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Long-term stress characteristics and load reduction effect of high-fill box culverts with EPS slabs

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Abstract

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Keywords

expandable polystyrene slab, load reduction, box culvert, long-term stress characteristics, creep, load reduction effect

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Abstract: Laying expandable polystyrene (EPS) slabs on the top of high-fill box culverts to reduce earth pressure has been used in engineering practice, but the creep of EPS slabs will cause the earth pressure on the box culvert to change over time. The present design theory of box culverts cannot clearly reflect the long-term load reduction effect of EPS slabs and the long-term stress characteristics of box culverts. In this analysis, model tests were carried out to investigate the short-term stress characteristics of the box culvert with EPS slabs, and a numerical model was validated by the model test results. Then the verified numerical simulation method was used to analyze the stress redistribution of the culvert-soil system and the long-term stress characteristics of the high-fill box culvert. On this basis, the mechanical model of the culvert-soil system was proposed, and the calculation method of long-term earth pressure on the top of the culvert was deduced and compared with the numerical simulation results for verification. The research results showed that the earth pressure on the top of the culvert decreased gradually with time, then increased slightly and finally became stable. Compared with the earth pressure at the completion of filling, the long-term earth pressure decreased by 52.12%. The vertical and horizontal earth pressure on the culvert side increased gradually with time and tended to be stable, and the long-term horizontal earth pressure in the upper range of the culvert side increased by 28.32% compared with that when the filling was completed. The foundation contact pressure also increased slightly at first and then tended to be stable. The increase of horizontal earth pressure caused by the creep of EPS slabs should be considered in the design of sidewalls in practical engineering so as to avoid bending failure of box culver sidewalls in the long-term use.

Keywords: expandable polystyrene slab; load reduction; box culvert; long-term stress characteristics; creep; load reduction effect

1 Introduction

The filling load over high-fill box culverts is commonly large, and the stress concentration on the top of the box culvert due to the difference in stiffness between the box culvert and the soil might further increase the earth pressure on the top of the box culvert, which are likely to cause structure disease. Therefore, it is of great significance to use expandable polystyrene (EPS) slabs to reduce the earth pressure at the top of culverts. Gu et al.[1−2] studied the load reduction effect of high-fill culverts using EPS slabs as load reduction material through field tests. Laying EPS slabs only on the top of a box culvert could significantly reduce the earth pressure on the top of the box culvert and also improve the earth pressure on the side of the culvert. However, laying EPS slabs on the top and side of the culvert at same time could lead to unloading of the horizontal soil pressure on the culvert side, forming an arching effect around the culvert and reducing the earth pressure. The monitoring results showed that this measure significantly affected the reduction of earth pressure on the top and side of the culvert. Zhang et al.[3] monitored the earth pressure and displacement through the in-situ EPS slab load reduction test for a large-scale high-fill culvert and numerically simulated it using Marc finite element analysis software. They obtained the relationship curves between the thickness, density of the EPS slab and the fill height under the premise of achieving the established load reduction effect. Sun et al.[4] found that the load reduction effect of EPS slabs could reduce the load of the culvert top fill by 90% based on the data of stress, strain and settlement of EPS slabs monitored in the field and speculated that the load reduction effect was likely to be maintained for a long period of time. Vaslestad et al.[5−6] carried out the observation of the earth pressure and deformation of three different projects using EPS slabs for load reduction for 5 consecutive years. The monitoring found that the effect of load reduction using EPS slabs was obvious. The last measurement after 25 years showed that the effect of load reduction with EPS slabs could be maintained in a long time. However, the long-term stress characteristics were not analyzed.

Culvert is usually used as a permanent structure, and the load reduction performance will be affected by the creep of the EPS slab and fill during the late stage of construction of high-fill culverts. Chen et al.[7] considered the friction between the sidewall of the box culvert and the fill, and proposed a culvert−soil interaction model. They also proposed theoretical formulas to calculate the earth pressure of the culvert top and the foundation. Lee et al.[8] investigated the distribution of lateral friction of box culverts by centrifuge model test and modified the existing method for calculating the horizontal earth pressure of the box culvert sidewall. Chen et al.[9] established a theoretical model of the time effect for the load reduction effect of high-fill culverts by analyzing the mechanism of load reduction measures for high-fill culverts, and they compared the numerical simulation with the theoretical results through the variation of earth pressure at the culvert top, which verified the correctness of the theoretical model.

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The field monitoring data in the literature[10] showed that the horizontal earth pressure in the middle of the box culvert sidewall was smaller than those at the bottom and top of the sidewall. The reason was that the inward bending deformation of the side wall of the box culvert caused unloading of the horizontal earth pressure in the middle, resulting in a minimum value point of the horizontal earth pressure in the middle of the culvert side. Zhang et al.[11] and Ge et al.[12] studied the long-term settlement of loess after construction, and then Ge et al.[13] conducted a microscopic study of loess creep deformation. Based on the study of loess creep in the literature[11−12], Jia-Nie et al.[14] and Li[15] used finite difference software to conduct long-term numerical simulation of two backfill methods after the construction of loess high-fill open cut tunnel, i.e., only loess was used as backfill material and a certain thickness of loess backfill material was laid over the culvert using sand and gravel without creep effect. The results showed that the creep property of backfill material had a great influence on the earth pressure around the culvert.

The long-term creep of EPS slabs has been extensively studied in the existing literature. Horvath[16] investigated the application of EPS slabs as an intermediate transition layer between the soil layer and the underground structure, whose large compressive deformation can significantly reduce the loads imposed on the structure, and verified the compressive deformation characteristics of EPS slabs experimentally. Kang et al.[17] conducted creep tests on the EPS slabs with three different densities and fitted the test data according to the Kelvin model and a Hookean spring connected in series. Gnip et al.[18−20] proposed a theoretical model for predicting the long-term creep of EPS slabs by conducting long-term creep tests on EPS slabs and verified that EPS slabs have creep characteristics that could not be neglected under long-term conditions by selecting a viscoelastic-related mathematical model to fit. The above work lays a foundation for the study of culvert long-term performance with load reduction measures.

