ANALYSIS OF BOX CULVERT - COST OPTIMIZATION FOR DIFFERENT ASPECT RATIOS OF CELL

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Abstract

Reinforced concrete box culvert consists of top slab, bottom slab and two vertical side walls built monolithically which form a closed rectangular or square single cell. By using one or more intermediate vertical walls multiple cell box culverts is obtained. Multiple cell reinforced box culverts are ideal bridge structure if the discharge in a drain crossing the road is large and if the bearing capacity of the soil is low the single box culvert becomes uneconomical because of the higher thickness of the slab and walls. In such cases, more than one box can be constructed side by side monolithically. In conventional method thickness of box culvert is assumed and later on check for thickness is taken. But this may leads to uneconomical design therefore an attempt is made to evaluate optimum thicknesses for economical design. In the present work 12 m channel length is consider for analysis with 2m to 6m height variation which is again divided into single cell, double cell and triple cell. IRC class AA tracked live load is considered. The analysis is done by using stiffness matrix method and a computer program in C language is developed for the cost evaluation. Study is carried out related to variation in bending moment; subsequently cost comparison is made for different aspect ratios. The percentage reduction in cost of single cell, double cell and triple cell based on optimum thicknesses are presented. The optimum thicknesses presented over here are used to achieve the economical design of box culvert. Based on these optimum thicknesses optimum cost per meter width of single cell, double cell and triple cell is evaluated. The study reveals that the cost of box culvert reduces if the optimum thicknesses which are presented in this study are considered.

Keywords: *Box culvert, Single cell, multiple cells, Aspect ratio, Stiffness method*

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1. INTRODUCTION

A basic assumption in analysis of the box culvert is the displacement and forces are uniform in the longitudinal direction of the culvert. This assumption holds true for certain type of loadings than others. For example soil loading applied to the surface or pavement maybe considered as uniform in the longitudinal direction. Solution therefore is independent of one of the three orthogonal axes and can be formulated in remaining two axes. Thus problem can be treated as two dimensional. Analysis of box culvert is done by stiffness matrix method. The model with respect to support conditions has been considered. Box culvert is assumed as externally determinate assuming discrete boundary conditions. Single cell box structure is assumed as rigid frame structure consisting of top slab, bottom slab and two vertical side walls which forms a closed rigid box frame. The analysis is performed considering a unit wide strip along the longitudinal axes. This strip is said to be in plain strain condition signifies the fact that the out of plane deformations are zero. The loads applied through small areas of contact between wheels and pavement. Such loads for practical are considered as point loads. While analyzing the box structure some basic assumptions are made to simplify the problem. It is assumed that structure is externally determinate. Also the pressure distribution at the bottom is assumed linear and bottom chord members are continuously supported. Axial and shear deformations are neglected. Based on above assumptions analysis is carried out by stiffness matrix method considering appropriate stiffness of the bottom chord members. Sujata Shreedhar and R.Shreedhar [1] has evaluated design coefficients for single and two cell box culverts. The study is done to evaluate the coefficient for bending moment, shear force and axial thrust for different loading cases and for different span to height ratios. Komal S.Kattimani and R.Shreedhar [2] has analyzed the box culvert by considering different Parameters. The study deals with the design parameters of box culverts like angle of dispersion of live load, effect of co-efficient of earth pressure and depth of cushion provided on top slab of box culverts. Kalyanshetti M.G and Malkhare [3] has analyzed box culvert by considering soil structure interaction and the results obtained are compare without considering soil structure interaction. The comparative study of bending moments was presented. In the present work IRC class AA tracked live load is considered on the box culvert. 12m channel length with 2m to 6m height variation is considered. For this channel length different configuration of box culvert are studied. The channel length is divided into single cell, double cell and triple cell. All these different sizes of cell are shown in **Table-1**. The objective of the study is to evaluate optimum thicknesses of the box culvert. The optimum cost per meter width is also calculated. The cost by considering optimum thicknesses and the cost without considering optimum thicknesses are compared. Accordingly results are presented which justifies that optimum thicknesses presented over here are leads to economical design of box culvert. An attempt is made to generate the charts of bending moments for top and bottom members. Such that from these charts at any intermediate aspect ratio the valves of bending moments can be evaluated. The average percentage reduction in the cost for single cell, double cell and triple cell is presented in **Table-6** and it is graphically presented in **Chart-8**.

