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Soil-structure interaction of unsymmetrical trench installation culvert

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Abstract: The computation of the design load on culverts in the current Chinese General Code for Design of Highway Bridges and Culverts (CGCDHBC) is primarily based on the linear earth pressure theory, which cannot accurately reflect the changes in vertical loads on trench installation culverts. So the changes in vertical earth pressure and soil arching effect in the backfill for an unsymmetrical trench installation culvert are studied based on a full scale experiment and finite element (FE) simulation. The variation laws of foundation pressure and settlement are also analyzed. Meanwhile, the influence of eccentric load induced by an unsymmetrical trench installation on the interaction of a soil-structure system is discussed. Results show that soil arch is formed when the backfill on the culvert reaches a certain height. It can relieve the earth pressure concentration on the crest of the culvert, but it is instable. The earth pressures obtained by full scale experiment and numerical simulation are greater than those calculated by the current CGCDHBC method. The eccentric load effect on the culvert has a significant influence on the stress states and deformation of the soil-structure system.
Key words: soil-structure interaction; soil arching effect; eccentric load effect; full scale experiment; numerical simulation

There are usually important geotechnical and pavement problems during the culvert installation in unsymmetrical trenches, which have not been well addressed. Series disease occurred during the construction process or service time[1-3]. The vertical earth pressure of backfill on the crest of the trench installation culvert is generally considered less than the results computed by the linear earth pressure theory (code method[4]). Accordingly, the vertical earth pressure coefficient is less than 1.0 because of the positive skin friction of the trench slopes, where the coefficient is defined as the ratio of the vertical earth pressure on the top of the culvert to the backfill overburden pressure.

Marston and Anderson[5] pioneered the research on the behavior of underground conduits in the early years of the 20th century. Spangler[6-7] presented that the primary factors influencing the load on the underground conduits are associated with the installation conditions. Karinski et al.[8] analyzed a buried structure response to static surface loading as well as the soil gravitational load at service-state conditions. Bennett et al.[9] analyzed the vertical loads on concrete box culverts under high embankment based on field tests. Gu et al.[10] presented the load reducing measurement of the culvert under high-stacked soil using EPS based on field tests and theoretical analyses. However, the above mentioned studies did not consider the influence factors of boundary conditions and the eccentric load effects. Yang and Zhang[11] presented the changes in vertical earth pressure on the top of a trench installation culvert based on model tests. Deng et al., Kim and Yoo, and Kang et al.[12-14] analyzed the soil-structure interaction behavior based on FE numerical simulation. But they also did not fully consider the eccentric load effects. The vertical earth pressure on the trench installation culvert is also not accurately calculated by the linear earth pressure theory in the current CGCDHBC[4].

The objective of this study is to investigate the interaction behavior of a soil-structure system, and to discuss the influence of eccentric load effects based on a full-scale experiment and an FE numerical simulation.

1 Full Scale Experiment Study

1.1 Description of the instrumented culvert

The results of the instrumented culvert presented in this paper are from a trench installation culvert in China. The culvert overlays the well graded crushed gravel that is the byproduct of the tunnel excavation near the trench. A 0.5 m layer of dry cement and sand-gravel is used immediately below the culvert to level the ground and adjust for the changes in the thickness of the bottom slab. The typical inner cell dimensions are 6.0 m high and 6.0 m wide, and the exterior dimensions of the culvert are 8.25 m high and 9.9 m wide for the upside, and a width of 15.6 m is chosen for the culvert foundation. The width of the trench is 72.0 m at the instrumented section No. 6 and No. 7, and the maximum height of the backfill over the culvert is 18.0 m for the two instrumented sections. The layout of the earth pressure cells and the settlement observation points in-situ are shown in Fig. 1.

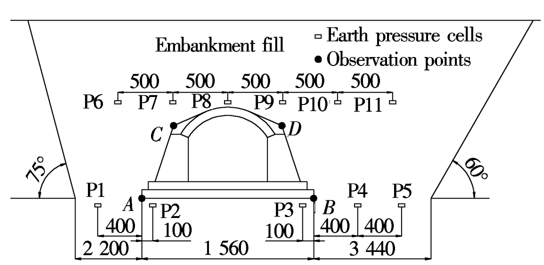

Fig. 1 Layout of cells and observation points (unit: cm)

1.2 Vertical earth pressure analysis

The measured vertical earth pressures on sections No. 6 and No. 7 during the filling process are described in Figs. 2 and 3. Fig. 2 shows that the vertical earth pressure at the level of the culvert top nonlinearly increases with the height of

