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Comparative Analysis and Design of Single Cell Circular Culvert in Eurocode using StaadPro and Manual approach

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ABSTRACT : *The paper made a comparison between single cell circular culvert designed based on Eurocode 2 using manual design approach and software design approach using StaadPro. Standard and appropriate load assumptions were made and structural analysis carried out using moment distribution method for manual approach. The percentile differences between bending moments obtained from the manual approach and software approach range from 16.93 to 59.96 % while that obtained for the shear forces range from 9.78 to 31.9 %. The differences were attributed to the fact that manual approach analyses and designs the culvert as 2D structure while the software approach analysis and designs the culvert as a 3D structure which the structure truly represents. Hence, numerous assumptions are usually made in the 2D analysis. It is adjudged that the software gives more conservative and economical analysis and design output and should be adopted in subsequent designs for economy and time savings.*

KEYWORDS: *culvert, single cell, circular culvert, Eurocode, Staadpro, Analysis and Design*

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I. INTRODUCTION

Culverts are one of the most widely used drainage facilities in road construction works. They are used to carry surface drainage, rainwater from one side of the road or highway to the other or under the crossing of the railways, roads, and flyover, and also is used where the bearing capacity of the soil is low (Ali, 2020). Culverts can be classified among the small-sized drainage facilities often in contrast to bridges. Culverts are advantageous over bridges in terms of cost where the discharge opening is less than 18 m² and particularly where the road crosses the waterway on relatively high embankment (Karadi and Krizek, 2003; Ali, 2020).

There are different types of configurations of culverts (Azam et al, 2022) such as circular (pipe), box (rectangular), elliptical, pipe-arch, and arch but the commonest are the box culvert and pipe culverts (FHWA, 2005). Pipe culverts found advantage over other types of culverts because of the following: any desired strength is achievable by proper mix design, thickness and reinforcement. It is economical and easy to install. Pipe culvert can withhold high tensile stresses and compressive stresses. Also, a pipe culverts don't create barriers in the path and they provide a continuous surface over the pipe.

Culverts are built to allow a continuous flow of water while different sizes of load (vehicles, pedestrian, goods etc.) are frequently applied on it on daily basis. Problems like erosion of streambed and embankments, inadequate flow capacity, corrosion and abrasion of metal in culverts, deterioration of concrete and masonry culverts are mainly as a result of poor hydraulic design. Again, problems like cracking of rigid culverts, undermining and loss of structural support, loss of the invert of culverts due to corrosion or abrasion, over-deflection and shape deformation of culverts, stress cracking of plastic culverts etc. are strength related problems and are as a result of inappropriate structural design. These problems led to the research and the design of a pipe culvert to determine the appropriate perimeters and dimensions for a pipe culvert.

The structural design of pipe culverts does not pose serious challenges when proposed to be used in construction. Unlike the manual method commonly used for the design, the study wants to investigate the capacity of software programmes such as StaadPro to design such structure.

A. Applied loads

Loads that were submitted to circular culverts were divided into dead load and live load by Kumar and Srinivas (2015). Dead load is made up of the circular culvert's self-weight, which is determined by the culvert's thickness and clear dimensions. Superimposed dead load is estimated using standards and specifications code of practice and depends on the nature of the road that was built above the culvert. Vehicle loading is the live load in the culvert. The culvert's top slab is moved by a set of wheel loads, which make up the vehicular live load. These loads are dispersed through the culvert's top. Both active and passive pressure can be applied by Earth. Earth pressure is measured in three different ways: active, passive, and median (earth pressure at rest). The structural components must be built to endure the greatest possible bending moment and shear force. For various load scenarios, a circular culvert is analyzed, and in crucial situations, a structural design is recommended.

B. StaadPro

In order to study and design structures for bridges, towers, buildings, transit, industrial, and utility structures, many people utilize the structural analysis and design program StaadPro (JBIT, 2022).

The benefit of StaadPro is that it supports several languages and international codes, making it multi-specialty for a wide range of users. StaadPro offers a visualization module of the building planner that creates building models that can be developed and examined in the software. It is adjudged better than most other structural analysis and design software as it provides more accurate answers and also indicate error if there's any (JBIT, 2022). This is why we intend to employ it in the research.

II. METHODOLOGY

Designs of sections of the culvert were carried out both manually and using software according to appropriate code of practice based on Eurocode. Section 6 of EN 1990:2002 describes how the partial factor method is applied in limit state verifications. It is best considered, however, in conjunction with EN 1990:2002, Annex A2 which gives supplementary bridge-specific requirements for establishing combinations of actions (except for fatigue verifications which are typically addressed in the relevant material part), provides ψ-factors and material-independent partial factors, and also gives methods and rules for some material-independent serviceability limit states (e.g. vibrations and deformations of rail culverts, bridges).

A. Hydraulic design information

The design is for urban town with high ground/slope and no pre-existing water body at its level due to presence of many buildings.

Due to the factors associated with topography map, and fish passage requirements which shows low height for headwater except during rainfall and flood, the culvert will be designed as an artificial circular culvert, the culvert being similar pipe and in shape and being an inlet type with the outlet submerged due to site investigation. See Fig.1 for image of culvert and Table 1 for Manning’s table for culvert.

