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NUMERICAL MODEL FOR THE ANALYSIS OF CONSTRUCTION PROCESS OF SOIL-STEEL CULVERTS

Waldemar St. SZAJNA*
*) PhD, University of Zielona Góra, Poland

Abstract

A numerical model of a metal arch culvert on concrete footings, subjected to a backfilling process is presented. A special procedure in ABAQUS commercial program is prepared to analyse the process via finite elements. The construction stages are taken into account. For each stage an additional layer of finite elements is added and an interaction task is solved, which results in calculating a new configuration of the structure and the state of stresses.
An elastic-plastic strain hardening constitutive model of soil and a unilateral soil culvert contact model is used.
An example of the analysis of a circular steel culvert is presented.

Key words: soil-structure interaction; finite element method; steel culverts; backfilling process; critical state soil model

1. INTRODUCTION

Understanding the mechanics of the behaviour of soil-steel culverts requires a detailed analysis of a shell-soil interaction problem. A flexible in bending culvert shell is able to sustain high vertical loads when properly installed in a soil.

During the construction process, the backfill soil is compacted in a sequence of layers, symmetrically on both sides of the arch. Lateral soil pressure moves the arch sides inward and the crown upward. The subsequent layers placed above the crown reverse the trend. The additional gravity and live loads acting on the culvert, cause lateral deformations of the shell and hence horizontal pressure against the backfill. The soil provides the necessary support to the shell, transforming vertical loads into radial forces so the culvert is mainly in a compression state. To model and to analyse the process numerical methods are needed.

Duncan (1979) investigated the behaviour of long span culverts using finite element method. He emphasised that in order to achieve good results of the analysis the non-linear, stress dependent constitutive model of the backfill and the subsoil must be taken into account. Additionally, the sequence of construction operations must be simulated. Duncan also stated that the effect of slip between the culvert and the soil is small.

A paper by Katona (1981) presents the formulation and application of a friction-contact interface element which simulates frictional slippage, separation and re-bonding of a steel culvert and a soil. An example of the analysis of a long-span arch culvert subjected to backfilling process is presented. Backfill soil is compacted in a sequence of layers. Three interface conditions are considered: fully bonded, frictional slip (coefficient of friction μ=0.5) and frictionless slip (μ=0). The results of a crown deflection are compared to experimental data. They show that the slipping conditions provide a much more reasonable representation of the experiment than a fully bonded one. He arrived at the conclusions contrary to the previous author that the soil-culvert interface model influenced significantly the behaviour of the structure during the backfilling process.

Abdel-Sayed *et al.* (1994) stated that the side wall of the lateral structure yields under the subsequent layer, causing the side wall to move away slightly from the previous layer of the backfill, relieving some of the horizontal pressure. It means that to handle the construction process properly, the soil model ought to be history stress dependent.

Massarsch and Fellenius (2002) explained that during the first loading cycle of compaction, the stress path follows the K_0 –line. Unloading occurs at zero lateral strain and horizontal stress remains locked in. Each reloading cycle increases the lateral earth pressure K_0 which can reach the passive earth pressure value.

Summarising, the complex, non-linear nature of the soil behaviour dominates in the soil-culvert interaction. Because of the non-linear characteristics of the soil-culvert system the initial state of stress and strains ought to be estimated in order to carry out any analysis of the culvert. This initial state created during the construction operations is vital for the future proper behaviour of the whole soil-culvert system. The application of a numerical model, which enables the evaluation of initial states and which makes the simulation and understanding of development of these states possible, is the aim of the paper.

The model and analysis procedure was prepared with the use of the general purpose commercial finite element system ABAQUS. The critical state soil model was used and the stages of the construction process were simulated assuming a unilateral soil-structure contact. Large-displacement formulation and plane strain conditions were took into account.