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the backfill. The pressures on the crest of the culvert are larger than the backfill overburden pressures. The vertical earth pressures are 426 kPa and 502 kPa, respectively, at the end of filling on sections No. 6 and No. 7. It also shows that the vertical earth pressures of the exterior prisms (beside the fill prism on the crest of the culvert) at the level of the culvert top are less than their deadweights. It can be concluded that the vertical earth pressure on the trench installation culvert is not always less than the results calculated by the linear earth pressure theory (the code method). The pressure depends on the boundary conditions of the trench, the height of the backfill, etc. The experimental results show that the test data are slightly larger than those of the linear earth pressure theory when the backfill load is at a lower level. The difference in vertical loads between the test and the code method nonlinearly increases with the height of the backfill, but it has a slight decrease when the backfill approaches 9.0 or 15.0 m. From the above presentation, it can be seen that the soil arch will be generated in the backfill when the backfill reaches a certain height, but the soil arch is instable.

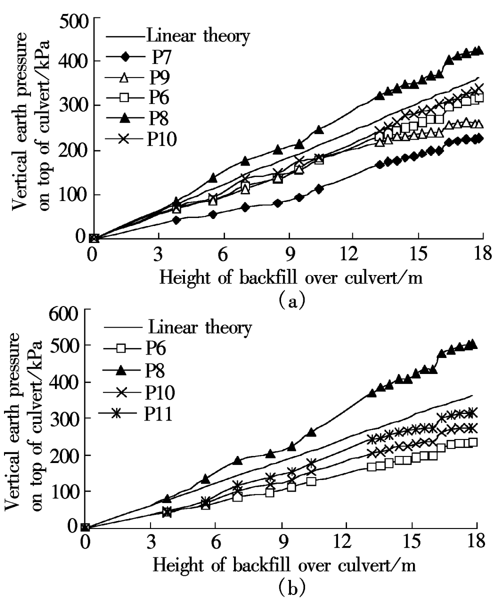

Fig. 2 Variations in vertical earth pressures on culvert top level. (a) Section No. 6; (b) Section No. 7

As shown in Fig. 3, at the level of the culvert top, the concentration of vertical earth pressure is induced on the culvert crest due to the differential stiffness between the culvert and the backfill, and the pressure concentration is more obvious with the increase in the height of the backfill. The vertical earth pressure on the edge of the culvert is comparatively less than that on the culvert top because of the existence of the shear stress between the exterior and interior backfill prisms over the culvert. The maximum differential pressures at the level of the culvert top are 200 kPa and 267 kPa, respectively, for the instrumented sections No. 6 and No. 7.

Test results show that the soil arch in the backfill is unsymmetrical, and the eccentric load effect on the culvert is generated due to unsymmetrical trench installation. The vertical earth pressure at point C is different from that at point D due to the friction and support of the trench slope. The maximum differential pressures between points C and D are 32 kPa and 40 kPa for sections Nos. 6 and 7, respectively.

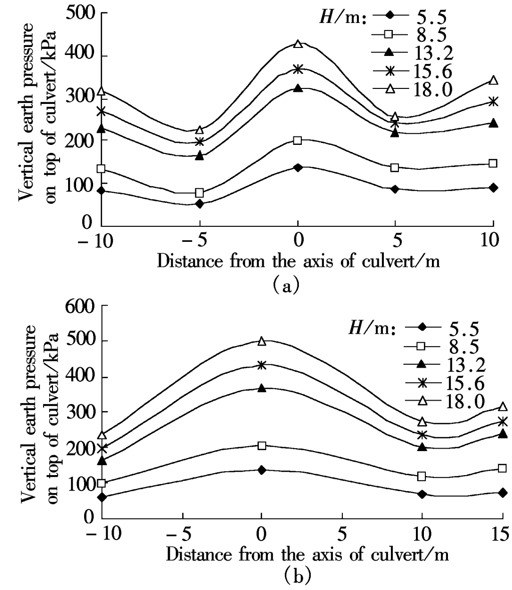

Fig. 3 Distribution of vertical earth pressure on culvert top level. (a) Section No. 6; (b) Section No. 7

1.3 Vertical earth pressure coefficient analysis

Fig. 4 shows the variations of the coefficients of the vertical earth pressure during backfilling from 1.00 to 1.21 and 1.00 to 1.43 for sections No. 6 and No. 7, respectively, as the height of the backfill, H, over the culvert increases from 0 to 18.0 m. When $H < 6.0$ m, the vertical earth pressure coefficients increase with the height of the backfill; when $H > 6.0$ m, the vertical earth pressure coefficients fluctuate with the continuous increase in the height of the backfill. It can be noticed that the soil arch will be formed when the backfill reaches a certain height. However, the differential settlement at the culvert top level increases with the height of the backfill. Consequently, large differential settlements will induce the failure of the soil arch. With the increase in the height of the backfill, a new soil arch will be generated in the backfill again. The load transfer between the soil and the culvert can be explained by the repetitive process of the failure of the original soil arch and the generation of the new soil arch.

