BEHAVIOR OF SINGLE CELL BOX CULVERT USING FINITE ELEMENT METHOD

Mithun Ray*[1], Dr. Bashir Ahmed[2]

[1] *Structural Safety Engineer, RMG Sustainability Council (RSC), Bangladesh, e-mail:* mithunray.ce@gmail.com
[2] *Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail:* bashir@ce.buet.ac.bd

***Corresponding Author**

ABSTRACT

Box culverts are widely employed structures in road construction due to their simplistic design and repetitive nature. However, the conventional design approach for box culverts relies on 2D-plane strain analysis, which may inadequately capture their intricate behavior. Recent research endeavors have sought to address this limitation by employing three-dimensional (3D) modeling techniques to explore the characteristics of box culverts.

The present study focuses specifically on the behavior of a single cell box culvert, utilizing the finite element method to model its response. By leveraging this numerical analysis technique, the primary aim is to observe and analyze the culvert's behavior under various conditions like fill height, culvert size and soil properties. The principal objective is to gain insights into its structural behavior, identify potential concerns, and highlight areas for improvement.

Through a comprehensive analysis, this research intends to provide valuable information that can augment the design and construction of box culverts. By incorporating the observed bending effects into the design process, engineers will be better equipped to ensure the long-term durability and safety of box culverts in road infrastructure projects. Furthermore, this study contributes to the expanding body of knowledge concerning the behavior of box culverts, paving the way for more accurate and efficient design methodologies in the future. By integrating advanced modeling techniques and conducting thorough observations, the study endeavors to advance the understanding of single cell box culverts and facilitate their optimized design and performance.

Keywords: *Box culvert, finite element method, 3D modelling, numerical analysis, structural behaviour*

1. INTRODUCTION

The conveyance of water, utilities, automobiles, or people may be accomplished cost-effectively using box culverts, which are frequently used in road and railroad bridge crossings. Two slabs and two vertical walls make up these constructions, which offer monolithic action and structural effectiveness. Despite their simplicity, box culverts are subject to complicated loading patterns because they are buried, which causes stress to be redistributed in the nearby soil layers. The amount of load transmitted to the culvert relies on several variables, including the stiffness, stiffness of the culvert, and the behaviour of the soil-culvert interaction. The research has three objectives. First, using finite element analysis, the study seeks to examine how box culverts respond to changes in fill height, culvert size, and material properties. In addition, it tries to comprehend how stress changes when the parameters are altered and how stress grows in the stream direction perpendicular to traffic. Thirdly, the study compares the numerical and experimental findings with those from earlier research projects carried out by other scholars. The study's approach and scope include several important topics. Using Finite Element software, a 3D model of the box culvert, surrounding soil with two distinct characteristics, and the soil-culvert interaction system is created. Based on the results of the sensitivity analysis, a reference model is developed, where the parameter values for the reference model are selected from the median values within the studied range. Sensitivity analysis includes optimizing mesh size and soil extension along the sides and beneath the culvert.

The effects of different parameters are observed, with other parameters kept constant at their median values while analysing the impact of a particular parameter. Finally, the study graphically represents the effects of parameters on normal stress, bending moment. Based on these representations, the study identifies the relatively significant parameters.

2. LITERATURE REVIEW

In recent years, numerous studies have been conducted by researchers focusing on various aspects of reinforced concrete box culverts. Tadros et al. (1989) critically examined the standards set by the American Association of State Highway and Transportation Officials (AASHTO) in 1978, specifically regarding soil pressure and design methods. Their analysis using the CANDE computer program demonstrated that the soil pressure could exceed the limits outlined by AASHTO. Based on their findings, Tadros et al. proposed new formulas to predict more realistic soil pressure on all four sides of the box culvert by performing computer analyses considering different soil conditions, including clay and silty sand.

