# Comparison of 2D and 3D Finite Element Analysis of RC Blocks Culvert Based on Soil-Structure Interaction Using GTS

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## Abstract

This paper presents a comparison of soil-structure interaction based on 2D and 3D finite element analyses of 'Reinforced Concrete Box Culvert' by using the software GTS (Geotechnical and Tunnel Analysis System). For buried Structures like Box Culvert, the soil below the structure is to be simulated by elastic spring while surrounding and overlying soil by superimposed load combinations. GTS is the most advanced software, presenting a new paradigm for Box Culvert and other specific geotechnical structures. It is based on expert analysis and advanced graphic technologies. GTS enables engineers to intuitively generate complex geotechnical models. Such modeling capabilities are armed with strong analytic features, powered by a uniquely developed multi-frontal solver with the fastest analysis speed. The difference in values of forces and moments, between 3D FEA and 2D FEA, is more in large sections (10ft x 10ft) than in small sections (5ft x 5ft) of Box Culverts

**Keywords**—Reinforced Concrete Box Culvert, Geotechnical and Tunnel Analysis System (GTS), Buried Structure, Geotechnical Engineering Modelling, Soil-Structure Interaction

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## 1 Introduction

The Understanding soil-structure interaction is necessary for the study, design, and performance of underground structures connected to transportation infrastructure, such as buried culverts, grade crossings, and soil-structure systems. Without relying on the strength of the surrounding soil in a complicated interaction, buried constructions often are unable to withstand the loads, including soil, to which they are subjected. The kind, location, and placement of the backfill material, as well as the external loads, all have an impact on the soil-structure interaction of a buried structure. Other factors to consider are the structure's material, size, and stiffness. The most important concept in understanding buried structures can be explained by the fact that the structural actions of the 'liner' (that is the buried structure) and the soil cannot be separated [1]. The magnitudes of the interplay between soil and structure depend on the boundary loadings. Moreover, the relative stiffness of soil and liner is not a simple relationship but is different in axial and fleural modes of deformation and is also dependent on the sequencing of backfill materials and the construction techniques [2]. Finally, a buried structure (culvert, tunnel, underground tank, etc) in the soil at a given depth and boundary loading will behave quite differently depending on its shape. All these variables can become crucial to the design and must be considered. Therefore, in order to understand the soil-structure interaction, in the case of buried structures, it is required to model the surrounding soil/rock as a material [3]. The modern tool of analysis and design (GTS) of soil-structure interaction is based on Finite. Element Analysis is so powerful that with enough resources to run the computer, almost any combination of shape, static or dynamic external loading, and nonlinear or anisotropic material properties can be modeled successfully. For buried Structures, the soil-structure interaction based on 2D & 3D Finite Element Analysis has been studied by many researchers. They simulated the underneath soil with an elastic spring. Moreover, the surrounding and overlying soil/rock has been simulated by superimposed loads. Arup (2003) [4] was one of the first to develop geotechnical investigation-related finite element techniques. In order to solve all problems, he had separate 2D and 3D

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software. A review study by Far (2017) and Anand and Kumar (2018) [5, 6] focused on presenting and comparing various approaches and modeling techniques to evaluate Soil Structure Interaction effects on structures. Homaei (2021) [7] investigated the impact of the inelastic response of the soil–foundation interface on the seismic demand of structures supported by shallow foundations. E. Awwad et.al, (2000) [8] investigated three different concrete box culverts parametrically under various soil loading and covering conditions. SAP 2000 [9] software was to analyze the structure under the finite element method. The modeling for the culverts was done using shell elements with a degree of freedom at each node of 6 and the results showed that finite element analysis was very much compatible with AASHTO (American Association of State Highway and Transportation Officials) [10] plane frame analysis. In the study by Zhanping You et.al, (2001) [11] the response of concrete pavements at top of tunnels and culverts was studied with the use of finite element analysis. He found out that at top of concrete pavement, there may develop tensile stress which may result in concrete pavement failure. In the work by R. M. Bennett et.al, (2005) [12] concrete box culverts were the focal point, and vertical loads on top of it were studied in parallel to the soil-structure interaction factor recommended by AASHTO [10]. It was found using FEA that all the specifications and factors do provide a satisfactory amount of safety. Xiaoxi Liu et.al, (2008) [13] investigated the total settlement, with the help of finite element software, in the soil under a box culvert. It was found out the settlement of box culverts immensely influenced the elastic modulus of soil under the culvert [9]. Ali Abolmaali and Anil Garg et.al., (2008) [14] evaluated the shear behavior and capacity of the precast concrete box culverts subjected to HS 20 truck wheel load using finite element analysis. This study showed that the AASHTO provision with regard to the shear transfer device across the joint was unsupported. The findings of a parametric study of the load distribution in 108 four-sided precast concrete box culverts conducted by A. E. Awwad et al. (2008) [15] were given. The study included two- and three-dimensional plane frame analysis with three-dimensional Finite Element Analysis (FEA). According to the study, for soil covers of less than 0.9 m, edge loading conditions were more important than center loading for a single box, and the influence of wheel loading along the mid-span was also significant (3 ft). Based on geotechnical engineering principles, it is envisaged that the earth's loading will progressively take over as the soil cover increases. Anil K. Garg et.al, (2007) [16] presented an investigation of the shear strength of precast reinforced concrete box culverts using an experimental program. In order to simulate the HS20 truckload as per AASHTO 2005, each culvert was exposed to a monotonically rising load through a 254 mm 508 mm (10 in. 20 in.) load plate. Four tests on box culverts measuring 1.22 m by 1.22 m by 1.22 m (4 ft by 4 ft by 4 ft) were carried out. Reporting the loads at which each fracture began to form and spread is part of the test results. The load versus maximum deflection for each culvert as well as the displacement profile of the top slab from the laser instrumentation output were also presented. DE Cossio et al. (1959) [17] explored the basis for calculating moments and shears in culverts and similar constructions that include members with parts that can be regarded as infinitely stiff. Applications of the aforementioned standards to the specific design of one-celled reinforced concrete Box Culverts were made, together with suggestions for acceptable bond stresses and placement and spacing of reinforcement. The study by Dhadse et al. (2021) [18] aimed to explore the advantages and difficulties of using finite element modeling (FEM) in soil-structure interaction (SSI) problems. The authors reviewed the mathematical modeling of FEM and discussed the appropriate soil constitutive models needed to solve non-linear problems, specifically focusing on the interface between the foundation and the soil. According to Jahromi et al. and Jabini Asli et al. (2008) [19, 20] investigations, the sub-structure technique is ineffective at appropriately addressing the material and geometric non-linearity in complex and significant structures. They thus advocated the use of more complex soil models, such as the direct method, which takes into account both soil and structural non-linearity.

