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Experimental study on concrete box culverts in trenches

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Abstract Concrete box culverts are widely used in expressways in mountain areas. Many problems frequently take place due to improperly estimated vertical earth pressures on culverts. The prevailing Chinese General Code for Design of Highway Bridges and Culverts (CGCDHBC) stipulates the computation of the design load on culverts primarily based on the linear earth pressure theory, which cannot accurately describe the variation of the vertical load on culverts in trenches. In this paper, a full-scale experiment and numerical simulation were conducted to evaluate the variation of vertical earth pressures on culvert and soil arching in backfill. The variations of foundation pressure and settlement were also analyzed. The result revealed that the soil arch forms when the backfill on the culvert reaches a certain height. The soil arching effect reduces the stress concentration on the crown of the culvert but it is unstable. The vertical earth pressure on top of the culvert is significantly different from that recommended by the CGCDHBC.

Keywords culvert, vertical earth pressure, soil arch, full-scale experiment, numerical simulation

1 Introduction

Geotechnical and pavement problems often occur during culvert installation in mountain areas, which have not been well addressed. Due to poor understanding of designers on the mechanism of soil-culvert system, many problems

happen during the construction process or service time as presented by Kang et al. [1,2]. For the design of concrete box culverts installed in trenches, it generally considers that the vertical earth pressure on top of the culvert is less than that computed using the linear earth pressure theory [3]. Typically, the coefficient of the vertical earth pressure is less than 1.0 because of the positive skin friction along trench slopes. This coefficient is defined as the ratio of the vertical earth pressure on top of culvert to the overburden pressure of backfill over the culvert.

Marston analyzed the behavior of underground conduits in the early 20th century [4,5]. Succeeding Marston, Spangler [6,7] concluded that the key factors influencing the load on the underground conduit are associated with installation conditions, the mechanism of load transfer and the direction of displacement as shown in Fig. 1.

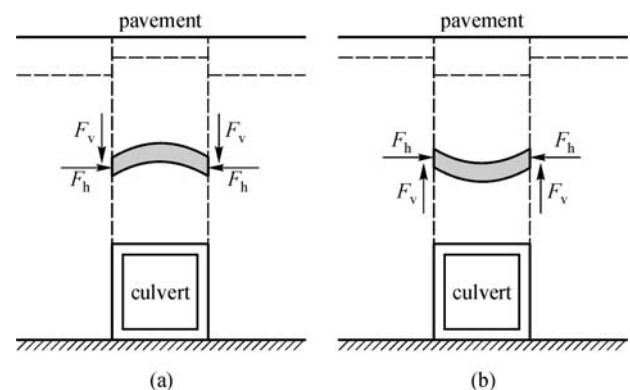


Fig. 1 Load transfer within fill-structure system. (a) Embankment installation; (b) trench installation

Karinski et al. [8] analyzed the behavior of a buried structure under a static surface load and the soil weight during service time. The model simulated the interaction between the soil and the buried structure. Bennett et al. [9] analyzed the vertical loads on concrete box culverts under high embankments based on a field test and concluded that the vertical load on the structure is independent of the ratio of the height of fill to the width of the structure. Gu et al. [10] presented a full-scale experimental and theoretical study on

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the reduction of the load on a culvert under a high embankment using EPS. Yang et al. [11] showed the variations of vertical earth pressures on top of a culvert in a trench with the height of backfill under different boundary conditions based on model tests. Kim et al. [12] and Kang et al. [13] analyzed the soil-structure interaction based on the finite element method (FEM) simulation. However, the dimensional effect of culvert was not investigated. The vertical earth pressure on culvert installed in a trench was not accurately predicted by the linear earth pressure theory in the CGCDHBC [3]. This vertical earth pressure can also be determined by the product of overburden pressure of backfill and the empirical coefficient recommended in the Chinese Fundamental Code for Design on Railway Bridges and Culverts (CFCDRBC) [14]. However, this method does not consider properly the interaction of soil-structure system.

The interaction of soil-culvert, especially in mountain areas, has not been well understood for the culvert installed in a trench. This study investigates the interaction of soil-culvert system, and examines the variation of vertical earth pressure on box culvert based on a full-scale experiment and numerical simulation.

2 Soil-culvert interaction

The interaction of fill-culvert-foundation soil is shown in Fig. 2. M_{1i} is the mass of the embankment fill over the top plane of the culvert, M_{22} is the mass of the culvert, M_{21} and M_{23} are the mass of the fills adjacent to the culvert on both sides, M_{3i} is the mass of the foundation soil under the bottom plane of the culvert. K_{1i} , K_{21} , K_{23} , and K_{3i} are the stiffness values corresponding to the above four soil masses, and K_{12} is the stiffness of the culvert. τ_1 and τ_2 are the shearing stresses between the fill mass, M_{12} and the adjoining fill mass, M_{11} or M_{13} .

