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EVALUATION OF STRESS OF BOX CULVERT FOR AGRICULTURAL DAM

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ABSTRACT: The current design for culverts is based on a two-dimensional analysis and only addresses the internal forces of the culvert members in the cross-section. The stress of a culvert in the direction of the culvert axis has not been given much attention; thus, there are no specific guidelines or provisions for it in the current standards. In the case of a culvert under a fill-dam placed on a soft foundation, the differences in settlement along the culvert axis may cause bending stress or tensile stress at the bottom of the culvert in the culvert axis direction. When this stress is beyond the capacity of the culvert material, excessive deformation and cracks in the culvert can occur. In the present study, this issue was explored through both two-dimensional (2D) and three-dimensional (3D) finite element methods (FEMs). This study reveals that the 2D plane strain FEM, although it can model with soil-structure interaction, it is incapable of recognizing stress along the culvert axis. In contrast, the 2D plane strain FEM can determine that stress but can not consider the influence of soil-structure interaction. Meanwhile, the 3D FEM provides excellent soil-structure interaction and considers the actual shape of the structures. Based on the results, it was shown that the 2D FEM is unreliable in its assessment of the tensile stress along the culvert axis compared to the 3D FEM when the box culvert was placed on a soft, deep foundation. The findings also revealed that when the foundation was soft (the stiffness of the foundation was low), other parameters such as the height of the dam and the depth of the foundation had a significant effect on the tensile stress at the bottom of the box culvert in the direction of the culvert axis.

Keywords: Box culvert, 2D FEM, 3D FEM, Tensile stress, Soft foundation, Soil arching, Agricultural dam

1. INTRODUCTION

Culverts are structures that convey water from a reservoir through low fill dams in a controlled manner for a variety of purposes. Culverts are often used to oversee the water supply and drainage, to control floods, or to meet a combination of multipurpose requirements. Compared with other types of culverts, the box culvert has many advantages such as being simple in structure but strong, stable, easy to construct, and low in cost. In particular, it can be placed on soft soil by providing a suitable base slab projection to reduce the base pressure [1].

The stability of a culvert dramatically affects the safety of the earthfill and rockfill embankment dams that it passes. Any leakage from the culvert may create openings in the dam that may gradually become enlarged until partial or complete failure occurs. Another hazard is the possibility of the structural collapse of the culvert, almost certainly causing the failure of the dam [2]. Therefore, having greater insight into the stress-strain of culverts would yield useful information about successful designs that will ensure safe structures.

The actual behavior of a culvert is complicated due to its complex soil-structure interaction mechanism. Technological advances over the past years have allowed design methodologies to evolve from the pioneering work of Marston and Spangler in the 1920s to the modern-day FEM [3]. Several studies have been done on culverts using both 2D and 3D FEMs by many researchers. Since the late 1960s, the 2D FEM has been used to model and analyze culverts under the assumption of plane strain conditions. Brown [4] was the first to perform a 2D FEM for obtaining approximate solutions to plane problems of linear elasticity. After that, a 3D FEM was first performed by Allgood and Takahashi [5].

In practice, engineers prefer simple analyses, so the 2D modeling of culverts is more frequently employed than the 3D modeling. Nevertheless, some problems are encountered when evaluating the stress in a box culvert with the 2D analysis. With the dam-culvert system, the 2D plane stress analysis is acceptable for modeling the dam longitudinal-section comprising the culvert cross-section (Fig. 1a), and the 2D plane strain analysis is suitable for modeling the dam cross-section comprising the culvert longitudinal-section (Fig. 1b). For culvert applications, the 2D plane stress analysis does model soil-structure interaction or soil arching action due to the differences in the stiffness of the culvert and surrounding soil. Because the stiffness of the culvert is higher than that of dam soil, the relative settlement of the soil column directly above the culvert was less than that of the adjacent soil columns. This relative settlement generates friction forces or shearing stresses that are added to the weight of the central soil column, as shown in Fig. 1a. As a result, the soil layers in the central soil column undergo an arch shape deformation, and the soil pressure on the box culvert was increased, which is referred to as negative arching. However, in this 2D plane stress analysis is concerned solely with calculating the axial load, bending moments, and deflections of the culvert members in the culvert cross-section; that means the stress in the direction of the out-of-plane or the culvert axis has not been given much attention. Meanwhile, as mentioned above, the 2D plane strain analysis model the longitudinal-section of the culvert, so it is possible to obtain stress in the culvert axis. Nevertheless, this analysis does not model soil-structure interaction due to there are no differential settlements between the installed structure and the surrounding soft soil, as shown in Fig. 1b. Besides, the 3D analysis provides excellent soil-structure interaction and also takes into account the actual cross-sectional shape of the culverts, which the 2D plane strain analysis cannot do. Based on these concerns, the dam-culvert system should be modeled and analyzed with a 3D model to investigate the stress along the direction of the culvert axis. Ahmed [6] performed a 3D FEM to investigate the reason for the formation of cracks along the culvert axis of two box culverts and showed the inadequacy of the 2D modeling done by the consultants who designed them. It is notable that none of the current standards consider the influence of the soil-structure interaction on the stress developing in the direction of the culvert axis, except for some provisions for the minimum reinforcement or distribution reinforcement in that direction [7].

In fact, agricultural dams are sometimes located on foundations of low strength or on soft foundations. Then, tensile stresses can accumulate in the culvert as a result of bending caused by differential settlement along the direction of the culvert axis. This, in turn, may lead to the cracking of the culvert and the opening of joints when the stress exceeds the capacity of the material of the culvert.