## 2 Experimental Program

### 2.1 Analysis of Culvert

The analysis deals with the study of soil-structure interaction with the help of GTS (software) for two typical sizes (5ft x 5ft & 10ft x 10ft) of Box Culverts, based on 2D and 3D Finite Element Analysis.

### 2.2 Properties of materials

The soil with the following material properties was taken to study the interaction of the culvert with the surrounding material:

- Modulus of elasticity of soil =138 ksf
- Poisson's ratio = 0.4
- Unit weight (dry) = 0.1155 kcf
- Unit weight (saturated) = 0.127 kcf

- Cohesion = 0.275 ksf
- Friction angle = 21o
- Tensile strength = 0.275 ksf
- Initial stress parameters = 0.64
- Modulus of sub-grade reaction =115 ksf

#### 2.2.1 Loads on 5 ft x 5 ft Culvert

Load on the model made up of 2D Finite Elements had been calculated as follows:

- $Roof Load = \gamma * H^{'}$
  $\sigma_v = 0.127 * 16 = 2ksf$
- $Wall Load = k_{o\gamma}(H + H^{'})$
  $\sigma_h = 0.64 * 0.127(6 + 16) = 1.79ksf$

Only self-weight was applied in the model comprising 3D Finite Elements.

#### 2.2.2 Loads on 10 ft x10 ft Culvert

Load on the model made up of 2D Finite Elements had been calculated as follows:

- $Roof Load = \gamma * H^{'}$
  $\sigma_v = 0.127 * 16 = 2ksf$
- $Wall Load = k_{o\gamma}(H + H^{'})$
  $\sigma_h = 0.64 * 0.127(11 + 16) = 2.2ksf$

Only self-weight was applied in the model comprising 3D Finite Elements.

### 2.3 Culvert geometry

The 2D Finite Elements Model had been developed by using shell elements. Linear elastic springs were provided under all nodes of the base slab equal to the product of contributing area and coefficient of modulus of sub-grade reaction. For stability of the structure, translations in principle horizontal directions were kept fixed and springs were provided only in the vertical direction. All three rotations were kept free as shown in Fig 1. In the 3D Finite Elements Model, the culvert had been developed by using shell elements and the surrounding soil had been modeled by using solid elements. For stability of the structure, translations in three principal directions were kept fixed. All three rotations were kept free as shown in Fig 2.

### 2.4 Loads on 2D Finite Element Model

A load of overlying soil was applied as uniformly distributed on the roof and triangularly distributed on the walls [11, 12] as shown in Fig 3.

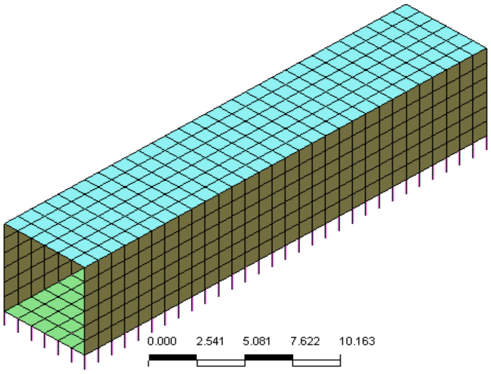

Fig. 1: Geometry of 2D FE Models

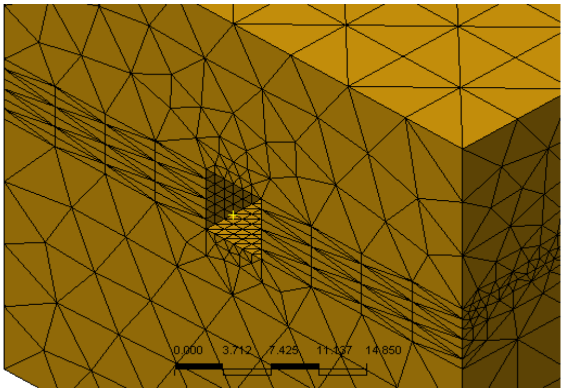

Fig. 2: Geometry of 3D FE Models

## 3 Results and Discussion

### 3.1 Finite element analysis on 5ft x 5ft culvert

2D and 3D Finite Element Analysis for a 5ft x 5ft culvert had been made on the basis of transverse moments and shear forces in the top slab, walls, and base slab. Results are given in Figures 4 to 15.

