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Research Paper

Model test and numerical simulation on rigid load shedding culvert backfilled with sand

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ABSTRACT

For reducing embankment load on box culvert, a new culvert structure called load shedding culvert (LSC) is proposed. First, model tests were conducted to investigate the performance of LSC, which was compared with embankment-installation box culvert (EBC) and imperfect-trench-installation box culvert (IBC). Then, numerical simulations were performed to investigate the stress states of the three culvert structures and associated important influencing factors. This study reveals that the LSC, compared with EBC and IBC, can not only reduce the vertical earth pressure on the top slab but also reduce the horizontal earth pressure on the culvert sidewall.

1. Introduction

Rigid box culverts under high embankment are widely used in highway and railway projects. Although culvert structures are relatively simple, the interaction between soil and structure can be complex. The rigid embankment-installation box culvert (EBC) has its top projecting the natural ground as shown in Fig. 1(a). The stiffness of the culvert is higher than that of the adjacent fill mass, and therefore, the settlement of surrounding soil prism is larger than that of the central soil prism above the culvert. The shear stress (or friction stress) between the surrounding soil prism and the central soil prism results in backfill pressure concentration on the culvert [1–5]. The extra load on culvert often leads to structural hazards of the culvert [6,7].

In order to reduce the backfill load on the culvert, several methods are commonly used in construction process, among which, the imperfect-trench-installation box culvert (IBC) is usually used in the embankment engineering. This IBC method was originally proposed by Marston [8,9]. In this method, a compressible layer is set on the culvert top to generate soil arch in the backfill, which can transfer the load of the central fill mass over the culvert to the adjacent fill mass, such that the vertical earth pressure on the culvert is reduced, as shown in Fig. 1(b). Based on of Marston's work, further study was carried out by Spangler [10]. The performance of imperfect-trench-installation culvert were investigated by field tests, experimental and numerical methods [11–14]. Kim and Yoo [15] conducted a numerical study to investigate the effect of several important factors (i.e., the width, thickness, location, and stiffness of the compressible layer) on the performance of the box culvert. Kim and Yoo also pointed out that the width of compressible layer should not be greater than 1.5 times the box culvert width and the greatest load reduction occurred when the compressible layer was placed immediately on the culvert top.

The imperfect-trench-installation method is recognized as one of the acceptable methods in the prevailing AASHTO LRFD bridge design specifications [16]. However, there is no guideline to guide the installation process of the box culvert. Instead, AASHTO suggests using previous experience to determine the load on the culvert. Moreover, the design method of the load reduction is not given in the prevailing Chinese General Code for Designing Highway Bridges and Culverts [17].

The current load reduction methods are applied on the normal culvert structures (i.e. single box culvert, pipe culvert, twin box culvert). The load of the central fill mass over the culvert is transferred to adjacent fill mass after the load reduction; however, it also increases the horizontal earth pressure on the culvert sidewall,

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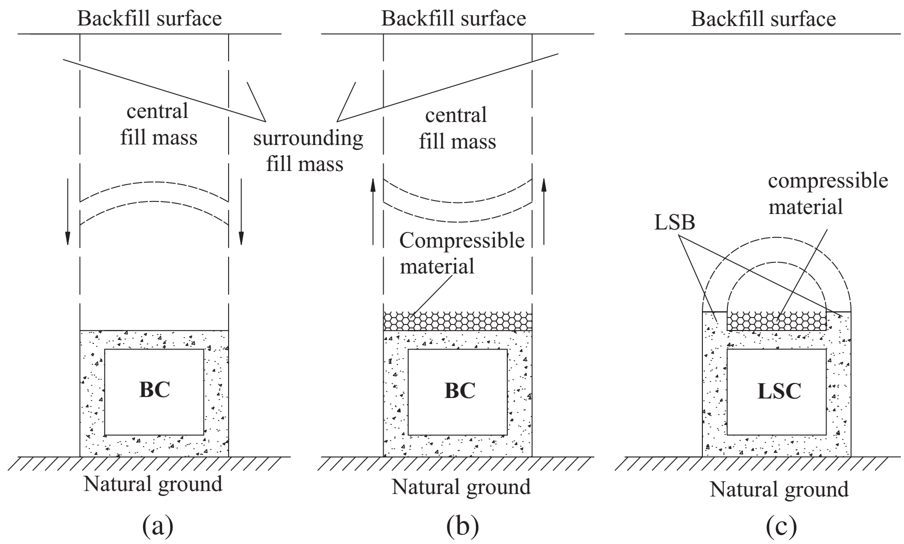

Fig. 1. Sketches of culverts. (a) Embankment-installation Box Culvert (EBC); (b) imperfect-trench-installation Box Culvert (IBC); (c) load shedding Culvert (LSC).

which is even larger than the vertical earth pressure on the top of the culvert [11,14,18–22].

