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THE INVESTIGATION OF STRUCTURAL PERFORMANCE OF MULTI-CELLULAR BOX CULVERTS USING COMPUTER PACKAGES

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ABSTRACT

In this work, three types of reinforced concrete box culverts were considered to investigate the structural performance using the structural analysis program SAP2000 and ETABS18. The discharge was calculated from a hydrological study and the dimension of box culverts were obtained through hydraulic study. Different load cases and their combinations were considered as follows: dead loads, vehicular lives load, surcharge, water, and soil pressures. The soil was modeled as springs with various springs' stiffness represented by the modulus of subgrade reaction. The results obtained from structural analysis were illustrated in graphical presentations to study the structural performance of the three types of box culverts Types 1, 2, and 3. It was taken the variations of internal forces (bending moments, shear, and axial forces) versus the height of internal and external walls for the three types of box culvert. The design of box culverts components was carried out using load resistance factor design (LRFD) according to the American Association of State Highway and Transportation Officials (AASHTO). From the variation of internal forces, it was concluded that box culvert Type 2 has the best performance compared with the other two box culverts. It is recommended to design wing walls to facilitate the discharge in the box culverts and a considerable amount of studies should be conducted for engineering studies.

KEYWORDS: Structural performance, box culvert, SAP2000, ETABS18, AASHTO, and LRFD.

INTRODUCTION

Box culverts are economical due to their rigidity and monolithic action and separate foundations are not required since the bottom slab rests directly on the soil, service as a raft slab. For small discharges, a single-celled box culvert is used and for larger discharges, multicellular box culverts can be employed. The barrel of the box culvert should be of sufficient length to accommodate the carriageway and the curbs.

The first paper presents the use of ABAQUS software to investigate the shear capacity of precast concrete box culverts and the results obtained were compared with the experimental models. The load-deflection curves from the 3D dimensional finite elements analysis compared with experimental results were practically suitable.[1]

The second paper introduces the structural response of R. C. box culverts by conducting numerical and experimental models. It was found that the nonlinear analysis of the box culvert showed good consistency with the observed behavior which affects the design stage.[2]

The third paper experimentally studies the shear capacity of different reinforced concrete box culverts by applying Hs20 truckload at varied positions to determine the maximum shear stresses and strains.[3]

The fourth paper is concerned with the evaluation of the soil-structure interaction manner of concrete box culverts buried to big depth using finite element analysis with various heights of backfill.[4]

The fifth work investigates the load- rating of two 2D box culvert models by the use of live-load data with varied embankment depth. The variations in moments were observed and with the improvement of models precision, it was found that the structural frame was not very accurate.[5]

The next work experimentally evaluates the shear capacity of 6 precast reinforced concrete box culverts using AASHTO HS 20 truckload applied at the varied position of the top slab to determine the critical shear section. It may be concluded that the shear behavior is not governing factor in the design of the box culvert.[6]

Another study investigates the nonlinear finite element analysis of box culverts with various dimensions the thicknesses under varied embankment heights. Simple linear regression formula was conducted to predict the dimensions for any soil fill height.[7]

The paper introduces the impact of the soil-structure interactions related to design methods (Working stresses and Strength) according to AASHTO standard specifications. With the increase in soil pressure, it is better to use the strength design method which will result in saving materials.[8]

Another study fixes at 3D finite element analysis taking into account the soil-culvert systems. It was observed that the obtained results of dynamic response were more accurate.[9]

The next work investigates the experimental and finite element models of box culverts under various load conditions using ABAQUS-V6.14-4 software. It was found that the load-deflection curves obtained by both experiments and finite element analysis are not vital.[10]

This work investigates the structural response of box culverts taking into account various compressibility conditions. The soil was modeled as springs with various spring stiffness represented by the modulus of subgrade reaction. The variations of axial forces, shear forces, torsion, and spring settlement were considered for highly compressible soils.[11]

This study fixes on soil-structure interaction utilizing finite element analysis by CANDE and centrifuge modeling technology.[12]

Another study investigates the structural behavior of precast concrete three-sided culverts utilizing 2D finite element analysis and field measurements. It was noticed that collapse may occur at the lowest backfill height of the non-yielding foundation case relative to the resulting yielding foundation case.[13]

This research conducts experimental and numerical methods of performance verification of embankment and trench installation box culverts through soil-structure interaction. It was suggested to take the impact of soil arch in the design of trapezoidal trench installation culverts.[14]

This research aims to study seismic soil-structure interaction between sandy soil of two various relative densities and buried box culverts and foundations.[15]

