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Numerical simulation of box culverts subjected to different physical actions and design regulations

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Abstract. This research work was intended to provide a broad and sufficient solution to areas of difficult vehicular traffic, where during the rainy season some watersheds present a non-negligible water flow. The research carried out the structural design of different geometries of box culverts, to provide a solution to vehicular continuity in areas affected by water flows that interrupt pedestrian and vehicle traffic, endangering human lives. The structural designs followed the standards established by the American Association of State Highway and Transportation Officials and the Colombian bridge code. The designs were carried out using commercial software SAP2000 for analysis and design through Visual Basic programming, allowing a wide range of geometries and boundary conditions to be established. The structural designs indicated a significant difference in quantities of work in the construction of the box culverts for different geometries, indicating higher volumes of concrete for the designs made using the American Association of State Highway and Transportation Officials code compared to Colombian bridge code. The Colombian bridge code has higher steel requirements for fills less than 3.00 m, while for greater heights the American Association of State Highway and Transportation Officials code has the highest steel requirements.

1. Introduction

Box culverts are low structures composed of two horizontal and two vertical slabs built monolithically. They are ideal for the crossing of railways, roads or overpasses with drainage areas or water channels, and are also used in areas where the bearing capacity of the soil is low; the box culverts is an ideal bridge structure. Culverts are reinforced concrete structures with square or rectangular openings, with spans of up to 4.00 m, clear heights generally not exceeding 3.00 m and embankment heights of up to 6.00 m [1].

The box culvert is only a name given to it because of its shape, although it can be found less frequently in various types of shapes. These structures are economical, have great rigidity due to their monolithic action and do not require isolated foundations, since the bottom slab rests directly on the ground. For small discharges, single cell or box culverts are used; for large discharges, multi-cell or multi-bin culverts are usually used [2]. Box culverts are designed so that the top slab supports dead load, live load from the moving vehicle, earth pressure on the side walls, hydrostatic pressure from the inside and finally pressure on the bottom slab, in addition to the weight of the slab itself [3–5].

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The earth exerts active (minimum), passive (maximum), and resting pressure (average pressure), which will depend on the condition of the soil [6]. When the structure is built before the backfill is placed and the structure is not in a position to yield on either side, the earth pressure will reach a state of rest. In the case of the box, since it is confined with earth on both sides, the earth state must be at rest and a coefficient higher than the active pressure is normally adopted in the design [6].

The earth is filled after construction of the box and the box is not in a position to move/yield, so the pressure should be at rest. It is common practice to take the box as a rigid frame. Also, the unit length of the box is taken to design the effect of all forces acting on the unit length, that is 1.00 m. Moments at center and supports for slabs and walls are obtained for combinations of service load and resistance, and elements are designed for the maximum moment they can be subjected to. While the shear force is evaluated at a distance equal to the effective depth of the wall face [5].

The theory of wheel load distribution through the fill was investigated by several researchers [7, 8], as a result, there are two general solutions available, the closed and numerical form. The characteristics of each approach were briefly outlined in this paper. The closed-form solution treats the soil as a continuum and the solution is given anywhere in the problem domain in the form of equation [9]. This type of solution is complicated to obtain for all types of loading and boundary conditions without making simplifications in stress-strain relationships, directional properties of the soil and geometry of the culvert box, decreasing appreciably the accuracy of the problem.

Finally, the numerical solution incorporates the nonlinearities that the closed-form method does not solve in a finite element model together with a calibration of experimental results, allowing the calibration of finite element models and their extrapolation to models using frame-type elements [10–12]; in the present work they will be used in their modeling. Different works have been carried out in Colombia, ranging from pre-design analysis and design [13], as well as pathological studies in culvert boxes [14], among others.

The importance of taking into account the different physical actions on the box culverts is reflected in the magnitude of the cutting forces and the bending moments generated by these physical actions. In addition, this research established a comparison between the amounts of concrete volumes and kilograms of steel for different backfill heights using the American Association of State Highwayand Transportation Officials standard (AASHTO) [5] and Colombian bridge code (CCP14) [3].