2. CHOICE OF A CONSTITUTIVE SOIL MODEL

Soils used for backfill are usually free draining sands and gravels. Choosing an appropriate soil model for the analysis of a culvert construction process is specific because of the phenomena which take place in the backfill.

During the backfilling the compaction effort in the lateral zone must be limited to a certain level. If the soil support prevents the culvert from lateral deformations when it is loaded in the vertical direction, the risk of buckling and overstressing of the structure appears. It means that a constitutive soil model ought to have a mechanism of volume deformation monitoring.

The compaction results in an increase in the overconsolidation ratio of the compacted sand and hence it increases the shear strength and stiffness of the backfill.

The next important element in the choice of the soil model is the availability of appropriate soil data for determination of the necessary model parameters.

The first choice is always a linear elastic analysis. The elastic analysis results in unrealistic prediction of the system behaviour. Tensile horizontal pressure zones and permanent soil-culvert separation regions have been detected. There is also no limit on the passive resistance that may develop in the front of the side wall. It means that the model ought to be rejected.

The second choice is a critical state soil model, see Wood (1990). An elastic-plastic strain hardening model requires a definition of an elastic behaviour, definitions of a yield surface and a plastic potential and also specification of a hardening rule.

It is assumed that recoverable changes in volumetric strain are connected with changes in mean effective stress *p'* and also recoverable changes in shear strain are connected with changes of deviator stress *q* according to formulae

$$\partial\varepsilon_p^e = \kappa \frac{\partial p'}{(1+e)p'}, \quad \partial\varepsilon_q^e = \frac{\partial q}{3G'} \tag{2.1}$$

where e is a void ratio, κ is a slope of unloading and recompression line (see Figure 1), G' is an effective shear modulus.

An elliptical yield surface (an ellipsoid in principal stress space) according to the expression (3.2) is assumed

$$\frac{\left(p'-p'_c/2\right)^2}{\left(p'_c/2\right)^2} + \frac{q^2}{\left(M\,p'_c/2\right)^2} = 1 \tag{2.2}$$

where p'_c is an effective overconsolidation pressure and M is a slope of a critical state line (see Figure 1).

It is assumed that the components of the plastic strain increment are normal to the yield surface (the identity of the yield surface and the flow rule is valid).

The isotropic hardening rule is defined in a such way that the magnitude of plastic volumetric strain is given by

$$\partial\varepsilon_p^p = \frac{\lambda - \kappa}{(1+e)} \frac{\partial p_c'}{p_c'} \tag{2.3}$$

where λ is a slope of a normal compression line (see Figure 1).

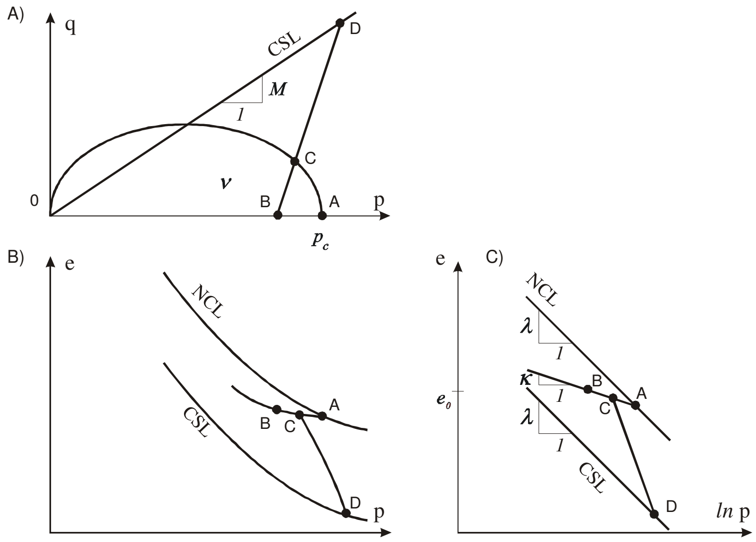

Figure 1. (A) Elliptical yield surface and critical state line (CSL); (B), (C) normal compression line (NCL) and unloading and recompression line; (0-A elastic-plastic hydrostatic compression, A-B elastic hydrostatic unloading, B-C elastic vertical loading, C-D elastic-plastic vertical loading of soil)

The model parameters: *M*, λ, κ, *G'* and initial state parameters p'_c and e_o presented in Figure 1, could be determined in a standard laboratory tests.