2. FORMATION OF A STIFFNESS MATRIX FOR SINGLE CELL

The force displacement relationship for a prismatic member is shown in **Fig -1** and **Fig -2**.

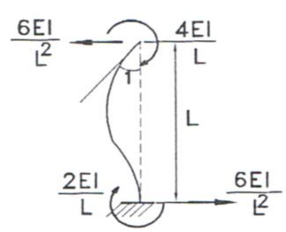

Fig-1: Forces and moments generated at the ends due to unit rotation.

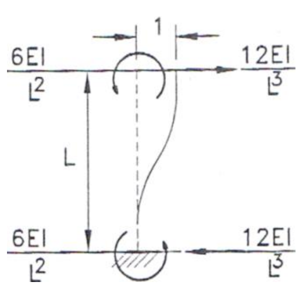

Fig-2: Forces and moments generated at the ends due to unit displacement.

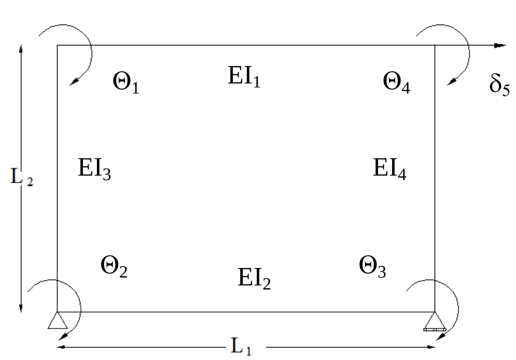

Fig-3: Single cell box culvert showing degrees of freedom

Consider a box structure as shown in the **Fig-3** In this case we have three unknown support reaction that is two at hinge support at left and one at roller support at, right. Since three equilibrium equations are available this single cell box structure is externally statically determinate. The internal static indeterminacy is three. This structure is kinematically indeterminate to fifth degree if axial deformations are neglected. Each joint of rigid jointed plane frame has three independent displacement components viz. two linear displacements and one rotational component. Therefore, Degree of kinematic indeterminacy of the rigid jointed plane frame is given by the equation given below.

$$D_{(IK)} = 3N_j - (N_R + N_m) \_\_\_\_\_\_\_ \quad (1)$$

Where,
$D_{(IK)}$ = degree of kinematic indeterminacy.
N_J = number of joints
N_R = number of reaction components.
N_m = number of constrains imposed by support condition and other factors such as inextensibility of members.

Applying the equation 1 degree of kinematic indeterminacy for the single cell box structure as shown in **Fig-3** can be calculated as below.

$$D_{(IK)} = (3x4)-(3+4) = 5$$

Therefore single cell box structure is kinematically indeterminate to fifth degree. In order to generate elements of stiffness matrix a unit displacement is imparted at each degree of freedom successively. The first four displacements are angular and fifth is linear. The equation 2 shows the stiffness matrix generated for single cell box culvert

$$[K]_{5X5} = E\begin{bmatrix} \left(\frac{4I_1}{L_1}+\frac{4I_2}{L_2}\right) & \frac{2I_2}{L_2} & \frac{2I_1}{L_1} & 0 & \frac{-6I_2}{L^2_2} \\ \frac{2I_2}{L_2} & \left(\frac{4I_1}{L_1}+\frac{4I_2}{L_2}\right) & 0 & \frac{2I_3}{L_1} & \frac{-6I_2}{L^2_2} \\ \frac{2I_1}{L_1} & 0 & \left(\frac{4I_1}{L_1}+\frac{4I_2}{L_2}\right) & \frac{2I_2}{L_2} & \frac{-6I_2}{L^2_2} \\ 0 & \frac{2I_3}{L_1} & \frac{2I_2}{L_2} & \left(\frac{4I_1}{L_1}+\frac{4I_2}{L_2}\right) & \frac{-6I_2}{L^2_2} \\ \frac{-6I_2}{L^2_2} & \frac{-6I_2}{L^2_2} & \frac{-6I_2}{L^2_2} & \frac{-6I_2}{L^2_2} & \left(\frac{-24I_2}{L^3_2}\right) \end{bmatrix} ----(2)$$

3. ASPECT RATIO

Aspect ratio is the non-dimensional quantity; it is ratio of span of culvert to its height. This terminology is used here to put variation in bending moment, percentage variation in steel and the total cost of Box culvert in simplified and specific manner.