In order to further clarify the long-term stress characteristics of high-fill box culverts under the load reduction effect of EPS slabs, this paper analyzed the stress redistribution of the culvert-soil system and the long-term stress characteristics of high-fill box culverts by using the verified numerical simulation method and combining the creep model of EPS slabs. On this basis, a mechanical model of the culvert-soil system was proposed, further a long-term earth pressure calculation method of box culverts was deduced, and the numerical simulation results were used for comparison and verification so as to provide a reference for the theoretical design.

2 Model test of short-term stress characteristics

2.1 Test model

2.1.1 Similarity ratio

It is assumed that the vertical earth pressure at any point in the fill of the prototype test is F_2, and the vertical earth pressure at the corresponding position in the model test is F_1. The fill heights of the prototype and model and their densities are H_2, H_1 and ρ_2, ρ_1. The gravitational accelerations of the prototype and the model are a_2 and a_1, respectively. According to the similarity theory, the geometric ratio of similitude C_l is obtained as

$$\frac{H_2}{H_1}=C_l \tag{1}$$

By employing the soil column method, the vertical earth pressures at the corresponding points between the prototype and the model are respectively

$$F_2=\rho_2\cdot a_2\cdot H_2 \tag{2}$$

$$F_1=\rho_1\cdot a_1\cdot H_1 \tag{3}$$

In order for the vertical earth pressure of the model test to be similar to that of the prototype test, the first law of similarity and Newton’s second law need to be satisfied, and the similarity coefficient can be obtained to meet the following equation:

$$\frac{C_F}{C_m C_a}=1 \tag{4}$$

where $C_F=\dfrac{F_2}{F_1}=\dfrac{\rho_2\cdot a_2\cdot H_2}{\rho_1\cdot a_1\cdot H_1}$; $C_m=\dfrac{m_2}{m_1}=\dfrac{\rho_2\cdot H_2}{\rho_1\cdot H_1}$; and $C_a=\dfrac{a_2}{a_1}$.

The prototype model and the test model use the same fill material and are conducted under 1*g* conditions, which satisfies the relationship of scale coefficient equal to 1 in the similarity law, and the similarity coefficient of the vertical earth pressure in the prototype model and the test model is C_l. Since the stiffness of reinforced concrete rigid box culverts in practical engineering and steel structure box culverts in model tests is much higher than the stiffness of soil, the influence of the rigid culvert stiffness is ignored in the analysis, so no similar simulation analysis is done for the material of the box culvert model. At the same time, in order to ensure the consistency between the test model and the numerical analysis, a numerical model with the same geometry as the test model is used for numerical simulation.

2.1.2 Model test scheme

The size of the culvert model was 0.2 m×0.2 m×1.5 m (width×height×length), which was welded with 3 mm thick 304 steel plates. A cement mortar of 2 mm thickness was applied to the outside of the box culvert sidewalls in order to make the interfacial contact between the fill and the culvert sidewall in accord with the actual situation. The model box was made of three steel plates and one tempered glass, measuring 1.5 m×1.5 m×1.5 m (width×height×length). The distance between the sidewall of the culvert and the model box was 65 cm, which was greater than three times the width of the culvert, and the sidewall of the model box was coated with vaseline to reduce the friction effect of the sidewalls.

The top of the box culvert was covered with a 3 cm thick EPS slab, and the top fill height was 1.0 m. The simulated foundation was rigid. In order to bury the earth pressure cell at the bottom of the foundation, a 3 cm thick compacted sand cushion was laid on top of the rigid foundation. The arrangement of the earth pressure cell measuring points is shown in Fig. 1.

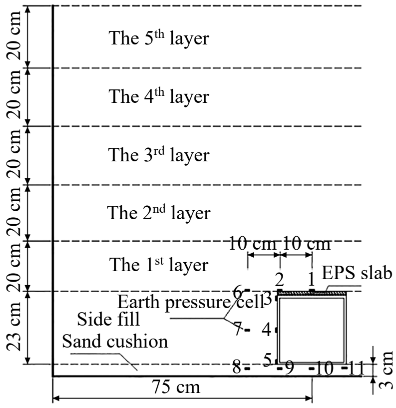


Fig. 1 Layout of measuring points for the model test

The earth pressure cells were adjusted to zero before laying. The earth pressure cells 8, 9, 10 and 11 were embedded after the culvert cushion was completed, and then the culvert and EPS slab were placed. The sand was filled simultaneously on both sides of the culvert and the earth pressure cells 3, 4, 5 and 7 were embedded at the corresponding positions. The earth pressure cells 1, 2 and 6 were placed when filling to the top of the culvert. After all the earth pressure boxes were embedded, let them stand for 1 hour and start the laying of the culvert top fill. The culvert top fill was filled in 5 times and the height of each layer was 20 cm. After each layer was filled, the corresponding earth pressure was recorded after standing for 1 h. The mass of sand was weighed according to the predetermined density and volume and then compacted according to the calculated thickness of each layer to meet the established density requirements of the test. The test model after filling is shown in Fig. 2.

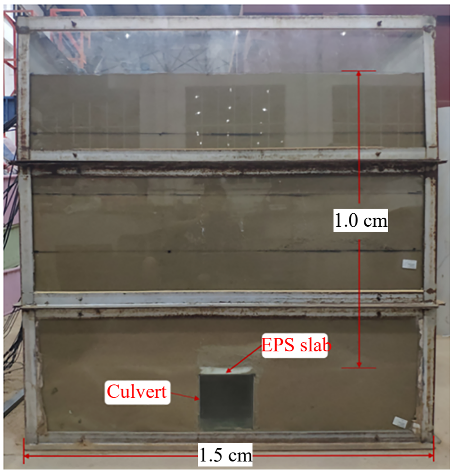
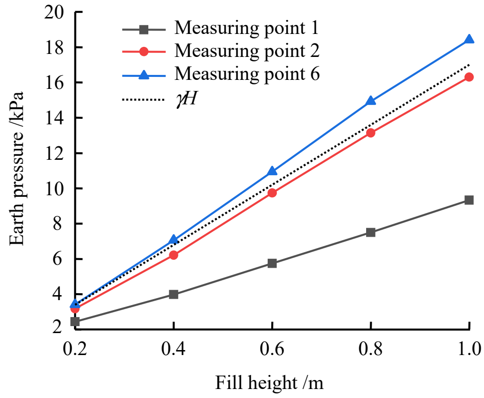


