moments of the culvert when the loads are located at the position 8 using hardening soil theory.

Figure F9 Distribution of the moments of the culvert when the loads are located at the position 9 using hardening soil theory.
Appendix G. Distribution of the moments in the truck test using the linear elastic theory

**Figure G1** Distribution of the moments Moment Distribution of the culvert when the loads are located at the position 1 using linear elastic theory.

**Figure G2** Distribution of the moments of the culvert when the loads are located at the position 2 using linear elastic theory.

**Figure G3** Distribution of the moments of the culvert when the loads are located at the position 3 using linear elastic theory.
Figure G4 Distribution of the moments of the culvert when the loads are located at the position 4 using linear elastic theory.

Figure G5 Distribution of the moments of the culvert when the loads are located at the position 5 using Linear Elastic theory.

Figure G6 Distribution of the moments of the culvert when the loads are located at the position 6 using linear elastic theory.
Figure G7 Distribution of the moments of the culvert when the loads are located at the position 7 using linear elastic theory.

Figure G8 Distribution of the moments of the culvert when the loads are located at the position 8 using linear elastic theory.

Figure G9 Distribution of the moments of the culvert when the loads are located at the position 9 using linear elastic theory.