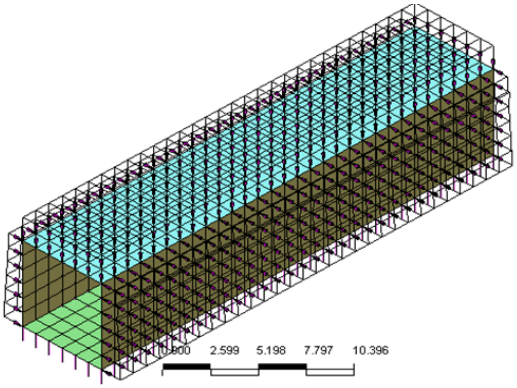

Fig. 3: Loads on 2D FE Model

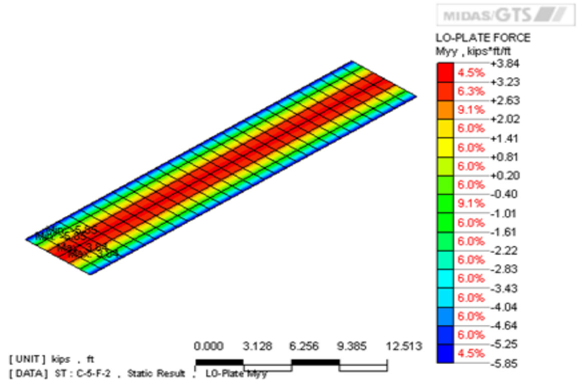

Fig. 4: Transverse moments in top slab in 2D FE Model (5ft x 5ft)

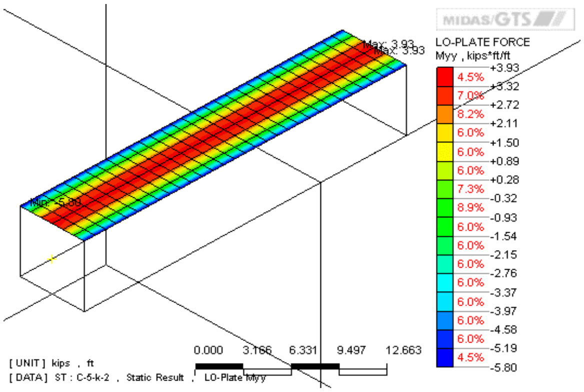

Fig. 5: Transverse moments in top slab in 3D FE Model (5ft x 5ft)

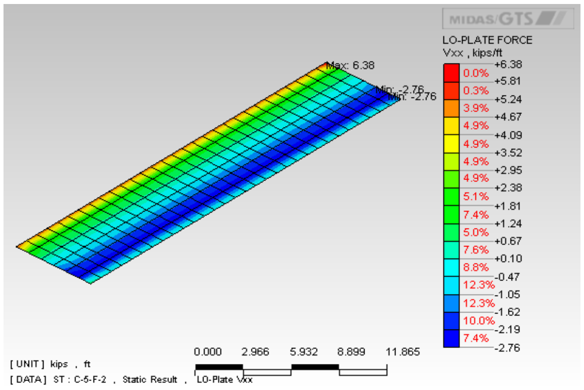

Fig. 6: Shear forces in top slab in 2D FE Model (5ft x 5ft)

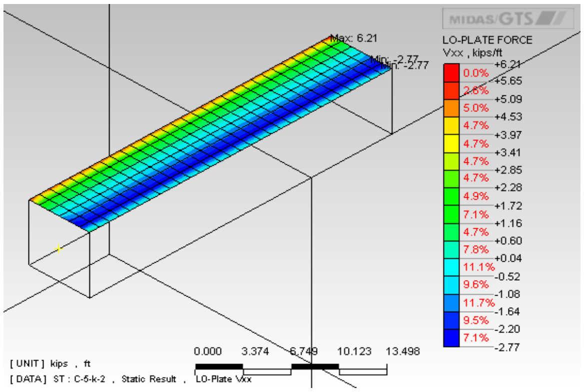

Fig. 7: Shear forces in top slab in 3D FE Model (5ft x 5ft)

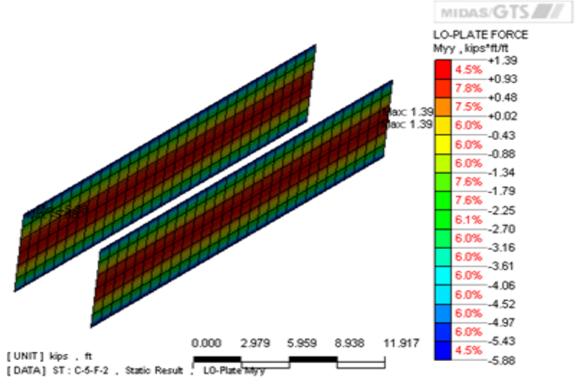

Fig. 8: Transverse moments in walls in 2D FE Model (5ft x 5ft)

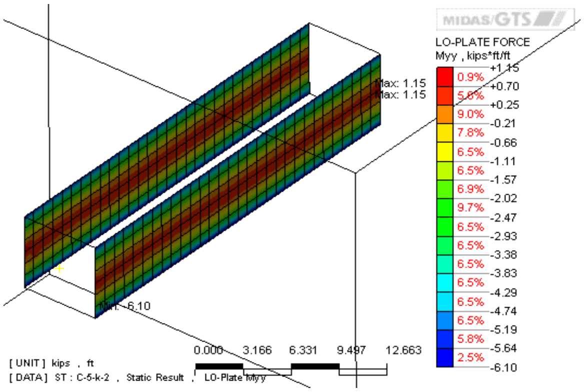

Fig. 9: Transverse moments in walls in 3D FE Model (5ft x 5ft)