The stress state of culvert in the ground is different from that of a footing in the soil because the interaction between

the culvert and the soil mainly depends on the characteristics of embankment fill and foundation soil. Assuming a uniform foundation (i.e., $K_{31} = K_{32} = K_{33}$), the settlement of M_{21} and/or M_{23} is larger than that of M_{22} due to the difference in the stiffness between the culvert and the adjacent fill mass ($K_{22} > K_{21}$ or $K_{22} > K_{23}$). Therefore, the vertical earth pressure on the culvert increases with the differential settlement due to the shear stresses between M_{12} and M_{11} (or M_{13}) and can be expressed as

$$p = M_{12}g + \tau_1 + \tau_2. \quad (1)$$

The shear stresses between M_{12} and M_{11} (or M_{13}) increase with the differential stiffness between K_{22} and K_{21} (or K_{23}) and so does the vertical earth pressure on the culvert. It is expected that with any improvement of the culvert foundation, the stiffness of K_{32} would induce stress concentration and increase the pressure on the top of the culvert.

3 Full-scale experiment

3.1 Description of instrumented culvert

The instrumented box culvert was installed above well-graded crushed gravel which was excavated from a tunnel near the trench. A cushion with a thickness of 0.5 m is placed below the culvert to create a leveling foundation. The culvert is 104.5 m long and cast-in-place with reinforced box concrete. The outer dimensions of the culvert are 8.25 m high, 9.9 m wide at the crown, and 15.6 m wide of the culvert foundation. The maximum height of the backfill over the culvert is 18.0 m. The layout of earth pressure cells and settlement observation points are shown in Fig. 3 while the instrumented sections are shown in Fig. 4. In Fig. 3, “C01” is the number of the earth pressure cell.

3.2 Vertical earth pressures over culvert

The vertical earth pressures on the culvert at section Nos. 4, 6 and 7 are presented in Figs. 5 and 6 during backfilling (the pressure cell C09 is non-functional). Figure 5 shows the variations of the vertical earth pressures at the level of culvert top with the height of backfill for the three instrumented sections. It is clear that the vertical earth pressures at the level of the culvert top increase nonlinearly with the height of backfill. The pressures on the crown of the culvert are higher than that calculated by CGCDHBC (the overburden pressure of backfill). The measured maximum vertical earth pressure on the crown of section No.4 is 258 kPa as the height of the backfill reaches 10.4 m, and those of section Nos. 6 and 7 are 426 kPa and 502 kPa at the end of backfilling (the maximum height of the backfill is 18.0 m), respectively. The measurements