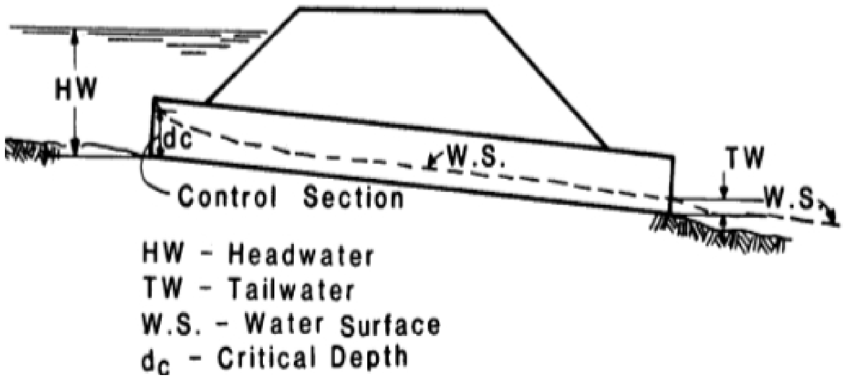

Fig. 1: A typical inlet control flow section (Adel Qasim, 2018)

Table 1: Manning`s n Table for Culvert

Type of Culvert	**Roughness or Corrugation**	**Manning`s n**
Concrete Pipe	Smooth	0.010-0.011
Concrete box	Smooth	0.012-0.015
Spiral Rib Metal Pipe	Smooth	0.012-0.013

Source: Hydraulic Design Series Number 5.

B. Analysis and design of circular culvert (assumptions)

a. Assumptions

The span of the culvert is taken to be 5 m and the culvert is to be designed for a single way service lane. Fig.2 shows the level of asphalt and earth fill sitting on the culvert. The top slab culvert is in direct contact with the carriage way. At top of the slab, there is 1.2 m thick fill on top culvert and overlaid with 75 mm thick of asphalt.

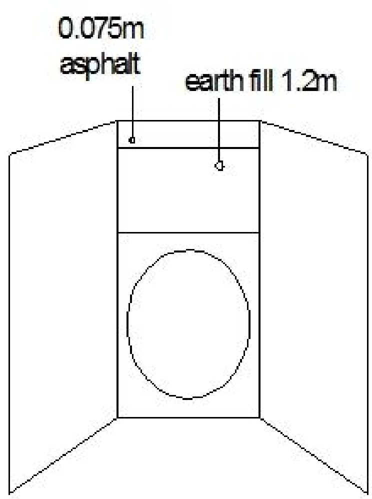

Fig.2: Level of asphalt and earth filling

C. Geometric plan of the culvert

Total length of culvert = 5 m; Width and height of culvert c/c of side walls = 1.2 m
Length of wing of wall = 2.12 m; Thickness of all elements = 300 mm
Thickness of asphalt = 75 mm.
Fig.3 shows the geometry of the culvert

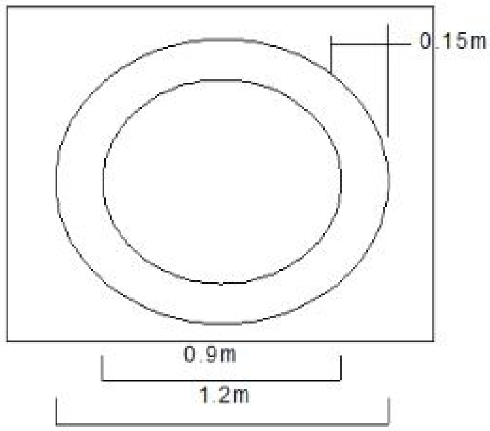

Fig.3: Geometry of culvert

D. Material property of culvert

Angle of internal friction =; Unit weight of water = 9.8 kN/m^3

Unit weight of backfill soil =19 kN/m^3; Unit weight of concrete = 25 kN/m^3

Unit weight of asphalt = 22.5 kN/m^3; F_{cu} = 25 N/mm^2; F_y=410 N/mm^2

Concrete line = 50 mm

Fig. 4 shows the side view of the culvert.

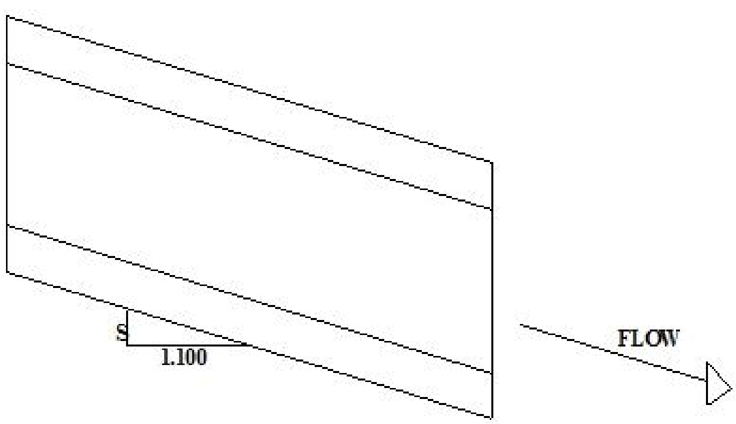

Fig.4: Side view of culvert

E. Loading of culvert

Self-weight of slab = thickness $\times$ density of concrete = 0.3 $\times$ 25 = 7.5 kN/m^2