A special feature in the behaviour of the compacted granular material which is handled by the critical state model is the fact that shearing can produce dilation of the soil. Potential dilation affects the shear strength of the soil.

3. CONSTRUCTION STAGES MODELLING

An important feature of ABAQUS is the ability to carry out a multiple step analysis. Additionally, the following items can be changed before each single step: loads, boundary conditions and the number of active finite elements. In order to obtain the results of the backfilling process simulation where subsequent layers of soil are added, a special procedure has to be prepared. Although elements cannot be created within the analysis, the same effect can be achieved by creating elements in the model definition, inactivating them in the first step, and reactivating them in the next step. It is important to reactivate a layer of elements as a strain-free one.

Figure 2 presents reactivation of the first backfill layer of an arch culvert with vertical plane of symmetry. To clarify the chart presenting the procedure, an inactive (white colour) elements are also presented in the final geometry configuration, which is unknown at this stage of backfilling.

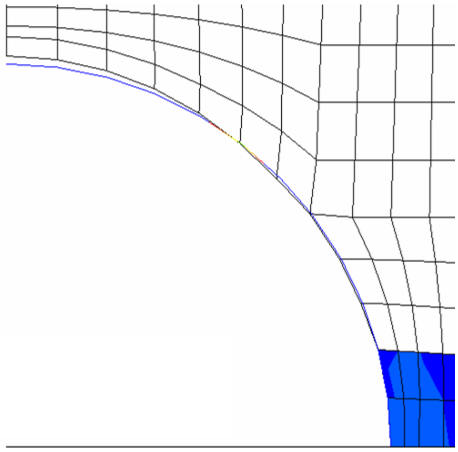

Figure 2. First layer reactivation. Inactive (white colour) elements present the final geometry configuration, unknown at this stage though

When the first layer of soil elements is reactivated at e_o initial void ratio, a contact region between the backfill and the culvert is redefined, the layer gravity loads and a portion of compaction loads are added. During the incremental compaction the changes of e are recorded in order to control the process. Compaction loads are added until the demanded value of this parameter is achieved. It is rather difficult to get similar values of the void ratio for each element of a compacted layer.

It is seen in Figure 2 that the crown will move up caused by the pressure of the compacted sidefills. So, before the next step is executed a correction of geometry of inactive elements has to be made, to remove any gaps and penetrations. When the geometry of the culvert and the second layer of soil elements coincide, the contact region is redefined and the layer is activated.

The procedure discussed above is repeated for each of the backfilling soil layers. A flowchart in Figure 3 presents the procedure of the construction process simulation. NL and TNL are a layer number and a total number of layers, respectively. The procedure is not fully automated and requires several restarts of analysis.

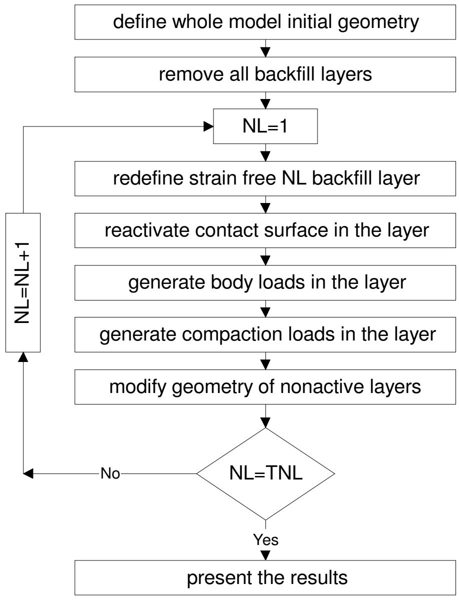

Figure 3. Flowchart of the procedure of construction process simulation. NL is a layer number, TNL is the total number of backfilling layers