Aspect ratio = span / height = L / H

Consider a single cell box culvert as shown in **Fig-4** having height 4m and span 6m.

Aspect ratio = L / H = 6 / 4 = 1.5

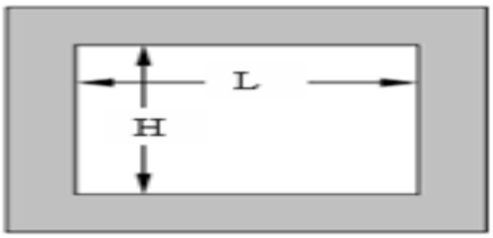

Fig-4: Single cell box culvert

In case of double cell and triple cell culvert L is taken as span of single cell only.

4. PARAMETRIC STUDY

IRC class AA tracked loading is considered on the box culvert. The parametric study contains variation of bending moment and optimum thickness for different aspect ratios for three load cases as shown in **Fig-5** to **Fig-7**. The optimum thicknesses and optimized cost are presented for critical load condition that is load case 1. The configuration of cells and their respective aspect ratios are presented in **Table-1**.

Table-1: Configuration of Cells And Aspect Ratios

Configuration of cells	Channel length	Span	Size of cell	Aspect ratio
4m length of each cell	12m	4m Triple cell	4 X 2	2
			4 X 3	1.3
			4 X 4	1
			4 X 5	0.8
			4 X 6	0.6
6m length of each cell	12m	6m Double cell	6 X 2	3
			6 X 3	2
			6 X 4	1.5
			6 X 5	1.2
			6 X 6	1
12m length of each cell	12m	12m Single cell	12 X 2	6
			12 X 3	4
			12 X 4	3
			12 X 5	2.4
			12 X 6	2

The loading conditions are given below and the analysis is done for the critical loading condition that is load case 1

Case 1: Considering live load and dead load on top slab, lateral load due to live load and earth pressure.

Case 2: Considering live load and dead load on top slab, lateral load due to live load and earth pressure and water pressure from inside.

Case 3: Considering live load and dead load on top slab, lateral load due to earth pressure, water pressure from inside and lateral load due to live load.

Fig-5: Load Case 1

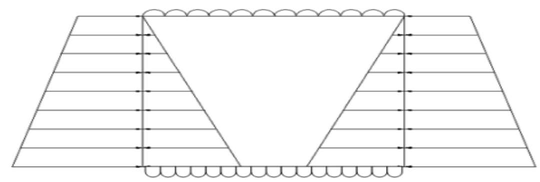

Fig-6: Load Case 2

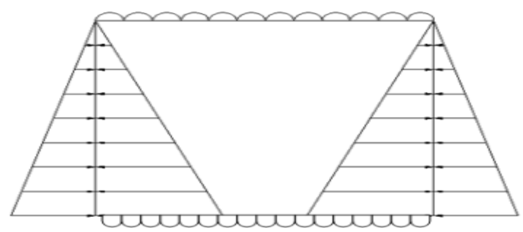

Fig-7: Load Case 3

The values obtained by analysis of load case 1 are considered in this work. The loading magnitudes for case 1 are shown in **Fig-8**, which is obtained for single cell box culvert carrying IRC class AA tracked loading.

