Study of Box Culvert using Finite Element Method

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Abstract— Culverts are required to be provided under earth embankment for crossing of water course like streams, Nallas etc. across the embankment, as road embankment cannot be allowed to obstruct the natural water way. The culverts are also required to balance the flood water on both sides of earth embankment to reduce the flood level on one side of road thereby decreasing the water head consequently reducing the flood menace, Box Culverts are ideally suitable monolithic structures across a highway or railway embankment to balance the flood water on both sides. It consists of top slab, bottom slab and two vertical side walls. It is most economical due to monolithic action and no separate foundation required since bottom slab serves as a mat foundation. The present study, an attempt is made to combine and study the effects of those parameters for live load. To perform a parametric study of the RCC box culvert with varying depth of cushion, coefficient of earth pressure and angle of dispersion for live loads. To compare results calculated by using IS code method with Software based on Finite Element Analysis, Depth of cushion, coefficient of earth pressure for lateral pressures on walls, width or angle of dispersion for live loads on box without cushion and with cushion for structural deformations are important.

Key words: Culvert, Finite Element Method

I. INTRODUCTION

It is well known that roads are generally constructed in embankment which come in the way of natural flow of storm water (from existing drainage channels). As such flow cannot be obstructed and some kind of cross drainage works are required to be provided to allow water to pass across the embankment. The structures to accomplish such flow across the road are called culverts, small and major bridges depending on their span which in turn depends on the discharge. The culvert cover upto waterways of 6 m (IRC: 5-1981) and can mainly be of two types, namely, box or slab. The box is one which has its top and bottom slabs monolithically connected to the vertical walls. In case of a slab culvert the top slab is supported over the vertical walls (abutments/ piers) but has no monolithic connection between them. A box culvert can have more than single cell and can be placed such that the top slab is almost at road level and there is no cushion. A box can also be placed within the embankment where top slab is few meters below the road surface and such boxes are termed with cushion. The size of box and the invert level depend on the hydraulic requirements governed by hydraulic designs. The height of cushion is governed by the road profile at the location of the culvert. Culverts are provided to allow water to pass through the embankment and follow natural course of flow but these are also provided to balance the water level on both sides of embankment during floods, such culverts are termed as balancers (IRC:78-2000[3]), although there is no difference in the design. Sometimes the road alignment may cross a stream at an angle other than right angle, in such situation a skew culvert may be provided. For a smaller span there would be no difference in the design of culvert but it may require an edge beam and the layout of wing walls will have to be planned as per skew angle.