The goal of the present study is to evaluate the stress of a box culvert placed on a soft foundation passing through an agricultural dam. The study also explores the effects of specific parameters, such as the dam height, foundation depth, foundation stiffness, and culvert stiffness, on the stress developing in the culvert axis. For this purpose, both 2D (plane strain and plane stress) and 3D FEMs were used to model the box culvert and the stress results were compared.

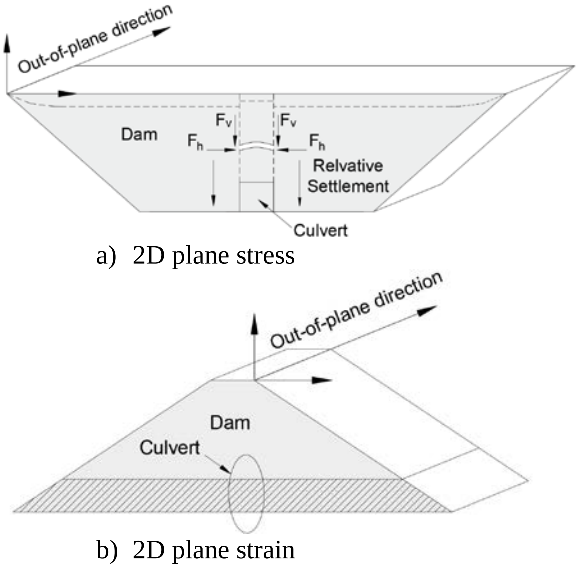

Fig. 1 2D (plane strain, plane stress) modeling for dam-culvert system

2. MATERIALS AND METHOD

2.1 Materials

One of the advantages of earth-fill dams is that they may be built upon soft soil foundations. However, the height of these dams should not be too high. In this study, therefore, a typical culvert with three dam models, having heights of 5, 10, and 15 m, was used to examine its stress, as sketched in Fig. 2. The depth of the foundation was chosen to be 5 or 10 m to suit the low earth-fill dam solution and also to investigate the impact on the stress of box culvert. The dimensions of these dam and culvert models were chosen according to the Design Standard of the Japanese Ministry of Agriculture, Forestry and Fisheries, and are listed in Table 1.

It is reasonable to assume that the deflection of the structure will be small, and that the displacement of the soil will be correspondingly limited due to the stiffness of the concrete box culvert. Consequently, the dam body, foundation, and box culvert were idealized as an isotropic, linear elastic constitutive model. Thus, each of these materials is characterized by the values of the elastic modulus and Poisson's ratio. Table 2 lists the values of the parameters used in all the models of the numerical analysis; almost all the values were taken from [8]. In order to assess the effect of the stiffness of the foundation, three elastic modules of the foundation (E_f), 2, 5, and 10 MPa, were tested. The effect of culvert stiffness was also evaluated through two elastic modulus values (E_c), 21 and 30 GPa.

2.2 Numerical Modeling

In the present study, the 2D and 3D analyses were built upon FEM. As mentioned in the Introduction, two types of 2D FEMs were used in this study, namely, 2D plane strain and 2D plane stress. The 2D plane strain FEM mesh, composed of 1,080 elements and 3,390 nodal points, is shown in Fig. 3. The 2D plane stress FEM mesh, composed of 1,273 elements and 3,993 nodal points, is shown in Fig. 4. All elements in the 2D FEM (plane strain and plane stress) are eight-node quadrilateral iso-parametric elements. For the 3D FEM, the dam, box culvert, and foundation underneath were discretized by 51,120 finite twenty-node hexahedral iso-parametric elements with 220,086 nodal points, as shown in Fig. 5. The mesh size for all the models was adjusted around the box culvert to improve the accuracy and the details of the stress distribution within the study area. Since the effect of the interface conditions was negligible with the soil-structure interaction in the embankment installation [9], no interface elements were used in this research to reduce the computational efforts.

For the 2D FEM, the nodal points along the vertical boundaries (z-direction) and the horizontal boundaries (x-direction for the dam cross-section in the 2D plane strain FEM and y-direction for the dam longitudinal-section in the 2D plane stress) were completely fixed. For the 3D FEM, the nodal points along the boundaries of the foundation in all models were constrained to not move in any direction.

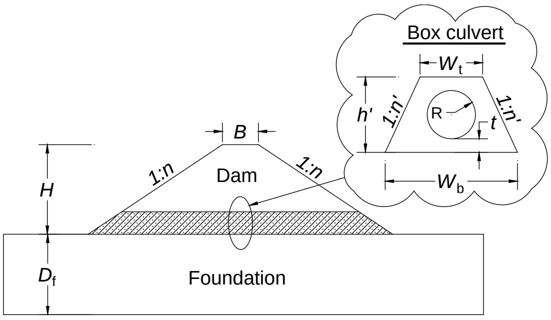

Fig. 2 Schematic illustration of typical dam-culvert-foundation system

Table 1 Dimensions of dam-culvert-foundation systems

Model	Dam			Box culvert						Foundation
	H (m)	B (m)	n	h' (m)	W_t (m)	W_b (m)	R (m)	t (m)	n'	D_f (m)
Dam A	5	3	1.8							
Dam B	10	4	2.1	1.2	1.2	1.44	0.3	0.2	0.1	5 , 10
Dam C	15	5	3.0							

Table 2 Material properties of the modeling

Material	E (MPa)	ν	ρ (kg/m^3)
Dam	16.8	0.3	2000
Culvert	21000, 30000	0.2	2400
Foundation	2, 5, 10	0.3	-

Note: E = modulus of elasticity, ν = Poisson's ratio, and ρ = mass density.