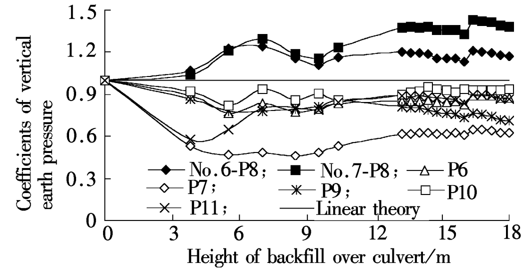

Fig. 4 Vertical earth pressure coefficients

Fig. 4 also shows the coefficients of the vertical earth pressure at two sides of the culvert at the top elevation of the culvert, which are less than 1.0. These coefficients also fluctuate but opposite to those on the culvert. And it also shows that the shorter the distance from the side wall of the culvert, the lower the coefficients.

1.4 Foundation pressure analysis

Fig. 5 shows that the foundation pressures by field tests are larger than those of the linear earth pressure theory, but the difference in foundation pressures between field tests and the results of the linear earth pressure theory decrease with the increase in the height of the backfill. The average pressure on side *A* is less than that on side *B* due to the eccentric load effect. It also shows that the earth pressures outside the foundation of the culvert are less than the values calculated by the linear earth pressure theory. The earth pressures at both sides of the foundation increase with the horizontal distance from the edge of the culvert foundation and approach the overburden pressure at a farther distance.

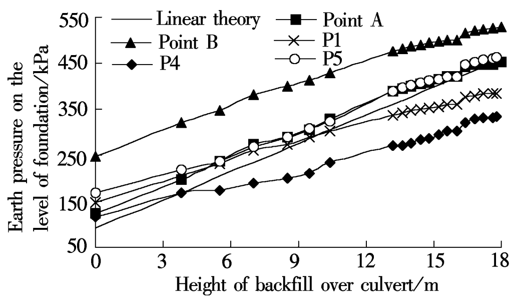

Fig. 5 Variations of earth pressures on the level of culvert foundation

1.5 Foundation settlement analysis

The variation laws of foundation settlements with the height of backfill for sections No. 6 and No. 7 are summarized in Tab. 1. The foundation settlements increase with the height of backfill. The maximum settlements of foundation are 123 mm and 117 mm, respectively, at the end of filling for sections No. 6 and No. 7. The maximum differential settlements of foundation between points *A* and *B* for the two instrumented sections are 9 mm and 10 mm. The transverse unequal settlements of foundation are mainly induced by the unsymmetrical installation of the culvert.

Tab. 1 Variation of foundation settlement with *H*

H/m	Foundation settlement/mm			
	No. 6		No. 7	
	Point *A*	Point *B*	Point *A*	Point *B*
0.5	−15	−19	−12	−15
4.8	−50	−54	−43	−49
8.2	−63	−69	−54	−61
9.5	−73	−79	−65	−72
10.4	−83	−90	−75	−82
13.2	−100	−108	−89	−98
18.0	−114	−123	−107	−117

2 Finite Element Numerical Simulation

2.1 Numerical modeling

PLAXIS is applied to investigate the interaction of the soil-structure system. The soil and culvert domains are modeled by 15-noded triangular elements. Slippage between backfill and culvert (or trench slope) is facilitated by interface (or slip) elements. The vertical sides of the model are constrained to move vertically while the bottom of the mesh is fixed. The backfill, ground soil and side-hill are modeled using the Mohr-Coulomb model, while the structure of the culvert is assumed to behave linearly elastic. A 12.0 m layer of in-situ ground soil (weathered gravel soil) underlain by a very stiff layer of moderately weathered rock is chosen in this numerical model. The bottom boundary of the model is assumed to terminate at the top of this rock layer. The dimensions of the numerical model are similar to that of the full-scale experiment for the sake of the comparison. The material properties used in the numerical analysis are obtained based on field and laboratory tests as shown in Tab. 2.