Types of Culverts

a) Slab Culverts
b) Pipe culverts
c) Box culverts

II. PARAMETRIC STUDIES OF BOX CULVERT

Box Culverts are ideally suitable monolithic structures across a highway or railway embankment to balance the flood water on both sides. It consists of top slab, bottom slab and two vertical side walls. Reinforced concrete rigid frame box culverts are used for square or rectangular openings with span up to 6m. The top of the box section can be at the road level or can be at a depth below road level with a fill depending on site conditions. In box culverts four sides of the structure are built monolithically and also provide haunch at corners to decrease the water pressure effect. In this type of culvert there is no need of extra foundation since bottom slab act as mat foundation. When discharge flood is small then we prefer single cell box culverts. In case of under passages we provide only three sides and those are built monolithically. When discharge of flood is high then we have to increase the size of the box culvert and hence this leads to increase in thickness of the walls. This may lead to uneconomical section. In this criteria we have to go for multiple celled box culvert, in this we can decrease the depth of slabs. The thickness of the box culvert is assumed and later checked in conventional method. But this may leads to uneconomical design therefore an attempt is made to evaluate optimum thicknesses for economical design. Pre cast culverts are more suitable than cast in-situ. For a box culvert, the top slab is required to withstand dead loads, live loads from moving traffic, earth pressure on sidewalls, water pressure from inside, and pressure on the bottom slab besides self weight of the slab. The structure is designed like a rigid frame considering one meter element and adopting moment distribution method for obtaining final distributed moments on the basis of the relative stiffness of the slab and vertical walls. The method is well known and does not need any elucidation. The mid span moments are computed with free supported ends and adjusting it for moments at support obtained after distribution. The moments at center and supports for slabs and walls are obtained for various combination of loads and the member is designed for the maximum moment it may be subjected to. Also the shear force at a distance of effective depth from the face of wall and shear stresses it produces in the section is considered in the design. A few things like coefficient of earth pressure for lateral pressure on walls, effective width (run of culvert) for live loads and applicability of braking force on box without cushion (or little cushion) for structural deformation are important items where opinion of the designers vary and need to be dealt in much detail. These affect the design significantly and therefore, required to be assessed correctly for designing a safe structure. It is customary to consider box a rigid frame and unit length of box is taken for design by considering the effect of all forces acting on this unit length (generally 1.0 m of box). While calculating weight of cushion on top slab, some designer take average height of earth fill coming over full length of box including sloping side fill. This is not correct and full height of cushion should be taken at the worst section of the box (central portion) will be subjected to this load and the section needs to be designed accordingly. A question has been raised frequently whether culverts designed for four lane divided carriageway are safe for more number of lanes, a situation which occurs on widening of the road and frequently encountered for road development, and whether the culvert designed for no cushion shall be safe for cushion loads which may become a necessity at a future date due to change in road profile. If so, up to what height of cushion, the box need not be reconstructed. These shall be addressed in this Paper giving appropriate solutions as required. Box culvert has many advantages compared to slab culvert or arch culvert. The box is structurally strong, stable and safe and easy to construct. The main advantage is; it can be placed at any elevation within the embankment with varying cushion which is not possible for other type of culverts. A multi cell box can cater for large discharge and can be accommodated within smaller height of embankment. It does not require separate elaborate foundation and can be placed on soft soil by providing suitable base slab projection to reduce base pressure within the safe bearing capacity of foundation soil. Bearings are not needed. It is convenient to extend the existing culvert in the event of widening of the carriageway at a later date as per future requirement, without any problem of design and/or construction.

A. Co-Efficient Of Earth Pressure

The earth can exert pressure, minimum as active and maximum as passive, or in between called pressure at rest. It depends on the condition obtained at site for example in case of a retaining wall where the wall is free to yield and can move away from the earth fill the pressure exerted by the earth shall tend to reach active state and thus be minimum. As to reach active state only a small movement is required which can normally be achieved in case of a retaining wall, also before failure of the wall by tilting, the back fill is bound to reach active state. The wall thus can safely be designed for active pressure of earth, with co-efficient applicable for active pressure. In case of an anchored bulk head, the earth pressure on the anchor plate will tend to achieve passive state because the anchor plate is dragged against earth and large displacement can be allowed, one can consider passive co-efficient for the design of anchor, of course, some factor of safety need be taken as required displacement to achieve passive state before the bulk head gives way may not be practical. In cases where the structure is constructed before back fill earth is placed in position and the situation is such that structure is not in a position to yield on either side, the earth pressure shall reach a state at rest. In such situation the co-efficient of earth pressure shall be more than the active condition. In case of box since it is confined with earth from both sides the state of earth shall be at rest and a co-efficient more than the active pressure is normally adopted in the design. The earth is filled after construction of the box further the box is not in a position to move/yield therefore the pressure shall be at rest. The value is designer’s choice. The co-efficient of earth pressure in case of box is taken to be 0.333 for a soil having $\phi = 30^\circ$ equivalent to active condition by many authors in their books of design. Some authors take this value = 0.5 for normal soil having $\phi = 30^\circ$. A typical box has been designed keeping all factors to be same for the two values of earth pressure co-efficient. It is seen that these co-efficient even when taken differently have little effect on the overall design of the section. To bring out difference in more appreciable form the two design. It is observed that difference in design of culvert without cushion is marginal. However, box with cushion shows more difference. Considering the situation typical to the box, it is close to at rest condition and a co-efficient higher than active pressure should be taken. For practical considerations a value of 0.5 can be taken for earth pressure. Whereas, there is no point of difference in taking this value for culverts with cushion, some reservations are shown where braking force is taken to act on culverts without cushion, where the box is assumed to deform pressing against the fill earth on one side and the pressure can be different on two sides, at least it may tend to be active on the side the box is tilting away from the fill. In design this difference of earth pressure on two sides of box is not taken, as the pressure on the passive side, which depends on amount of deformation of culvert, cannot be evaluated within reasonable limits. However, the earth pressure on both sides of box before and after deformation can be assumed to be at rest/active pressure as the earth pressure co-efficient has little overall effect on the structural sizes of box members