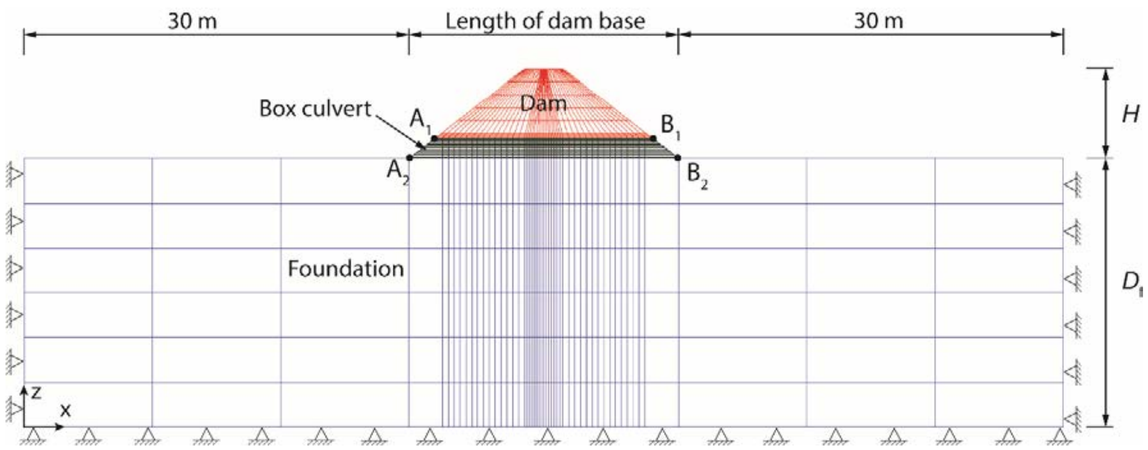

Fig. 3 Finite element mesh for dam cross-section (2D plane strain FEM)

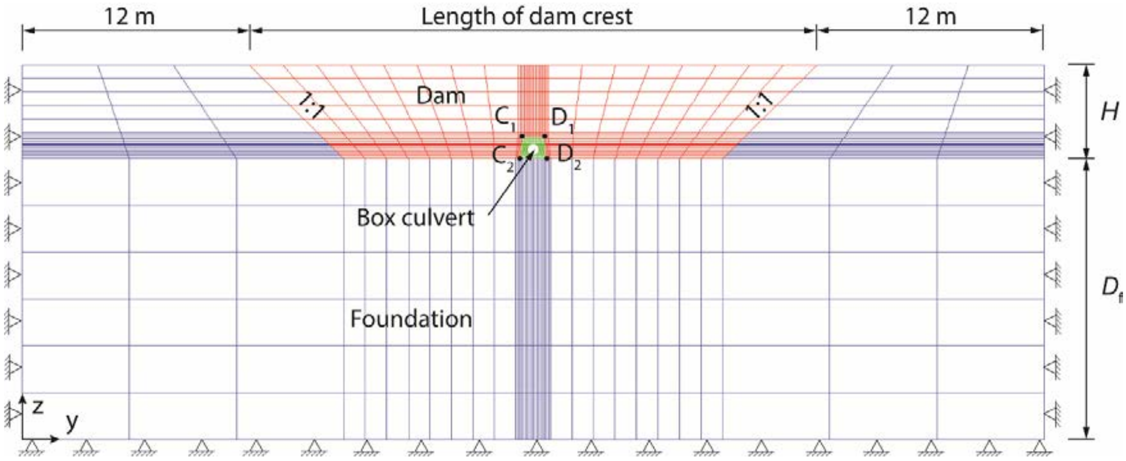

Fig. 4 Finite element mesh for dam longitudinal-section (2D plane stress FEM)