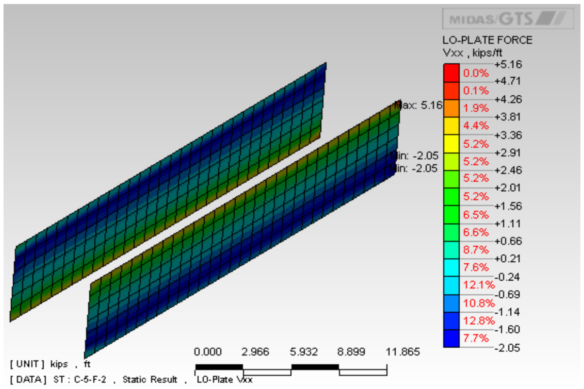

Fig. 10: Shear forces in walls in 2D FE Model (5ft x 5ft)

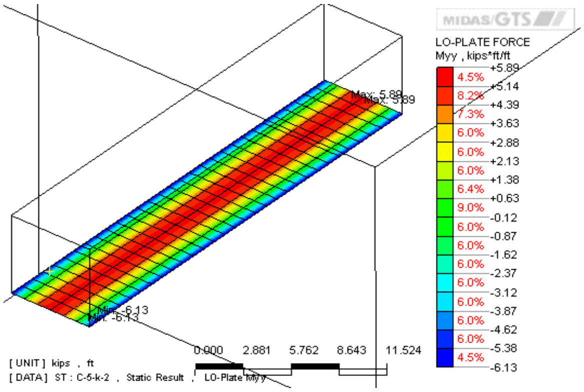

Fig. 13: Transverse moments in base slab in 3D FE Model (5ft x 5ft)

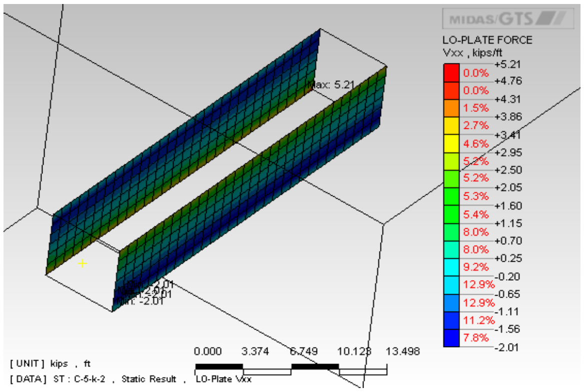

Fig. 11: Shear forces in walls in 3D FE Model (5ft x 5ft)

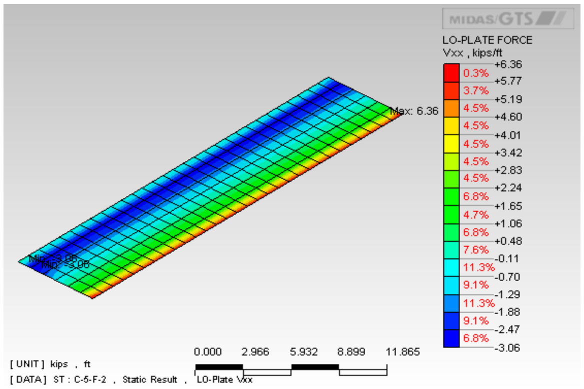

Fig. 14: Shear forces in base slab in 2D FE Model (5ft x 5ft)

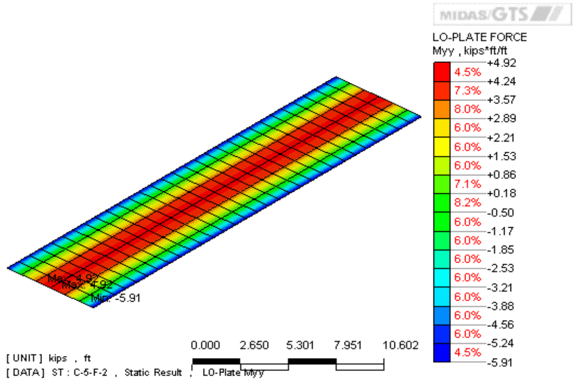

Fig. 12: Transverse moments in base slab in 2D FE Model (5ft x 5ft)

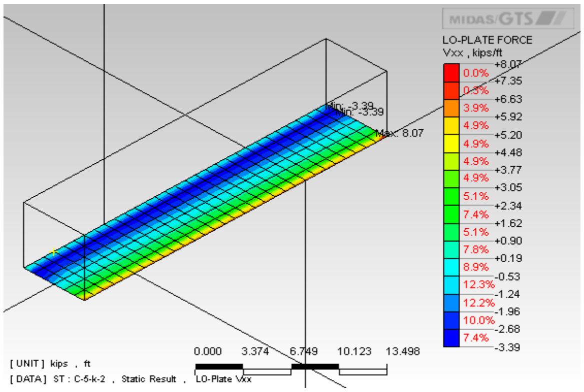

Fig. 15: Shear forces in base slab in 3D FE Model (5ft x 5ft)