The numerical simulation was performed in SAP2000 [15] and the design was carried out using the Visual Basic programming language [14]. The objective of this research was to design box culverts for different fill heights using the [3] and [5], as a result it was found that the AASHTO [5] requires larger volumes of concrete than the CCP14 [3].

2. Materials and methods

This research work determined the box culvert designs of 2.00 m $\times$ 2.00 m and 2.50 m $\times$ 2.50 m since these are the most commonly used sections in Colombia with different fill heights (H). Figure 1 shows truck axle, tandem and their respective loads used in the design of box culverts and defined below.

Table 1 shows the geometric dimensions and the analysis and design parameters used in this work; the note below Table 1 indicates the difference between the two box culverts under study. For the tandem axle, the expressions are the same as for the design truck, only the variables $S_a = 1200$ mm and $P = 125$ kN change. A schematic representation of the loads used for the analysis performed in the SAP2000 software [15] and design are shown in Figure 2.

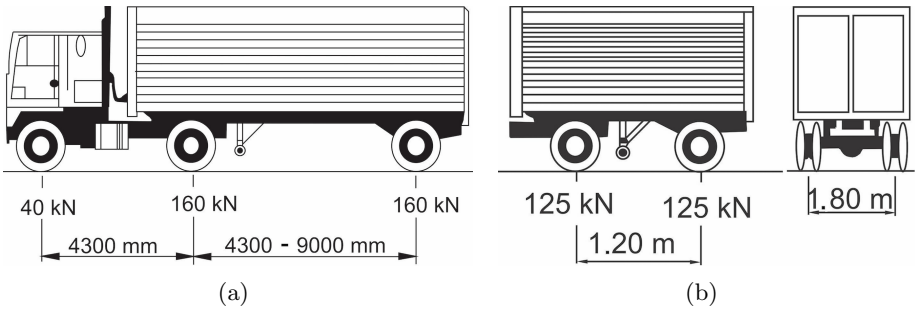


Figure 1. Design vehicle configuration, (a) truck and (b) tandem.

Table 1. Design parameters for box culvert 2.00 m × 2.00 m and fill height of 5.00 m

Variable	Value
Concrete compressive strength, f'_c (MPa)	34.47
Yield strength of steel, f_y (MPa)	413.69
Unit weight of concrete, γ_c (kN/m)	23.20
Unit weight of soil, γ_s (kN/m^3)	19.25
Clear height of box culvert, H_l (mm)	2000
Free base of box culvert, B (mm)	2000
Wall thickness, T_s (mm)	200
Thickness of top slab, T_t (mm)	180
Thickness of bottom slab, T_b (mm)	200
Backfill height, h_f (mm)	5000
Soil friction angle, (degrees)	30

Note: thickness of the upper slab is 230 mm and the thickness of the lower slab is 250 mm.