Self-weight of asphalt = thickness × density of asphalt = 0.075 × 22.5=1.69 kN/m^2
Earth loads on the top of culvert at depth of 1.2m, P=1.2 × 19 = 22.8 kN/m^2

F. Horizontal pressure on culvert

Since the culvert is buried under ground the horizontal pressure is given by,
$P = K_oPH$
At P_{min}, P = 0.5 × 19 × 1.2 = 11.40 kN/m^2
At P_{max}, P = 0.5 × 19 × 2.4 = 22.80 kN/m^2

Fig.5 shows the pressure distribution diagram.

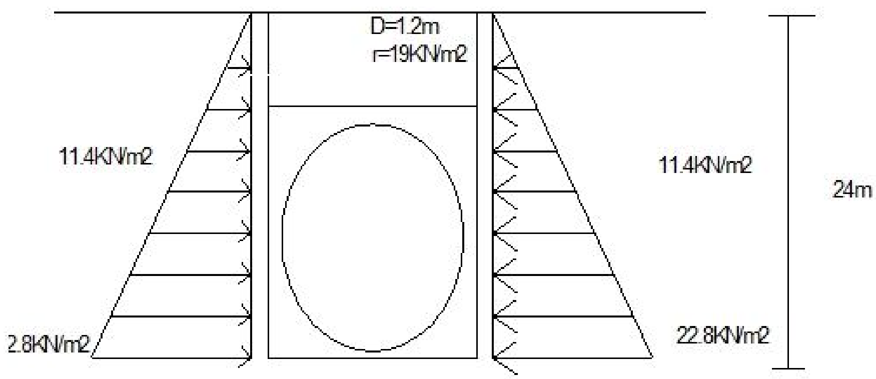

Fig. 5: Pressure distribution diagram of culvert

Traffic loads that are acting on the circular box culvert, if greater than the thickness of the fill (0.6 m), we must consider wheel load of the traffic actions dispersed to the slab of culvert as uniformly distributed load. Using load model 1 from EN 1991-2 which is recommended by clause 4.9.1 of the European code EN 1991-2, the tandem loads can be considered to be dispersed through the earth fill and uniformly distributed on the top of circular box culvert. Fig.6 shows single wheel load distribution diagram.

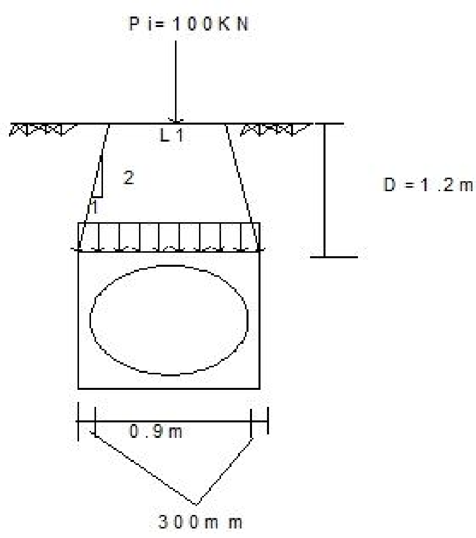

Fig.6: Single wheel load distribution diagram

P_1=100 kN; L_1=0.4 m; L_2 = 0.4 + 1.2 (contact length of the fill); L_2=1.6m
Then the equipment uniformly load distribution from each wheel to the circular box culvert is

$Q_{ec} = \frac{p}{l2+l2} = \frac{100}{1.6+1.6}$ = 39.06 kN/m^2

G. Loading of top slab

Dead load

Self-weight of top slab = 0.3 $\times$ 25 $\times$ 1. 35=10.125 kN/m

Finishes = 1.2 $\times$ 1.35 = 1.62 kN/m

Total dead load = 11.745 kN/m

Live load

Vehicular load = 39.06 $\times$ 1.5 kN/m

Self-weight of asphalt = 1.69 $\times$ 1.5 kN/m

Earth fill on slab = 22.8 $\times$ 1.5 kN/m

Total live load = 95.325 kN/m

Total load W = dead load + live load = 11.745 + 95.325 =107.07 kN/m

Taking W to be 120 kN/m to account for variable factors.

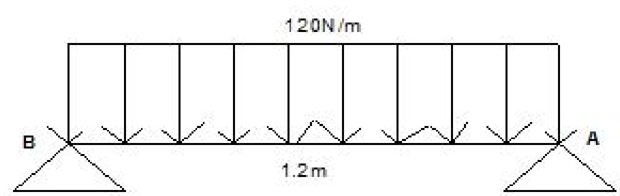

Fig. 7: UDL loading

$M_{max} = \frac{wl^2}{8} = \frac{120\times1.2^2}{8}$ = 21.6 kNm; $V_{max} = \frac{wl}{2} = \frac{120\times1.2}{2}$ = 72 kN

H. Loading of Wall Slab

This is done by taking into consideration cases where the wall is slant or contributes to the hydrostatic soil pressure against the structure.