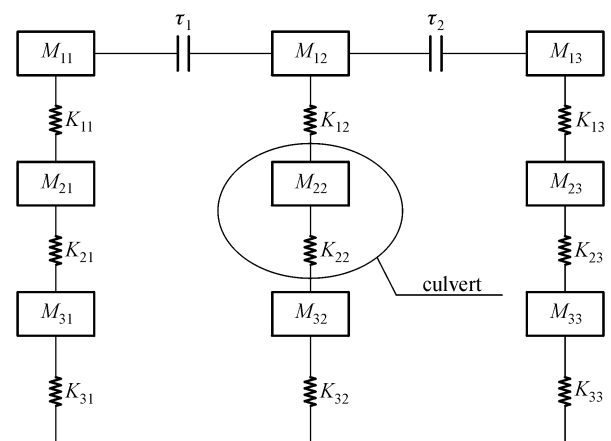


Fig. 2 Interaction of fill-culvert-foundation soil

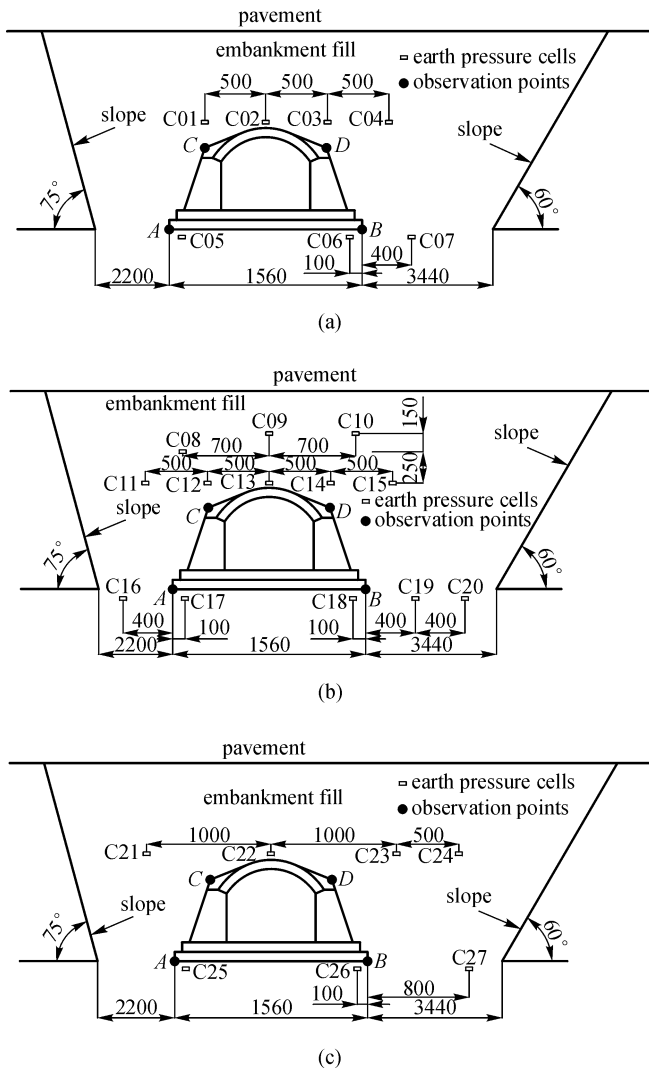


Fig. 3 Layout of cells and settlement points in field. (a) Section No. 4; (b) section No. 6; (c) section No. 7 (unit: cm)

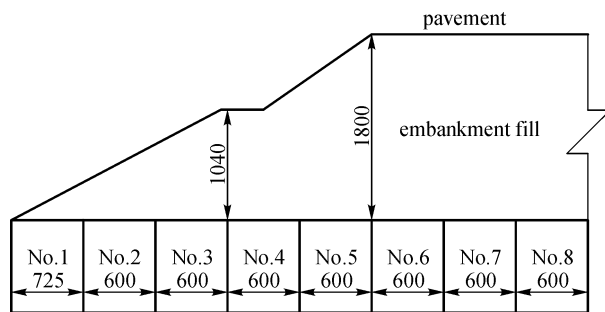


Fig. 4 Layout of instrumented sections

show that the vertical earth pressures at the elevations above the top of the culvert but outside the culvert are lower than that calculated by CGCDHBC. It can be concluded that the vertical earth pressures on the crown of

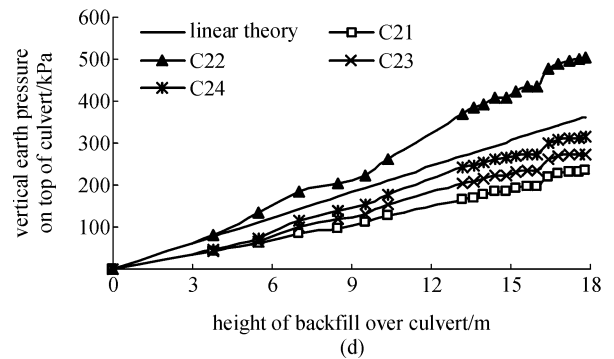
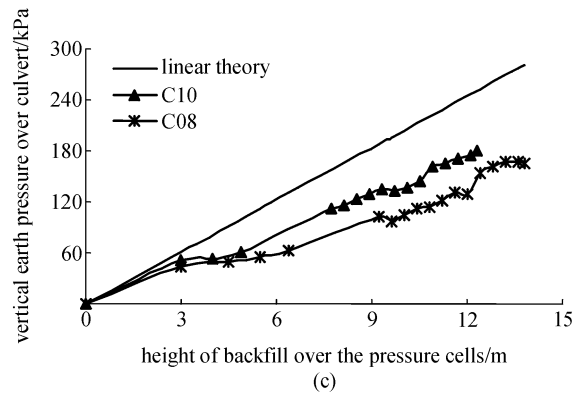
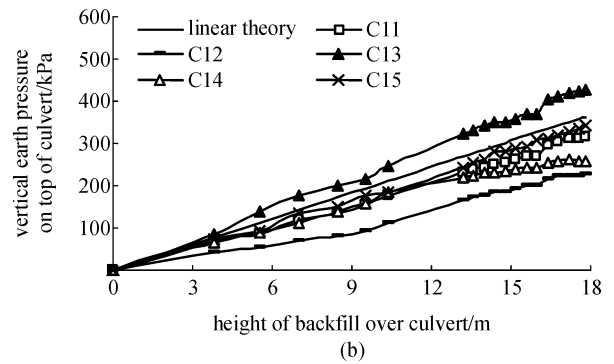
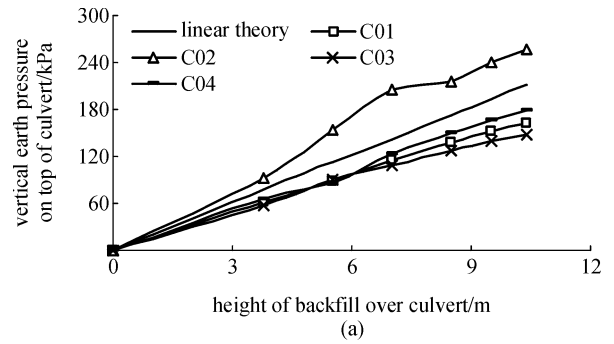


Fig. 5 Variations of vertical earth pressures on culvert. (a) Section No. 4; (b) section No. 6 (on top of culvert); (c) section No. 6 (distance above culvert); (d) section No. 7

the culvert is not always lower than that calculated by the CGCDHBC based on the linear earth pressure theory. The

actual vertical earth pressure is dependent on the boundary conditions of the trench, the height and properties of the backfill, and the dimensions of the culvert. The experimental results indicate that the measured vertical earth pressures on the crown of the culvert are slightly higher than those calculated by the CGCDHBC (linear earth pressure theory) at a lower height of backfill. However, the differences become more significant with an increase of the height of the backfill.