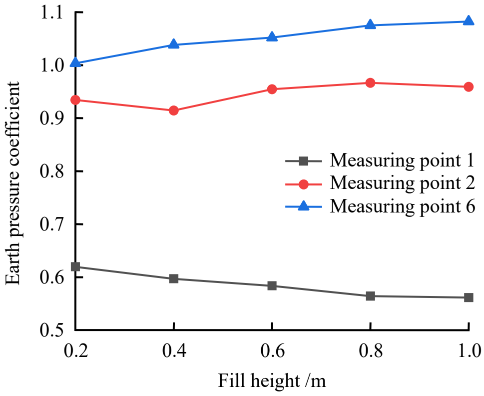
Fig. 2 Test model

2.2 Test results

During the filling process, the vertical earth pressure at the measuring points in the culvert top plane all increased with the increase of the fill height (as shown in Fig. 3, where γ is the soil unit weight above the load reduction material, and H is the height of the top plate of the box culvert to the natural ground surface). The vertical earth pressure directly above the culvert top (measuring points 1 and 2) was less than the fill self-weight pressure, and the vertical earth pressure at the measuring point 6 outside the culvert top was greater than the fill self-weight pressure. The vertical earth pressure coefficient of the measuring point 1 in the culvert top plane decreased gradually. Because the measuring point 2 was located on the top of the sidewall and there was stress concentration, its vertical earth pressure coefficient had a small variation range, but the value was less than 1.0. The vertical earth pressure coefficient of the measuring point 6 was greater than 1.0, and with the gradual increase of the fill height, the self-weight of the inner soil column of the culvert top was gradually transferred to the soil column out of the culvert top plane. The earth pressure at the top of the culvert was reduced to 44% of the fill self-weight at the completion of filling. The vertical earth pressure on both sides of the culvert top gradually increased with the increase of the fill height and reached 108.30% of the fill self-weight pressure after the completion of filling.



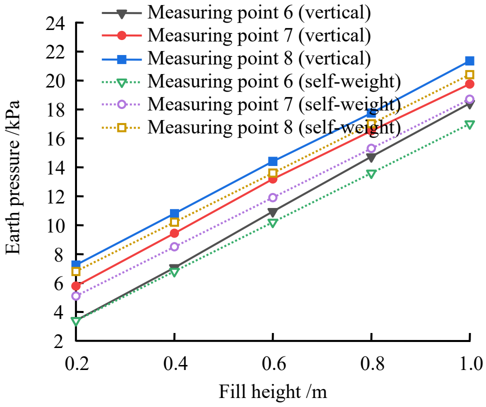
(a) Variation of the vertical earth pressure in the culvert top plane with the fill height



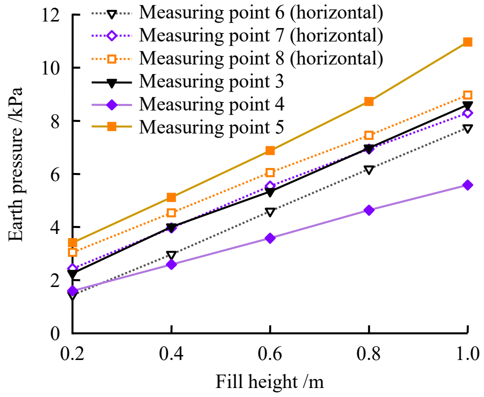
(b) Variation of the vertical earth pressure coefficient in the culvert top plane with the fill height

Fig. 3 Variations of vertical earth pressure and earth pressure coefficient in the culvert top plane with fill height

The vertical earth pressure at the measuring points 6, 7 and 8 showed a positive correlation with the increase of the fill height, as shown in Fig. 4(a), and the vertical earth pressure coefficients of the measuring points 6, 7 and 8 were all greater than 1.0 after the completion of each layer. Additionally, the difference between the measured vertical earth pressure and the earth pressure of the fill self-weight at each point increased gradually with the increase of the fill height. The vertical earth pressure at the measuring point 6 was 18.41 kPa at the completion of filling, which increased by 8.29% compared with the fill self-weight.



(a) Variation of verticle earth pressure of the culvert side with the fill height



(b) Variation of horizontal earth pressure of the culvert side with the fill height

Fig. 4 Variations of earth pressure on the sidewall with fill height

From the measured vertical earth pressure at the measuring points 6, 7 and 8 and the coefficient of earth pressure of sand at rest k_0 ($k_0 = 0.95-\sin\varphi$ [21–22], k_0 is obtained as 0.42 and φ is the internal friction angle), the corresponding horizontal earth pressure at the measuring points can be calculated. The comparison of the horizontal earth pressures at the measuring points 3, 4 and 5 is shown in Fig. 4(b). It could be seen that with the increase of the fill height, the difference of the horizontal earth pressure between the measuring points 4, 7 and 5, 8 gradually increased; the difference of the horizontal earth pressure between the measuring points 3 and 6 increased first and then decreased with the increase of the fill height, but the magnitude of the variation was small. The horizontal earth pressure in the immediate range of the box culvert sidewall decreased first and then increased with the increase of depth, while the horizontal earth pressure at 0.5*D* from the culvert sidewall (*D* is the width of the box culvert) increased gradually along the depth. The vertical earth pressure coefficients of the measuring points 6, 7 and 8 were 1.06 on average. It could be speculated that the influence range of EPS slabs on the culvert sidewall in engineering projects could be taken from 0 to *D* from the box culvert sidewall.

The vertical earth pressure at the measuring point 10 increased with the increase in the fill height and was 0.76 kPa when the filling was completed. Since the positions of the measuring points 9 and 11 were symmetrical and the difference of the measured values was small, the mean value of the vertical earth pressure of the two measuring points was taken as the vertical earth pressure at the measuring point 9. The vertical earth pressure at the measuring point 9 increased gradually with the increase of the fill height, and it was 41.42 kPa at the completion of filling, which reached 203.04% of the soil self-weight. The vertical earth pressure at the measuring point 8 exceeded 4.66% of the soil self-weight at the completion of filling (as shown in Fig. 5).