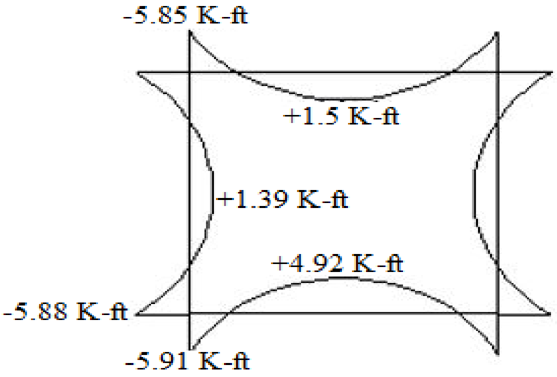

Fig. 16: Transverse moments in 2D FE Model

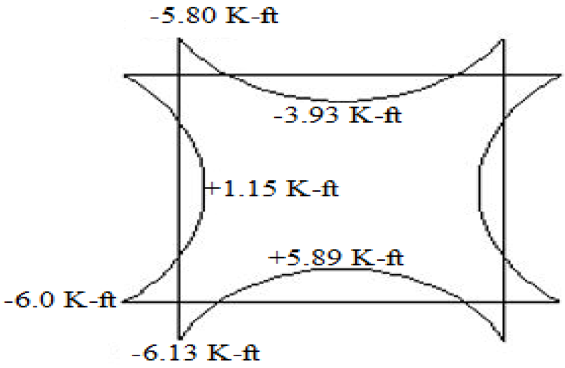

Fig. 17: Transverse moments in 3D FE Model

### 3.2 Comparison between 2D & 3D Analysis for 5ft x 5ft Culvert

The results of the 2D Finite Element Analysis of a 5ft x 5ft culvert as compared with the 3D Finite Element Analysis of the same section are represented in Figures 16 to 19 and summarized as follows:

1) In 3D FEA, the negative transverse moment in the top slab is reduced by 0.86%, the positive transverse moment is increased by 2.3%, and the sheer force is reduced by 2.86% as compared with 2D FEA.
2) In 3D FEA, the negative transverse moment in walls is increased by 2%, the positive transverse moment is reduced by 20%, and the sheer force is increased by 1.3% as compared with 2D FEA.
3) 4 In 3D FEA, the negative transverse moment in the base slab is increased by 3.72%, the positive transverse moment is increased by 18.7%, and the sheer force is increased by 2.5% as compared with 2D FEA.

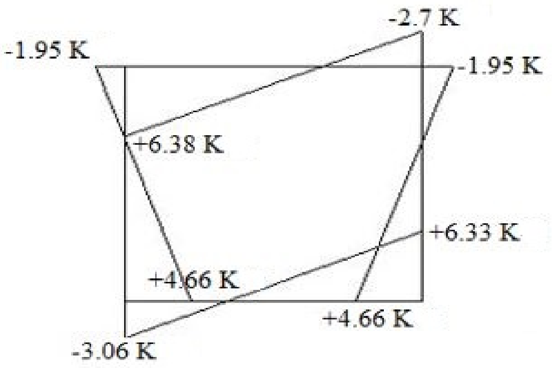

Fig. 18: Shear force in 2D FE Model

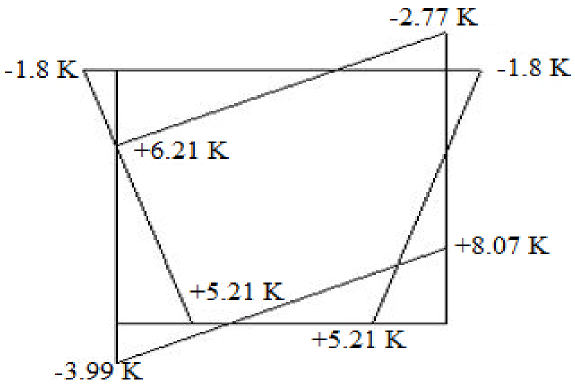

Fig. 19: Shear force in 3D FE Model

### 3.3 Reasons of finite element analysis of 10ft x 10ft Culvert

The figures 20 to 31 demonstrate the reasons of finite element analysis of 10ft x 10ft Culvert.

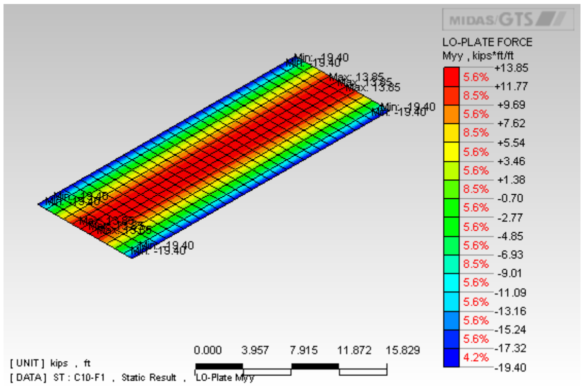

Fig. 20: Transverse moments in top slab in 2D FE Model (10ft x 10ft)

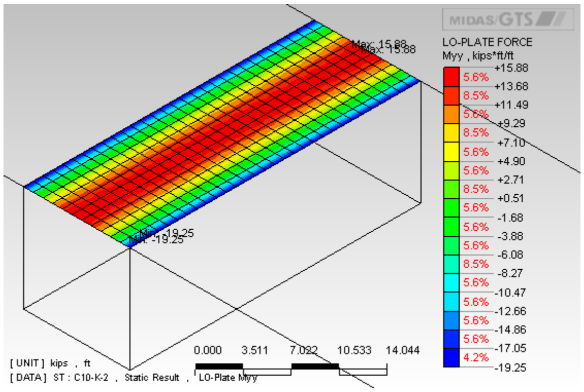

Fig. 21: Transverse moments in top slab in 3D FE Model (10ft x 10ft)