Another work aims to study the shear capacity of two r. c. box culverts with a uniform distributed load on the top slab. The study was done using experimental and verified numerical models and the results of shear strength between numerical models and ACI 318-14 formulae differed.[16]

This work concentrates on studying experimental and numerical checks of the shear capacity of r. c. box culverts utilizing AASHTO specifications and ACI 318-14 code.[17]

The next work is concerned with the structural behavior of a low-embankment box culvert under static and truck loadings that influences roadway sections. It was noticed that the values of deflections gradually increased through the roadway sections under static load and more deflections resulted when the truck moved at a higher speed.[18]

In this work, the finite element analysis of box structures of straight and circular shapes of haunches was done using ANSYS program. It was noticed that circular haunches gave good results in stresses and deflections compared with straight haunches.[19]

Another study concentrates on the structural design of box culverts of various shapes and sizes that are subjected to identical traffic load and other different load cases utilizing STAAD PRO software. The results of structural design by software have a good agreement with manual calculation using MATLAB.[20]

Another paper aimed to study the effect of loading distribution in various precast box culverts of different dimensions and spans length utilizing 3D finite element analysis and 2D plane frame analysis. The AASHTO HS-20 truckload is applied at the center and edge of the deck slab. It was noticed the 2D frame analysis underestimates the values internal forces compared with 3D finite element analysis.[21]

The final work aims to establish a computerized design method of single-cell precast concrete box culverts according to AASHTO requirements for the ultimate strength approach. The analysis of single-box culverts under various loading conditions was carried out using the stiffness method program.[22]

OBJECTIVES

The paper is aimed to study the structural performance of three types of multi-cell box culverts under load cases and their combinations utilizing two structural programs SAP2000 and ETABS18 taking into account the variations internal forces distributions and design of box culverts elements.

MODELS AND ANALYSIS

This study is concerned with calculating the value of discharge passers-by the culvert throughout its operation. Also, to determine the value of the maximum discharges which are expected to pass and the period of passage for use in determining the shape and dimensions of the various parts of the culverts. In this work, the discharge is calculated using the Manning equation. The hydraulic study and general data of the box culvert are tabulated as shown in Table 1.

Table 1: Hydraulic characteristics and general data of box culverts.

Parameter	Value
Length of cross-section ($\mathbf{L_C}$)	10 m
The height of creek (**H**)	2 m
Sectional Area (**A**)	20 m^2
Wetted perimeter $\mathbf{P = (L_C + 2H)}$	14 m
Manning coefficient (**n**) for clay channel	0.03
Flow Velocity by Manning equation $\mathbf{V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}}$	1.34 m/s
Discharge **Q = V. A**	26.8 m^3/s
Box culvert area ($\mathbf{A_B}$) = $\mathbf{\frac{Q}{V}}$	18.74 m^2
Flow width $\mathbf{B = \frac{A}{H}}$	10 m
The assumed box culvert width	2.5 m
The box culvert height	4m
Allowable bearing capacity of the soil	200 kN/m^2
The soil density (γ_s)	19 kN/m^3
The friction angle (θ)	35˚

In this investigation, three types of box culverts with various numbers of cells were considered as illustrated in Table 2. The loads applied to those structures were calculated manually. The applied load cases were categorized as self-weight, wearing surface, lateral earth pressure, water pressure, vehicular live load, and surcharge as illustrated in Table 3. Details of application and calculation of Design vehicular live load are explained in “AASHTO Bridge Design Specifications Cl 3.6.1.2”. It was suggested to use HL-93 as vehicular live load.Various load combinations are considered in this work to obtain the maximum internal forces on box culverts.

The box culverts were analyzed as 3D shell elements using SAP2000 and ETABS18. The program ETABS18 was used to verify the results obtained by SAP2000. The program SAP2000 was taken as a basic reference for the comparison of internal forces. Figures 1- 3 illustrate the configurations of the three mentioned types of box culverts.

Table 2: Box Culvers Geometry.

Parameter	Box Culvert Type (1)	Box Culvert Type (2)	Box Culvert Type (3)
Box dimensions	4m x 2.5m	4m x 3.3m	4m x 2 m
Number of boxes	4 boxes	3 boxes	5 boxes
Thickness of slab	200 mm	250 mm	200 mm
Thickness of wall	200 mm	200 mm	150 mm
Thickness of footing	400 mm	400 mm	400 mm

Table 3: Applied loads on three types of box culverts.