Expanding on the capabilities of the CANDE computer program, Tsuji et al. (1988) investigated the application of expansive cement concrete to prevent flexural cracking in precast box culverts. Their research built upon the work of Okamura et al. (1974) and Tsuji (1975) on chemical pre-stress introduction in reinforced concrete members. The study showcased the shapes and dimensions of precast box culverts, and while it focused on concentrated load only, it did not account for the effects of earth fill, soil pressure, stream size, or the direction of stress and subsequent flexural cracks. As a result, this study may not provide comprehensive insights for the current design study.

Jao et al. (2003) investigated the behaviour of box culverts located beneath engineering structures such as roadways and buildings. They highlighted the significance of considering the overlaying foundation loading, which could induce substantial soil pressure on the culverts, leading to excessive deformation. Existing studies on earth pressure distribution around concrete box culverts primarily focused on embankment loading that passed over the culverts. Jao et al. emphasized the need for a comprehensive analysis that accounts for both elastic and plastic behaviours of the soil, as considerable culvert deformation could trigger plastic yielding in the surrounding soil.

Additionally, Alkhrdaji et al. (2000) presented an overview of the design and construction of a culvert that replaced a bridge from the 1980s. The new culvert consisted of three concrete-increased corrugated steel pipes. However, further details and findings of this investigation were not provided in the given context.

These studies contribute to the evolving understanding of reinforced concrete box culverts, addressing aspects such as soil pressure, design methods, utilization of expansive cement concrete, and the effects of overlaying foundation loading. However, there is a need for further research that comprehensively considers various factors, including earth fill, soil pressure, stream size, stress direction, and culvert deformation, to improve the design and performance of box culverts in diverse scenario.

3. METHODOLOGY

3.1 Creating Finite Element Model

In the field of civil engineering, numerous computer tools and packages are available for dealing with finite element models, each varying in terms of versatility and complexity. Examples of such packages include ABAQUAS, STRAND, ANSYS, DIANA, ADINA, FEMSKI, and STAAD. Among these options, ANSYS has demonstrated advantages in terms of its extensive capabilities, flexibility, and detailed documentation. For this study, ANSYS 16.0 was employed.
ANSYS stands out as the most powerful software package not only in civil engineering but also in other engineering disciplines such as naval, aeronautical, and mechanical engineering. Engineers utilize ANSYS to analyse aircraft bodies, ship halls, structural houses, as well as to design and analyse small machine components, pistons, fluid structures, and car bodies. The ANSYS family of products provides a range of analysis techniques, including static analysis, modal analysis, harmonic analysis, transient dynamic analysis, spectrum analysis, buckling analysis, and explicit dynamic analysis.

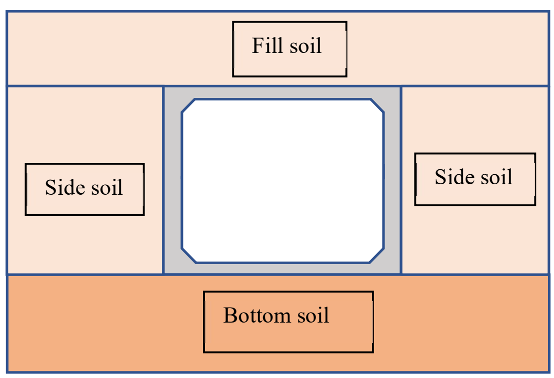


Figure 1: Schematic diagram of single cell box culvert

The figure presented below illustrates the components of the box culvert under investigation. The culvert consists of two types of soil layers: the site soil beneath the bottom of the culvert and the fill soil layer above it. These soil layers possess slightly different properties. The site soil is characterized as clay with an elastic modulus (Es) of 60 MPa, while the fill soil is classified as medium clay with an Es of 16 MPa. The height of the fill soil layer is 10 feet. The properties of the side soil layer are like those of the fill soil layer. The box culvert itself has dimensions of 10' x 10', with a thickness of 1.5' and a haunch of 6 feet. For modelling purposes, ANSYS Workbench 16.0 with its Graphical User Interface was utilized. The "Static Structural" package within ANSYS was employed for the analysis. This package facilitates the determination of displacements, stresses, strains, and forces in structures or components under loads that do not induce significant inertia and damping effects. The analysis assumes steady loading and response conditions, where the loads and structural responses vary slowly over time. A static structural load can be performed using ANSYS, Samcef, or ABAQUS solvers. Various types of loading can be applied in a static analysis, including externally applied forces and pressures, steady-state inertial forces (e.g., gravity or rotational velocity), imposed (nonzero) displacements, and temperatures (for thermal strain).