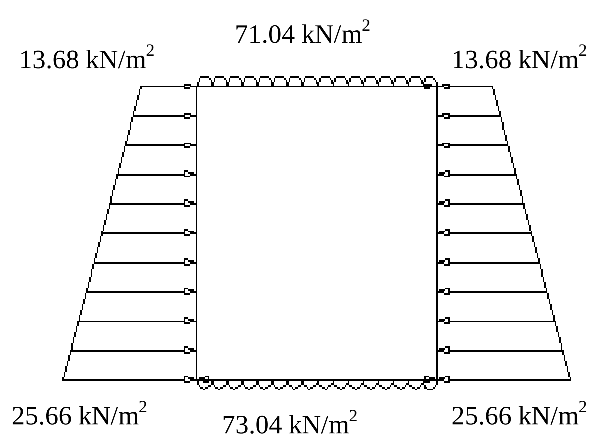

Fig-8: Loading On Single Cell Box Culvert

In the similar manner IRC class AA live load coming on double cell and triple cell box culvert is calculated. The single, double and triple cell models are prepared in STAAD PRO software. The loading is applied on the box frame and the bending moments values are obtained from STAAD PRO. A computer program is developed in C language to calculate the percentage of steel of each member and to evaluate the cost of box culvert. Bending moment of the member, characteristic strength of concrete, yield strength of steel are the input values and percentage of steel, quantity of steel and the total cost of culvert are the output values. The bending moment values and cost of culvert are presented in **Table-2**. The single cell, double cell and triple cell box culverts are shown in **Fig-9**.

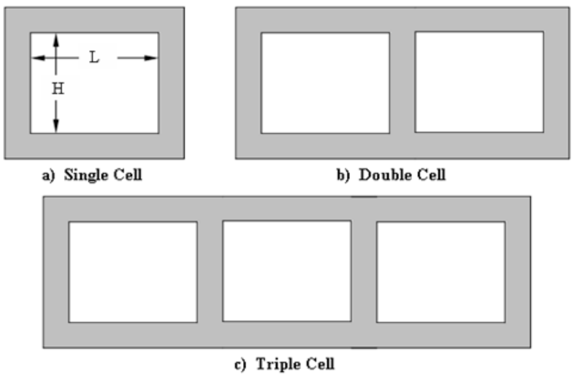

Fig-9: Single and Multiple Cell Culverts

Table-2: Variation In Bending Moment And Cost For Different Aspect Ratios

Height	Aspect ratio			Top member Bending moment kNm	Bottom member Bending moment kNm	Cost per meter width in Rs
	S	D	T			
2 m	6			906.55	597.86	1,36,061
		3		230.35	186.1	83,024
			2	82.95	70.2	58,516
3 m	4			856.4	576.78	1,44,722
		2		236.8	197.97	92,857
			1.3	82.39	71.78	67,084
4 m	3			812.2	564.57	1,54,319
		1.5		238.58	204.9	1,01,713
			1	80.16	71.45	75,673
5 m	2.4			775.83	560.22	1,65,558
		1.2		235.7	206.98	1,10,074
			0.8	76.29	69.1	85,023
6 m	2			747.92	564.07	1,80,029
		1		228.09	203.71	1,18,264
			0.6	82.2	90.5	1,00,199

The information given in **Table-2** is graphically shown as follows. The bending moment variation for top and bottom members of single cell, double cell and triple cell for their respective aspect ratios are shown in **Chart-1** to **Chart-5**.