Due to the difference in the stiffness between the reinforced concrete box culvert and the adjacent backfills, the vertical earth pressures on the culvert crown are considerably higher than those on the adjacent backfills (at the elevation of the top of the culvert). The difference in the vertical earth pressure between the measured and that from the linear earth pressure theory is attributed to the shearing stresses developed within the backfill over the culvert. Figure 5(c) shows that the shear stresses in the backfill over the culvert decrease with the height from the culvert crown. It is well known that with an increase of backfill height, an equal settlement plane may develop in backfill at a certain height where differential settlement and shear stress between central and side backfill prisms equal to zero. This equal settlement plane should be limited below the surface of embankment in the design.

The vertical earth pressures concentrated at the crown of the culvert due to the difference in the stiffness between the culvert and the adjacent backfill as shown in Fig. 6. The stress concentration becomes more obvious with an increase of the height of the backfill. The vertical earth pressures on the sides adjacent to the culvert are comparatively lower than those on the crown of the culvert mainly because of the shear stresses between the central and side backfill prisms. The maximum differences in the vertical earth pressures at the top level of the culvert for section Nos. 4, 6 and 7 are 110 kPa, 200 kPa, and 267 kPa, respectively. Test results in Fig. 6 also show that the distribution of the vertical earth pressures above the culvert is slightly unsymmetrical due to the unsymmetrical installation of the culvert in the trench. The maximum differences in the pressures between both sides of culvert are 15 kPa, 32 kPa, and 40 kPa for section Nos. 4, 6 and 7, respectively.

3.3 Coefficient of vertical earth pressure over culvert

Figure 7 shows the variations of the coefficients of the vertical earth pressure on the crown of the culvert. During backfilling, the coefficients change from 1.00 to 1.21 and 1.00 to 1.43 for section Nos. 6 and 7, respectively, as the height of the backfill over the culvert increases from 0 to 18.0 m. It is shown that the coefficients of the vertical earth pressure fluctuated with the increase of the height of the backfill. This fluctuation can be explained as follows. The soil arch between the culvert and the slope forms due to the friction and the support of the slope when the backfill

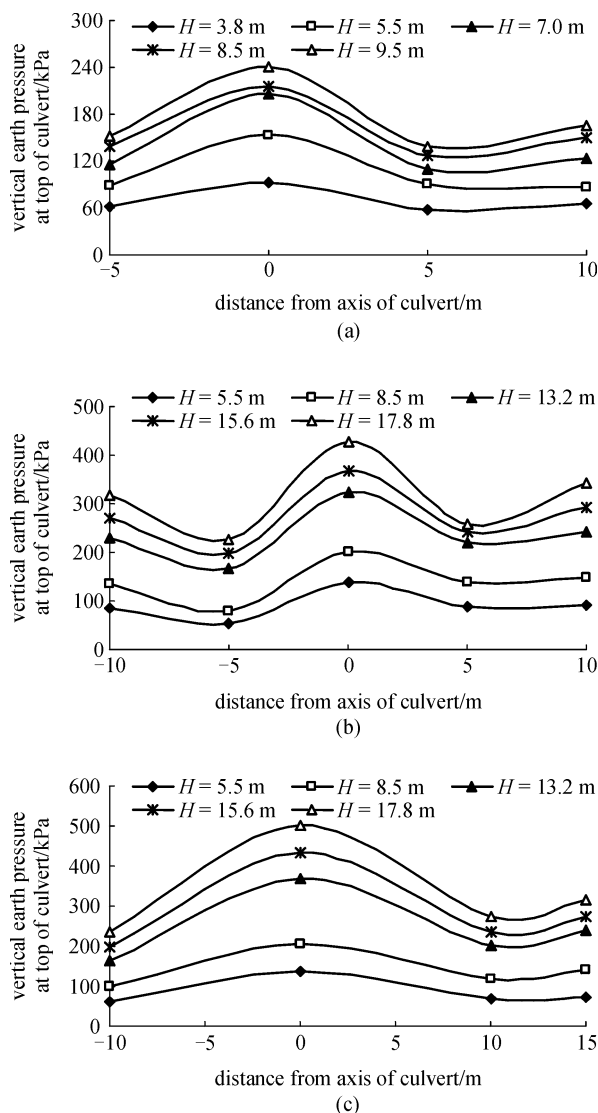


Fig. 6 Distribution of vertical earth pressures at top of culvert. (a) Section No. 4; (b) section No. 6; (c) section No. 7

