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Reliability of concrete box culverts designed for vertical loads

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ABSTRACT

The design vertical loads on box culverts under embankments are commonly calculated using the soil-structure interaction factors (F_e) recommended by the American Society of Highway and Transportation Officials (AASHTO). Non-linear finite element analyses were used to update F_e given by AASHTO by considering the effects of backfill height, culvert stiffness, backfill material stiffness, backfill compaction, and the rigidity of the layer on which the culvert rests. A simplified reliability analysis was performed to determine the adequacy of safety level in AASHTO load resistance factor design (LRFD) code specifications.

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1. Introduction

Culverts are underground structures that are utilized to convey water, small vehicles, and utilities. Soil-structure interaction effects increase the complexity of stress distribution around culverts. The load that acts on the culvert may be influenced by the characteristics of the backfill and the in-situ material, the installation methodology, and the geometry and structural characteristics of the culvert itself. However, due to the large number of these structures that are being built for various purposes, a relatively simple design procedure is required for analysis and design.

Currently, the most common procedure to estimate design vertical loads on concrete box culverts is to use the soil-structure interaction factors recommended by the American Society of Highway and Transportation Officials (AASHTO). Based on the study by Akbaş and Yüksel (2007), this study examines the vertical loads on reinforced concrete box culverts under embankments using non-linear finite element analyses, considering the effects of backfill height, culvert stiffness, backfill material stiffness, backfill compaction, and the rigidity of the layer on which the culvert rests. A simplified reliability analysis is then performed to determine the adequacy of safety level for culvert design using AASHTO load resistance factor design (LRFD) code specifications.

2. AASHTO Design Methodology

According to the installation methodology, culverts can be classified as embankment or trench installations, with an embankment installation having its top projecting above the natural ground surface, and covered with an embankment. A trench installation is constructed in a narrow ditch such that its top is below the natural ground surface and then is covered with an embankment. The behavior of these two installation types are quite different. In embankment installations, the relative settlement of the soil prism directly above the structure is usually less than that of the adjacent soil prisms, the layers of soil in the central prism are subjected to an arch shape deformation, and the earth pressure on the structure is increased, which is referred to as negative arching (Vaslestad et al., 1993). On the other hand, the relative settlement of soil prism directly above the structure is more than that of the adjacent soil prisms for the trench installations. Therefore, a reverse arch shape deformation occurs in the layers of soil in the central prism, and consequently the earth pressure on the structure is reduced.

Based on their stiffnesses, culverts can further be classified as rigid or flexible. Reinforced concrete box culverts are typically considered to be rigid culverts, and are generally constructed using embankment installation methodology (Bennett et al., 2005).

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For the design vertical loadings on cast-in-place or precast concrete box culverts, the current AASHTO LRFD bridge design specifications (AASHTO, 1998) and AASHTO standard specifications for highway bridges (AASHTO, 2002) use soil-structure interaction factors based on the method developed by Spangler (1947) and on the studies initiated by Marston in 1919 at Iowa State University.

For embankment installations the soil-structure interaction factor, which is equal to the ratio of the vertical load on the culvert to the weight of the soil prism directly above it, is determined as:

$$F_e = 1 + 0.20\frac{H}{B}, \tag{1}$$

in which F_e need not be taken greater than 1.15 for installations with compacted fill at the sides, and need not be taken greater than 1.4 for uncompacted fill at the sides.

3. Finite Element Model and Its Verification

A non-linear, two-dimensional, plane strain finite element analysis of the concrete box culvert-soil system was conducted using the commercial finite element program PLAXIS. Soil behavior was represented by the Hardening-Soil model, which is an advanced model for simulating both stiff and soft soil behavior (Schanz et al., 1999). The elements representing the culvert are based on Mindlin's beam theory and they allow for beam deflection due to both bending and shearing. Each node has three degrees of freedom per node: two translational and one rotational. These elements can become plastic if a prescribed maximum bending moment or axial force is reached.

Due to symmetry, for increased computational performance, only the right-hand side of the soil-structure system was modeled. The domain was discretized using 15-noded triangular soil elements with fourth order interpolation for displacements and 5-noded beam culvert elements. A typical geometry and finite element mesh used in this study is shown in Fig. 1. There is a line of symmetry along the centre of the culvert and this was replaced by a rolling, rigid boundary. Rigid boundaries were located remote from the culvert, so as not to interfere with failure mechanisms or affect the effective stresses in the deforming zone. The boundary conditions and fixities are also shown in Fig. 1.

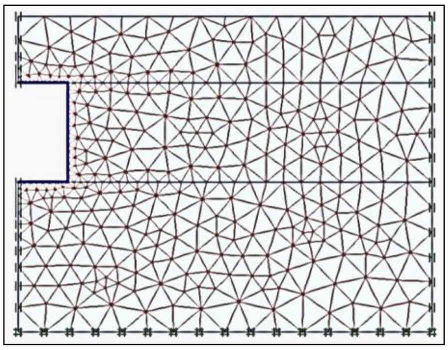

Fig. 1. Typical finite element mesh and boundary conditions.