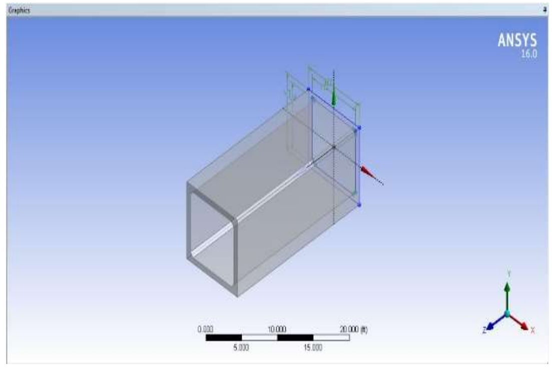


Figure 2: Three-Dimensional model by ANSYS

For the development of the model, the following boundary conditions were imposed: vertical planes at the centreline of the roadway and at the end parallel to traffic on the roadway (x-y plane) restrained movement in the z-direction, vertical planes parallel to the direction of stream or traffic of the culvert (z-y plane) restrained movement in the x-direction, and the bottom surface of the soil surface modelled (x-z plane) restrained movement in the y-direction.

The soil unit weight, Poisson's ratio, and modulus of elasticity were specified as 2300 kg/m³, 0.4, and 60 MPa, respectively. For modelling the reinforced concrete box culvert, the modulus of elasticity of concrete (E_c) and the Poisson's ratio were set as 2300 kg/m³, 0.18, and 30 MPa, respectively.

3.2 Optimizing mesh size

Optimizing the mesh is crucial in the finite element method, as it involves dividing the structure into smaller elements that represent the geometry and mechanical properties in each region. Finer mesh sizes tend to yield more accurate results, but beyond a certain level of fineness, the solutions do not change significantly. This optimum mesh size ensures accurate results while minimizing computational time. In this study, different mesh sizes were utilized and analysed repeatedly to determine the optimal mesh size for the structure. Specifically, the normal stress (ksf) was analysed using different mesh sizes. It was observed that a mesh size of 0.5 ft provided consistent results for the structure. Finer mesh sizes may offer increased accuracy, but they also lead to a significant increase in computational time. Table 1 provides a comparison between mesh size and computation time. Therefore, a mesh size of 0.5 ft was chosen for this analysis.

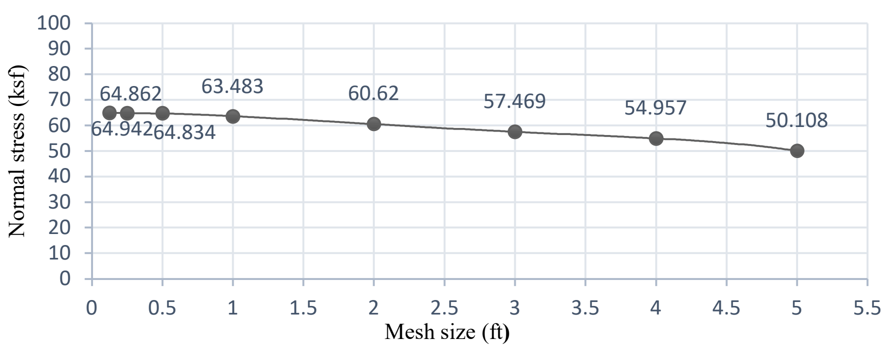


Figure 3: Relation between Normal stress vs. Mesh size

A comparison has been made between different mesh size and computation time below to consider efficient mesh size.