Applied Load	Elements of Box Culvert		
	Slab kN/m^2	Wall kN/m^2	Mat footing kN/m^2
Self- weight (S.W)	4.8	19.2	9.6
Wearing Surface(W.D)	1.1	N/A	N/A
Lateral Earth Pressure (E.H)	N/A	32.4	N/A
Surcharge	N/A	2.71	N/A
Water pressure (W.P)	N/A	40	40
Vehicular live load	3.1	N/A	N/A

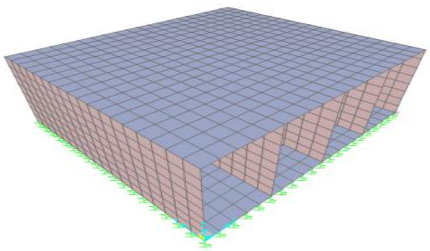


Figure 1: The geometry of 4 cells Box Culvert Type 1.

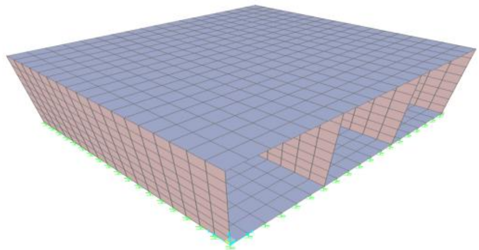


Figure 2: The geometry of 3 cells Box Culvert Type 2.

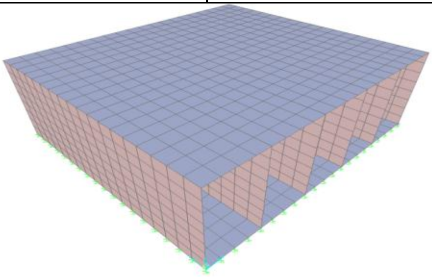


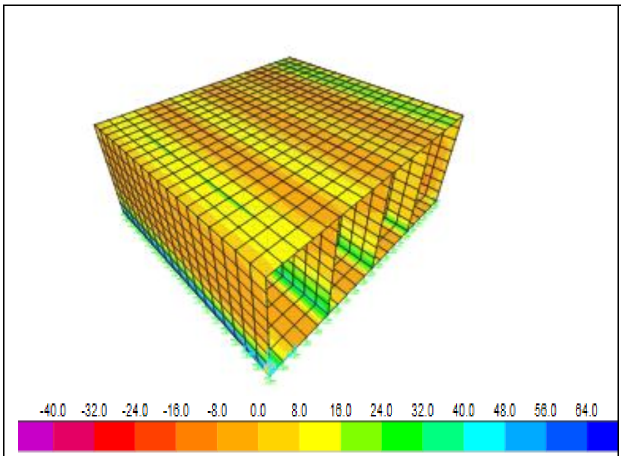
Figure 3: The geometry of 5 cells Box Culvert Type 3.

RESULTS

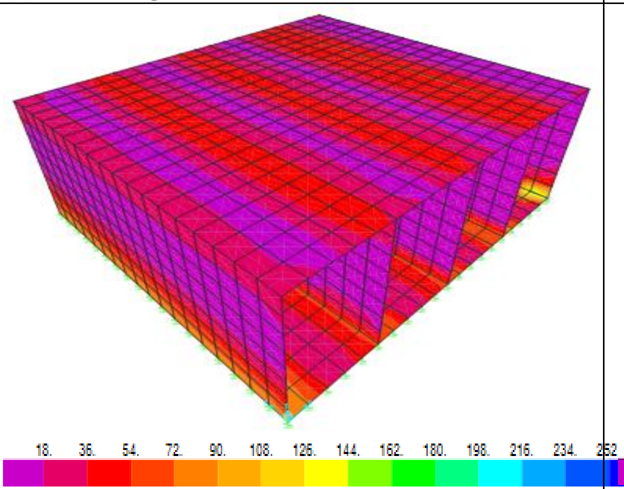
Samples of bending moments shear forces, and axial forces were obtained from selected load combinations as shown in Figures 4 - 5. The comparison of results on maximum axial forces, shear forces, and bending moments in the top slab, internal and external walls, and mat footing of three mentioned types of box culverts presented in Table 4, which were obtained using SAP2000 and ETABS18. To study the structural performance of the three-box culverts, the variations of axial forces, shear forces, and bending moments to the height of external and internal walls were presented as shown in Figures 6 – 11. The elements of box culverts were designed according to AASHTO specification using Load Resistance Factor Design (LRFD). It was assumed that the compressive strength of concrete and yield strength of reinforcement were 28 MPa and 420 MPa respectively. The summary of top slabs and mat footings design for the three types of box culvert was illustrated in Table 5 which includes the positive, negative, and secondary reinforcements. They were designed as one-way solid slab systems. The internal walls were designed as compressive elements by checking the buckling effect and moment capacity. They consist of only vertical and horizontal reinforcements as illustrated in Table 6. The external walls were designed as a compressive members but subjected to moments by checking shear resistance and moment capacity. The main reinforcement should be positive and negative reinforcements and secondary once should include only horizontal reinforcement as illustrated in Table 7. The total weight of box culverts was also calculated to select the more efficient and economical box culvert as illustrated in Figure 11.