In order to assess the validity of the soil-structure system modeling techniques and the accuracy of the finite element analysis results, a large-scale reinforced concrete box culvert tested by Dasgupta and Sengupta (1991) was reanalyzed. The details are given in Akbaş and Yüksel (2007). Both the comparison of top slab pressures as shown in Table 1, and the maximum deflections suggest that the finite element model can successfully simulate the behavior of concrete culverts.

Table 1. Undisturbed sample properties.

Pressure Cell	Dist. From Inner Face (mm)	Measured Pressure (kPa)	Calculated Pressure (kPa)
A	50	72.0	74.1
B	325	40.0	45.9
C	600	25.0	25.0

4. Updated Design Vertical Loads on Concrete Box Culverts

In this section, for various conditions, the verified finite element model was used to estimate the design vertical loads, which are calculated in terms of the soil-structure interaction factor, F_e, on concrete box culverts. The change in the vertical design load with increasing fill height expressed as the dimensionless H/B, is shown in Fig. 2, along with the soil-structure interaction factors recommended by AASHTO. Note that for each case, the soil structure interaction factor was obtained by fitting a parabolic regression equation to the shear force distribution of the top slab, and then by differentiating it to obtain the equivalent vertical load. The r^2 value was obtained to be bigger than 0.97 in all cases.

The stiffness, i.e., the thickness of the culvert was varied such that the maximum deflections obtained at the top slab are about 1/300 of the span. For reinforced concrete beam elements, the deflections are generally limited to values ranging from 1/1000 to 1/300 of the span, depending on the type and importance of the structure. Since structural integrity is the main issue for culverts, for this study, a limiting deflection of 1/300 of the span length was targeted in the analyses.

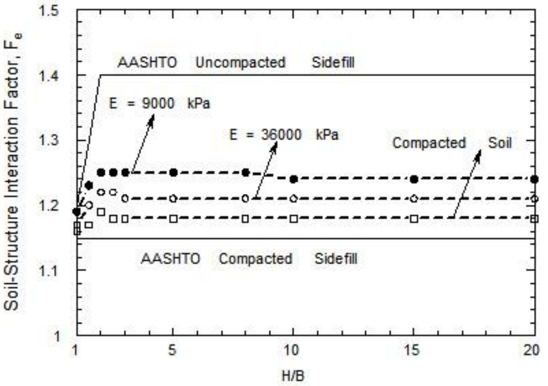

Fig. 2. Effect of soil stiffness and compaction on F_e.

The initial analyses were performed with the soil conditions specified in Dasgupta and Sengupta (1991), where the internal friction angle (ϕ') was 30°, and the modulus (E) was 9000 kPa. For these conditions, as can be seen from Fig. 2, F_e can be specified as a constant 1.25 for H/B values greater than 2. To determine the effect of soil stiffness on the vertical design load, the analyses were repeated with a much stiffer soil, with ϕ'=44°, and E=36000 kPa, respectively. It can be stated that these two soils span the usual range of conditions that can be encountered in practice. The results are also shown in Fig. 2. It can be seen that the effect of soil stiffness is minimal, and can be neglected for all practical purposes.

The effect of compaction is also investigated. Compaction not only increases the density of the soil but it also permanently increases the ratio of the horizontal to vertical pressures. Thus, it produces an effect similar to that of overconsolidation. Sherif et al. (1984) presented data for the effect of compaction on the properties of Ottawa silica sand with ϕ'=32°, and horizontal to vertical stress ratio K_o=0.466. The K_o value becomes 0.69 for a compaction effort which increases ϕ' to 38°. Using the fact that the internal friction angle is not an effective parameter for F_e, and assuming a similar increase in K_o value for the soil specified in Dasgupta and Sengupta (1991), the analyses were repeated for the compacted soil. The results are shown in Fig. 2. It can be seen that, although not by much, the effect of compaction is to reduce F_e. However, since it is difficult to quantify the effect of compaction, it is not recommended to use the reduced F_e, except for cases where compaction effort is rigorously measured. It can also be seen that the F_e values recommended by AASHTO for compacted side fills are unconservative even for compacted soil.

Although a rare occasion, a solid rock layer can be encountered immediately under the concrete box culvert. AASHTO (2002) stipulates that a special soil-structure analysis is required for "unyielding" foundations. In this section F_e values are estimated for a concrete box culvert underlain by a rigid rock layer of modulus equal to that of concrete. The results are shown in Fig. 3. It can be seen that F_e values are much higher for culverts with unyielding or "rigid" bases than those with yielding or "non-rigid" bases. Also, for culverts with unyielding bases, soil-structure interaction factors increase as the backfill heights increase. The results for culverts with unyielding bases are comparable to those obtained by Kim and Yoo (2005).