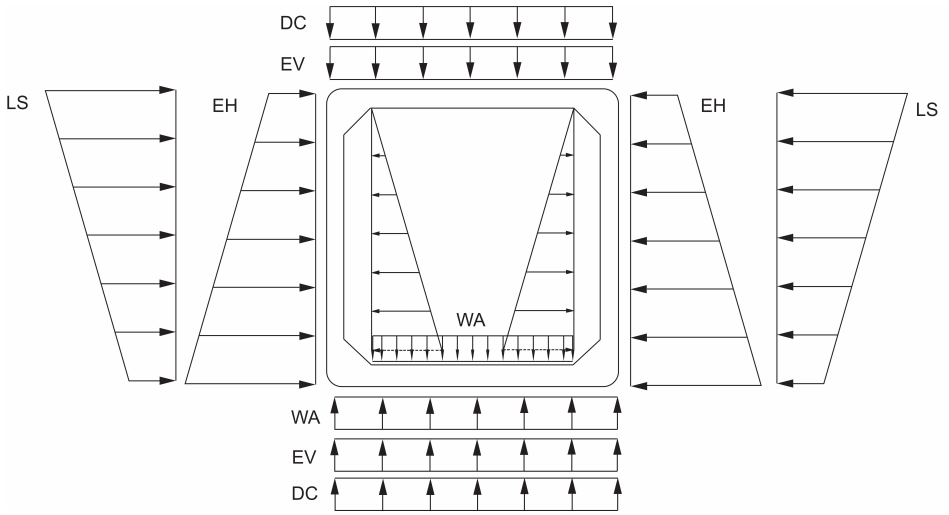


Figure 2. Compressive strength envelope of solid clay brick masonry units.

The design combinations used for both the CCP14 [3] and AASHTO [5], for the strength limit state and the serviceability limit state. For the resistance limit state condition, three

combinations are identified: Ia, Ib and Ic. Combination Ia takes into account the factored loads; maximum vertical load and maximum horizontal load, Equation (1).

$$1.25DC + 1.30(1.05)EV + 1.75(LL + IM) + 1.35(1.05)EH_{max} + 1.75LS, \quad (1)$$

where DC represents dead load, EV is vertical thrust of the ground, LL corresponds live load, IM represents dynamic load capacity, EH_{max} is maximum earth pressure on the walls and LS corresponds live load overload. Combination Ib takes into account the factored loads; maximum vertical load and minimum horizontal load, see Equation (2).

$$1.00DC + 1.00EV + 1.00(LL + IM) + 1.00WA + 1.00EH_{min}, \quad (2)$$

where WA represents water load and EH_{min} is minimum horizontal load. Combination Ic takes into account the factored loads; minimum vertical load and maximum horizontal load, see Equation (3).

$$0.90DC + (0.90/1.05)EV + 1.35(1.05)EH_{max} + 1.75LS. \quad (3)$$

The serviceability limit state condition, also has three combinations are identified: Ia, Ib and Ic. Combination Ia takes into account the unfactored loads; maximum vertical load and maximum horizontal load, see Equation (4).

$$1.00DC + 1.00EV + 1.00(LL + IM) + 1.00EH_{max} + 1.00LS. \quad (4)$$

Combination Ib takes into account the unfactored loads; maximum vertical load and minimum horizontal load, see Equation (5).

$$1.00DC + 1.00EV + 1.00(LL + IM) + 1.00WA + 1.00EH_{min}. \quad (5)$$

Finally combination Ic takes into account the unfactored loads; minimum vertical load and maximum horizontal load, see Equation (6).

$$1.00DC + 1.00EV + 1.00EH_{max} + 1.00LS. \quad (6)$$

3. Results and discussions

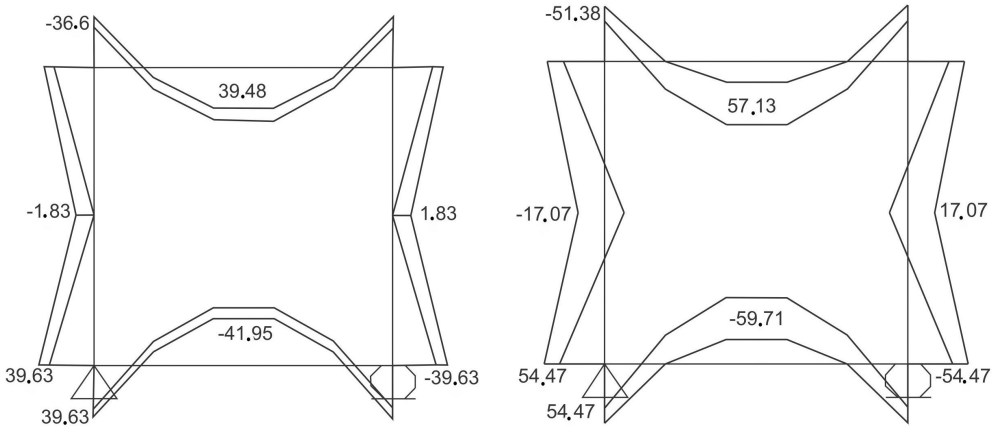
This was performed from the numerical model made in [15] and taking into account the envelope of results for bending moments and shear force. Figure 3 shows the envelope of moments (kN-m) for the strength limit state, see Figure 3(a) and serviceability limit state, see Figure 3(b) using the CCP14 [3].