Table 1: Mesh size vs computation time

Mesh size	Computational Time (seconds)
5 feet	148 s

4 feet	214.2 s
3 feet	314.5 s
2 feet	414.2 s
1 foot	656.11 s
0.5 foot	1043.3 s
0.25 foot	1714.7 s

3.3 Effect of soil extension

The effect of soil extension in different directions was also investigated in the FE model. In the Y-direction, trials were conducted with varying depths of soil layers beneath the edge of the bottom slab of the culvert. The results indicated that the effect did not change significantly beyond a depth of 40 ft of soil layer.

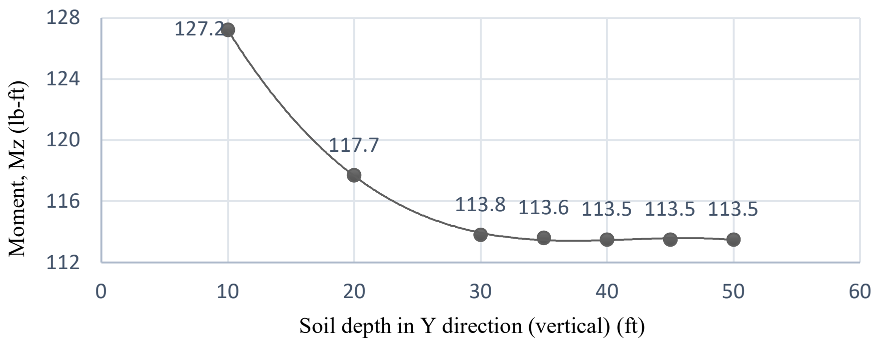


Figure 4: Optimizing depth of bottom soil

Similarly, the effect of soil extension in the X-direction was examined. The figures presented below illustrate the impact on Moment (M_z) and due to soil extension in the X-direction. It was observed that both moment (Mz) and normal stress did not undergo significant changes beyond an extension of 30 ft in the X-direction.

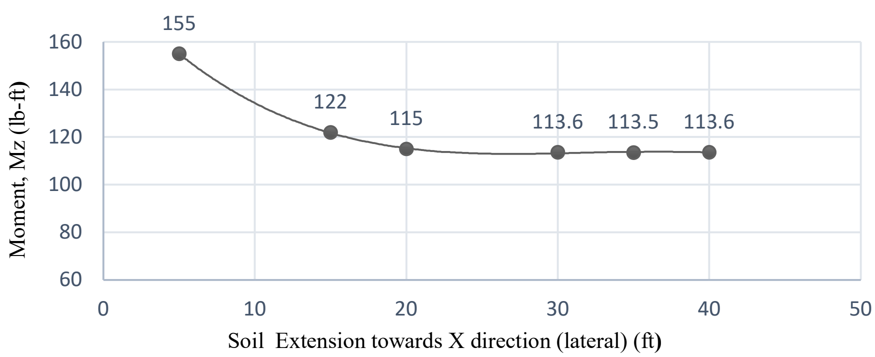


Figure 5: Optimizing extension of bottom soil

3.4 Verification of FE Model

A comparison was made between the present study and previous experimental data. The CANDE-1980 model developed by Katona et al. (1981) was compared with field data obtained by Russ (1975) and Allen et al. (1978) from a concrete box culvert installation. The instrumentation on the box included eight normal pressure gauges and several strain gauges on the reinforcement, although some of the strain gauges were reported to have malfunctioned. Katona aimed to publish predicted soil normal stress from CANDE using a linear elastic soil model. In this present study, the same model was developed in ANSYS Workbench 16.0 and compared with the previous results. The graphical representation in Figure 6. demonstrates a comparison among different experimental results, including CANDE (1980), AASHTO (1978), and Kentucky Test (1978) and Ahmed (2005)