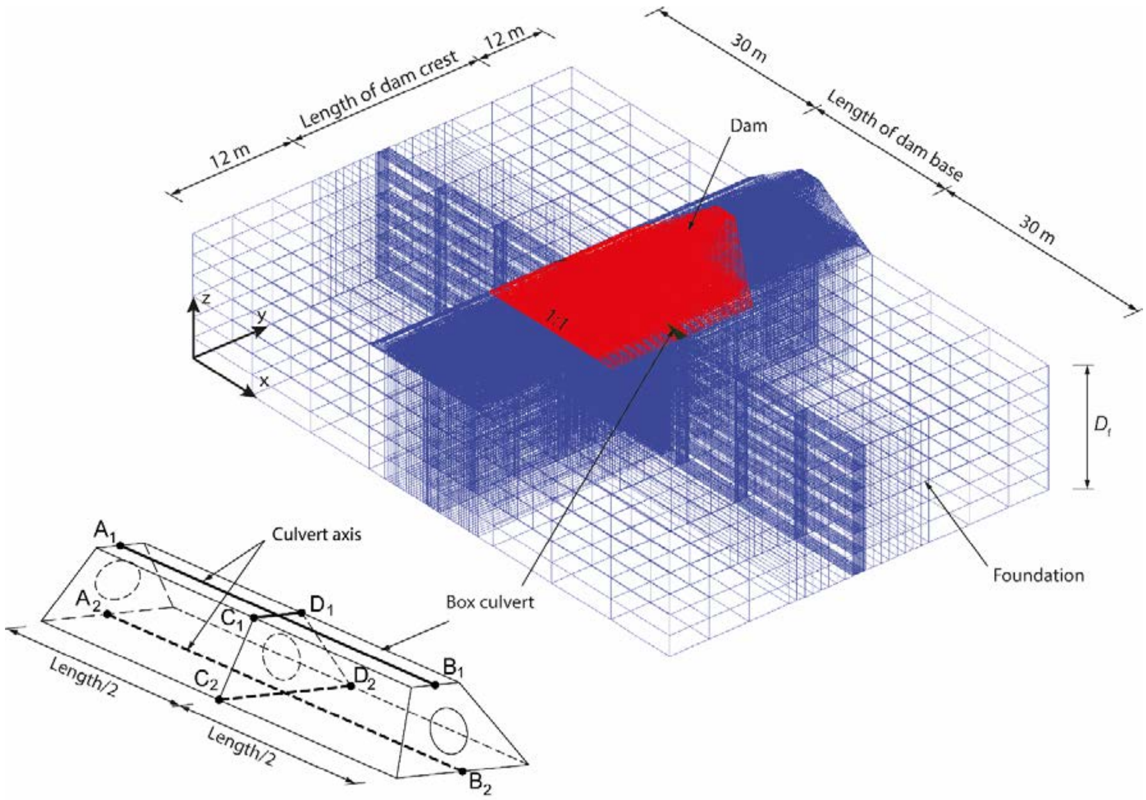

Fig. 5 Finite element mesh for 3D FEM

3. RESULTS AND DISCUSSIONS

The internal forces are affected by the external loads applied to the structure. In comparison to other structures, the external loads are known or specified. The external loads for buried culverts, namely, the earth pressure acting on the culvert, are complicated by the mechanism of the soil-structure interaction [3, 9, 10]. For culvert applications, soil-structure interaction is expressed primarily in terms of soil arching. As indicated in the Introduction, for embankment installation culverts, soil arching produces a negative arching effect, which leads to the vertical earth pressure on the culvert becoming higher than the overburden pressure. Therefore, the vertical earth pressure acting on the box culvert needs to be examined before evaluating the stress of the box culvert.

3.1 Vertical Earth Pressure σ_z

The vertical earth pressure is the earth pressure acting on the culvert top in the z-direction. These pressure were obtained along the culvert axis

(A_1B_1) and the culvert width (C_1D_1) at the top of the box culvert, as shown in Figs. 3, 4, and 5. Figure 6 shows the distribution of vertical earth pressure (σ_z) along A_1B_1 in the 2D plane strain and the 3D FEMs of three different dam models A, B, C. For all three models, given an elastic modulus of 21 GPa for a concrete box culvert (E_c) and a foundation depth (D_f) of 5 m, vertical earth pressure σ_z on the top of the culvert decreased when the stiffness or elastic modulus of the foundation (E_f) decreased from 10 MPa to 2 MPa in the 2D and 3D FEMs, which means the foundation became softer. The reduction was not significant, especially in the 2D plane strain FEM. The maximum values of vertical earth pressure σ_z were in the middle of A_1B_1, in 2D plane strain and 3D FEMs, but these values for the 3D FEM were higher than those for the 2D plane strain FEM. These differences were the result of the soil arching effect, which is covered in the 3D FEM but not in the 2D plane strain FEM, as mentioned in the Introduction. The vertical earth pressure σ_z on the box culvert in this 2D plane strain FEM was the overburden pressure, which calculated from the product of the unit weight of dam soil above the box culvert multiplied by the height of soil above the box culvert. Meanwhile, the 3D FEM fully reflected the actual behavior of soil around the culvert – soil arching action due to the differences in their stiffness. This led to vertical earth pressure that is significantly larger than the overburden pressure above box culvert.

The distribution of vertical earth pressure σ_z along C_1D_1 also decreased in the 2D plane stress and the 3D FEMs when the stiffness of the foundation (E_f) decreased or the foundation became softer in the three dam models, as shown in Fig. 7. This decrease was also not significant for the two methods. It is also seen in Fig. 7 that there was quite good agreement between the results of the 2D plane stress and 3D FEMs, and the maximum values of vertical earth pressure σ_z were at both ends of the width of the culvert top (C_1 and D_1). This is due to