The moment diagrams presented in Figure 3(a) have a expected behavior and its maximum positive and negative moment values are as expected, likewise the results obtained in Figure 3(b). The results obtained from the analysis of loads, moments and shear forces were processed for design purposes in the Visual Basic programming language. The results obtained were compared using the CCP14 [3] and AASHTO [5] codes, as well as the document of the "Ministerio de Transporte", Colombia [16]. The design concrete volumes for a 2.00 m $\times$ 2.00 m and 2.50 m $\times$ 2.50 m box culvert with free discharge length and fill heights of: 0.60 m, 1.00 m, 2.00 m, 3.00 m, 4.00 m and 5.00 m are shown in the Figure 4.

Figure 4(b) presents differences due to the minimum thickness requirements defined in the CCP14 [3] and AASHTO [5], the design load and the clear span between walls; this did not generate changes in the wall and slab thicknesses for the different fill heights. The concrete volumes using [16–18] do not present variations in the thicknesses for fill heights $\leq$ 3.00 m, although they are less than those found in the two previous codes; however, for fill heights 3.00 $<$ H $\leq$ 5.00 m, the concrete volumes increase, becoming equal to those found

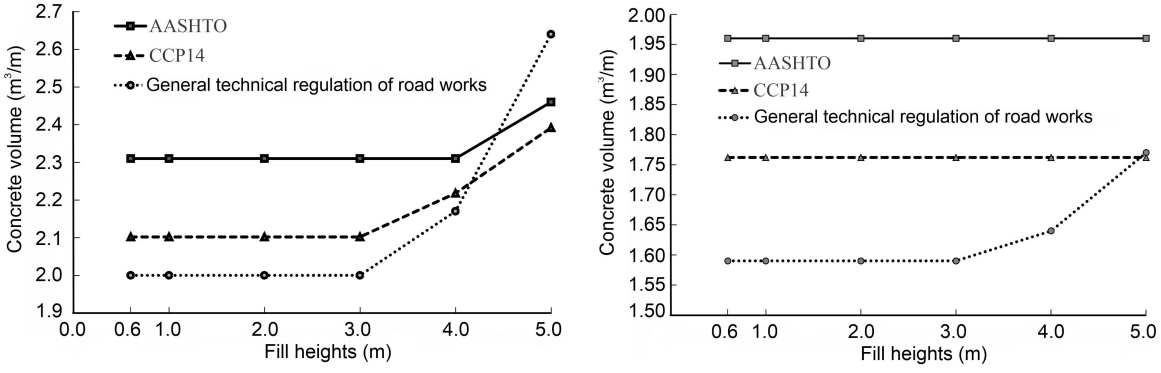
using CCP14 [3]. The difference in concrete volume/m (per meter of box culvert) for the two codes is due to the fact that AASHTO [5] requires the use of the four haunches (diagonal elements located at the four corners of the box), while CCP14 [3] does not.

A similar analysis was performed for box culverts of 2.50 m × 2.50 m and variable fill height; the results can be seen in Figure 4(a). The difference in quantities of m^3 of concrete per meter of box culverts shown in Figure 4(a) is due to the presence of the haunch in the design using [5], although this difference in volumes is slightly reduced due to the increase in wall thickness in the design using [3]. The technical regulation presents lower quantities of concrete up to a fill height of 4.15 m with respect to CCP14 [3], and does not meet the minimum requirements established in [3].