B. Effective Width

Effective width in the run of culvert (length across span) is expected to be affected by a moving live load. This width plays a significant role as far as consideration of live load in the design of culvert. Where however, there is large cushion the live load gets dispersed on a very large area through the fill and the load per unit area becomes less and does not remain significant for the design of box, particularly in comparison to the dead load due to such large cushion. In case of dead load or uniform surcharge load the effective width has no role to play and such loads are to be taken over the entire area for the design.

Effective width plays an important role for box without cushion as the live load becomes the main load on the top slab and to evaluate its effects per unit run for design as a rigid frame, this load is required to be divided by the effective width. As such evaluating effective width correctly is of importance. The relevant IRC Codes, other Codes, books, theory/concepts are at variance as far as effective width is concerned and requires discussions at some length.

It is required to understand the concept behind effective width. Basically, it is the width of slab perpendicular to the span which is affected by the load placed on the top of slab. It shall be related to the area of slab expected to deform under load. It can be well imagined that this area of slab which may get affected will depend on how the slab is supported whether in one direction or both directions and secondly on the condition of support that is whether free or continuous or partially or fully fixed. It can also be imagined that the width shall be larger if slab is allowed to slide over support under the load as in case of freely supported, and the same will reduce if the slab is restrained from sliding and more the restraint the less shall be the width. In this view the effective width shall be least for fully fixed and gradually increase for partially fixed, increase further for continuous slab and shall reach maximum for slabs freely supported at ends. Where support on one side is different than on the other side the effective width should be obtained taking this fact in consideration. The distance of the load from the near support affects effective width, more the distance larger will be the effective width and will reach highest when the load is at center. The ratio of breadth (unsupported edges) and the span also affects effective width. The IRC:21-20006 Clause 305.16 gives an equation for obtaining effective width for simply supported and continuous slab for different ratio of overall width verses span for these two kinds of supports. The Code does not provide if one of the support is continuous while other is simply supported. The Code is silent for other types of supports such as fixed or partially fixed. Some designers use this formula and factors for continuous slab is taken valid for partially restrained support in a situation like box culvert. This does not appear to be in order.

C. Cushion

A box culvert can have more than single cell and can be placed such that the top slab is almost at road level and there is no cushion. A box can also be placed within the embankment where top slab is few meters below the road surface and such boxes are termed with cushion The size of box and the invert level depend on the hydraulic requirements governed by hydraulic designs. The height of cushion is governed by the road profile at the location of the culvert. While calculating weight of cushion on top slab, some designers take average height of earth fill coming over full length of box including sloping side fill.

III. FINITE ELEMENT ANALYSIS

Finite Element analysis is a discretized solution to a continuum problem using Finite element method. Finite element method is a numerical procedure for solving differential equations associated with field problems, with an accuracy acceptable to engineers. For stress analysis of problems the FEM was first used, and has since been applied to many other simple to complex problems. Sometimes we may have to find out variables like displacements in stress analysis. It is done by dividing the problem domain into discrete elements. Physical properties are applied to each discrete element. The variation of stresses in a system depends upon the geometrical property or effective area of the system of the system, the material property or surrounding environment, the boundary conditions and loading conditions. The domain and geometry are very complex in an engineering system. After that, the initial and boundary conditions are also be complicated. So generally it is difficult to get solution of governing differential equation by analytic methods. Numerical methods are most frequently using to get those solutions of the problems. So we are discretizing the problem by using Finite element techniques because of its practicality and versatility.