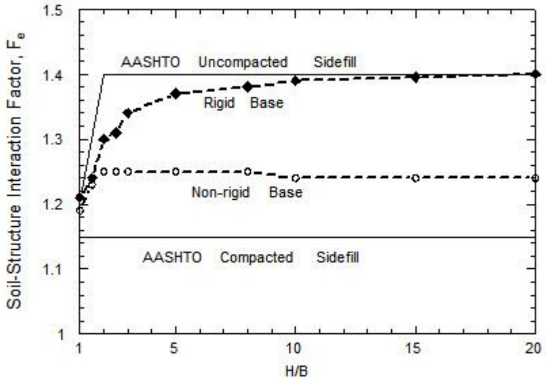

Fig. 3. Effect of rigid base on F_e.

Accordingly, F_e given by AASHTO were slightly modified as follows for culverts on a yielding base:

$$F_e = 1 + 0.20\frac{H}{B}, \tag{2}$$

in which F_e need not be taken greater than 1.18 for installations with compacted fill at the sides, and need not be taken greater than 1.25 for uncompacted fill at the sides. Also soil-structure interaction factors for culverts on unyielding bases are introduced:

$$F_e = 1.242 + \left(\frac{H}{B}\right)^{0.047}. \tag{3}$$

5. Inherent Reliability in the AASHTO LRFD Code

The safety levels in concrete box culverts designed by AASHTO LRFD code are estimated by a simplified reliability analysis. Assuming that all random variables are log-normally distributed, the reliability index (β) can be calculated as:

$$\beta = \frac{\overline{\ln R} - \overline{\ln Q}}{COV_R^2 + COV_{RQ}^2}, \tag{4}$$

in which R=resistance; Q=load; COV=coefficient of variation; and an overbar indicates a mean value. The resistance is assumed to follow the same statistics as the moment of a reinforced concrete T-beam with a bias of 1.14, and a COV of 13% (Nowak, 1995). The load is composed of two components: the soil unit weight (γ), and F_e. The COV value for soil unit weight is given to be between 3% and 20% with a mean value of 9% by Phoon and Kulhawy (1999). γ can be assumed to have a bias of 1.00 (Duncan, 2000). Assuming that the results obtained by FEM are perfectly accurate, the bias for F_e can be calculated as the ratio of equations 2 or 3 to the value obtained by AASHTO procedure.

In LRFD, a load factor of 1.3 is used for the dead load, and a resistance reduction factor of 0.9 is used for flexure. These should also be incorporated into the calculation of β. Note that a target reliability index of 3.5 was chosen for the development of the AASHTO LRFD code (Nowak, 1995).

The obtained reliability indices (β) as a function of H/B are shown in Fig. 4 for culverts on yielding and unyielding bases designed against vertical loads using AASHTO procedure. For culverts on yielding bases, inherent design reliability is higher than the target reliability except for very low values of H/B. The lowest β obtained for these culverts are about 3.1. For culverts on unyielding bases inherent design reliability is lower than the target reliability for most values of H/B, with a minimum value of about 2.9.

Although for some values of H/B, AASHTO procedure results in lower reliability index values than the specified target reliability index of 3.5, the safety level can be considered to be adequate. A lower reliability index can be justified for culverts (Bennett et al., 2005). For most cases, failure of a culvert does not directly result in a lifesafety problem although it might create serious economic consequences. Even for more important structures such as certain bridge beams in service, Nowak (1995) reported reliability indices as low as 2.0. Therefore the estimated β values above, with a minimum value of about 2.9 may be high enough.

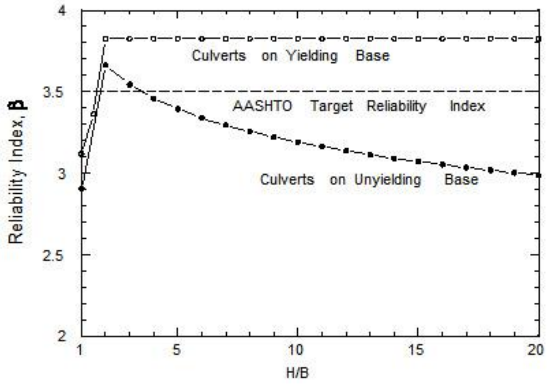

Fig. 4. Reliability indices for culverts designed by AASHTO procedure.

Note that, in addition, if the load factor is increased 5%, following the AASHTO LRFD bridge design specification (AASHTO, 1998), where it is required that the buried structures be considered as nonredundant under earth fill, the minimum value of estimated β increases to 3.2. These facts combined with the general successful behavior of culverts in practice indicate that the current methodology results in designs with high enough safety levels.

6. Conclusions

Non-linear finite element analyses were used to update the soil-structure interaction factors (F_e) for culverts on yielding and unyielding bases. The effects of backfill height, culvert stiffness, backfill material stiffness, and backfill compaction were considered. The results were then used to estimate the safety levels in concrete box culverts designed by the AASHTO LRFD code by a simplified reliability analysis. Although the obtained reliability index values for some cases are less than the target reliability index value of 3.5, it can be stated that, in general, the safety levels inherent in the culverts designed by the AASHTO code are adequate.

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