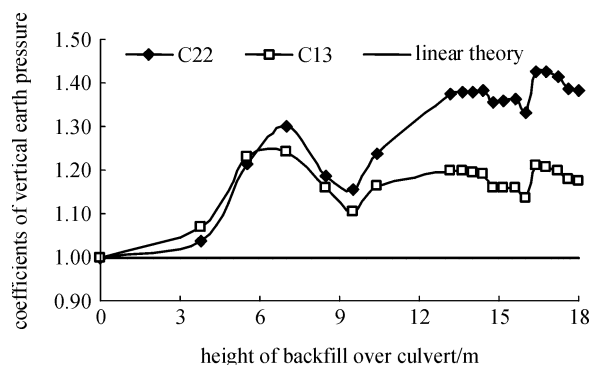


Fig. 7 Coefficients of vertical earth pressure on crown of culvert

reaches a certain height. However, the differential settlement at the top elevation of the culvert increases with the

height of the backfill. The soil arch collapses when the differential settlement becomes too large; therefore, the coefficient of the vertical earth pressure between the culvert and the slope increases but that on the culvert decreases. With the increase of the height of the backfill, a new soil arch forms and the coefficient of the vertical earth pressure on the crown of the culvert increases again. The process of load transfer between the soil and the culvert repeats during backfilling.

Figure 8 shows that the coefficients of the vertical earth pressure at two sides of the culvert at the top elevation of the culvert, are less than 1.0. These coefficients also fluctuate but opposite to those on the culvert.

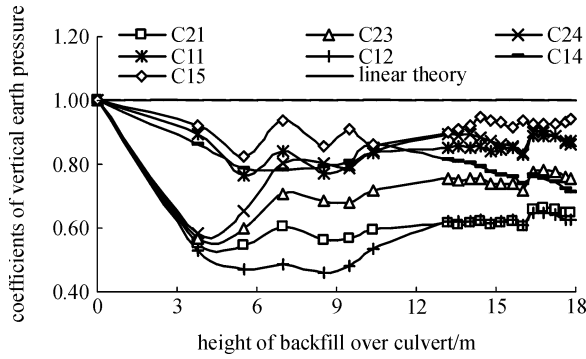


Fig. 8 Coefficients of vertical earth pressure at both sides of culvert crown

The abovementioned test results show that the vertical earth pressures on the crown of the concrete box culvert are significantly larger than those calculated by the prevailing Chinese General Code for Design of Highway Bridges and Culverts.

3.4 Foundation pressure of culvert

Figures 9 and 10 present the foundation pressures under and beside the culvert. It is shown in Fig. 9 that the measured foundation pressures are higher than that calculated using the linear earth pressure theory (i.e., the overburden of backfill plus the weight of culvert). The foundation pressure on point *A* is lower than that on point *B* due to the unsymmetrical trench installation. This result is consistent with the distribution of the vertical earth pressures on both sides of the culvert at the top level. Figure 9 shows that the difference in the foundation pressure between what was measured in the field and the theoretical value by the linear earth pressure theory narrow with the increase of the height of the backfill. Figure 10 shows that the measured earth pressures at both sides of the culvert foundation are lower than those calculated by the linear earth pressure theory. It is also shown that the earth pressures at both sides of the foundation increase with the distance from the edge of the culvert foundation and approach to the overburden pressure at a farther distance.