IV. PROBLEM STATEMENT

Clear span:	3 m
Clear height:	3 m
Top slab thickness:	0.42 m
Bottom slab thickness:	0.42 m
Side wall thickness:	0.42 m
Thickness of wearing coat:	0.065 m
Unit weight of concrete:	24 kN/m^3
Unit weight of earth:	18 kN/m^3
Unit weight of water:	10 kN/m^3
Co-efficient of earth pressure at rest:	0.5
Total cushion on top:	0.0 m
Carriageway:	4 lane (17m)
Concrete grade M 25:	25 MPa
Steel grade Fe 415:	415 MPa

Table 1:

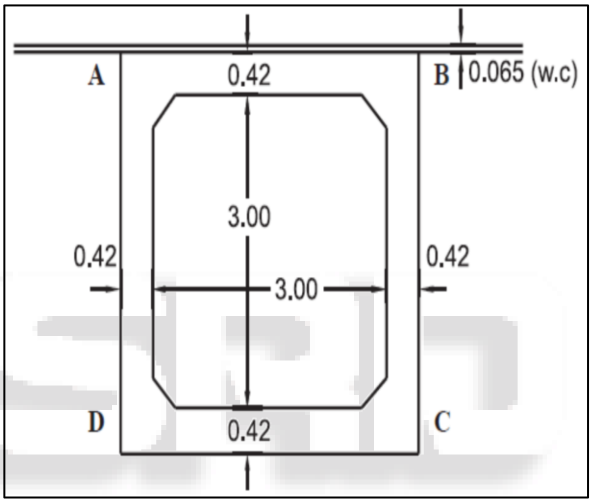

Fig. 1: Cross Section of Box Culvert

A. Case 1: Box Empty, Earth Pressure With Live Load Surcharge On Side Fill.

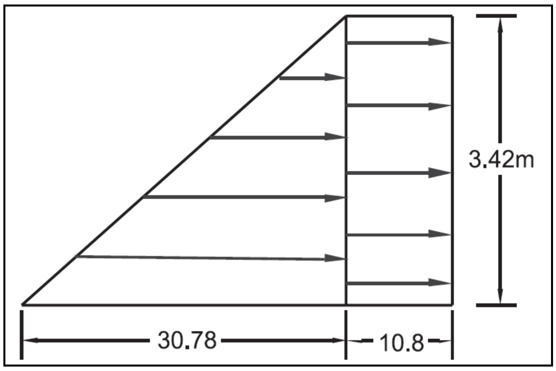

Fig. 2: Box without Cushion

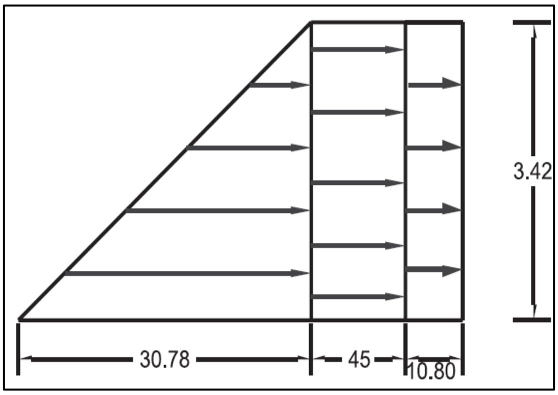

Fig. 3: Box with Cushion 5m

B. Case 2: Box Full With Water, Live Load Surcharge On Side Fill

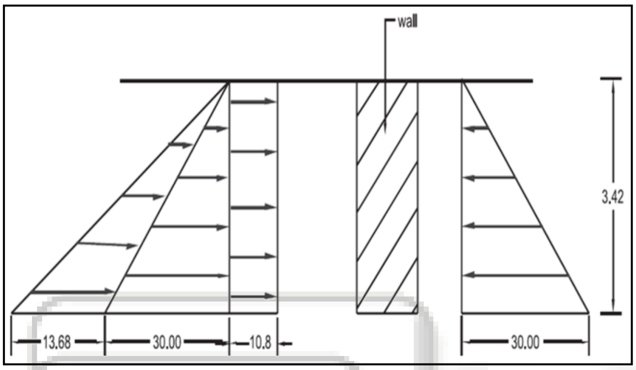

Fig. 4: Box without Cushion

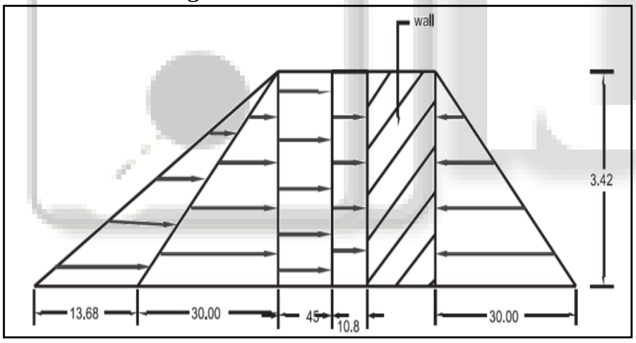

Fig. 5: Box with cushion 5m

C. Case 3 : Box Full With Water, No Live Load Surcharge On Side Fill

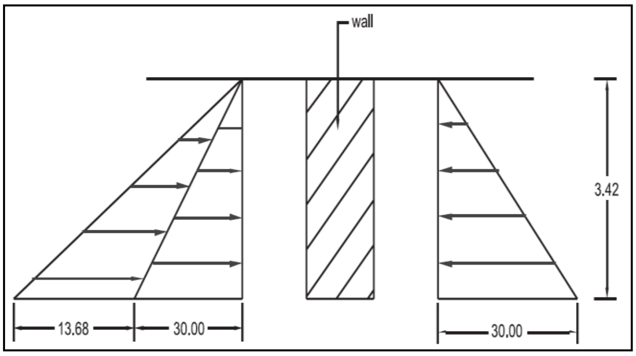

Fig. 6: Box without Cushion

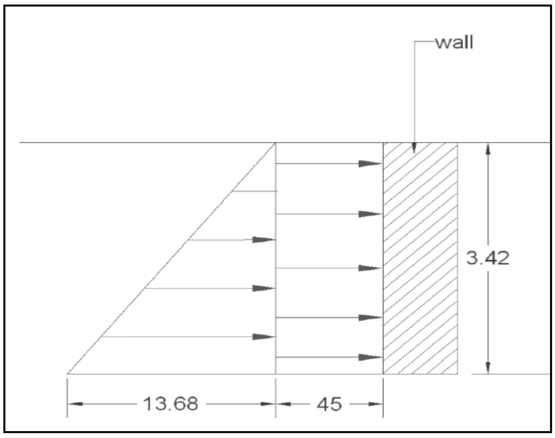

Fig. 7: box with cushion 5m

V. CONCLUSION

A. Co-Efficient Of Earth Pressure

1) The co-efficient of earth pressure has a little influence on the final moments therefore for safer design the co-efficient of earth pressure can be taken 0.5 which gives higher results than 0.33.
2) Small variation in co-efficient of earth pressure has little influence on the design of box particularly without cushion.

B. Cushion Depth

a) From Cushion depth study, it is possible to design box culvert with 0m or no cushion which shall be safe for cushion loads which may become a necessity at future date due to change in road profile.
b) When cushion above the top slab is less than 1m, the tire load dominated the behavior of culverts and cases considered.
c) When the cushion above the top slab of the culvert is between 1m and 2m, the behavior of the culverts is affected by both cushion and tire loading.
d) When the cushion above the top slab of the culvert exceeds 2m, the tire load effect is negligible and could be totally ignored for covers more than 3m.

The angle of dispersion affects the intensity of live load but when overall effect of all loads is taken into account, moments remain constant. Therefore the angle of dispersion considered in IRC 6-2000; which is 450, can be considered for design

The analysis & design of box culvert with and without cushion done by FEM based software STAAD. Pro compares very close to manual design (IS Code Method).

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