DISCUSSION

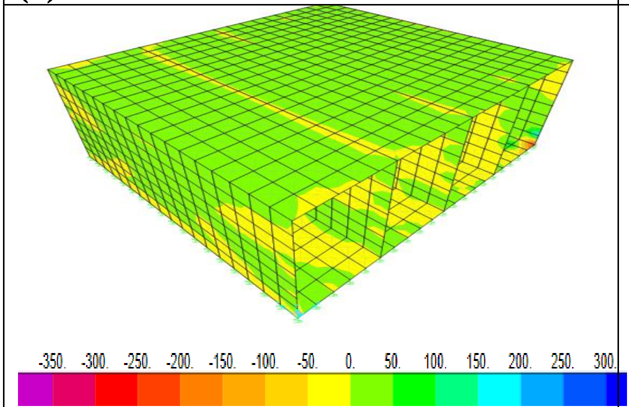
The software SAP2000 was taken as the basic reference for comparison purposes. From the comparison of the two programs, it was noticed that the differences in negative moments, positive moments, shear, and axial forces obtained were about (-0.7 to -17.9%), (-1.4 to -17.1%), (-0.4 to 13.8%), and (0.5 to 16%) respectively as illustrated in Table 4. It may be concluded the obtained results using two programs within limits of engineering accuracy. To study the structural performance, the variation of internal forces in the external and internal walls should be considered. It noted that the internal forces reach their maximum values at the base of external walls and gradually decrease at their top level for the three types of box culverts. It was found that the box culvert type 2 gave the maximum variation in bending moments, shear, and axial forces compared with the other two types for both external and internal walls. It was observed that the variations of internal forces in the internal walls gave semi-regular distribution for all box culvert types. After the design, all thicknesses have the same values as calculated for the analysis process. It was found that Type 2 gave the minimum total weight compared with types 1 and 3 as illustrated in Figure 11.



(a) Bending moments distribution.

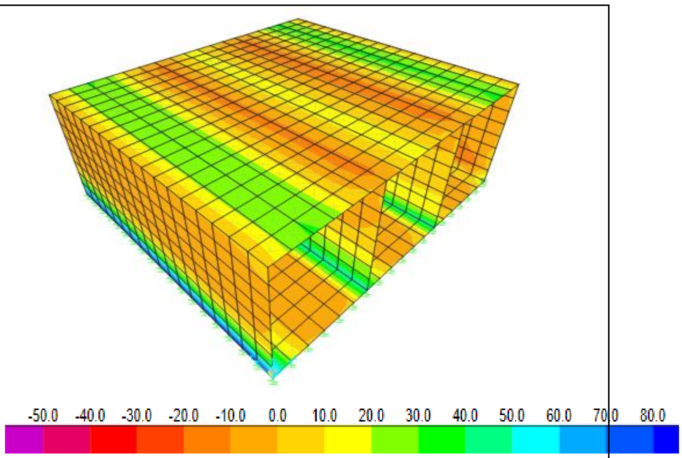


(b) Shear forces distribution.

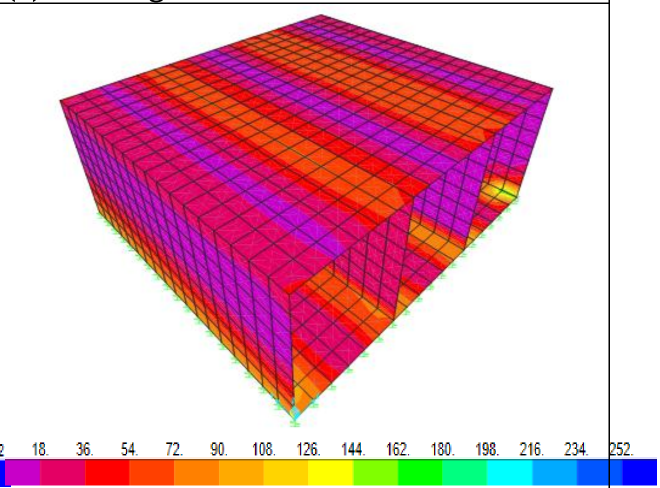


(c) Axial forces distribution.