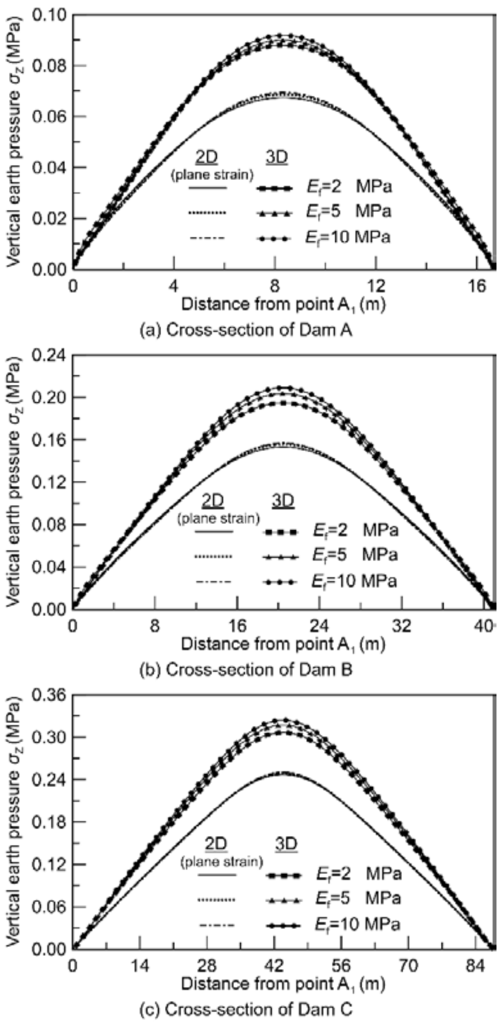

Fig. 6 Distribution of vertical earth pressure along A_1B_1 (D_f = 5 m, E_c =21 GPa)

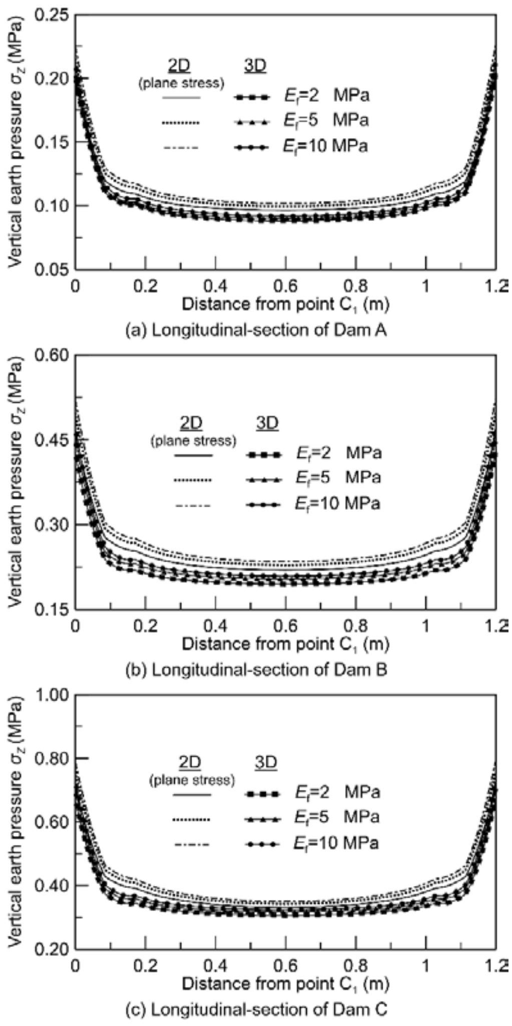

Fig. 7 Distribution of vertical earth pressure along C_1D_1 (D_f = 5 m, E_c =21 GPa)

the influence of soil arching action are expressed in both the 2D plane stress and 3D FEMs. As mentioned in the Introduction, the shearing stresses on the slip surface are added to the weight of the central soil column, resulting in vertical earth pressure had the highest values at both ends of the width of the culvert top. This result is also in full agreement with previous studies [6, 9, 11-17]. In contrast to the distribution along A_1B_1, the distribution results along C_1D_1 of the 2D plane stress FEM were slightly higher than those of the 3D FEM. This could possibly be the result of the idealization of the plane stress conditions, that is there is no stress in the out-of-plane direction, resulting in more conservative results than those of the 3D FEM.

When increasing the elastic modulus of the box culvert (E_c) from 21 to 30 GPa in the three dam models on the soft foundation (E_f = 2 MPa) with a depth (D_f) of 5 m, the vertical earth pressure along A_1B_1 and along C_1D_1 of the culvert top was almost unchanged in both 2D and 3D FEMs, respectively. Besides, the vertical earth pressure decreased slightly when the depth of the foundation (D_f) changed from 5 to 10 m with the elastic modulus (E_f) of 21 MPa.

3.2 Tensile Stress of the Box Culvert σ_x

Compared to the present study, most previous studies did not investigate the tensile stress in the culvert axis direction (σ_x), as mentioned in the Introduction. The tensile stress σ_x results for both 2D (plane strain and plane stress) and 3D FEMs were obtained along the culvert axis (A_2B_2) and the culvert width (C_2D_2) at the bottom of the box culvert, as shown in Figs. 3, 4, and 5. As predicted, the tensile stress σ_x at the bottom of the culvert was large when the stiffness of the foundation were low (E_f = 2 MPa) in the 2D and 3D FEMs, as shown in Figs. 8 and 9.