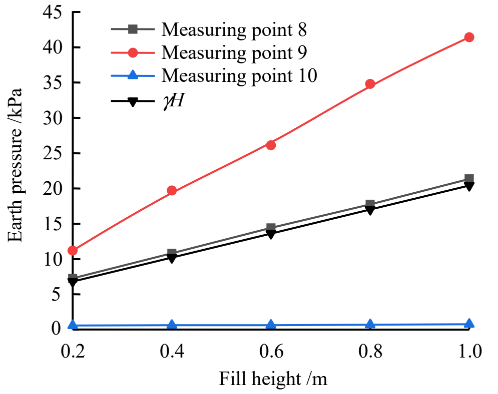


Fig. 5 Variations of foundation contact pressure with fill height

2.3 Numerical simulation and verification

2.3.1 Numerical simulation

Due to the limitations of the long-term model test, numerical simulation was used to analyze the long-term stress characteristics of the culvert-soil system under the creep effect of the EPS slab. In the numerical model, the constitutive relationship of the material and parameters in the short-term and long-term simulations maintained the same. The difference was that the short-term simulation process did not activate the creep calculation module, and the model test results were used to verify the correctness of the numerical model. After the filling was completed, the creep analysis module was activated to analyze the long-term stress characteristics of the culvert-soil system under the creep effect of EPS slabs.

The numerical model was the same as the above model test. For boundary conditions, the horizontal displacement was constrained around the model and the vertical displacement was constrained at the bottom. The contact surface between the culvert sidewall and the fill was established to consider the friction effect between the culvert and soil, and the Mohr-Coulomb failure criterion was adopted for the contact surface in FLAC^{3D}. The sketch of the numerical model is shown in Fig. 6.

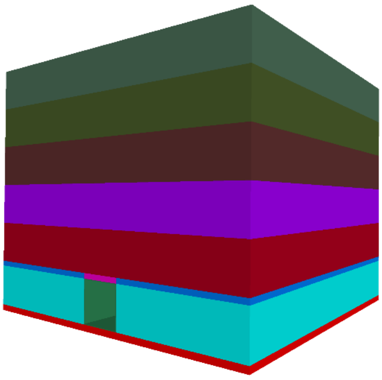


Fig. 6 Numerical model

2.3.2 Material parameters and constitutive relationship

The Mohr-Coulomb model was used for the fill, the elastic model was adopted for the culvert, and the material parameters are shown in Table 1. According to the literature[17, 10, 23], it was known that the Burgers model could reflect the creep law of EPS slabs. The EPS slab parameters were derived from the literature[9, 17], see Table 2 for details.

Table 1 Material parameters

Material	Elastic modulus /MPa	Density /(kg • m^{-3})	Poisson's ratio	Internal friction angle /(°)	Cohesion /kPa
Sand fill	30.0	1 700	0.310	32	0
Culvert model	195 000.0	7 950	0.300	—	—
EPS slab	1.5	12	0.035	—	—

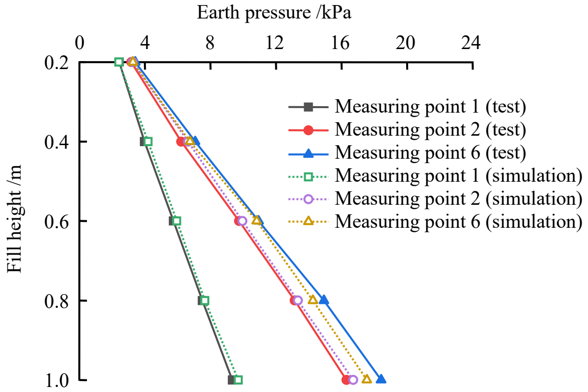
Table 2 Burgers model parameters of the EPS slab

Material	E_m /MPa	E_K /MPa	η_m/(MPa • h)	η_k/(MPa • h)
EPS slab	7.91	6.63	4.01×10^5	0.38

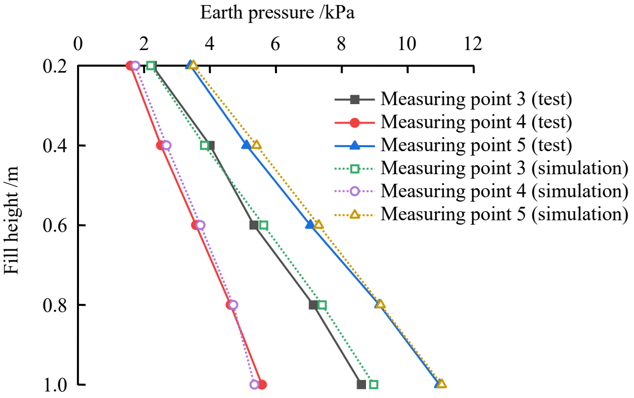
Note: E_m is the Maxwell elastic modulus; η_m is the Maxwell coefficient of viscosity; E_k is the Kelvin elastic modulus; and η_k is the Kelvin coefficient of viscosity.

2.3.3 Numerical model validation

The earth pressures at six measuring points on the culvert side and culvert top in the numerical model with the same location as the test were selected for comparison and verification, as shown in Fig. 7. Both the test and numerical results indicated that the vertical earth pressure in the culvert top plane increased with the increase of the fill height, and the error between the numerical result and the test result was within 5%. In the numerical model, the horizontal earth pressure at the measuring points within the range of the culvert side showed a minimum value in the middle of the culvert side, which was consistent with the test result. The error between the numerical and the test results under different fill heights was within 10% at most, indicating that the numerical result was consistent with the test result and the numerical model was correct and feasible.