Dead load

Self-weight of wall = 0.3 $\times$ 24 $\times$ 1.35 = 10.125 kN/m

Finishes = 1.2 $\times$1.35 kN/m

Total dead load = 11.745 kN/m

Live load

Soil pressure (minimum) = 11.4 $\times$1.5 = 17.1 kN/m

Soil pressure (maximum) = 22.8 $\times$ 1.5 = 34.2 kN/m

Total minimum pressure = 11.745 + 17.1=28.845 kN/m, say 30 kN/m

Total maximum pressure = 11.745 + 34.2 = 45,945 kN/m, say 48 kN/m

By using principle of superimposition (see Fig.8)

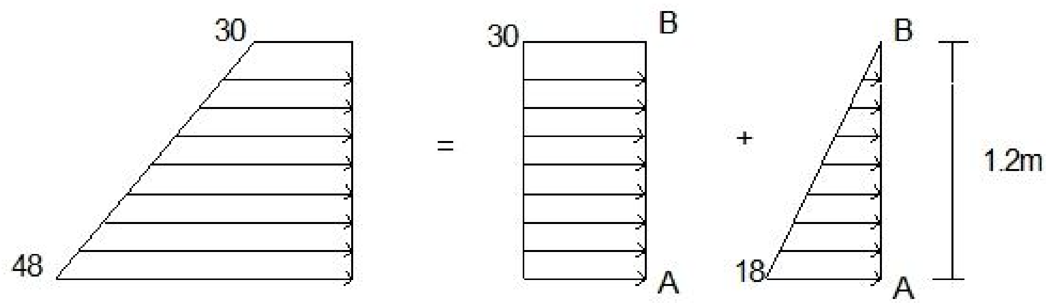

Fig. 8: Principle of superposition

M_{max} = 0.1283wl + $\frac{wl^2}{8}$ =1.283 $\times$ 18 (1.2) + $\frac{30(1.2^2)}{8} =$ 8.17 kN/m

V_{max} = $\frac{2w}{3} + \frac{wl}{2}$ = $\frac{2(18)}{3} + \frac{30(1.2)}{2} =$ 30 Kn

I. Loading of bottom slab

Top slab = 120 kN/m

Self-weight of bottom slab =11.745 kN/m

Self-weight of wall = 11.745 $\times$ 2 23.49 KN/m

Total load = 120 + 23.49 + 11.745 = 155.235 kN/m

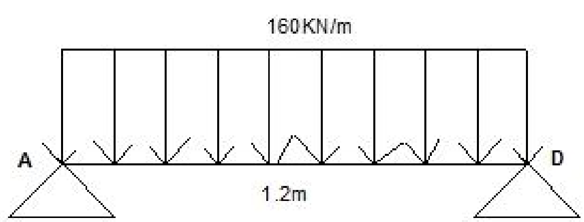

Fig. 9: Loading on bottom slab

M_{max} = $\frac{wl^2}{8} = \frac{160\times1.2^2}{8}$ = 28.8 kNm; V_{max} = $\frac{wl}{2}$ = $\frac{160\times1.2}{2}$ = 96 kN