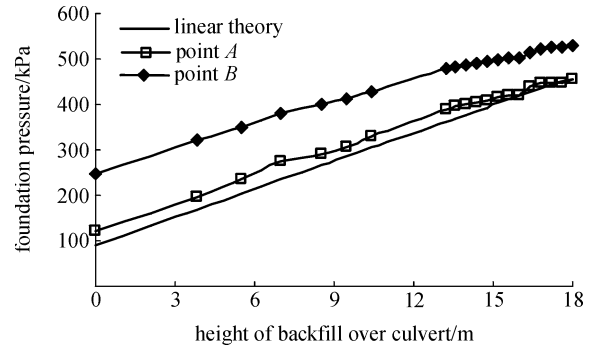


Fig. 9 Foundation pressures of culvert

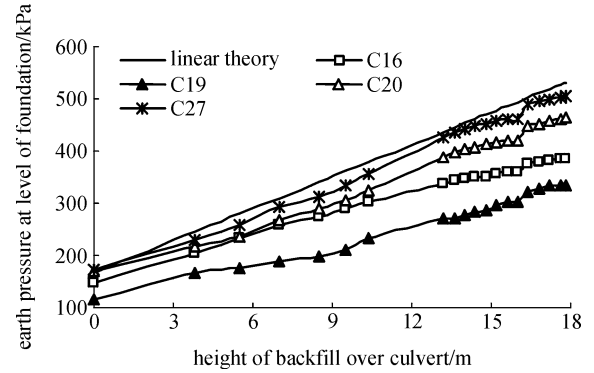


Fig. 10 Earth pressure on both sides of culvert foundation

3.5 Foundation settlement of culvert

Figure 11 presents the variations of the foundation settlements with the height of the backfill for the instrumented sections. The foundation settlements increase with the height of the backfill during the filling. The maximum foundation settlements at section Nos. 4, 6 and 7 are 91 mm, 123 mm, and 117 mm at the end of loading, respectively. The maximum differential foundation settlements between both sides for these three instrumented sections are 3 mm, 9 mm, and 10 mm respectively. The transverse unequal settlements of the foundation are mainly induced by the unsymmetrical installation of the culvert. It is also consistent with the distribution laws of the vertical earth pressures and the foundation pressures.

4 FEM numerical simulation

4.1 Numerical model

Plaxis Version 8.2 was used to investigate the interaction of the soil-culvert system. The 15-node triangular element was used to generate the mesh of the model. The interface elements are created at the interfaces of the soil-structure and the soil-slope. Each interface has been assigned a “virtual thickness” which is an imaginary dimension used

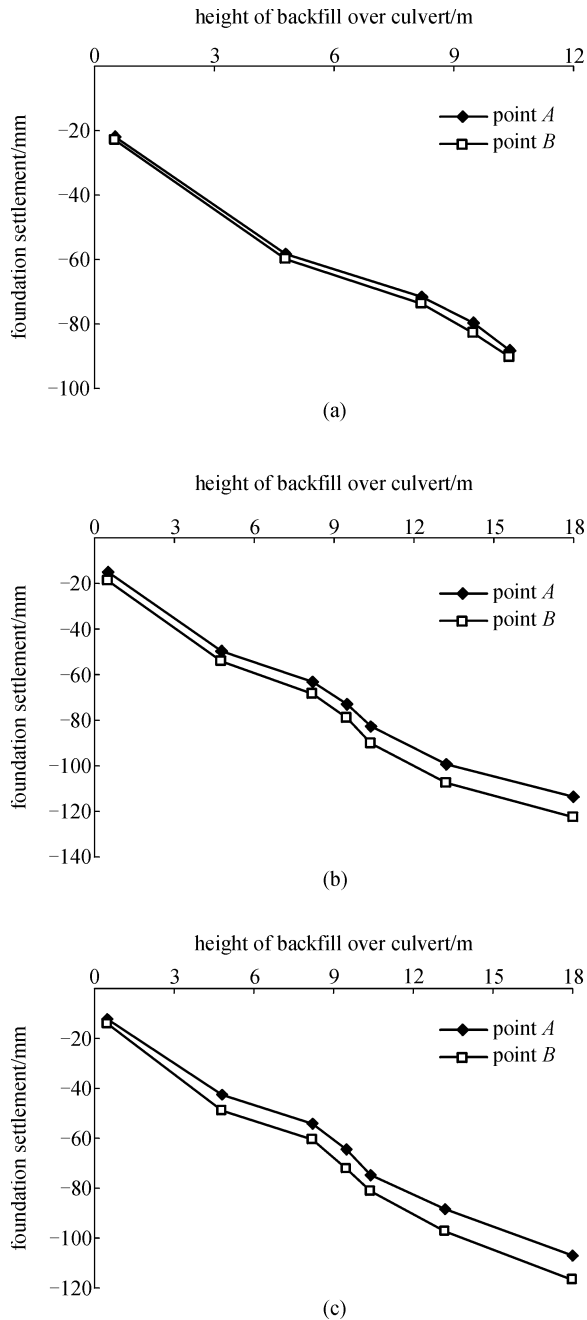


Fig. 11 Foundation settlement versus height of backfill. (a) Section No. 4; (b) section No. 6; (c) section No. 7

to define the material properties of the interface. In general, interface elements are supposed to generate very little elastic deformations and therefore the virtual thickness should be small. On the other hand, if the virtual thickness is too small, numerical ill-conditioning may occur. The virtual thickness is calculated as the virtual thickness factor (i.e., δ) times the average element size. Moreover, the roughness of the interaction is modeled by choosing a suitable value for the strength reduction factor in the interface (R_{inter}), which relates the interface strength (the

culvert or the slope surface friction and adhesion) to the soil strength (friction angle and cohesion). In this numerical simulation, $\delta = 0.1$ and $R_{\text{inter}} = 0.8$, the two side boundaries of the model are horizontally restrained while the bottom of the model is fixed. The backfill, the foundation soil, and the slope are modeled as Mohr-Coulomb elasto-plastic materials. The reinforced concrete culvert is modeled as a linear elastic material. The dimensions of the numerical model are identical with those of the full-scale experiment in the field for the sake of comparison. The medium meshing was chosen for the soil-culvert system as shown in Fig. 12. The material properties used in the numerical model were obtained from field tests as shown in Table 1.