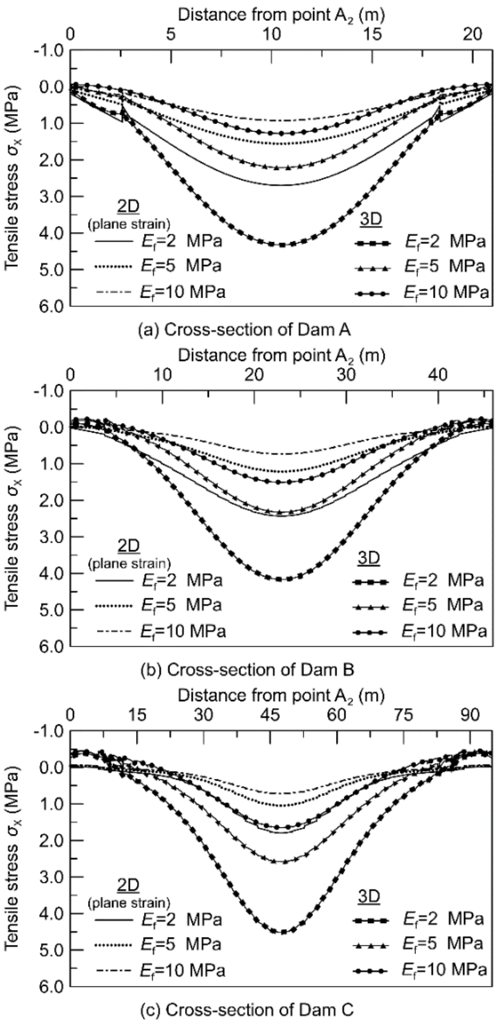

Fig. 8 Distribution of tensile stress σ_x of box culvert along A_2B_2 (D_f = 5 m, E_c =21 GPa)

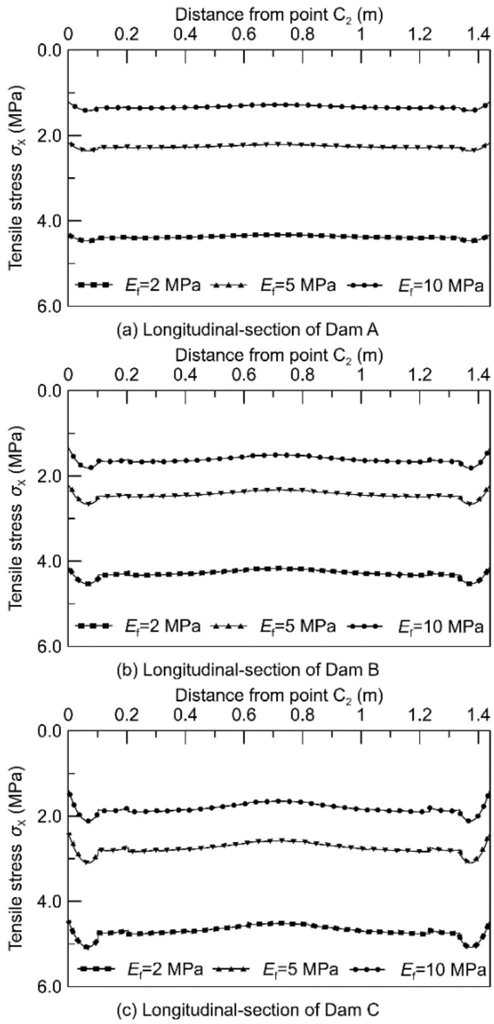

Fig. 9 Distribution of tensile stress σ_x of box culvert along C_2D_2 (D_f = 5 m, E_c =21 GPa)

Figure 8 shows the distribution of tensile stress σ_x along the culvert axis A_2B_2 at the bottom of the culvert when elastic modulus of the foundation (E_f) decreased from 10 MPa to 2 MPa or the foundation became softer. Similar to the vertical earth pressure, it is shown in Fig. 8 that the 3D FEM results were higher than those of the 2D plane strain FEM. The difference was even more marked when the dam is higher. The maximum values of tensile stress σ_x at the bottom of the box culvert were also found in the middle of culvert axis A_2B_2 at the bottom of the box culvert in both 2D plane strain and 3D FEMs. These values for the 5-m, 10-m, and 15-m dam models in the 3D FEM were, on average, 1.47, 1.89, and 2.42 times higher, respectively, than for the 2D plane strain FEM. This is because the 3D FEM had a greater external force, i.e., vertical earth pressure σ_z due to the soil arching effect, so the internal force, i.e., tensile stress σ_x at the bottom of the box culvert was also greater than that of 2D plane strain FEM.

Since the 2D plane stress FEM did not provide the stress in the out-of-plane direction (σ_x), hence Fig. 9 only shows the distribution of tensile stress σ_x along the culvert width C_2D_2 at the bottom of the culvert in the 3D FEM. It can be seen that all three dam models in the 3D FEM witnessed the highest tensile stress σ_x in two elements at both ends (C_2 and D_2) at the bottom of the box culvert. This is also due to the soil arching effect as mentioned above. These values for the A, B, and C dam models were 4.47, 4.53, and 5.08 MPa, respectively, which were higher than the tensile strength of the concrete box culvert (2.1-3.15 MPa). With elastic modulus of 21 GPa, the compressive strength of the concrete culvert is 21 MPa. The tensile strength of the culvert is usually approximately taken as 10–15% of its compressive strength [18]. These results suggest that tensile failure occurred in the 3D FEM, cracks could be formed in the box culvert as the tensile load is transferred to the steel. Meanwhile, for the 2D plane strain FEM in Fig. 8, the maximum values of tensile stress σ_x of dam models A and B were 2.7 and 2.43 MPa, all within the range of the tensile strength; in particular, the result of dam model C was 1.8 Mpa, which was lower than the tensile strength of the culvert material. In other words, for the 2D plane strain FEM, tensile failure likely occurred but uncertainty occurred in 3D, particularly in the case of a 15-m high dam (dam model C).