(a) Vertical earth pressure at the culvert top plane measuring points



(b) Horizontal earth pressure at the culvert side measuring points

Fig. 7 Comparison of experimental and numerical results

3 Numerical simulation of long-term stress characteristics

3.1 Culvert top earth pressure

The creep analysis was carried out after the completion of filling. The variation of vertical earth pressure at the measuring points 1, 2 and 6 during 600 months is shown in Fig. 8. The vertical earth pressure at the measuring point 1 decreased from 9.69 kPa at the completion of filling to 2.88 kPa after 100 months with a decrease of 70.28%, and after which a slow increase occurred. After the 300th month, it stabilized at 4.64 kPa, which was 52.12% lower than that at the completion of filling. The vertical earth pressure at the measuring point 2 decreased rapidly in the first 100 months and gradually stabilized at about 13.17 kPa after 300 months. The vertical earth pressure at the measuring point 6 increased with time during the first 100 months and then stabilized at 18.43 kPa, which was 5.19% higher than that at the completion of filling. As the time passed by, the effect of the creep of EPS slabs

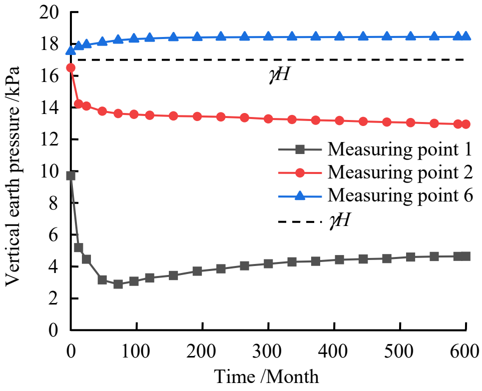


Fig. 8 Variations of vertical earth pressure with time at the culvert top plane measuring points

on the vertical earth pressure at the culvert top gradually became stable. The vertical earth pressure after 50 a in the top range of the EPS slab was much smaller than the vertical earth pressure when the filling was completed, and the method of using EPS slabs to reduce load could maintain good performance for a long time.

3.2 Vertical and horizontal earth pressures on culvert sidewall

The vertical earth pressures at the measuring points 6, 7 and 8 increased slowly after a rapid increase with time during the first 100 months and then stabilized after 300 months, which finally reached 18.43, 20.79 and 21.52 kPa, respectively. The increase rates were 5.19%, 6.89% and 5.75% respectively, compared with those at the completion of filling. The vertical earth pressures at the measuring points 3, 4 and 5 on the side of the culvert increased gradually over time to 23.60, 15.50 and 26.70 kPa respectively within 100 months after the completion of filling, which were 15.97%, 16.63% and 3.89% higher than those at the completion of filling. After that, the vertical earth pressures at the measuring points 3 and 5 tended to be stable with time. However, the vertical earth pressure at the measuring point 4 gradually decreased with time and finally tended to be stable, it was 9.03% lower than that at the completion of filling after 100 months (shown in Fig. 9).

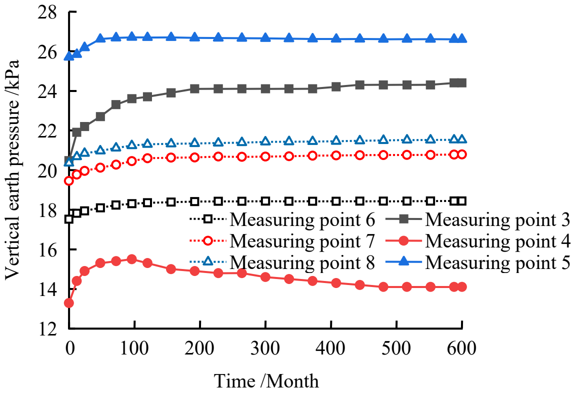


Fig. 9 Variations of vertical earth pressure with time at the culvert side measuring points

The horizontal earth pressures at the measuring points 3, 4 and 5 increased rapidly with time during the 100 months after the completion of filling (as shown in Fig. 10) and gradually stabilized after 300 months. The final horizontal earth pressures increased by 28.54%, 19.11% and 9.07% respectively, compared with those at the completion of filling. The horizontal earth pressures at the measuring points 6, 7, and 8 gradually increased with time and became stable at 100 months after the completion of filling; the final horizontal earth pressure increased by 11.57%, 26.29%, and 19.94% respectively after 600 months compared with those at the completion of filling. The horizontal earth pressures at the measuring points 3, 6 and 5, 8 in the same horizontal plane on the culvert side decreased gradually as the distance increased from the box culvert sidewall; they decreased respectively by 22.79% and 15.12% at 600 months after the completion of filling. The horizontal earth pressure difference between the measuring points 4 and 7 gradually increased with time and increased by 60.69% after 600 months compared with those at the completion of filling. From Figs. 9 and 10, it could be seen that the creep of the EPS slab caused the vertical and horizontal earth pressures to increase in the soil within the box culvert sidewall range, and had a larger influence on the horizontal earth pressure at the measuring point of the box culvert sidewall than on the vertical earth pressure.

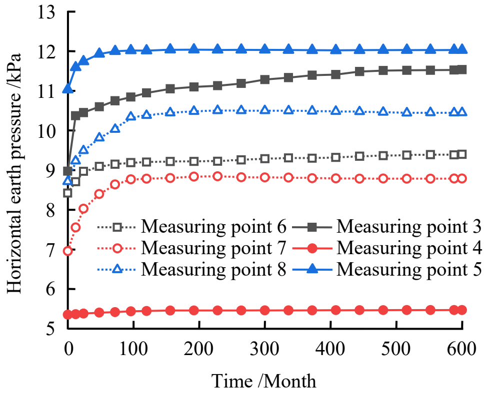


Fig. 10 Variations of horizontal earth pressure with time at the culvert side measuring points

3.3 Earth pressure on the foundation contact plane

The vertical earth pressure in the foundation contact plane with time is shown in Fig. 11. The vertical earth pressure at the measuring 10 was small and the increase rate with time was also small, after 300 months the vertical earth pressure stabilized at around 0.8 kPa. Since the measuring point 9 was under the culvert sidewall and there was a stress concentration in this range, the increase rate of its vertical earth pressure was large in absolute value. Within 100 months after construction, the earth pressure increased rapidly with time and then stabilized at 48.23 kPa, which was 16.95% higher than that at the completion of filling and 2.32 times the fill self-weight pressure. The vertical earth pressure at the measuring point 8 increased slowly with time and finally stabilized at 21.52 kPa, and the vertical earth pressure coefficient was 1.03.