J. Moment Analysis using Moment Distribution

Fig.10 show the moment distribution nomenclature of the culvert

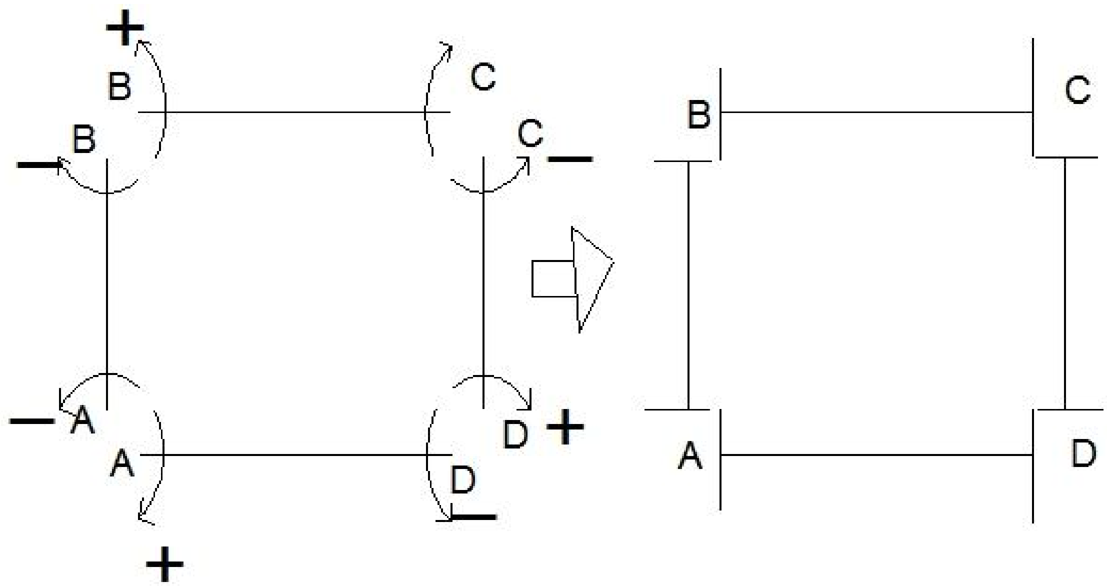

Fig.10: Moment distribution nomenclature of the culvert

From Fig.10, the fixed end moments are obtained as follows

$$M_{BC} = \frac{-wl^2}{12} = \frac{120 \times 1.2^2}{12} = -14.4$$

$$M_{CB} = \frac{wl^2}{12} = \frac{120 \times 1.2^2}{12} = 14.4$$

$$M_{BA} = \frac{wl^2}{30} + \frac{wl^2}{12} = \frac{18 \times 1.2^2}{30} + \frac{30 \times 1.2^2}{12} = 4.46$$

$$M_{AB} = \frac{-wl^2}{20} - \frac{wl^2}{12} = \frac{18 \times 1.2^2}{20} - \frac{30 \times 1.2^2}{12} = -4.90$$

$$M_{DA} = \frac{-wl^2}{12} = \frac{-160 \times 1.2^2}{12} = -19.2$$

$$M_{AD} = \frac{wl^2}{12} = \frac{160 \times 1.2^2}{12} = 19.2$$

$$M_{CD} = \frac{-wl^2}{30} - \frac{wl^2}{12} = \frac{-18 \times 1.2^2}{30} - \frac{30 \times 1.2^2}{12} = -4.46$$

$$M_{DC} = \frac{wl^2}{30} + \frac{wl^2}{12} = \frac{18 \times 1.2^2}{30} + \frac{30 \times 1.2^2}{12} = 4.9$$

Table 2 shows the breakdown of the final total moment obtained from the analysis while Fig.11 shows the bending moment diagram of the culvert.

Table 2: Final total moment obtained from the moment distribution analysis

Joints					
Members	AD	$ABAB$	BC C B	CD C D	AD
DF.	-0.5	$-0.5-0.5$	$-0.5-0.5$	$-0.5-0.5$	-0.5
FEM.	19.2	-4.9 4.46	-14.4 14.4	-4.46 14.4	-19.2
Balance	-7.15	$-7.154.97$	$4.97-4.97$	$-4.97-4.97$	7.15
Carry over	3.575	2.485 -3.575	-2.485 2.485	$3.575-$2.485	-3.575
Balance	-3.03	-3.03 3.03	3.03 3.03	-3.03 3.03	3.03
Total moment	12.6	-12.6 8.885	-8.89 8.89	-8.89 12.595	-12.595

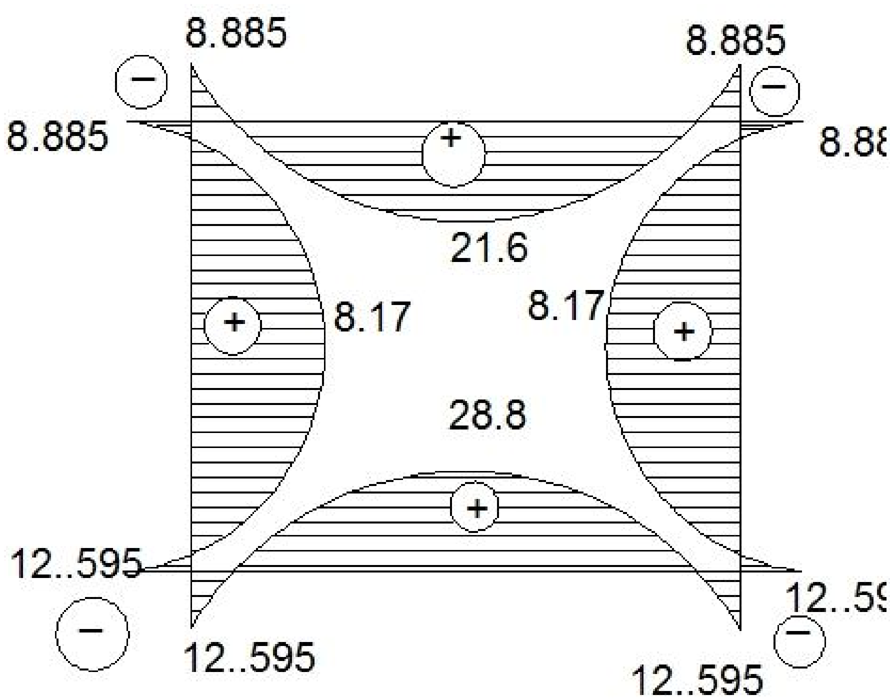

Fig.11: Bending moment diagram of the culvert

J. Structural design of the box culvert

The structural design of the box culvert was carried out using manual analysis and StaadPro. Fig. 12 shows the detail of the box culvert arising from the manual design output.