(a) (b)

Figure 3. Moment envelope for a section of 2.00 m × 2.00 m and a fill height of 5.00 m, for (a) combination by serviceability and (b) combination by strength.



(a) (b)

Figure 4. Comparison of concrete volumes for culverts box of (a) 2.50 m × 2.50 m and (b) 2.00 m × 2.00 m.

An analysis of the amount of kg/m of culvert box for a section of 2.00 n x 2.00 m free and variable fill height is shown in Figure 5. The steel requirements in kg/m box culverts present in Figure 5(b) are higher in CCP14 [3] than all other papers under study, for fill heights $\leq$ 2.00 m. For heights $>$ 2.00 m both codes are similar, and for all fill heights [9] has less reinforcing steel performance. The differences between the [3] and [5] are because in AASHTO [5] the moments are taken at the beginning of the haunch, while in CCP14 [3] the bending moments are evaluated in the axis of the box wall thickness, where the moments increase even more due to the presence

of the dynamic load. This generates an important difference in the design moments due to the increased stiffness provided by the haunch.

The behavior curve of the reinforcing steel in kg/m for the 2.50 m × 2.50 m box culverts shown in Figure 5(a) is very similar to the one found for the 2.00 m × 2.00 m box culverts, influenced by the presence of the haunch in the AASHTO [5].

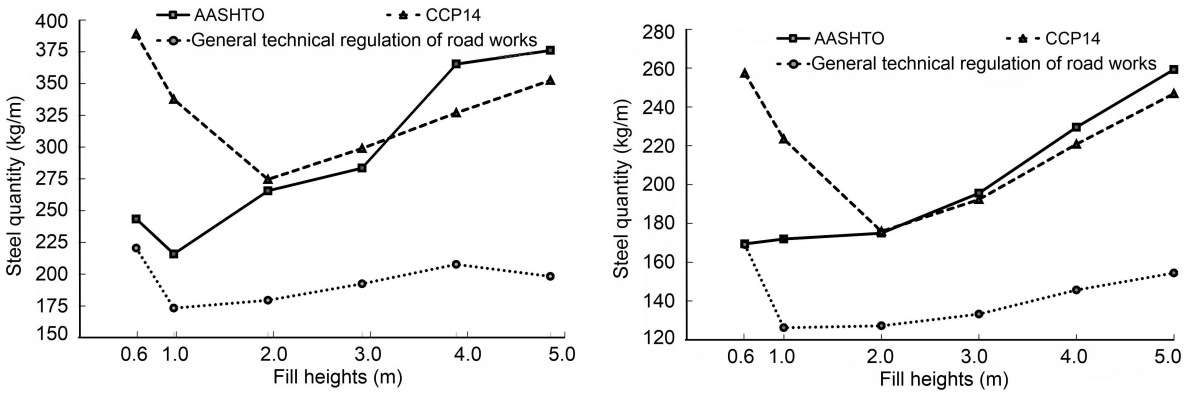


Figure 5. Comparison kilograms of reinforcing steel for culverts box of (a) 2.50 m × 2.50 m and (b) 2.00 m × 2.00 m.

4. Conclusions

This research work makes a contribution to the design of box culverts taking into account different physical actions such as earth fill load, live load, over live load, dead load, water pressure and impact load, as well as different load combinations that seek to increase the effects on the structure. The Colombian bridge standard estimates lower quantities of cubic meters of concrete than its similar one from the American Association of State Highway and Transportation Officials standard, and the use of the old general technical regulation of road works provides for lower quantities of concrete, possibly due to ignorance of the behavior and the demand for resistance for the road works. years 1988. For steel, the Colombian bridge standard has greater requirements for fills of less than 3.00 meters, while for fills greater than 3.00 m, the American Association of State Highway and Transportation Officials standard has greater steel requirements.

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