4. EXAMPLE OF ANALYSIS

A semicircle shape cross-section, corrugated steel culvert, of a diameter 2.5m and 2mm thick plate, with ends anchored into concrete footings is going to be tested in the laboratory of Roads & Bridges Research Institute in Żmigród. The soil-culvert model is 3.75m high and 6m wide (the soil volume results from dimensions of the laboratory stand). Depth-of-cover of the culvert is 0.5m.

A numerical model of the soil-steel structure is subjected to simulation of a symmetric construction process according to the procedure presented in the previous chapter. The geometry and the mesh of the finite element model is presented in Figure 4. For the purpose of the analysis the values of soil parameters are assumed as follows: M=1.0, λ=0.014 , κ=0.0024, ν =0.28, p'_c,=70 kPa, e_o =1.08 (Poisson ratio ν is taken instead of effective shear modulus G' in the elastic region). Unilateral contact model is assumed. The objective of the chapter is the verification of the construction process simulation procedure.

To verify the procedure, only five construction stages are simulated. The initial strain free stage is the installation of the culvert on earlier backfilled foundations. Geostatic conditions of the soil are also generated in this step. In the second stage of the construction, the first layer of culvert's backfill is placed. Figure 4 presents the state of the system in the second stage before the layer compaction process. The following three stages consist in construction of three subsequent layers of backfill.

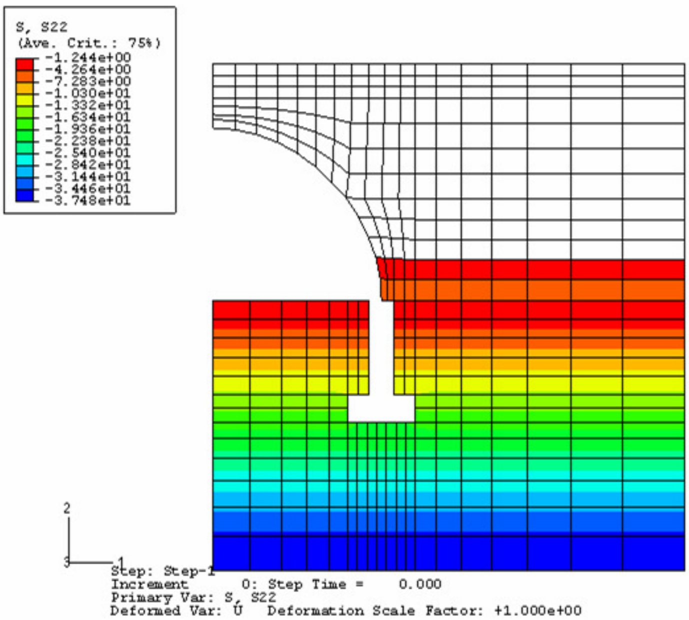

Figure 4. Finite element mesh and vertical stress distribution after generation of geostatic stress conditions and placement of the first backfill layer

Figure 5 presents the distribution of the culvert's bending moments during the backfilling process. The left figure depicts the state of the culvert after the first layer compaction. The distortion and bending of the culvert arise directly from the pressure around the culvert and the induced strains. The response of the flexible culvert during symmetric backfilling depends in this case on variation of compaction pressure and backfill layer thickness. Several different distributions of final bending moments can be achieved. The right part of Figure 5 illustrates an exemplary distribution after the compaction of three additional layers (this final state of the arch shows the excessive compaction of the second layer of soil and the excessive inward deformations of culvert's shoulder).