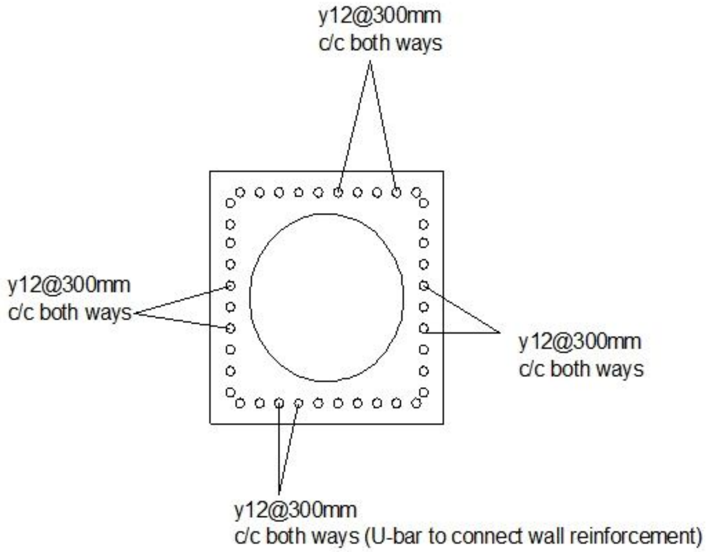

Fig. 12: Detail of box culvert arising from the design output

K. Analysis using StaadPro

Fig.13a shows the geometry of the culvert as input in Staadpro while Fig.13b shows the soil pressure distribution on the culvert. Fig.14a shows the live load on culvert while Fig.14b shows the shear force on culvert while Fig. 15 shows the reinforcement detailing based on design output from the StaadPro.

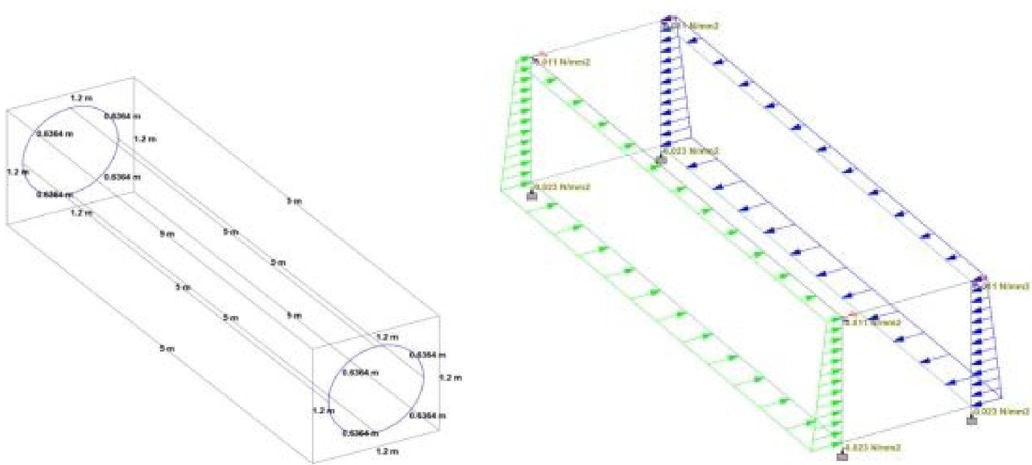

Fig.13: a (culvert geometry) and b (soil pressure distribution on culvert)

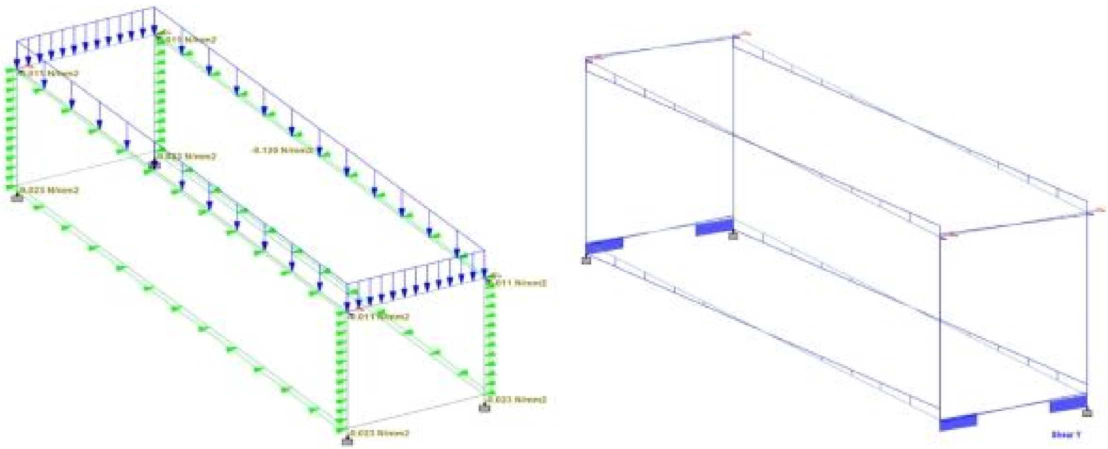

Fig.14: a (live load distribution on culvert) and b (shear force distribution on culvert)