A new culvert structure, called load shedding culvert (LSC), is proposed in this paper. In the LSC, two load shedding blocks (LSB) are set on both sidewalls of box culvert as an integral structure. The load shedding hole (LSH) between two load shedding blocks is filled with compressible material, as shown in Fig. 1(c). In this study, the stress states of the LSC were investigated by physical model tests and numerical analyses. The results of LSC were compared with those of EBC and IBC. A parametric study was conducted to analyze the significant influencing factors on culvert performance, including the friction angle of backfill, the heights of load shedding blocks (for comparison, the thicknesses of compressible material layer in cases IBC and LSC are equal to those of load shedding blocks), the width of load shedding blocks, and the elastic modulus of compressible material.

2. Model test

2.1. Model test setup

Model test system consists of a tank and two types of culvert. The tank is 1500 mm long, 1500 mm wide and 1650 mm high as shown in Fig. 2. Steel plate (2 mm thick) was used for three sidewalls of the tank and a toughened glass (10 mm thick) was used for the other sidewall of the tank for observation. Two types of culvert model, i.e., normal Box Culvert and LSC, are shown in Fig. 3. Aluminum alloy plate (6 mm thick) was used for both of the culvert models.

The tank was placed directly on the concrete floor in laboratory with a maximum filling height of 1650 mm. In view of the low compressibility of the ground, it was assumed that the model tests were conducted on a rigid foundation.

2.2. Model test procedure

Three different cases (EBC, IBC, and LSC) were considered for comparison and to investigate the performance of the culvert. The thickness of compressible layer was 30 mm and the widths were equal to that of the top slab of the culvert in both IBC and LSC.

A total of 14 miniature pressure cells (LY350 produced by Changsha Kun Peng Testing Technology Co., Ltd.) were used in the model test. The miniature pressure cell is 10 mm thick and 28 mm in diameter, with a maximum stress range of 100 kPa and sensitivity of 0.01 kPa.

The layout of all the earth pressure cells is shown in Fig. 2. The pressure cells were symmetrically placed along the axis of culvert. To measure the vertical earth pressure, four pressure cells were set on the culvert (No. 1 to No. 4) and four pressure cells were placed in sand within the same plane (No. 5 to No. 8). Another six pressure cells were set on both sidewalls of culvert to measure the horizontal earth pressure (No. 9 to No. 14).

For comparison, the pressure cells (from No. 1 to No. 8) were placed in the same plane and 30 mm over the culvert top slab, which is exactly the thickness of the compressible layer for cases IBC and LSC. Thus, the maximum height of backfill on pressure cells (from No. 1 to No. 8) was 1400 mm.

The procedural steps of these model tests are described as follows:

(1) For all tests, a culvert model was installed in the tank (A normal box culvert model was used for the EBC and IBC cases).
(2) Backfilling with sand. For the EBC case, the initial filling height was 30 mm above the top slab, whereas for the IBC and LSC cases, a 30 mm-thick compressible layer was placed on the top slab of culvert and the surrounding fill should be graded to the top of the compressible layer.
(3) The backfill over culvert was installed step by step. In each step a 200 mm-thick layer was filled in one day, until the backfill reached a maximum height of 1430 mm.

2.3. Material properties

The sands used in the model tests were from Hankou riverside of Yangtze River. The properties of the sand are presented in Table 1. The average unit weight of the fill in the tank is 17.5 kN/m^3.

Sponge (polyurethane foam) was used as the compressible material in the model tests. The density of the sponge was 3.2 kg/m^3, the elastic modulus was 300 kPa and the Poisson’s ratio was 0.01 (all of the mechanical parameters were supplied by the sponge factory).