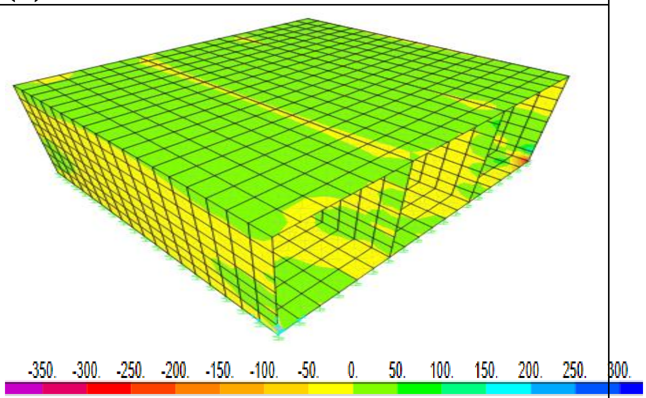
Figure 4: Distribution of Internal Forces on Box Culvert Type (1).



(a) Bending moments distribution.



(b) Shear forces distribution.



(c) Axial forces distribution.

Figure 5: Distribution of Internal Forces on Box Culvert Type (2).

Table 4: Comparison of maximum internal forces in elements of the box culverts using software programs SAP2000 and ETABS18.

Box Culvert Type	Element of Box culvert	Maximum Negative moment, kN.m/m		Difference %	Maximum Positive Moment, kN.m/m		Difference %	Maximum Shear Force kN/m		Difference %	Maximum Axial Force kN/m		Difference %
		SAP 2000	ETABS 18		SAP 2000	ETABS 18		SAP 2000	ETABS 18		SAP 2000	ETABS 18	
Type 1	Top slab	45.3	44.5	1.8	39.0	38.0	2.7	64.5	65.7	-1.9	40.2	43.0	-7.0
	External wall	34.5	33.3	3.5	66.8	59.8	10.5	75.6	76.8	-1.6	146.7	138.6	5.5
	Internal wall	20.8	21.7	-4.3	35.2	34.0	4.3	17.4	15.0	13.8	225.1	222.1	1.3
	Mat footing	96.6	106.9	-10.7	67.9	59.2	12.1	135.4	149.6	-10.5	85.8	85.5	0.5
Type 2	Top slab	77.2	68.6	11.1	43.9	38.1	13.2	84.0	75.8	9.8	42.5	42.8	-0.7
	External wall	84.2	86.9	-3.2	51.0	59.7	-17.1	84.2	89.8	-6.7	242.3	237.4	2.0
	Internal wall	56.8	59.4	-4.6	40.2	45.3	-12.7	24.0	26.0	-8.3	311.2	296.9	4.6
	Mat footing	68.0	58.0	14.7	75.9	69.0	9.1	121.0	127.0	-5.0	91.0	86.0	5.5
Type 3	Top slab	32.2	28.2	12.4	24.1	20.2	16.2	53.1	48.6	8.5	50.2	57.1	-14
	External wall	34.6	40.8	-17.9	61.2	57.7	5.7	75.6	75.9	-0.4	121.1	102.3	-16
	Internal wall	31.1	30.4	2.3	31.2	33.3	-6.7	16.4	15.6	4.9	229.9	227.0	1.3
	Mat footing	40.5	40.8	-0.7	56.9	57.7	-1.4	138.6	145.8	-5.2	84.8	79.6	6.1

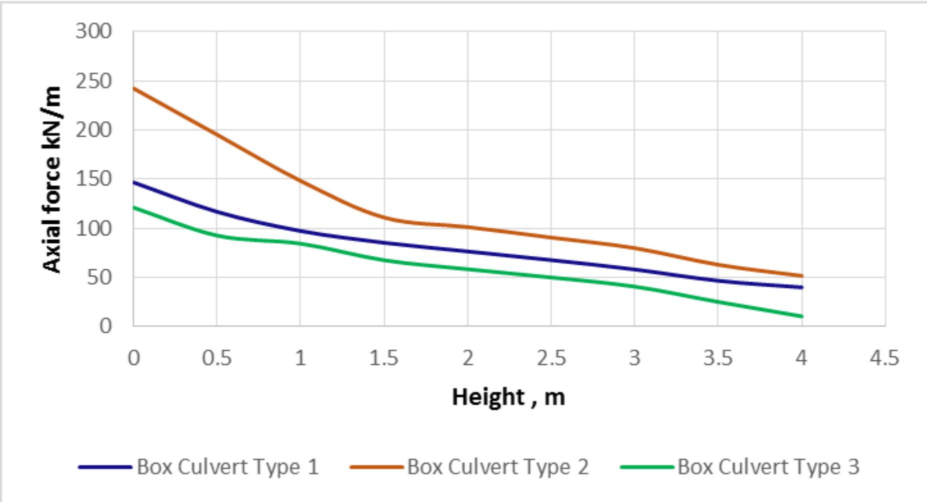


Figure 6: Variation of axial forces vs. height on the external walls.