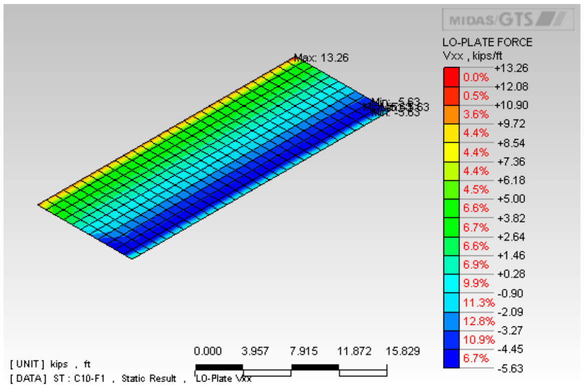

Fig. 22: Shear forces in top slab in 2D FE Model (10ft x 10ft)

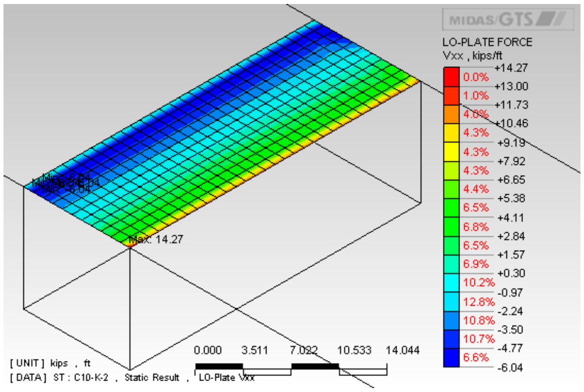

Fig. 23: Shear forces in top slab in 3D FE Model (10ft x 10ft)

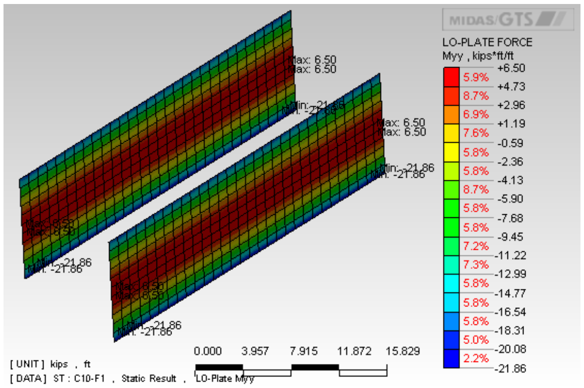

Fig. 24: Transverse moments in walls in 2D FE Model (10ft x 10ft)

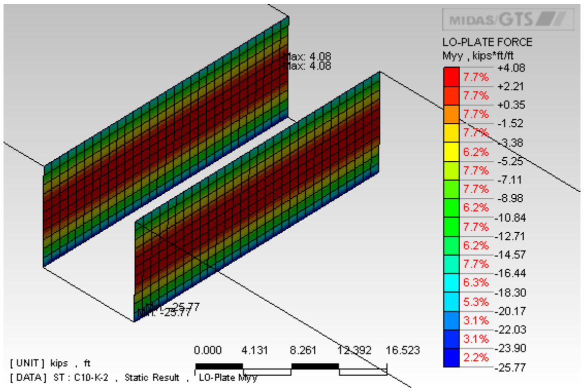

Fig. 25: Transverse moments in walls in 3D FE Model (10ft x 10ft)

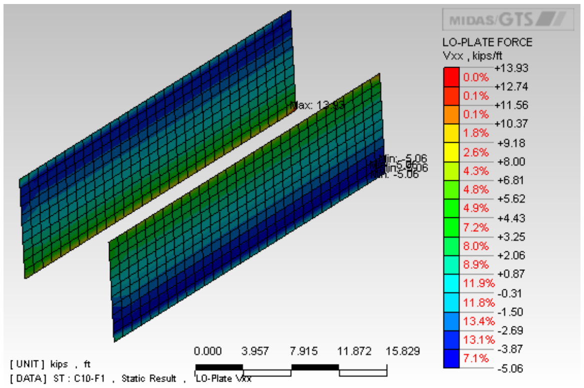

Fig. 26: Shear forces in walls in 2D FE Model (10ft x 10ft)

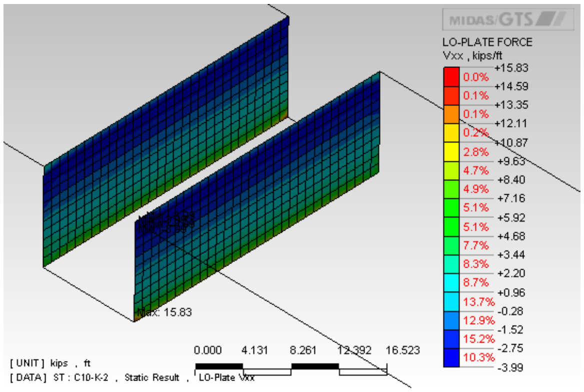

Fig. 27: Shear forces in walls in 3D FE Model (10ft x 10ft)