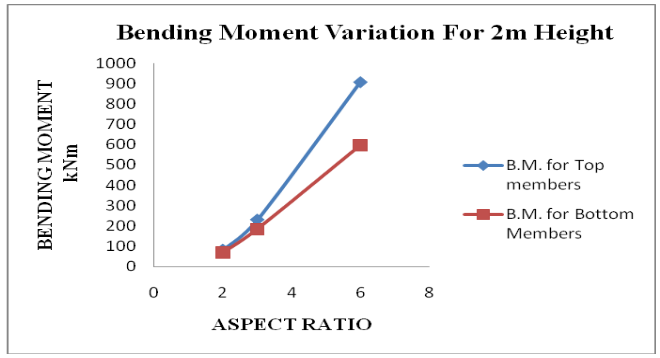

Chart-1: Bending Moment Variation In Top And Bottom Members For 2m Height

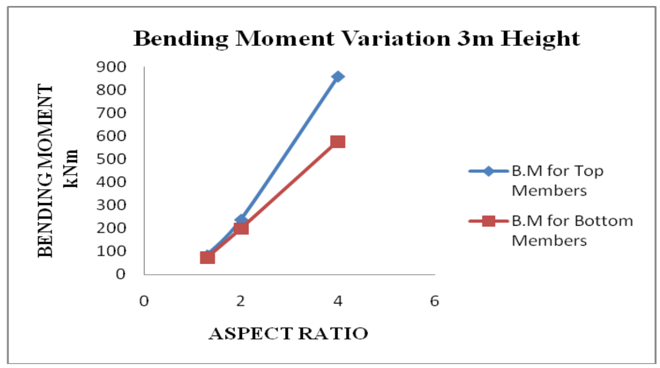

Chart-2: Bending Moment Variation In Top And Bottom Members For 3m Height

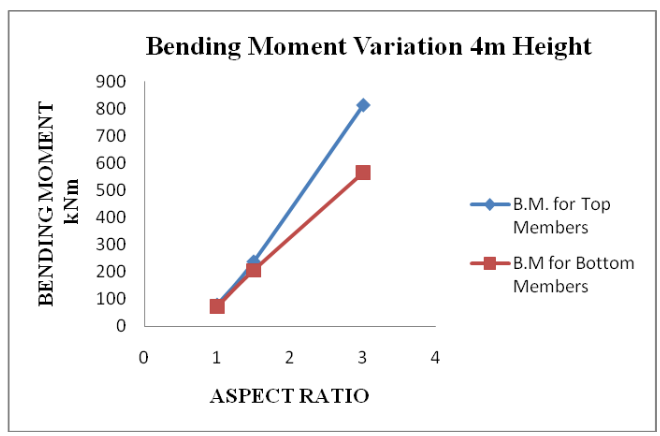

Chart-3: Bending Moment Variation in Top And Bottom Members For 4m Height

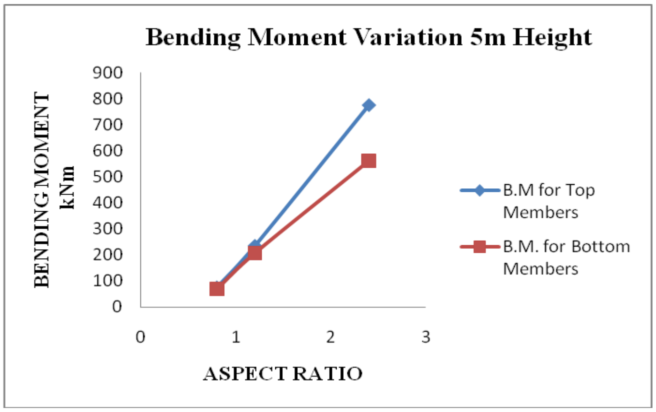

Chart-4: Bending Moment Variation in Top And Bottom Members For 5m Height

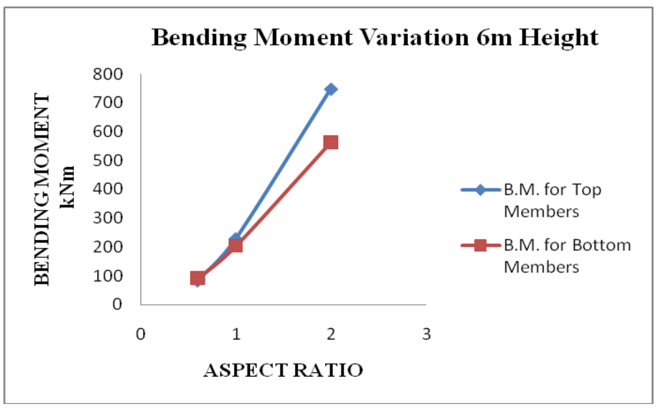

Chart-5: Bending Moment Variation in Top and Bottom Members for 6m Height

The combined variation of bending moments for top and bottom members of all the heights that is from 2m to 6m are shown in **Chart-6** and **Chart-7**.

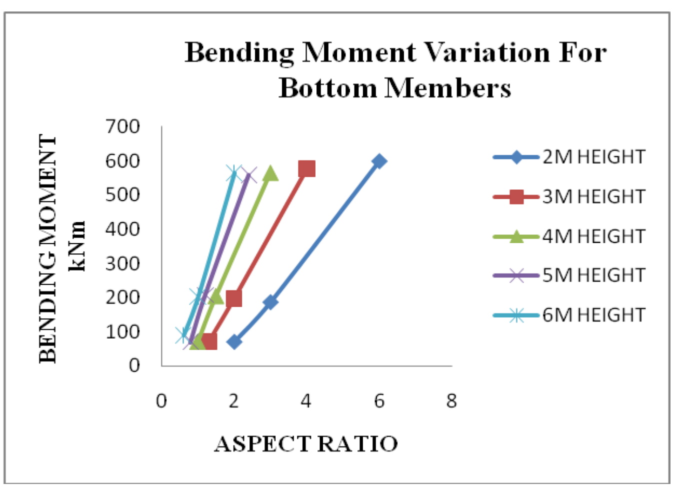

Chart-6: Bending Moment Variation In Bottom Members For Different Heights And Aspect Ratios