In majority of cases the simulation of the construction process is neglected. An initial strain and stress-free state is assumed for the design of the structure under operational load. However, the simulation of the construction process reveals significant stresses and deformations which should be taken into account in the initial state for modelling and analysis of operational use.

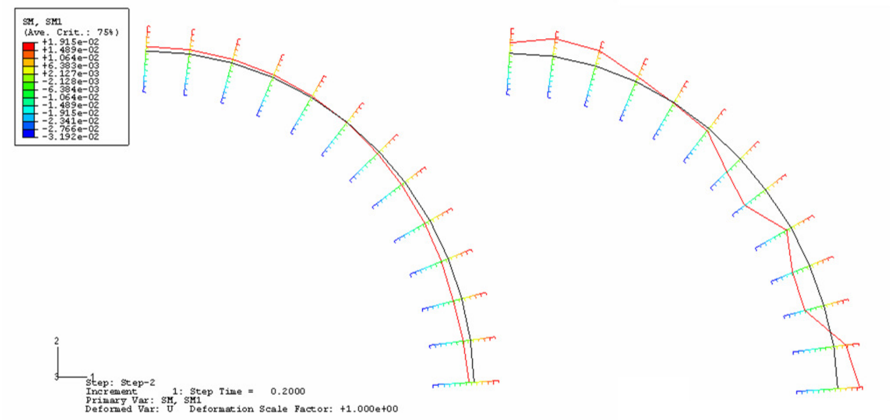

Figure 5. Distribution of bending moments during backfilling: (a) after first layer compaction; (b) final distribution

5. CONCLUSIONS

Placement and compaction of the backfill layers creates a difficult to estimate state of stress and strain in the soil-culvert system. The determination of the state is a necessary condition for further analyses and design of the structure under service loads.

From the mechanical point of view the construction process is a quite complicated task to simulate. A soil-structure contact is unilateral and the contact surface is changed. Large displacements of the culvert take place. The mass of the backfill and the loads are altered. The stiffness of the backfill varies because of: the compaction, successive layer placement and the soil-structure interaction.

The culvert behaviour throughout backfilling operation can be understood in details by carrying out laboratory tests or applying numerical models. Preparation of such a model was the main aim of the paper. Because irreversible deformations and volumetric changes in the soil are meaningful phenomena in the backfilling process, the elastic-plastic strain hardening constitutive model of soil has been used. The prepared numerical model requires calibration with a field or laboratory data. Soil parameters ought to be evaluated. The structural response of a culvert investigated by numerical methods ought to be compared and tuned in to the behaviour of a real structure during backfilling. A calibrated, reliable numerical model is supposed to be an important tool for the analysis of the influence of factors such as: variation of compaction pressure, variation in backfill layer thickness, symmetric and non-symmetric backfilling, parameters of the soil, contact surface features and others on the soil-culvert behaviour.

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MODEL NUMERYCZNY ANALIZY PROCESU WZNOSZENIA
GRUNTOWO-STALOWEGO PRZEPUSTU

Streszczenie

W pracy przedstawiono numeryczny model procesu zasypywania gruntem metalowego przepustu o kształcie łuku, spoczywającego na fundamentach betonowych. Do analizy procesu wykorzystano metodę elementów skończonych, przygotowując specjalną procedurę do programu ABAQUS. Analizowano poszczególne etapy procesu wznoszenia przepustu. Dla każdego etapu wznoszenia tworzona jest dodatkowa warstwa elementów skończonych i rozwiązywane jest zadanie interakcji, które daje w efekcie nową konfigurację i stan naprężenia w konstrukcji. Przyjęto sprężysto-plastyczny model konstytutywny gruntu ze wzmocnieniem gęstościowym oraz jednostronne warunki kontaktu przepustu z podłożem. Zamieszczono przykład analizy kołowego przepustu stalowego.

Słowa kluczowe: interakcja konstrukcji gruntowej, metoda elementów skończonych, przepusty stalowe, proces zasypywania, model konstytutywny gruntu.