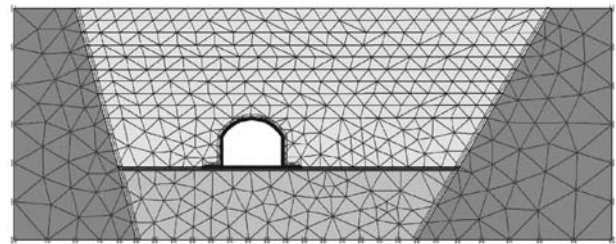


Fig. 12 Numerical mesh of soil-culvert system

Table 1 Materials properties in numerical simulation

material	E/MPa	ν	c/kPa	$\phi/(^{\circ})$	$\gamma/(\text{kN} \cdot \text{m}^{-3})$
culvert	30000	0.20	—	—	25.2
backfill	30	0.27	2.5	30.2	20.4
cushion	48	0.25	0	33.0	21.5
weathered rock	43	0.25	20	32.0	21.3
slope	3000	0.20	150	35.0	26.7

4.2 Analysis of numerical results

The maximum height of the backfill in this numerical model is 18.0 m. The comparisons of the numerical results with the field data are presented in Figs. 13 and 14. The numerical simulation results of the vertical earth pressures on the crown of the culvert are in good agreement with the measured ones. The maximum differences in the vertical earth pressures from the numerical simulation and the field measurement are 5.75% and 11.06% for section Nos. 6 and 7, respectively. The coefficient of the vertical earth pressure is 1.23 from the numerical simulation while they are 1.21 for section No. 6 and 1.43 for section No. 7, respectively, based on field test.

From the comparison results, it is clear that the results calculated by the linear earth pressure theory, which is recommended in the Chinese General Code for Design of Highway Bridges and Culverts, are obviously less than these of the field test and numerical simulation.

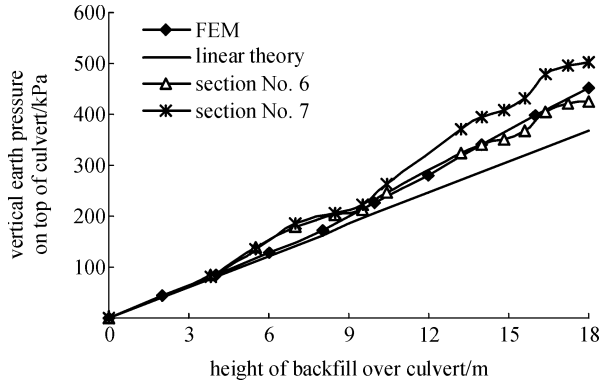


Fig. 13 Variations of vertical earth pressure on top of culvert

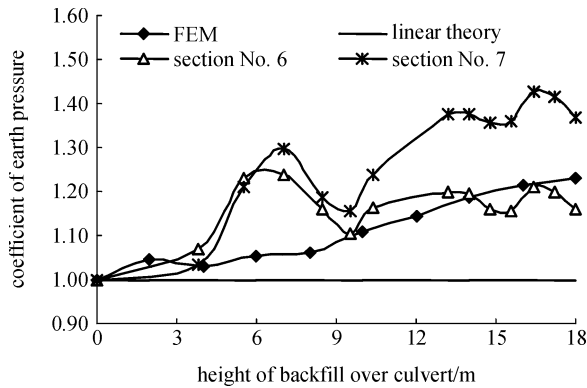


Fig. 14 Variations of coefficient of vertical earth pressure on top of culvert

Figures 15 and 16 present the distribution of the vertical earth pressure and the settlement at the top elevation of the culvert. It is shown that stress concentration developed on the top of the culvert and became more obvious with the increase of the height of the backfill. Figure 16 shows that the differential settlement at the top elevation of the culvert increases with the height of the backfill. The maximum differential settlement reaches 74 mm when the height of the backfill is 18.0 m. It is also shown that the distribution of the settlement at the top elevation of the culvert is unsymmetrical because of the unsymmetrical installation of the culvert.

Figure 17 shows the distribution of the foundation pressure at the base elevation of the culvert. It is clearly shown that the pressures are concentrated at the corners of the culvert foundation and the difference in the foundation pressure enlarges with the height of the backfill.

Figure 18 shows the increase of the settlement of the foundation with the height of the backfill. The maximum settlement and the differential settlement between points *A* and *B* are 109 mm and 6 mm, respectively, at the end of backfilling based on the FEM, which is in good agreement with the field data.