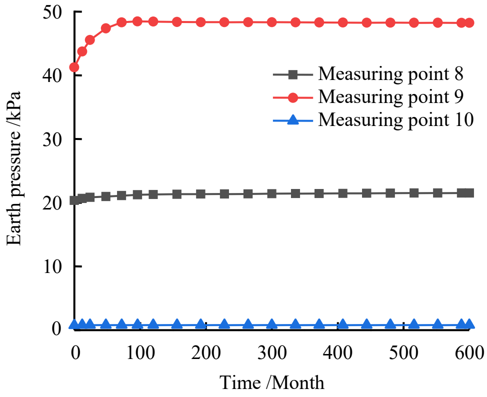


Fig. 11 Variations of earth pressure with time at the foundation contact plane measuring points

3.4 Load reduction effect evaluation

Considering the creep of EPS slabs, the vertical earth pressure at the top of the culvert was 27.29% of the soil self-weight after 600 months, which was 52.12% higher than the load reduction effect after construction. Within 100 months after the completion of filling, the vertical earth pressure at the culvert top decreased rapidly, and the stress redistribution occured between the culvert and the soil, so that the load of the soil column at the top of the culvert was transferred to the culvert sidewall, and the vertical earth pressure outside the culvert sidewall increased with the decrease of the earth pressure at the culvert top. The influence range of the load reduction effect of the EPS slab on the vertical earth pressure at the culvert sidewall was approximately the width of the culvert. The vertical earth pressure at the measuring point 6 after 600 months of filling increased by 5.19% compared to that at the completion of filling, but its horizontal earth pressure increased by 11.57%. The verticle earth pressure of the measuring point 3 increased by 15.97% and the horizontal earth pressure increased by 28.54%. Meanwhile, the increase rate of the horizontal earth pressure on the culvert sidewall with time was large than that of the verticle earth pressure. The increase rate of the verticle earth pressure at the measuring point 9 in the foundation contact plane of the box culvert was large, and the verticle earth pressure was 2.32 times the fill self-weight after 600 months of filling, while the verticle earth pressure at the measuring point 10 was less affected by the creep of the EPS slab.

The creep of the EPS slab had a small effect on the horizontal earth pressures in the lower and middle parts of the culvert sidewall and the vertical earth pressures at a distance of twice the width of the culvert from the sidewall. With the increase of time, the increase rate of the horizontal earth pressure at the measuring points within the culvert sidewall range was larger than the increase of vertical earth pressure. The vertical earth pressure at the top of the culvert showed a significant decrease and then a slow increase in the whole life cycle and finally tended to be stable. The vertical earth pressure at the time of stabilization under long-term conditions was much smaller than that at the time of the completion of filling. The EPS slab had a good load reduction effect in the whole life cycle.

4 Theoretical analysis of long-term stress characteristics

4.1 Mechanical model of long-term behavior of culvert-soil system

According to the force analysis in the previous section, a particle-element model of the long-term stress characteristics of the high-fill box culvert-soil was established, as shown in Fig. 12. In the figure, M_{32}, M_{31}, M_{33} and C_{f32}, C_{f31}, C_{f33} represent the mass and stiffness elements of the box culvert foundation soil and the foundation soil at its two sides. M_{21}, M_{23} and C_{f21}, C_{f23} are the fill masses at the culvert side and its stiffness elements. M_{22} and K_{22} represent the mass and stiffness of the culvert. M_{12}, M_{11}, M_{13} and C_{f12}, C_{f11}, C_{f13} respectively represent the mass and stiffness elements of the inner soil column over the culvert top and the outer soil column on both sides of the culvert top. τ_1 is the friction between the internal and external soils above the culvert top plane. τ_2 is the friction between the culvert sidewall and the soil on the side of the culvert. τ_3 denotes the friction between the soils inside and outside the culvert bases. C_e is the element that reflects the constitutive model of the EPS slab.

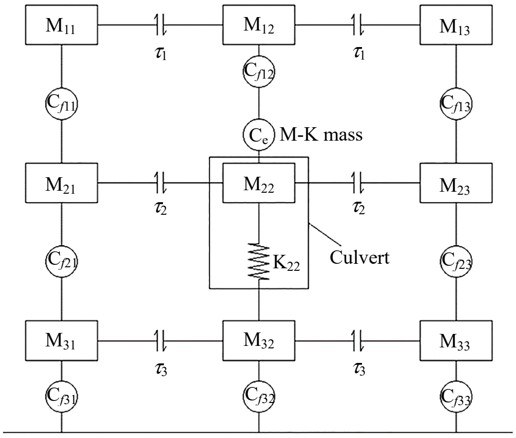


Fig. 12 Particle-element model of the culvert-soil system

The stiffness of the load reduction material was much less than that of the filling soil, making the equivalent stiffnesses of the inner soil column and EPS slab less than that of the outer soil column. The settlement of the inner soil column M_{12} was greater than that of the outer soil columns M_{11} and M_{13}. The settlement difference between the inner and outer soil columns caused part of the self-weight of the inner soil column to be transferred to the side soil column by friction, and the earth pressure on the top of the culvert was less than the self-weight of the soil column above the culvert, thus achieving the purpose of load reduction[7].

4.2 Calculation method of long-term earth pressure on the culvert top

It was assumed that the stress on the EPS slab at the top of the culvert was uniformly distributed and the self-weight of the EPS slab was negligible, the vertical earth pressure in the inner and outer soil columns at the top of the culvert was uniformly distributed and the horizontal earth pressure in the inner and outer soil columns was the active earth pressure, and the box culvert as well as the foundation soil were rigid. Based on the above time effect model, the equilibrium equation for the vertical earth pressure on the top of the load reduction material is derived as

$$\gamma(H-h_{\mathrm{p}})D = D\cdot P_{\mathrm{t}} + 2\tau_1 \tag{5}$$

where P_t is the vertical earth pressure on the top of the load reduction material; and h_p is the thickness of the load reduction material.