When the stiffness or elastic modulus of the box culvert (E_c) increased from 21 to 30 GPa, while the foundation was soft (E_f = 2 MPa) and had a depth (D_f) of 5 m, there was a significant change in tensile stress σ_x along line A_2B_2 at the bottom of the box culvert. Figs. 10 and 11 show the effect of the culvert stiffness on tensile stress σ_x along A_2B_2 for the case of a 10-m high dam (dam model B), the other dam models tended to be similar. It can be seen that when this parameter was large, the maximum tensile stress σ_x of the box culvert was also large in both 2D and 3D FEMs. The tensile stress σ_x in the culvert increased for 2D plane strain FEM, the maximum values were still much smaller than the tensile strength. Meanwhile, the results of the 3D FEM were in the range of tensile strength. The tensile strength of the concrete culvert is (4.1-6.15) MPa [18] as modulus elastic E_c is 30 GPa. Thus, it can be seen that although the stiffness of the box culvert parameter changed the tensile stress of the culvert, this change did not have much effect as the capacity of the culvert material also increased.

When the depth of the foundation (D_f) changed from 5 to 10 m and the stiffness of the foundation (E_f) and the box culvert (E_c) were 2 MPa and 21 GPa, respectively, tensile stress σ_x changed considerably in the 2D plane strain and 3D FEMs. However, the results of 2D plane strain FEM was still smaller than those of 3D FEM. Figs. 12 and 13 show the effect of the depth of the foundation on tensile stress σ_x along A_2B_2 for the case of a 10-m high dam (dam model B), the other dam models tended to be similar. Like the stiffness of the culvert parameter, the depth of the foundation parameter was large, the maximum tensile stress σ_x of the culvert was also large. When the foundation was 10 m deep, these values in both 2D and 3D were 4.14 MPa and 5.79 MPa, which were much greater than

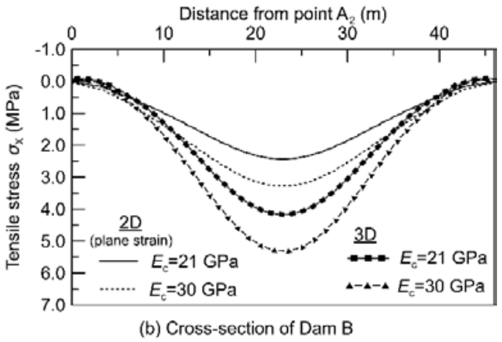

Fig. 10 Effect of stiffness of culvert on tensile stress σ_x of box culvert along A_2B_2 (D_f = 5 m, E_f =2 MPa)

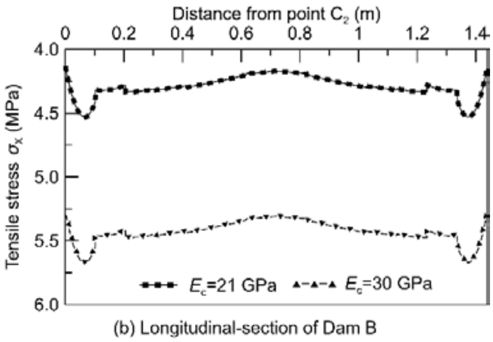

Fig. 11 Effect of stiffness of culvert on tensile stress σ_x of box culvert along C_2D_2 (D_f = 5 m, E_f =2 MPa)

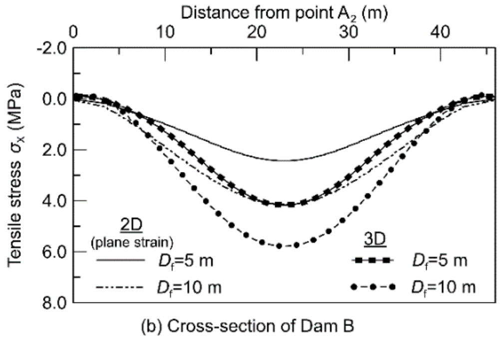

Fig. 12 Effect of depth of foundation on tensile stress σ_x of box culvert along A_2B_2 (E_f =2 MPa, E_c =21 GPa)

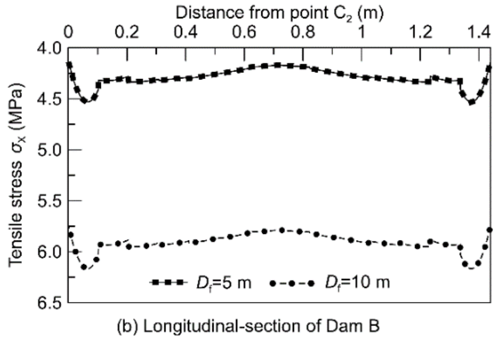

Fig. 13 Effect of depth of foundation on tensile stress σ_x of box culvert along C_2D_2 (E_f =2 MPa, E_c =21 GPa)

the tensile strength of the culvert material (2.1-3.15 MPa). This proves that when the foundation became softer and deeper, the tensile stress at the bottom of the box culvert was very large. In other words, the possibility of tensile failure of the box culvert was even more certain when the foundation depth parameter increased.

The results obtained in this study provided insight into the stress at the bottom of a box culvert on soft soil by carrying out 2D and 3D FEMs. The findings showed that the 2D FEM is unreliable for evaluating the tensile stress σ_x along the culvert axis when the box culvert is placed on a soft foundation. For the 2D plane stress FEM, the tensile stress σ_x is not considered due to the idealization of the plane stress conditions. As for the 2D plane strain FEM, the tensile stress is underestimated compared to the 3D FEM. This can lead to an unsafe design, the consequences of which can be dire, as indicated in the Introduction.