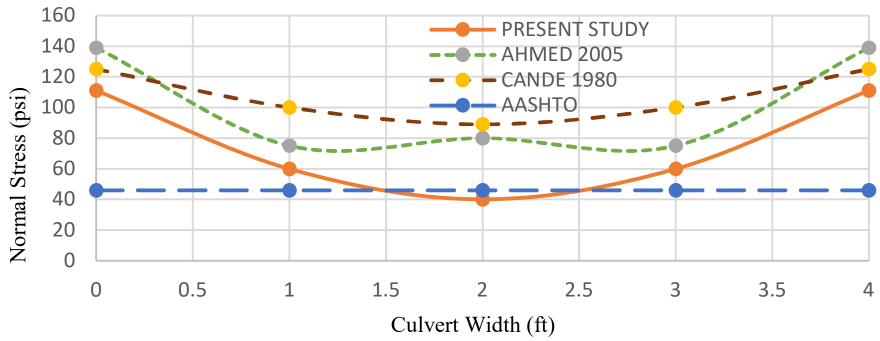


Figure 6: Comparison of CANDE (1980), AASHTO (1978), Kentucky Test (1978), Ahmed (2005) and Present Study Results for Normal Stress on the Top Slab of the Culvert (4ft by 4ft).

The comparison revealed agreement between the previous studies and the present study. For instance, the soil pressure on the top of the culvert at a fill height of 6.6 m was found to be 40 psi, which aligns closely with the values of 46 psi in AASHTO and 80 psi in Ahmed's 2005 study. Similar agreement was observed for the bottom slab, where the maximum normal stress in our study was -50 psi, compared to -56 psi in AASHTO and Ahmed's 2005 study. Figure 7 visually represents this comparison among the studies.

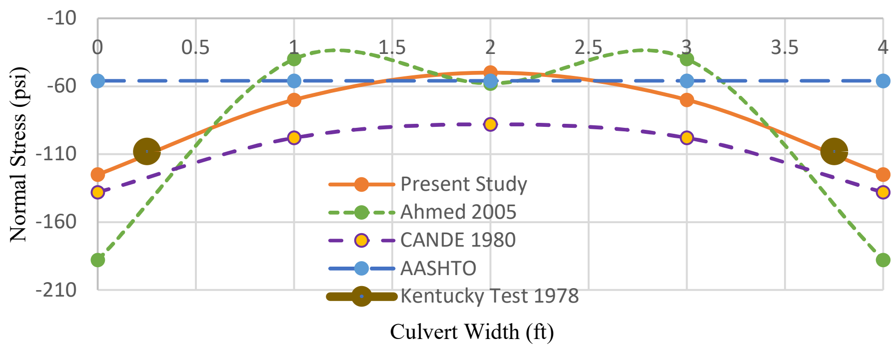


Figure 7: Comparison of CANDE (1980), AASHTO (1978), Kentucky Test (1978), Ahmed (2005) and Present Study Results for normal stress on bottom slab of the culvert

These results provide a validation on the utilization of ANSYS 16.0 as the chosen software package for the development of the finite element model. It outlines the modelling techniques available in ANSYS and explains the properties of the soil layers and box culvert dimensions considered in the model. The section also covers the optimization of the mesh size, the investigation of soil extension effects, and the comparison of the present study with previous experimental data so that the model can be proceed for further study.

4. BEHAVIOUR OF THE BOX CULVERT

In this parametric study, a reference model has been subjected to analysis and optimization. Prior to the study, the depth of the bottom soil layer and the extension of side soil layers were determined. The mesh sizing in the developed model was also optimized. The following parameters were chosen for the parametric study:

1. Fill height of the culvert (d)
2. Modulus of elasticity of the site soil (Es of site soil)
3. Culvert width (B)
4. Effect of interface friction (μ)

The bottom and top slabs of the culvert are thought to be sensitive to the coefficient of interface friction—that is, the coefficient of friction(μ) between earth and concrete. To investigate this effect, a range of values for μ is chosen, ranging from 0.1 to 0.4. Various analyses are conducted using the standardized model to examine the behaviour of the buried box culvert under different μ values. The fill height and number of roadway lanes in the reference model are held constant. The impact of interface friction (μ) on the behaviour of the culvert in fill soil is illustrated in figure 8.

