Effects of Soil-structure Interaction and Different Simulation on the Response of Concrete Box Culverts

Salah R. Al-Zaidee¹,a, Ashraf Hameed Alsalmani²,b* and Alhusain Salam¹,c

¹Civil Engineering Department, University of Baghdad, Baghdad, Iraq
²Mechanism and Equipment Department, University of Baghdad, Baghdad, Iraq
a salah.r.al.zaidee@coeng.uobaghdad.edu.iq, b ashraf.hameed@coagri.uobaghdad.edu.iq
³alhusainsalam2018@gmail.com

Abstract. This paper shows how different simulation and soil-structure interaction can affect the response of concrete culverts embedded in dry cohesionless soils. Three simulations have been considered. In the first, second, and third simulations, the applied loads have been determined based on empirical relations of PCA without including the soil-structure interaction. The differences between these simulations are in using the beam element for the first one while using the frame element for the second one and the plane strain element for the third one. In addition to neglect the soil-structure interaction, the axial and shear deformations have been neglected in the first simulation. The axial deformations have been included in the second simulation; finally, all of the axial and shear deformations are included in the third simulation.

Keywords: Culverts, Traditional Analysis, Finite Element Analysis, Soil-structure interaction.

1. Introduction

The civil engineer routinely encounters analysis and design of box culverts in work. In traditional analysis and design, loads acting on culvert are determined based on analytical solutions of the theory of elasticity. In these solutions, the soil is simulated as a semi-infinite elastic isotropic media [1]. The main drawback of these solutions is they are derived from the absence of the embedded structure; therefore, they cannot simulate soil-structure interaction. Although the culverts are rather simple structures, the loadings applied to these structures during their construction and subsequent service life can be complex. These structures are subjected to substantial vertical and lateral earth pressure and are often subjected to significant temporary loadings during the construction of the embankment [2]. Both AASHTO Standard Specifications for Highway Bridges and AASHTO LRFD Bridge Design Specifications stipulate procedures for calculating the design loads on culverts based on the Marston-Spangler theory [2]. This theory reflects how the construction process may affect the loads transfer to the buried culvert. In the trench installation, some of the weight and applied load on the more deformable central prism transmits to the stiffer adjacent soil. In the embankment installation, forces transmit for the softer side soils to the stiffer central prism [3]. An analytical solution of the differential equilibrium equation is used in the Marston-Spangler theory to quantify these effects. Solution results have been presented in a nondimensional form to be suitable in the design practice [4].

In 1975, the Portland Cement Association adopted the Marston-Spangler theory to prepare design charts for analysis of the concrete box culverts. In these charts, the walls, slabs, and foundations of the culverts are considered a beam with neglecting the effect of concrete Poisson’s ratio, axial deformation,
and soil-structure interaction [5]. Spite the powerful of analytical solutions, they are limited in nature and applied to regular geometry and typical load conditions. In contrast, the approximate finite element solutions are general and can be applied for different geometry and loads conditions, and they can deal with nonhomogenous and nonlinear soil nature [6]. Neglecting the soil-structure interaction remains the main drawback in the traditional analytical solutions [7]. This paper aims to show how different modeling of the culverts with and without soil-structure interaction may affect the resulting design forces. Three different simulations have been considered. These simulations have been arranged in a hierarchy form. In the first simulation, traditional analysis of PCA has been used as the reference case. In the second modeling, the loads acting on the culvert have been determined using the PCA approach. At the same time, structural analysis has been achieved using frame elements to include the effect of axial deformation. Finally, the contribution of the shear deformations of the deep culvert members have been mimicked in the third simulation by using the plane strain finite element model. This paper aims to use plane strain finite element models to simulate the interaction between the culvert and the surrounding soil and to show how design forces and soil pressures are affected due to the interaction. Finite element models have been prepared with Abaqus commercial finite element packages.

2. Loads on the Culvert

According to [8], loads acting on the culverts include the weight embankment and the wheel loads due to highway traffic. How the wheel load is distributed through soil media to act on the culvert depends on the nature of pavement, i.e., rigid or flexible, the soil nature and stiffness, and the embankment depth [5]. It is relatively difficult to have a mathematical expression for the embankment load transmitted to the culvert as it depends on different factors, including the angle of internal friction, the density, the homogeneity, and the moisture content of the soil. Until now, the Marston-Spangler theory stills the most accurate analytical basis to determine the weight of the embankment on the culvert. According to this theory, the acting load would equal to the weight of the prism located directly above the culvert and the upward or downward shear forces depending on the construction method. As the stresses due to lateral earth pressure generally counteract the stresses due to the vertical loads acting on the culvert, therefore they can be neglected conservatively [5]. When they have to be computed, the lateral pressures are estimated based on the at-rest condition as there is no significant soil yielding or movement due to lateral bracing of the walls [9].

3. Finite Element Analysis

For the time being, the finite element method represents the most powerful computation approach that can be used to simulate complex structures with complicated boundary conditions. It has been developed in the later 1950s. It uses a piece-wise polynomial to approximate the field variation in the considered media. In the stress analysis discipline, the displacements are considered the main unknown that are approximated with the shape functions. Currently, an isoparametric formulation is used where the same polynomial is adopted to approximate the field and the geometry [10]. From the geotechnical point of view, the finite element technique can simulate both deformations and mobilization in one model rather than in two, like it is done in classical soil mechanics. It also can deal with the coupled analysis of deformation and flow [11]. Katona pioneered using the finite element technique to model the buried pipes and culverts. This work developed the well-known public software CANDE (Culvert Analysis and Design) [12]. [13], and [14] also achieved contributions to adopt the finite element method for the analysis of buried structures.