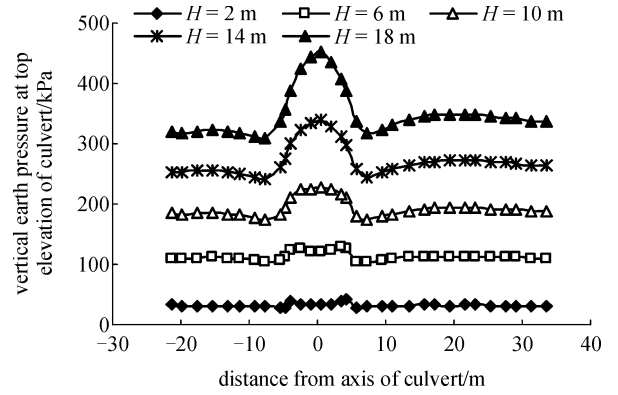


Fig. 15 Distribution of vertical earth pressure at top elevation of culvert

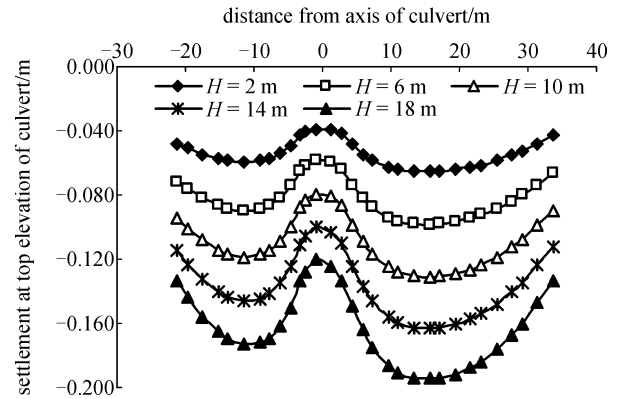


Fig. 16 Distribution of settlement at top elevation of culvert

5 Conclusions

A full-scale test and numerical simulation were conducted to investigate the interaction of the soil-culvert system and to evaluate the vertical earth pressure on top of the concrete box culvert in trenches. The following conclusions can be drawn:

1) The vertical earth pressure on the crown of the culvert increases nonlinearly with the height of the backfill over the culvert. The soil arch is formed as the backfill reaches a certain height. The soil arch can reduce the stress concentration on the crown of the culvert, but it may not be stable during backfilling. The process of load transfer between the soil and the culvert could be explained by the repetitive failure processes of the original soil arch and the generation of the new soil arch.

2) The shear stresses between the central and side soil prisms in the backfill over the culvert decrease with the height from the culvert crown. With the increase of backfill height, an equal settlement plane in the backfill develops at a certain height where the differential settlement and the shear stresses between the central and side backfill prisms equal to zero.

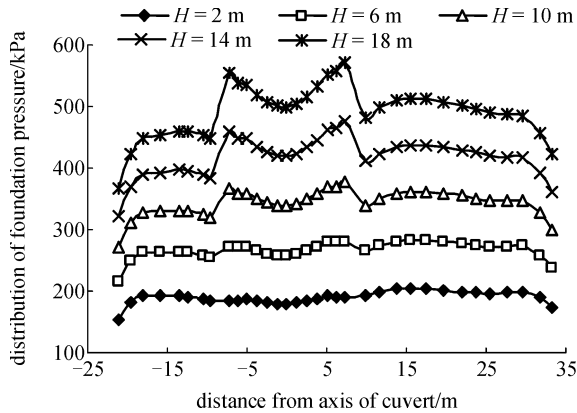


Fig. 17 Distribution of foundation pressure by FEM

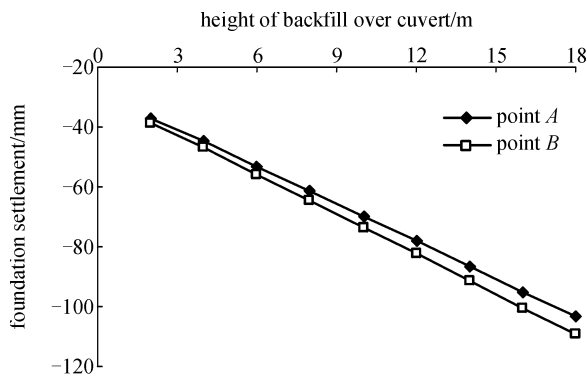


Fig. 18 Variation of foundation settlement

3) The concentration of the vertical earth pressure develops at the top of the culvert for a wide trench due to the difference in the stiffness between the culvert and the backfill. The stress concentration becomes more obvious with the increase of the height of the backfill. The vertical earth pressure near the edge of the culvert is comparatively lower than that on the crown of the culvert because of the shear stresses between the central and side backfill prisms. The coefficients of the vertical earth pressure adjacent to the culvert first fluctuate with the increase of the backfill and then approach asymptotic values due to the backfill being gradually compacted. The shorter distance from both side walls of the culvert has a lower coefficient.

4) The unsymmetrical installation of the culvert induces unsymmetrical pressures on the level of the culvert top and unequal settlements of the foundation.

5) The vertical earth pressures near the foundation of the culvert are lower than the overburden pressure of the backfill, increase with the distance from the edge of the culvert foundation, and approach the overburden pressure of the backfill at a farther distance.

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