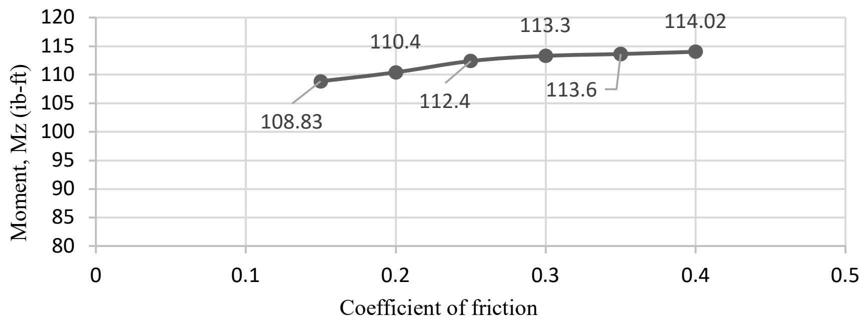
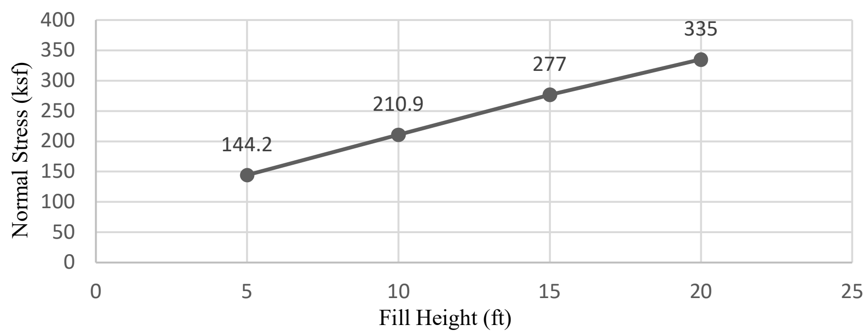


Figure 8: Relation between Maximum Bending moment vs Co-efficient of friction

From figure 8, it seems that there is no significant variation in the values of maximum mid span moment (Mx) with the change of frictional coefficient. However, value of 0.3 has been used for further study. Starting with the effect of fill height. Figure 9 illustrates the observed effects on the reference model. Fill heights ranging from 5 feet to 20 feet at 5-feet intervals were examined, with a focus on the bending moment at the midspan of the slab and normal stress. As expected, the maximum bending moment was observed at the midspan, which increases linearly with the culvert height. The increased fill height leads to additional soil load on the horizontal slab, resulting in an increased bending moment of the Z-axis. Figure 9 demonstrates the relationship between culvert normal stress along the Y-axis and with respect to fill height. Like the bending moment, normal stress increase with increasing fill height due to the additional load imposed on the culvert.



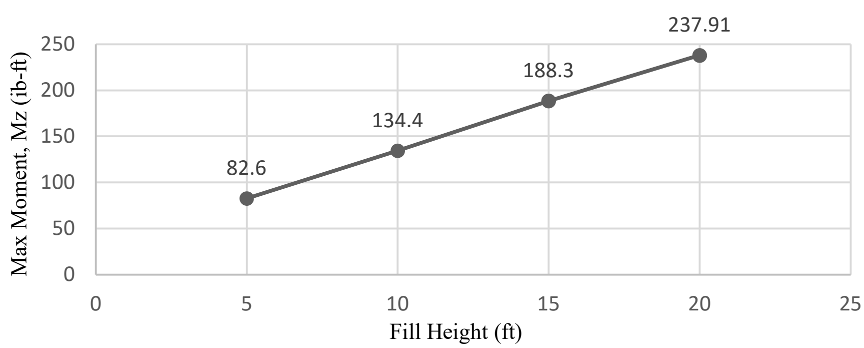


Figure 9: Relation between Maximum bending moment and Normal stress vs Fill height of Box Culvert