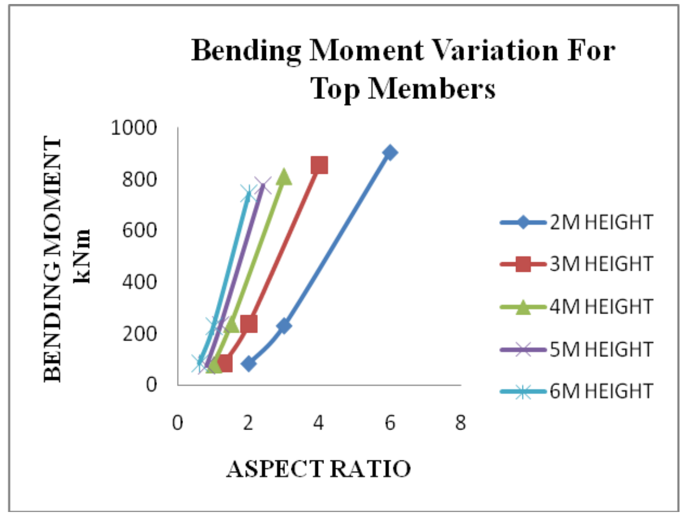

Chart-7: Bending Moment Variation In Top Members For Different Heights And Aspect Ratios

5. OBSERVATIONS AND INFERENCES

The box structure is analyzed for various conditions by changing number of cells, for IRC class AA tracked load. Based on above study prominent observations are presented below.

- Increase in height of culvert leads to substantial increase in BM at the centre of all the members and particularly at the bottom of side walls. It leads to increase in additional steel required at supports.
- It is observed that moment at the centre of top and bottom slab reduces tremendously in a triple cell box culvert as compared to that in a single cell culvert. The reduction in central moment is of the order of 90% to 95% in top slab and 92% to 94% in bottom slab. However, the support moments reduces by 90% to 91% for top slab and by 85% to 87% for bottom slab.
- It is observed that moment at the centre of top and bottom slab reduces tremendously in a double cell box culvert as compared to that in a single cell culvert. The reduction in central moment is of the order of 83% to 85% in top slab and 80% to 84% in bottom slab. However, the support moments reduces by 70% to 75% for top slab and by 63% to 69% for bottom slab.
- In a single cell box culvert for top and bottom slabs central moments are on higher side than the support moments. On the other hand, in a double and triple cell box culvert the top and bottom slabs are continuous therefore; the support moments are on higher side than the central moment.

The optimum thicknesses single cell, double cell and triple cell are presented in **Table-3, 4** and **5** respectively**.** These thicknesses are used to achieve economical design of box culvert for different configuration of cells presented in this study.

Table-3: Optimized Thicknesses For Single Cell

Total size	Single cell width	Cell height	Aspect ratio	Top slab	Bottom slab
12 X 2	12 M	2 M	6	L / 18.5	L / 17
12 X 3	12 M	3 M	4	L / 18.5	L / 17
12 X 4	12 M	4 M	3	L / 18.5	L / 17
12 X 5	12 M	5 M	2.4	L / 18.5	L / 17
12 X 6	12 M	6 M	2	L / 18.5	L / 17

Side wall optimum thickness is L / 17.

Table-4: Optimized Thicknesses For Double Cell

Total size	Single cell width	Cell height	Aspect ratio	Top slab	Bottom slab
12 X 2	6 M	2 M	3	L / 17	L / 17
12 X 3	6 M	3 M	2	L / 17	L / 17
12 X 4	6 M	4 M	1.5	L / 17	L / 17
12 X 5	6 M	5 M	1.2	L / 17	L / 17
12 X 6	6 M	6 M	1	L / 17	L / 17

Side wall optimum thickness is L / 17.