Tab. 2 Material properties in numerical simulation

Materials	Elastic modulus/MPa	Poisson ratio	Cohesion/kPa	Friction angle/(°)	Unit weight/($kN\cdot m^{-3}$)
Culvert	30×10^3	0.20			25.2
Backfill	30	0.27	2.5	30.2	20.4
Cushion	48	0.25	1.0	33.0	21.5
Ground soil	43	0.25	2.0	32.0	21.3
Side-hill	3×10^3	0.20	150	35.0	26.7

The maximum height of the backfill in this numerical model is 18.0 m. The filling process consists of 18 continuous phases, in which 10 d are required for each phase of construction. The average rate of simulated construction is 0.1 m/d. "Activate" or "inactivate" geometric clusters of fill are applied to simulate the process of backfilling.

2.2 Numerical results analysis

The numerical results show that the phenomenon of earth pressure concentration on the top of the culvert is more obvious with the increase in the height of the backfill. The vertical earth pressures on the culvert crest are in good agreement with those of field tests as shown in Fig. 6. The maximum differences of vertical earth pressures between the numerical method and the experiment are 5.75% and 11.06% for sections No. 6 and No. 7, respectively. The maximum vertical earth pressure coefficient is 1.23 by the numerical method, and the coefficients are 1.21 and 1.43, respectively, for sections No. 6 and No. 7 by field tests.

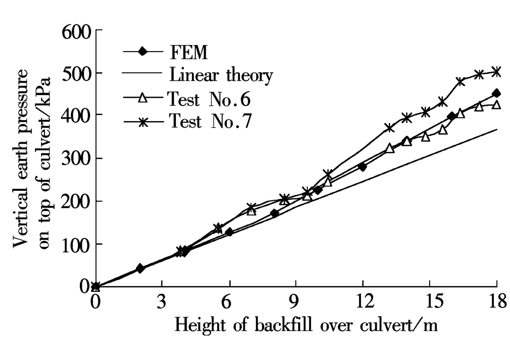

Fig. 6 Comparison of vertical earth pressure on the culvert top

The distribution of settlement at the level of the culvert top is shown in Fig. 7. Fig. 7 shows that the differential settlement at the culvert top level increases with the height of the backfill. It is clear that the distribution of settlement at the level of the culvert top is unsymmetrical because of the unsymmetrical installation of the culvert.

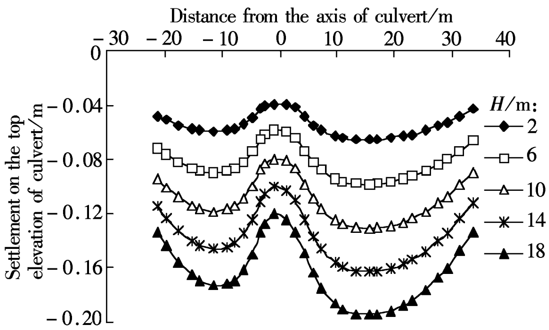

Fig. 7 Distribution of settlement at culvert top level

The numerical results show that the differential foundation settlement increases with the height of the backfill. The maximum settlement and differential settlement between points *A* and *B* are 109 mm and 6 mm, respectively; at the end of filling, those are in good agreement with the field test results.

2.3 Eccentric load effect

The eccentric load effect of the unsymmetrical trench installation culvert is analyzed by numerical simulation. An angle of 90° is chosen as the trench slope angle for simplification. The distance from the axial line of the culvert to the left slope is $L_L = 10$ m, and the distance from axial line of the culvert to the right slope is L_R, which varies from 10 to 45 m in this study.

The settlements at the level of the culvert top are summarized in Tab. 3. The maximum and minimum settlements and the maximum differential settlements at the culvert top level increase with the value of L_R, and these appear to approach asymptotic values at large differential distances (the difference between L_R and L_L).

Tab. 3 Variation of settlement at culvert top level

Distance L_R/m	Settlement/mm		
	S_{max}	S_{min}	ΔS
10	114.7	78.1	36.6
13	135.9	84.9	51.0
15	146.9	80.3	66.6
25	183.3	96.0	87.3
35	200.2	97.2	103.0
45	203.1	97.8	105.3

The foundation settlements of the culvert are summarized in Tab. 4. It is clear that the foundation settlement on the left side first increases and then has a slight decrease with the increase in the differential distance. The foundation settlement on the right side increases with the differential distance and reaches an asymptotic value at large differential distances. It also shows that the differential foundation settlement increases with the differential distance, and it appears to approach asymptotic value at large differential distances. Fig. 8 shows that the differential foundation pressure first increases with the differential distance, and then decreases with the increase in the differential distance, and it appears to approach a limiting value at large differential distances.