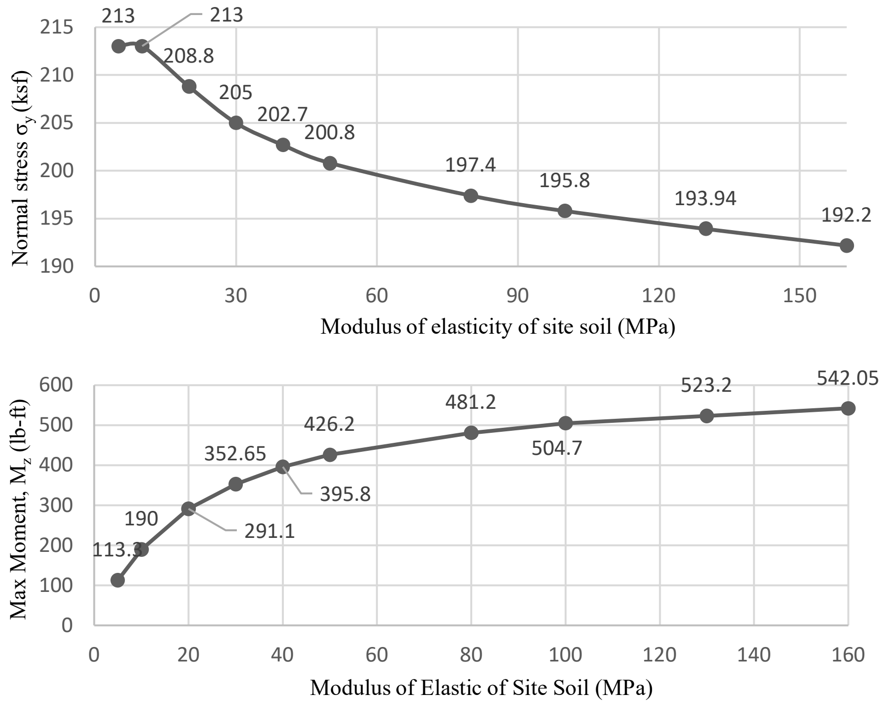


Figure 10: Relation between bending moment and Normal stress vs Modulus of Elasticity of soil

Another parameter investigated was the modulus of elasticity of the site soil (E_{site}). It was found to exert a significant influence on the culvert's moment (M_z) and axial force (F_x). Various analyses were conducted on the reference model using different E_{site} values within the range of 5 MPa to 100 MPa. Higher E_{site} values correspond to stiffer soil, while lower values represent softer soil. The remaining parameters of the reference model were kept unchanged.