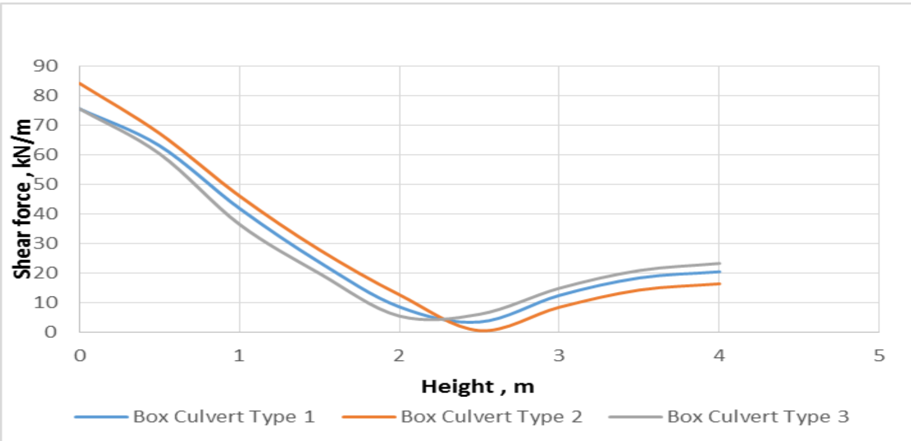


Figure 7: Variation of shear forces vs. height on the external walls.

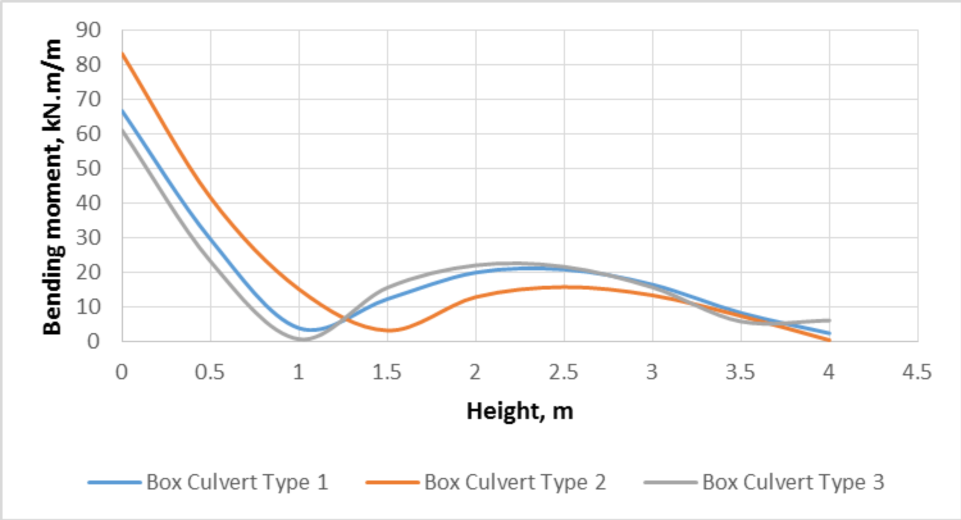


Figure 8: Variation of bending moments vs. height on the external walls.