Central wall optimum thickness is L / 30.

Table-5: Optimized Thicknesses For Triple Cell

Total size	Single cell width	Cell height	Aspect ratio	Top slab	Bottom slab
12 X 2	4 M	2 M	2	L / 18	L / 18
12 X 3	4 M	3 M	1.3	L / 18	L / 18
12 X 4	4 M	4 M	1	L / 18	L / 18
12 X 5	4 M	5 M	0.8	L / 18	L / 18
12 X 6	4 M	6 M	0.6	L / 18	L / 18

Side wall optimum thickness is L / 18.

Central wall optimum thickness is L / 26.66.

For evaluating the optimum thickness mentioned in the above tables take L is the single cell width only and the obtained optimum thickness is the effective thickness of the cell.

The optimum cost per meter width of single cell, double cell and triple cell are evaluated by using the optimum thicknesses presented above. This optimum cost is compared with cost of culvert which is calculated without considering the optimum depths. Based on this percentage reduction in the cost is evaluated and presented in **Table-6**.

Table-6: Optimized Cost Of Single, Double And Triple Cells For 12m Channel Length

Ht.	Aspect ratio			Cost per Meter Width (Rs)	Cost for optimum dimensions (Rs)	% Reduction in cost per meter width
	S	D	T			
2m	6			1,36,061	1,32,548	2.65
		3		83,024	79,992	3.79
			2	58,516	56,949	2.75
3m	4			1,44,722	1,41,800	2.06
		2		92,857	89,062	4.26
			1.3	67,084	65,147	2.97
4m	3			1,54,319	1,51,878	1.60
		1.5		1,01,713	97,466	4.35
			1	75,673	73,369	3.14
5m	2.4			1,65,558	1,63,369	1.33
		1.2		1,10,074	1,05,507	4.32
			0.8	85,023	82,683	2.83
6m	2			1,80,029	1,77,225	1.58
		1		1,18,264	1,13,468	4.22
			0.6	1,00,199	98,028	2.21

The percentage reduction for their respective aspect ratios given in the above **Table-6** is represented graphically in **Chart-8**.

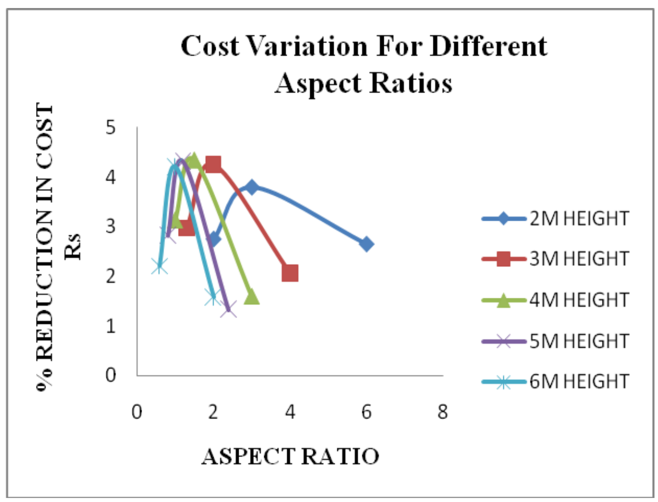

Chart-8: Percentage Reduction In Cost For 12m Channel Length

6. CONCLUSIONS

- Top slab of box culvert is critical member which carries maximum bending moment.
- The bending moments of different members of box culvert are determined for various aspect ratios and are presented in the form of charts. Using these charts bending moment can be calculated for intermediate aspect ratios also. The charts can be used as a readily reference for obtaining the bending moment for any different aspect ratio.
- In the conventional method of analysis thickness is approximately consider as L/20. However the optimum thickness are different for different aspect ratios for 12m channel length which is divided into single cell, double cell and triple cell they are in the range of **L/17 to L/18.5** for 12 m span, **L/17.6 to L/21.5** for 6 m span & **L/10 to L/20** for 4 m span.
- Based on the optimum thicknesses evaluated for 12m channel length average percentage cost reduction per meter width for single cell is **1.84%,** for double cell **4.18%** and for triple cell **2.78%.**

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