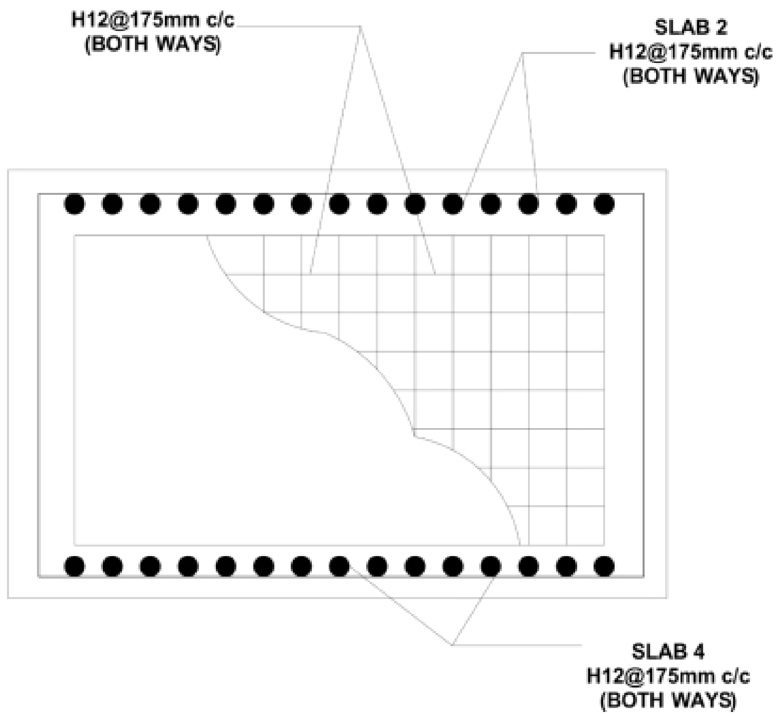

Fig. 15: Reinforcement detailing based on design output from StaadPro

III. RESULTS AND DISCUSSION

The aim of the project was to compare the results of analysis from manual approach of the design of single cell circular culvert and design using software, StaadPro. Table 3 shows the results of bending moment and shear force from the manual approach and software approach for critical members, AB, BC, CD, and DA while Figs 16 and 17 shows the graphical representation of these Figures.

Table 3: Comparison of the resulting Bending moment and Shear forces between manual method and StaadPro

Beam	**Manual design**		**StaadPro**	
	Max. B.M (kN/m)	Max S.F (kN/m)	Max B.M (kN/m)	Max S.F (kN/m)
AB (4)	8.17	30	2.245 (My)	27.237 (Fy)
BC (5)	21.6	72	15.344 (Mz)	40 (Fz)
CD (3)	28.8	96	19.32 (Mz)	49.6 (Fy)
DA (2)	8.17	30	2.245 (My)	27.867 (Fy)

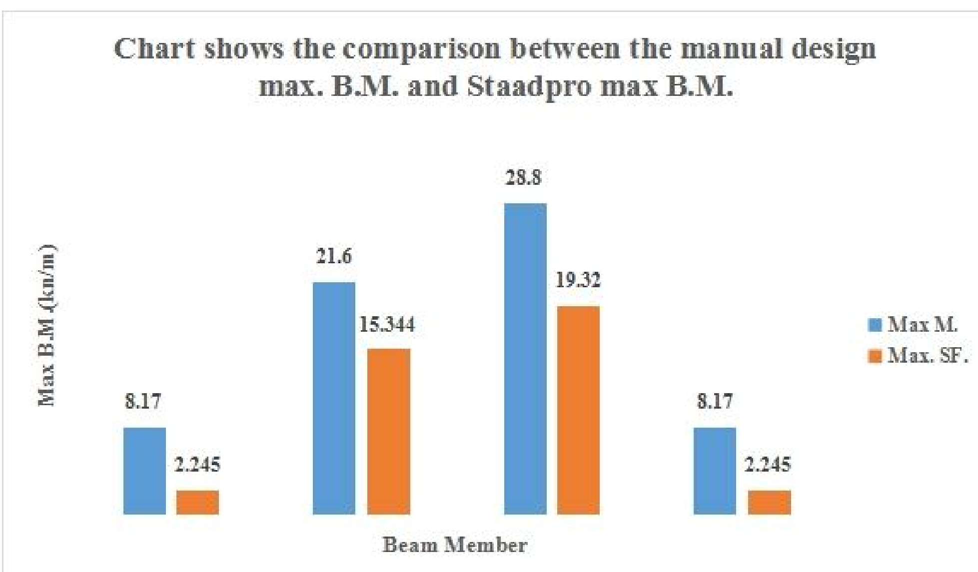

Fig. 16: Chart showing the comparison between the Manual design max B.M and StaadPro max B.M. at critical points.