However, some limitations of the study should be acknowledged. One limitation of this study is that the material models (dam soil, foundation, and culvert) only considered the linear behavior. Furthermore, these findings are limited in that is the study was primarily focused on the loading due to the dam body's and box culvert's weight and did not explore other loadings (seepage loading or dynamic loading). This means that the study did not adequately consider the problems that can appear in real situations. These limitations should be addressed in future studies.

4. CONCLUSIONS

In this study, through an analysis of linear elasticity, which is the most commonly used analysis in current engineering practice, both 2D and 3D FEMs were conducted to model a box culvert placed on a soft foundation and to evaluate the tensile stress that had developed at the bottom of the culvert in the direction of the culvert axis. Several parameters for the dam, foundation, and culvert were also investigated to consider the effects on these stresses. The following conclusions can be drawn from the current study.

The lower the stiffness of the foundation (E_f) and the deeper the depth of the foundation (D_f), the higher the tensile stress σ_x at the bottom of the box culvert in the direction of the culvert axis. These values for the 3D FEM could be higher than the tensile strength of the box culvert material, while those for the 2D plane strain FEM were not. The 2D FEM was shown to be unreliable for evaluating tensile stress σ_x at the bottom of the box culvert in the culvert axis direction when the foundation was soft and deep. Parameters such as the height of the dam (H), and the depth of the foundation (D_f) had a significant effect on tensile stress σ_x at the bottom of the box culvert in the direction of the culvert axis. In particular, when these parameters increased, tensile stress σ_x also increased.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] Kattimani K. S. and Shreedhar R., Parametric Studies Of Box Culverts, International Journal of Research in Engineering and Science, Vol. 1, No. 1, 2013, pp. 58–65

[2] Reclamation U.B.O., Design of small dams, Water Resources Technical Publication, 1987, pp. 435-489.

[3] Katona M.G., History of Soil-Structure Interaction Models for Buried Culverts, Culverts and Soil-Structure Interaction, Transportation Research Circular, Vol. 3, No. E-C230, 2018, pp. 13–20.

[4] Brown C.B., The Forces on Rigid Culverts under High Fills, Journal of the Structural Division, Vol. 93, Issue 5, 1966, pp. 195-214.
[5] Allgood J.R. and Takahashi S.K., Balanced Design and Finite-Element Analysis of Culverts, Highway Research Record, No. 413, 1972, pp. 45-56.
[6] Ahmed B., Amanat K.M., Saflullah A.M.M. and Choudhury J.R., Causes of Cracking of Culverts on Filled Soil and Their Performance after Repair, Journal of the Civil Engineering Division, Vol. 30, No. 1, 2002, pp. 1-12.
[7] Ahmed A. U. and Amanat K. M., Need of 3D Finite Element Analysis for Buried RC Box Culvert in Fill Soil, Proceedings, Annual Conference - Canadian Society for Civil Engineering, Vol. 3, 2008, pp. 2078–2087.
[8] Tran D.Q., Nishimura S., Senge M. and Nishiyama T., Research on Cause of Dam Failure from Viewpoint of Hydraulic Fracturing-Case Study of a Dam Failure in Vietnam, International Journal of GEOMATE, Vol. 14, No. 41, 2018, pp. 86–94.
[9] Kim K. and Yoo C. H., Design Loading on Deeply Buried Box Culverts, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 131, No. 1, 2005, pp. 20–27.
[10] Bennett R.M., Wood S.M., Drumm E.C. and Rainwater N.R., Vertical Loads on Concrete Box Culverts under High Embankments, Journal of Bridge Engineering, Vol. 10, No. 6, 2005, pp. 643–649.
[11] Katona M. G. and Vittes P. D., Soil-Structure Analysis and Evaluation of Buried Box-Culvert Designs, Transportation Research Record, No. 878, 1981, pp. 911-930.
[12] Ngambi S., Nakano R., Shimizu H. and Nishimura S., Cause of Leakage along the Outlet Conduit Underneath a Low Fill Dam with Special Reference to Hydraulic Fracturing, Transactions of the Japanese Society of Irrigation, Drainage and Reclamation Engineering, Vol. 1997, No. 188, 1997, pp. 263-272.
[13] Pimentel M., Costa P., Félix C. and Figueiras J., Behavior of Reinforced Concrete Box Culverts under High Embankments, Journal of Structural Engineering, Vol. 135, No. 4, 2009, pp. 366–375.
[14] Abuhajar O., Newson T. and El Naggar H., Scaled Physical and Numerical Modelling of Static Soil Pressures on Box Culverts, Canadian Geotechnical Journal, Vol. 52, No. 11, 2015, pp. 1637–1648.
[15] Abuhajar O., El Naggar H. and Newson T., Static Soil Culvert Interaction the Effect of Box Culvert Geometric Configurations and Soil Properties, Computers and Geotechnics, Vol. 69, 2015, pp. 219–235.
[16] Abuhajar O., El Naggar H., and Newson T., Numerical Modeling of Soil and Surface Foundation Pressure Effects on Buried Box Culvert Behavior, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 142, No. 12, 2016, pp. 4016072(1-13).
[17] Tao Q., He Z. and Jia Y., Influence of Filling Properties and Culvert Structure Parameters on the Soil Arching Effect of Upper-Buried-Type Culverts, Results in Physics, Vol. 16, 2020, pp. 103003(1-15).
[18] Mehta P. K. and Monteiro P. J. M., Concrete microstructure, properties and materials, 4th ed, McGraw Hill, New York, 2017, pp. 1-120.

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