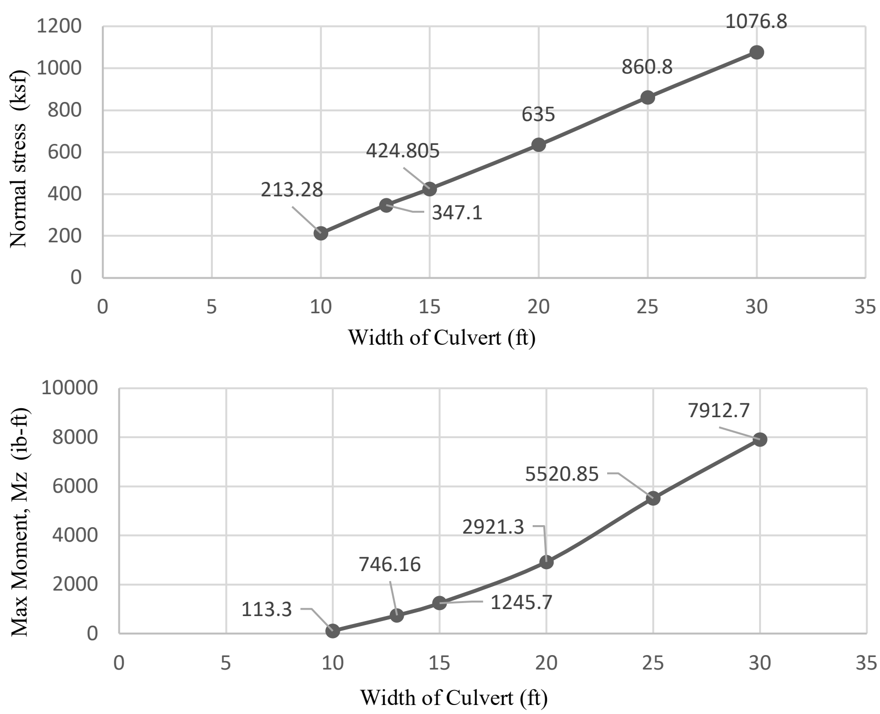


Figure 11: Relation between bending moment and Normal stress vs Culvert Width

A set of six culvert sizes, ranging from 10 ft X 10 ft to 30 ft X 30 ft, was selected to represent a comprehensive range. The fill height for all culverts was fixed at 10 ft. The roadway width and culvert span length remained constant during the analysis. The culverts were assumed to have a square shape, with equal dimensions of B feet X B feet, for the purpose of this parametric study.

Figure 11 illustrates the impact of culvert size on the maximum bending moment that results at the culvert's midspan for various values of B. It is clear from Figure 11 that as culvert size increases, so do the bending moment and the normal stress.

5. CONCLUSIONS

Throughout the investigation, the single cell buried box culvert finite element model was created and verified using previous computational and experimental findings. Variations in stress and bending moment were related to changes in several factors. Stress and bending moment measurements were performed in a longitudinal orientation (stream-facing). The study demonstrates unequivocally that when there is substantial stress fluctuation in the longitudinal direction, a two-dimensional analysis of a box culvert is insufficient. The current situation cannot be replicated by two-dimensional numerical analysis. Three-dimensional analysis is required in this situation. The distinctive impacts of the many factors that substantially affect normal stress and bending moment have been discovered. This impact must be considered throughout the design process. The parametric study reveals many factors, including fill height, soil elasticity modulus, and Culvert size. While some elements have a substantial impact on these, other parameters, such as the frictional coefficient between the soil and the concrete and the fill soil, have little or no impact on normal stress and bending moment.

REFERENCES

Allen, D. L., and Russ, R. L. (1978), "Loads on Box Culvert Under High Embankments: Analysis and Design Considerations," Report No. 491, Kentucky Department of Transportation, Lexington, Jan. 1978, pp 19

Alkhrdaji, T. and Nanni, A. (2000), "Design, Construction, and Field-Testing of an RC Box Culvert Bridge Reinforced with GFRP Bars", The Center for Infrastructure Engineering Studies, University of Missouri-Rolla, CIES 02-25, 2000

A. U. (2005), "Behavior of Buired Box Culvert in Fill Soil", M.Sc. Engineering Thesis, Department of Civil Engineering, BUET, Dhaka, 2005.

Jao, M., Ahmed, F., Nulwala, H. M. and Wang, M. C. (2003), "Footing-Induced Soil Pressure around Box Culverts" EJGE paper, www.eige.com.

Katona, M. G., Vittes, P. D., Lee, C. H., and Ho, H. T. (1981), "CANDE-1980: Box Culverts and Soil Models," Report No. FWHAIRD-80/172, Federal Highway Administration, Washington, D.C., May 1981, pp 214.

Okamura, H., and Tsuji, Y. (1974), "Behavior of Chemically Prestressed Concrete Members," Transactions, Japan Society of Civil Engineers, Tokyo, No. 225, May 1974, pp. 101-108.

Russ, R. L. (1975), "Loads on Box Culverts Under High EI ments: Positive Projection,Without Imperfect Trench," Report No. 431, Kentucky Department of Transportation, Lexington, Aug. 1975, pp 34.

Tadros, K. M., Benak, J. V. and Gilliland, M. K. (1989), "Soil Pressure on Box Culverts",ACI Structural Journal, Vol. 86, No.4, July-August 1989, pp. 439-450.

Tsuji, Y. and Miyake, N. (1988), "Chemically Prestressed Precast Concrete Box Culverts", Concrete International, ACI Journal, Proceedings Vol. 10, No.5, May 1988, pp. 76-82