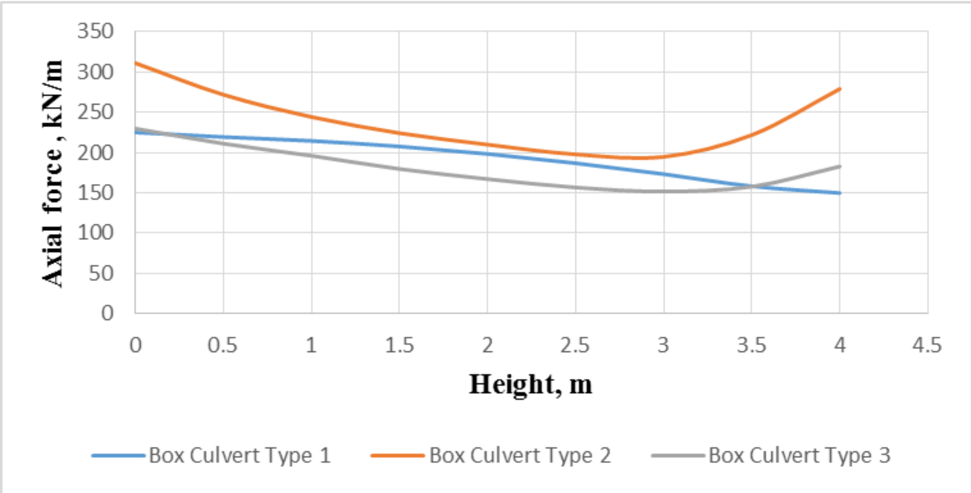


Figure 9: Variation of axial forces vs. height on the internal walls.

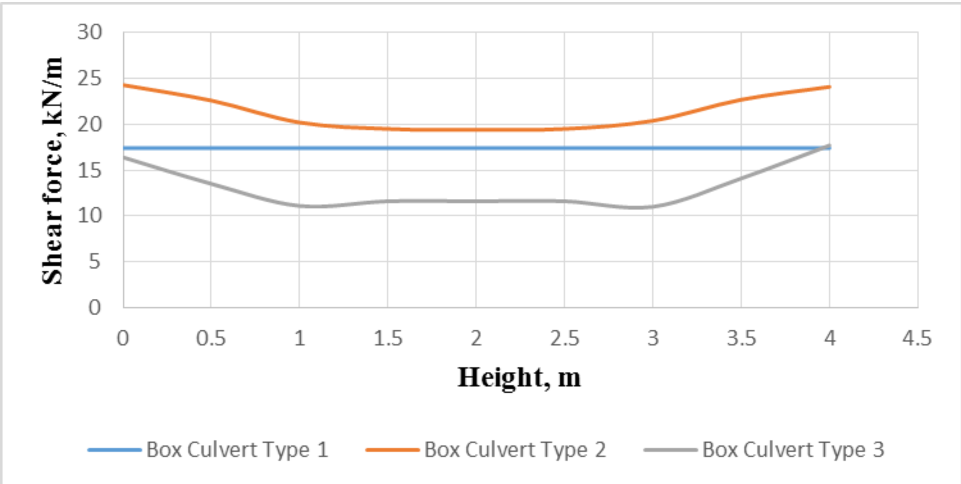


Figure 10: Variation of shear forces vs. height on the internal Walls.

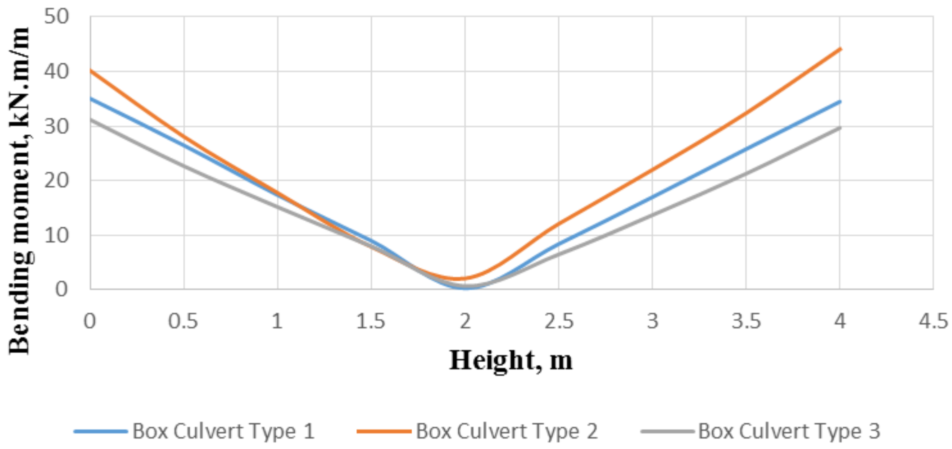


Figure 11: Variation of bending moments vs. height internal walls.

Table 5: The summary of top slabs and mat footing design for the box culverts.

Box culvert type	Element	Thickness mm	Positive reinforcement	Negative reinforcement	Secondary reinforcement
Type 1	Top slab	200	Ø 16@ 330 mm c/c	Ø 16@ 250 mm c/c	Ø 10@ 250 mm c/c
	Mat footing	400	Ø 16@ 220 mm c/c	Ø 16@ 275 mm c/c	Ø 10@ 300 mm c/c
Type 2	Top slab	200	Ø 16@ 250 mm c/c	Ø 16@ 330 mm c/c	Ø 10@ 250 mm c/c
	Mat footing	400	Ø 16@ 150 mm c/c	Ø 16@ 200 mm c/c	Ø 12@ 150 mm c/c
Type 3	Top slab	200	Ø 16@ 250 mm c/c	Ø 16@ 300 mm c/c	Ø 10@ 250 mm c/c
	Mat footing	400	Ø 16@ 250 mm c/c	Ø 16@ 250 mm c/c	Ø 12@ 350 mm c/c

Table 6: The summary of internal walls design for the box culverts.