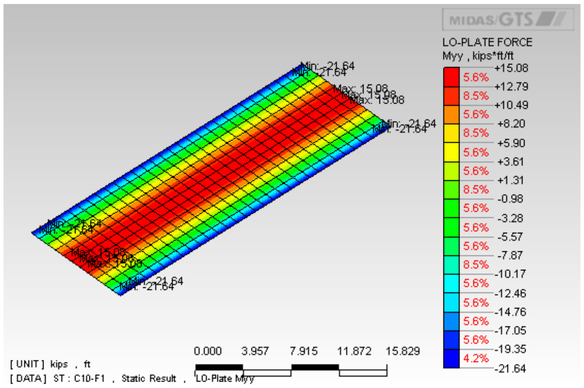

Fig. 28: Transverse moments in base in 2D FE Model (10ft x 10ft)

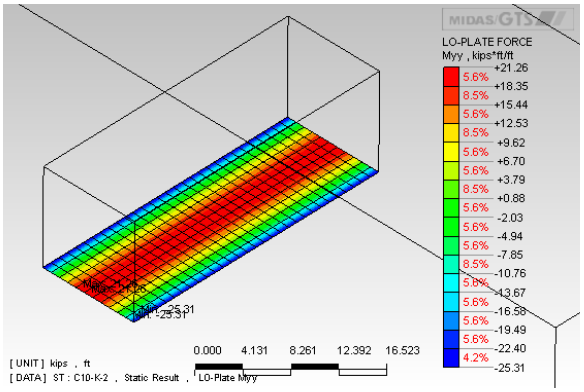

Fig. 29: Transverse moments in base in 3D FE Model (10ft x 10ft)

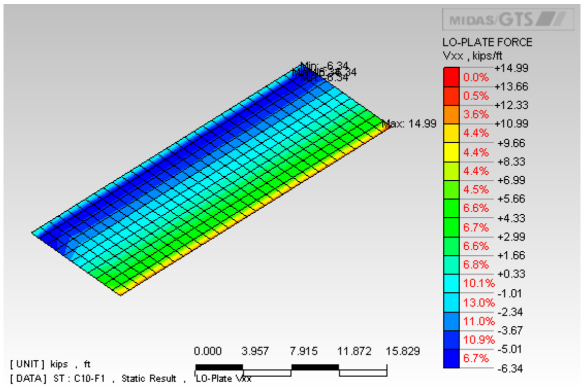

Fig. 30: Shear forces in base in 2D FE Model (10ft x 10ft)

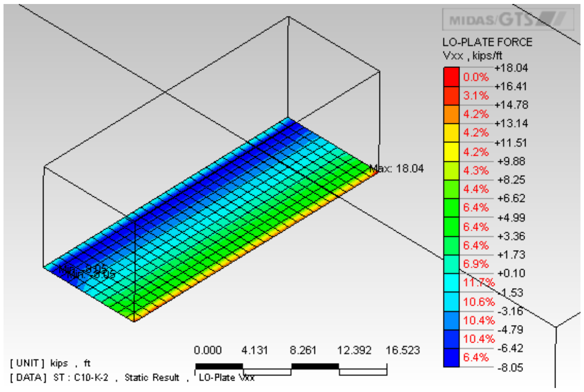

Fig. 31: Shear forces in base in 3D FE Model (10ft x 10ft)

### 3.4 Comparison between 2D and 3D analysis for 10ft x 10ft culvert

The results of 2D Finite Element Analysis of a 10ft x 10ft culvert as compared with 3D Finite Element Analysis of the same section are shown in Figures 32 and 33 and summarized as follows:

1) In 3D FEA, the negative transverse moment in the top slab is reduced by 0.78%, the positive transverse moment is increased by 14.66%, and the sheer force is increased by 7% as compared with 2D FEA.
2) In 3D FEA, the negative transverse moment in the walls is increased by 17.89 %, the positive transverse moment is reduced by 59.3%, and the sheer force is increased by 12% as compared with 2D FEA.
3) In 3D FEA, the negative transverse moment in the base slab is increased by 16.96%, the positive transverse moment is increased by 40%, and the

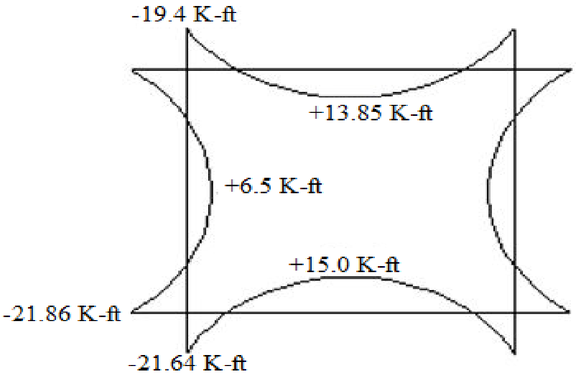

Fig. 32: Transverse moments in 2D FE Model

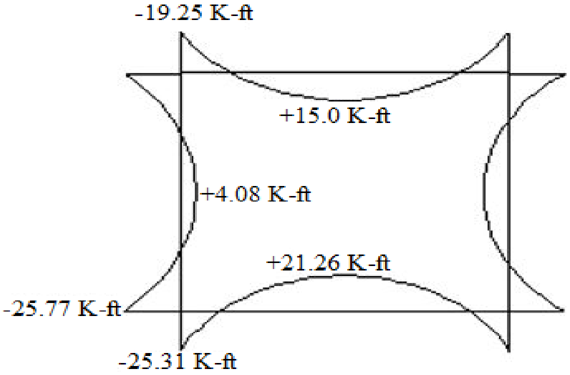

Fig. 33: Transverse moments in 3D FE Model

sheer force is increased by 16.9% as compared with 2D FEA

## 4 Conclusion

1) In 3D Finite Element Analysis of culverts, the values of forces and moments were slightly greater than 2D FEA. The minor difference in the results is due to selecting the conservative values of properties of soil.
2) The difference in the values of forces and moments, between 3D FEA and 2D FEA, in both types of structures, has been found to be more in large sections than small sections.
3) 3. The results obtained from 2D FEA or 3D FEA in Box Culverts were very specific with the properties of the materials mentioned & cannot be generalized. As the values of the properties of soil/rock have a very wide range, just changing the value of one parameter changes the behavior of the structure altogether. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions. Authors are strongly encouraged not to reference multiple figures or tables in the conclusion—these should be referenced in the body of the paper.