Tab. 4 Variations in foundation settlements

Distance L_R/m	Foundation settlement/mm		
	S_L	S_R	ΔS
10	69.1	69.1	0
13	72.2	80.1	7.9
15	72.0	85.4	13.4
25	71.8	100.3	28.5
35	70.9	103.3	32.4
45	69.6	103.7	34.1

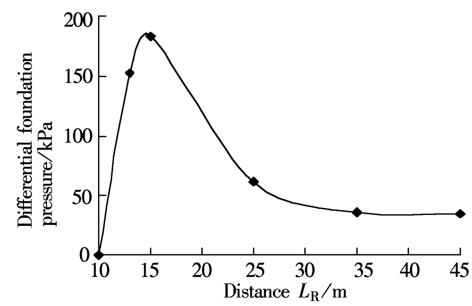

Fig. 8 Variation in differential foundation pressure

The influence of the differential trench slope angle (the difference between left and right slope angles) on the stress states and deformation of the soil-structure system are also simulated. The distances from the axial line of the culvert to both slopes of the trench are assumed to be equal ($L_L = L_R = 10$ m), and an angle of 90° is chosen as the left slope angle for simplification; the right slope angle varies from 0 to 90°.

Fig. 9 shows that the maximum differential and total settlements at the level of the culvert top increase with the differential slope angle. It also shows that the settlement at the culvert top slightly increases with the increase in the differential slope angle. As shown in Fig. 10, the foundation settlement on the left side (S_L) increases with the differential slope angle, but the change of that on the right side (S_R) is not obvious. It can be noticed that the differential foundation settlement increases with the differential slope angle. Numerical results demonstrate that the differential foundation pressure first increases, and then decreases with the increase in the differential slope angle. When the differential slope angle is about 30°, the differential foundation pressure approaches the maximum value.

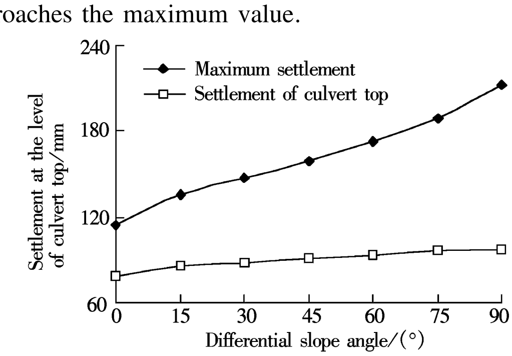

Fig. 9 Variation of settlement at the level of culvert top

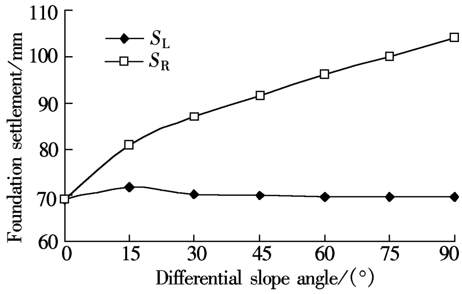

Fig. 10 Variation of foundation settlement

3 Conclusions

A full scale experiment and numerical simulation are conducted to investigate the interaction of a soil-structure system and to evaluate the vertical earth pressure on the top of unsymmetrical trench installation of a culvert. Furthermore, the influence of eccentric load effects on the interaction of the soil-structure system is discussed. The following conclusions are drawn from this study:

1) The vertical earth pressure on the top of the culvert nonlinearly increases with the height of the backfill over the culvert. The soil arch is formed as the backfill reaches a certain height. It can relieve the earth pressure concentration on the culvert crest, but it is instable. The interaction of soil-structure can be explained by the repetitive process of the failure of the original soil arch and the generation of the new soil arch.

2) The experimental and numerical results show that the vertical earth pressure coefficient is not always less than 1.0. The vertical earth pressure on the top of the culvert depends on the boundary and installation conditions.

3) The eccentric load effect on the culvert is generated due to the unsymmetrical trench installation of the culvert, which has a significant influence on the stress states and deformation of the soil-structure system. The eccentric load effect can bring on large differential settlement and foundation pressure.

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非对称沟埋式涵洞涵-土作用机理

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摘要:现行公路桥涵设计通用规范中的线性土压力理论不能准确反映非对称沟埋式涵洞结构的实际受力特性.结合现场试验和数值模拟研究了沟谷非对称设涵时,涵-土体系的受力状态和变形特性以及涵顶填土内部的土拱效应.讨论了偏载效应对涵-土体系受力和变形的影响.研究结果表明,涵顶填土达到一定高度后填土内部产生土拱效应,该土拱效应能够缓解涵顶的应力集中,但其具有不稳定性.现场试验和数值模拟得到的涵顶土压力均大于现行公路桥涵设计通用规范的计算结果,而且偏载效应对涵-土体系的受力状态和变形特性的影响也不容忽视.

关键词:土与结构物作用机理;土拱效应;偏载效应;足尺试验;数值模拟

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