4. Case Studies

In this paper, three case studies have been considered to include a square one-cell box culvert, rectangular one-cell culvert, and a two-cell culvert. Geometry and dimensions for the case studies are presented in Fig. 1 below. To be comparable with the classical solution of PCA, the units have been maintained in their original imperial form. The soil mass has been taken large enough to simulate the deformation vanishing at the constrained boundaries. All considered soils have been assumed dry with 35° angle of internal friction. A corresponding Poisson’s ratio of 0.333 and at rest condition, ks, have been assumed based [15].
For each case study, three simulations have been considered. In the first simulation, the loads have been computed according to [5], see Fig. 2, and the culvert has been simulated as a beam element with neglected axial deformation. Points, where internal forces have been determined, are presented in Fig. 3 for the case study. For the second simulation, the frame elements have been used to include the axial deformation, as indicated in Fig. 4. Finally, as indicated in Fig. 5, the plane strain elements, with two degrees of freedom per node, have been used to meshed the culvert for the third simulation. For the first, second, and third simulations, the underneath soils have been replaced by Winkler foundations with a subgrade coefficient determined based on Eq. 1.

\[
k_s = 0.65 \frac{E_s B^4}{E_{sf} B(1-\mu^2)}
\]  

(1)
While, where $E_s, E_f =$ modulus of soil and footing respectively; $B, I_f =$ footing width and its moment of inertia based on cross-section. $\mu =$ soil’s Poisson’s ratio.

Figure 2. Loads acting on the case study culverts determined according to [5].

Figure 3. Points where internal forces have been determined for the first case study.
5. Results and Discussion
To simplify the result's visualization and interpretation, they have been presented in a bar chart to compare the variation between the three models for each case study. The presentation has been by referring to the points presented in Fig. 3 and to the load case of Load Case 1, Load Case 2, and Load Case 3 to refer respectively to the self-weight, hydrostatic pressure, and the combination of soil and truck pressures. The results for the three case studies have been presented in Fig. 7 through Fig. 14.

**Figure 4.** Frame element simulation for the culverts.

**Figure 5.** Plane-strain element simulation for the culverts.

**Figure 6.** Moments variation at Section 4 of case study 1.
Figure 7. Shear variation in Section 4 of case study 1.

Figure 8. Thrust variation in section 4 of case study 1.

Figure 9. Moments variation in section 5 of case study 2.
Figure 10. Shear variation in section 5 of case study 2.

Figure 11. Thrust variation at Section 5 of case study 2.

Figure 12. Moments variation at Section 5 of case study 3.
6. Conclusions
The figures above indicate significant differences between different analysis models due to the differences in adopted assumptions for each model. Consider the first case study for an instant. From Fig. 4, one can see that for the first load case, which represents the culverts self-weight, the results for the first three models are close to each other. Insignificant axial and shear deformations in this section make the adopted assumptions more representative and the traditional analysis more valid. Moreover, for the more sophisticated soil-interaction model, a significant difference can be seen compared with the other models due to the significant effect of the soil-structure interaction. In load case three, which represents the combined effect of soil weight, truckload, and the lateral pressure from the earth and surcharge load, a more profound difference can be observed between the first two models and the second two models. The first two models with the traditional analysis and frame element models neglecting the shear deformations affect the calculated stress as the finite element method determines the stresses from the strains. These stresses are, in turn, affecting the moment in those sections.

References
[1] M.E. Harr, Foundations of Theoretical Soil Mechanics., McGraw-Hill Book Company, 1966.
[2] K. Kim and C. Yoo, Design Loading for Deeply Buried Box Culverts, Alabama: Highway Research Center Auburn University, 2002.

[3] G.F. Sowers, Introductory Soil Mechanics and Foundation: Geotechnical Engineering, Fourth Edition., Macmillan Publishing Co., Inc., 1976.

[4] M.G. Spangler and R.L. Handy, Soil Engineering, Fourth Edition., Harper&Row, Publishers, New York, 1982.

[5] PCA, Concrete Culverts and Conduits., Illinois: Portland Cement Association, 1975.

[6] F. Azizi, Applied Analysis in Geotechnics., E&FN Spon, 2000.

[7] R.E. Hunt, Geotechnical Engineering Techniques and Practice., McGraw Hill, 1986.

[8] AASHTO, AASHTO LRFD Bridge: Design Specification., American Association of State Highway and Transportation Officials., 2012.

[9] J.E. Bowles, Foundation analysis and design, 5th Edition., McGraw-Hill Companies, Inc., 1996.

[10] K.J. Bathe, Finite Element Procedures., PHI Learning Private Limited., 1996.

[11] G.S. Vegard and N. Steinar, Development and Implementation of Effective Stress Soil Models, Norwegian University of Science and Technology Department of Civil and Transport Engineering, 2014.

[12] M.G. Katona, A simple contact–friction interface element with applications to buried culverts, International Journal for Numerical and Analytical in Geomechanics, 7(3) 1983 371-384.

[13] J. Duane, R. Robinson, and C.A. Moore, Culvert-soil interaction finite element analysis, Journal of Transportation Engineering, 112(3) 1986 250-263.

[14] G.A. Leonards, C.H. Juang, T.H. Wu, and R.E. Stetkar, Predicting performance of buried metal culverts, Transportation Research Record, TBR., 1985 42-52.

[15] B.M. Das, Principles of Foundation Engineering, 7th Edition, CENGAGE Learning, 2010.