Box culvert type	Wall thickness mm	Vertical reinforcement	Horizontal reinforcement
Type 1	**200**	**Ø 16 @ 110 mm c/c**	**Ø 10 @ 300 mm c/c**
Type 2	**200**	**Ø 16 @ 110 mm c/c**	**Ø 10 @ 300 mm c/c**
Type 3	**200**	**Ø 16 @ 140 mm c/c**	**Ø 10 @ 200 mm c/c**

Table 7: The summary of external walls design for the box culverts.

Box culvert type	Wall thickness mm	Positive reinforcement	Negative reinforcement	Horizontal reinforcement
Type 1	**200**	**Ø 16 @ 150 mm c/c**	**Ø 16 @ 200 mm c/c**	**Ø 10 @ 300 mm c/c**
Type 2	**200**	**Ø 16 @ 150 mm c/c**	**Ø 16 @ 150 mm c/c**	**Ø 10 @ 300 mm c/c**
Type 3	**200**	**Ø 16 @ 100 mm c/c**	**Ø 16 @ 100 mm c/c**	**Ø 10 @ 200 mm c/c**

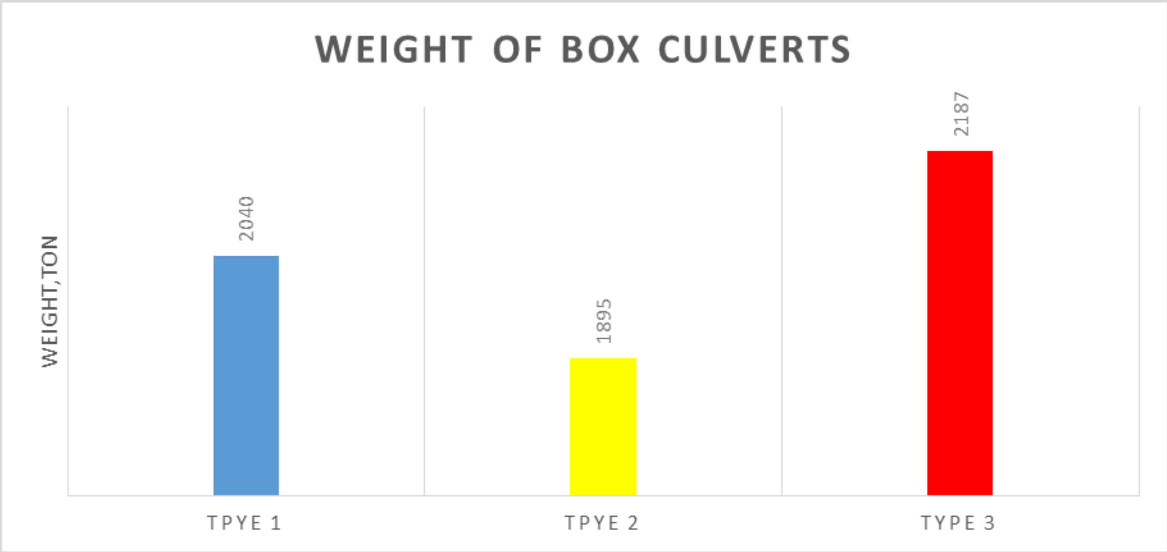


Figure 12: Comparison of the total weight for box culverts.

CONCLUSION

The conclusion of the study includes the following points. Variations of loading cases and their combinations gave differences in the internal forces distribution patterns of box culverts. The design of box culvert elements was provided according to AASHTO (LRFD method) using manual calculation with concrete compressive and yield stress of steel equal to 28 and 420 MPa respectively. It found no significant difference in the amount of steel reinforcement for the various elements of the box culverts. It was noticed that Type 2 gave a minimum weight compared with Type 1 and Type 3. It was observed that box culvert Type 2 was the most efficient in structural performance and considered the best choice.

RECOMMENDATIONS

It suggested designing wing walls to facilitate the discharge in the box culverts and the study did not implement the box culvert in Sudan in detail, so a considerable amount of studies is needed to be of use for researchers, the libraries, and engineering studies.

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CONFLICTS OF INTEREST

The authors declare that they have no competing interests in the research.

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