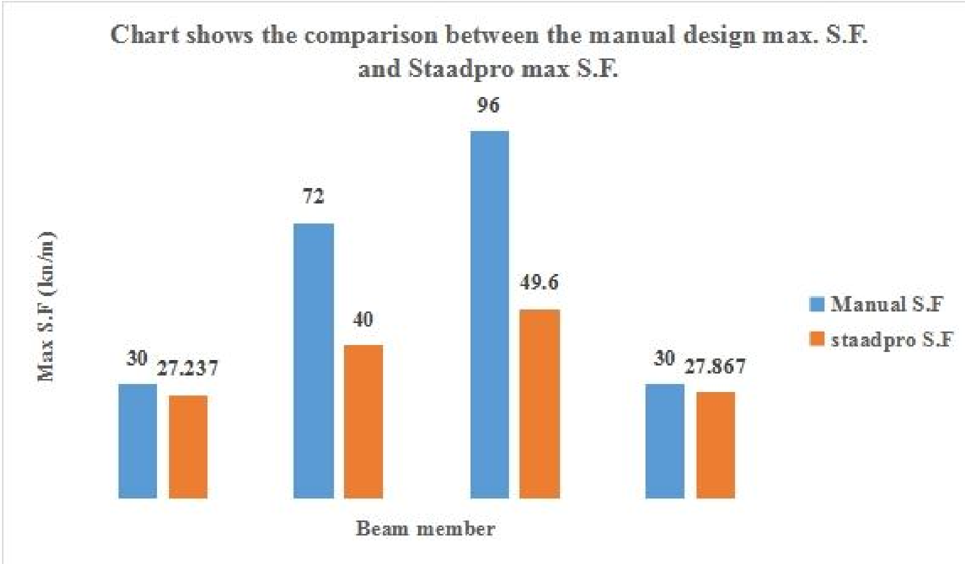

Fig.17: Chart showing the comparison between the Manual design max S.F. and StaadPro max S.F. at critical points.

A. Percentile difference of the resulting Bending Moment and Shear force between Manual method and StaadPro

Table 4 shows the summary of the percentile difference between B.M. and S.F. results from StaadPro and manual approach. The percentages show the amount by which the value from manual approach is greater than the value from the software approach.

Table 4: Percentile difference between B.M. and S.F. from manual approach and StaadPro

Beam Fraction	Bending Moment (%)	Shear Force (%)
AB	59.96	9.78
BC	16.93	28.57
CD	19.70	31.9
DA	56.88	3.68

From the table, it is observed that the resulting percentile difference indicates the wide gap in values between both methods. The reasons for the wide gap can be summarized as follows:

1. The Staadpro is a 3-dimensional design CAD, while the manual approach is a 2-dimensional design method. This brings about lesser accuracy of results in the manual method than that of StaadPro.

2. In the manual design, the structure was analyzed in one direction (2D). The structure was analyzed when acting perpendicularly. Take the top slab as an example, the force acting on the X direction was coming from the Y direction, making it a limited 2D analyses and same goes for the wall slab. But the work is actually a 3D structure and this poses as a notable limitation to the manual method. Now, Staadpro analyzed the structure in a 3-dimensional (3D) flow having both the X, Y and Z direction, leading to a more accurate analyses than the manual method.

3. In the manual method, calculation of loads was done from top to the bottom, while in the StaadPro design, in which the calculation was also done from top to bottom, the structure was given a certain behavior or character. This implies that, a wall slab in the structure can behave in such a way that the force being applied will not have

a residual moment at the top (meaning that, FX was analyzed to be 0). It also implies that, the structure was analysed to be able to stand alone and the wall slab should be able to counter balance any force below the design FX.

In summary, the analysis of both the manual and StaadPro approach, the maximum moment and shear force of the manual design approach exceeded that of StaadPro which shows a high safety factor and less economical value of the manual design. StaadPro program has more advantage over the manual method because of its accuracy and speed which makes work easier and faster.

The difference in comparison between moment and shear force analysis in manual and StaadPro design is inferred to be caused by load patterns analysis of using both methods. In the manual design, a 2-dimensional analysis of the cross section where all loads where visible and applied per meter length was done while in StaadPro, a 3-dimensional analysis was done for the single cell culvert structure as a whole leading to a comprehensive and more accurate results. The limit of the manual design was accounted for the engineer's aesthetics.

IV. CONCLUSION AND RECOMMENDATION

A. CONCLUSIONS

The dimensions of the circular culvert were obtained from the hydraulic design. The circular box culvert was designed as a single cell culvert with a total length of 1.2 m and diameter of 0.9 m and thickness of 0.15. The circular box culvert structural elements are top slab, floor slab and two exterior side walls. The circular box culvert structural design was carried out for the maximum bending moment and shear force in each structural element. The design was analyzed by StaadPro software which gave results similar to the hand calculated results. The determined reinforcements are: Y12@ 300mm C/C both walls and Y12@ 300mm C/C at top and bottom for the top and bottom slab for manual design and Y12@ 250mm C/C both walls and Y12@ 175mm C/C at top and bottom for the top and bottom slab for StaadPro

B. RECOMMENDATIONS

It is suitable to use a circular culvert with a high inlet head and low out let. This is because the velocity at the inlet of the culvert is more than that of the water entering it and will further cause the culvert not to ever full which is a great advantage over erosion.

Using StaadPro software for the design is helpful and saves a lot of time. And when compared to manual design, it is much better as it checks every factor that can lead to failure and indicate for the designer to correct error if there's any.

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Conflict of Interest: There is no conflict of interest associated with this project

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