## References

[1] Swoboda, G., Laabmayer, F., and Mader I., Principles and developments in shallow tunnel construction, Part 2, Computers and Geotechnics, 3(1), 61-68, 1987.
[2] Read, R. S., Chandler, N. A., and Dzik, E. J., In situ strength criteria for tunnel design in highly-stressed rock masses, Int. Journal of Rock Mechanics and Mining Sciences, 35(3), 261-278, 1998.
[3] Kjartanson, B. H., Heilers, G. A., Lohnes R. A., and Klaiber, F. W., Soil-Structure Interaction Analysis of the Longitudinal Uplift of Culverts, Journal of Geotechnical and Geoenvironmental Engineering, 124(2), 128-139, February 1998
[4] Arup, "Finite Element Modeling of 3D Geotechnical Problems and Comparison with Simple Solutions", A Research Project of the Department of Civil, Environmental and Geomatic Engineering, University College London in collaboration with Arup, 2003.
[5] Far, H., "Advanced computation methods for soil-structure interaction analysis of structures resting on soft soils". Int. J. Geotechnical Eng. Vol. 13, pp. 352–359, 2019. https://doi.org/10.1080/19386362.2017.1354510
[6] V. Anand and S. R. Satish Kumar, "Seismic soil-structure interaction: A state-of-the-art review," Structures, vol. 16, pp. 317–326, 2018. https://doi.org/10.1016/j.istruc.2018.10.009
[7] F. Homaei, "Investigating the effects of inelastic soil–foundation interface response on the seismic demand of soil–structure systems," Canadian Journal of Civil Engineering, vol. 48, no. 2, pp. 202–219, 2021. https://doi.org/10.1139/cjce-2020-0059
[8] E. Awwad, M. Mabsout, S. Sadek, and K. Tarhini, "Finite element analysis of concrete box culverts," Eighth International Conference on Computing in Civil and Building Engineering (ICCCBE-VIII), pp. 1051-1053, 2000.
[9] CSI, "SAP2000 Integrated Software for Structural Analysis and Design," Computers and Structures Inc., Berkeley, California
[10] AASHTO (2002). AASHTO Standard Specifications for Highway Bridges, 17th Edition. American Association of State Highway and Transportation Officials, Washington, D.C.
[11] Z. You, Y. Xia, C. Hu, and B. Wang, "Finite element analysis of concrete pavements over culverts," International Journal of Geomechanics, vol. 1, no. 3, pp. 337–350, 2001..
[12] R. M. Bennett, S. M. Wood, E. C. Drumm, and N. R. Rainwater, "Vertical loads on concrete box culverts under high embankments," Journal of Bridge Engineering, vol. 10, no. 6, pp. 643–649, 2005.
[13] Xiaoxi Liu, Guoping Cen, Xu Wang, and Yitong Liu, "Settlement Prediction and FEM Analysis of Culvert Section under High-Filled Embankment", Pipeline Asset Management: Maximizing Performance of our Pipeline Infrastructure, pp. 71-82, 2008
[14] A. Abolmaali and A. Garg, "Shear behavior and mode of failure for ASTM C1433 Precast Box Culverts," Journal of Bridge Engineering, vol. 13, no. 4, pp. 331–338, 2008.
[15] E. Awwad, M. Mabsout, S. Sadek, and K. Tarhini, "Parametric study of load distribution in four-sided concrete box culverts," Bridge Structures, vol. 4, no. 2, pp. 99–107, 2008.

[16] A. K. Garg, A. Abolmaali, and R. Fernandez, “Experimental investigation of shear capacity of precast reinforced concrete box culverts,” Journal of Bridge Engineering, vol. 12, no. 4, pp. 511–517, 2007.
[17] DE Cossio,R. Diaz and Siess, “Development of Design Criteria for Reinforced Concrete Box culverts”, published by Illinois University Urbana, Department of Civil Engineering, Feb 1959.
[18] G. D. Dhadse, G. D. Ramtekkar, and G. Bhatt, “Finite element modeling of soil structure interaction system with interface: A Review,” Archives of Computational Methods in Engineering, vol. 28, no. 5, pp. 3415–3432, 2020. https://doi.org/10.1007/s11831-020-09505-2
[19] H. Z. Jahromi, B. A. Izzuddin, and L. Zdravkovic, “Partitioned analysis of nonlinear soil-structure interaction using iterative coupling,” Interaction and multiscale mechanics, vol. 1, no. 1, pp. 33–51, 2008. https://doi.org/10.12989/imm.2008.1.1.033
[20] S. Jabini Asli, H. Saffari, M. J. Zahedi, and M. Saadatinezhad, “Comparing the performance of substructure and direct methods to estimate the effect of SSI on seismic response of mid-rise structures,” International Journal of Geotechnical Engineering, vol. 15, no. 1, pp. 81–94, 2019. https://doi.org/10.1080/19386362.2019.1597560