τ_1 can be obtained according to the force equilibrium of the differential element within the soil column outside the culvert top as follows:

$$\tau_1=\int_{H-H_\mathrm{e}}^{H-h_\mathrm{p}}[(\gamma zk-2c\sqrt{k})f+c]\mathrm{d}z=$$

$$\frac{1}{2}(H_\mathrm{e}-h_\mathrm{p})[\gamma kf(2H-H_\mathrm{e}-h_\mathrm{p})-4c\sqrt{k}f+2c] \qquad (6)$$

where H_e is the height of the equal settlement section; $k=\tan^2(45^\circ-\varphi/2)$; c is the cohesion of the fill; and $f=\tan\varphi$.

The earth pressure P_s of the soil column outside the plane of the culvert top is

$$P_\mathrm{s}=H\gamma+\frac{(H_\mathrm{e}-h_\mathrm{p})}{2}[\gamma kf(2H-H_\mathrm{e}-h_\mathrm{p})-4c\sqrt{k}f+2c] \qquad (7)$$

Considering the creep properties of load reduction materials, a viscoelastic (M-K system) creep model was used to describe the long-term creep performance of EPS slabs based on the lab test data and the predicted long-term creep process of EPS slabs[23–25]. The creep strain of the EPS slab is

$$\varepsilon(t)=\frac{1}{E_\mathrm{m}}+\frac{t}{\eta_\mathrm{m}}+\frac{1}{E_\mathrm{k}}\left[1-\mathrm{e}^{\left(-\frac{E_\mathrm{k}t}{\eta_\mathrm{k}}\right)}\right] \qquad (8)$$

The unloading process strain[26] is

$$\varepsilon(t)=\frac{1}{E_\mathrm{m}}+\frac{1}{E_\mathrm{k}}\left[1-\mathrm{e}^{\left(-\frac{E_\mathrm{k}t}{\eta_\mathrm{k}}\right)}\right] \qquad (9)$$

Then the creep deformation of the EPS slab can be written as

$$\delta(t)=h_\mathrm{p}\cdot P_\mathrm{t}\cdot\varepsilon(t) \qquad (10)$$

where δ is the compression deformation of the overall thickness of the EPS slab.

When the height of the fill reaches above the equal settlement section, the settlements of the inner and outer soil columns are equal. According to Chen et al.[7], the calculation of the equal settlement section is

$$\varDelta_1+\varDelta_4=\varDelta_2+\varDelta_3 \qquad (11)$$

where $\varDelta_1$ is the compression of the soil column below the equal settlement section, i.e.,

$$\varDelta_1=\frac{(H_\mathrm{e}-h_\mathrm{p})[(\gamma-2\gamma kf)(2H-H_\mathrm{e}-h_\mathrm{p})+8c\sqrt{k}f-4c]}{2E} \qquad (12)$$

where E is the deformation modulus of the fill in the culvert top plane.

$\varDelta_2$ is the compression of the outer soil column below the equal settlement section, which is

$$\varDelta_2=\frac{[(2H-H_\mathrm{e})\gamma+(2H-H_\mathrm{e})\gamma kf-4c\sqrt{k}f+2c]\times H_\mathrm{e}}{2E} \qquad (13)$$

$\varDelta_3$ is the compression of the fill within the height of the culvert side and can be expressed as

$$\varDelta_3=\frac{(1-k_0f_0)(2P_s+\gamma_\mathrm{k}h)h}{2E_\mathrm{k}} \qquad (14)$$

where $k_0=\mu/(1-\mu)$, μ is the Poisson's ratio of the fill; h is the height of the sidewall; γ_k is the unit weight of the culvert side fill; E_k is the mean deformation modulus of the fill within the culvert side range; and $f_0=\tan\delta'$, δ' is the friction angle between the sidewall and the fill.

$\varDelta_4$ is the compressive deformation of the load reduction material, which is of the form

$$\varDelta_4=h_\mathrm{p}\cdot P_\mathrm{t}\cdot\varepsilon(t)+\varDelta_0 \qquad (15)$$

where $\varDelta_0$ is the compression of the EPS slab at the completion of filling (elastic compression of the EPS slab).

P_t can be obtained by combining Eqs. (5) and (6)

$$P_\mathrm{t}=H\gamma-\frac{(H_\mathrm{e}-h_\mathrm{p})[\gamma kf(2H-H_\mathrm{e}-h_\mathrm{p})-4c\sqrt{k}f+2c]}{D} \qquad (16)$$

The function relationship between the compression deformation of the EPS slab at different times and the height of the equal settlement section can be obtained by combining Eqs. (7), (11) and (16). The compressive deformation of the EPS slab at different time points can be found iteratively by substituting the soil pressure on the top of the culvert at the completion of the filling as the initial value into Eq. (15). Hence the value of H_e at different times in the whole life cycle after the completion of filling could be calculated. The obtained H_e was substituted into Eqs. (7) and (16) to obtain the values of P_t and P_s at different times after the completion of filling and plotted as curves, as shown in Figs. 13 and 14.

The theoretical calculation and numerical simulation results of the vertical earth pressure over the top of the culvert and the vertical soil pressure of soil columns outside the culvert top e plane over a period of 600 months are shown in Figs. 13 and 14. The theoretical calculation and numerical simulation results showed that the earth pressure on the top of the culvert decreased gradually in the first 100 months and then increased slowly with time and eventually tended to be stable. The vertical earth pressure of the outer soil column of the culvert side gradually increased with time within 100 months, then a small decline appeared and also tended to be stable in the end. The variations of the two were the same, exhibiting that the theoretical calculation method was reasonable and feasible.

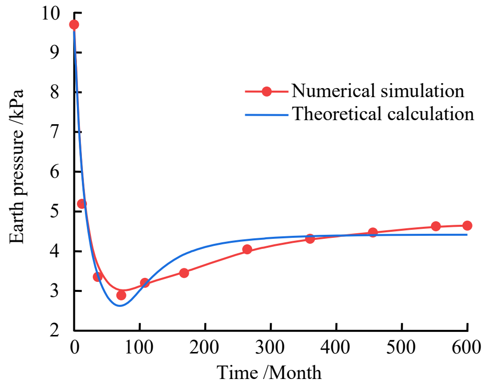


Fig. 13 Comparison of earth pressure on the culvert top between the theoretical calculation and numerical simulation results

4.3 Comparison of theoretical results with existing literature

In the literature[5–6], long-term vertical earth pressure monitoring of the culvert top was carried out on the culvert project in which EPS slabs were laid on top of the culvert to reduce the stress. In the project, the thickness of the EPS slab was 0.5 m, the unit weight was 0.2 kN /m^3, the distance from the EPS slab to the top of the box culvert was 0.5 m, the fill height was 10.8 m, and the fill unit weight was 20 kN /m^3. The monitoring results showed that the vertical earth pressure on the top of the culvert was 132 kPa and the vertical earth pressure coefficient was 0.63 after the filling was completed at the beginning of 1990; with the increase of time the vertical earth pressure gradually decreased to 88 kPa at the end of 1991; and in early 1993, the vertical earth pressure on the top of the culvert increased slightly to 100 kPa and tended to be stable. Later in 2015, monitoring data indicated that the vertical earth pressure on the top of the culvert was 94 kPa, and the vertical earth pressure coefficient at this time was 0.48 (see Fig. 15).

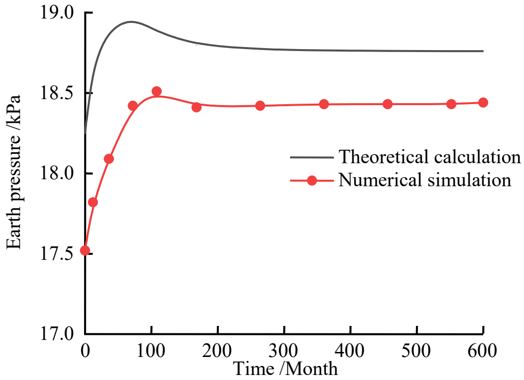


Fig. 14 Comparison between theoretical calculation and numerical simulation results of soil column earth pressure outside the culvert top

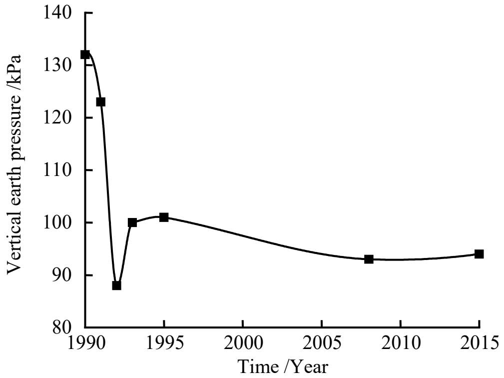


Fig. 15 Variation of measured vertical earth pressure with time on the culvert top

In this paper, the theoretical results were consistent with the engineering monitoring results in the literature[5−6], the vertical earth pressure on the top of the culvert first decreased and then increased slightly with the increase of time, and finally tended to stabilize. After stabilization, the vertical earth pressure on the top of the culvert was smaller than the vertical earth pressure on the top of the culvert when the filling was completed. By the theoretical formula proposed in this paper, the vertical earth pressure coefficient at the top of the culvert when the filling was completed was obtained as 0.57 and the vertical earth pressure coefficient at stabilization was obtained as 0.25. Since the geometric dimension and fill type used in the literature[5−6] were not exactly the same as the parameters in this paper, there were some differences between the two numerical results.

In the literature[1−2], an actual engineering project with EPS slabs laid on the top of the culvert was monitored. In the case of load reduction with EPS slabs, the vertical earth pressure on the top of the culvert when the filling was completed was reduced by 1/2 to 2/3 compared with the self-weight of fill, which was consistent with the result in this paper that the vertical earth pressure on the top of the culvert when the filling was completed was reduced by about 1/2 compared with the self-weight of fill by the theoretical calculation. Considering the creep of the EPS slab, after 600 months, the vertical earth pressure on the top of the culvert after stabilization analyzed in this paper was reduced by 3/4 compared with the self-weight of fill. The reduced self-weight of the fill on the top of the culvert was transferred to the outer soil column through the friction generated by the differential settlement between the inner and outer soil columns. Without laying the EPS slab, the theoretical result in the literature[1−2] showed that the vertical earth pressure of the outer soil column at the top plane of the box culvert when the filling was completed increased by about 17%, and the horizontal earth pressure at this place increased by the same magnitude, which was 11% larger than the theoretical vertical earth pressure of the outer soil column at the top plane of the culvert in the paper. The reason for this was that the theoretical analysis in this paper considered the friction effect between the culvert side and the fill, which reduced the vertical earth pressure increment of the outer soil column at the top plane of the culvert. In contrast, when the EPS slab was laid on the culvert side, the horizontal earth pressure on the sidewall in the literature[1−2] was reduced by about 50% compared to the culvert side without the EPS slab laid on the culvert side.

In the literature[7], the friction of the box culvert sidewall was considered in the calculation of horizontal earth pressure according to the equal settlement section theory, and this paper considered the effect of the creep of EPS slabs on the horizontal earth pressure of the box culvert sidewall on the basis of this theory. The results showed that the horizontal earth pressure on the box culvert sidewall under the creep effect of EPS slabs was finally increased by about 20% on average compared with that at the completion of filling, which was about 40% greater than the horizontal earth pressure of the box culvert sidewall calculated using *General Specifications for Design of Highway Bridges and Culverts* (JTG D60—2015)[27]. Therefore, the creep effect of EPS slabs on the stress characteristics should be considered in the design of box culverts.

5 Conclusion and suggestions

The short-term test of high-fill box culverts under the EPS slab load reduction condition was used to verify the correctness of the corresponding numerical model. After that, the verified numerical method was used to analyze the long-term stress characteristics of high-fill box culverts, based on which the particle-element model of the long-term stress characteristics of the culvert-soil system was established, and the theoretical formula for computing the earth pressure on the top of the box culvert was derived and verified. The main conclusions were drawn as follows:

(1) Under the creep condition of EPS slabs, the vertical earth pressure on the top of the culvert decreased with time and the load reduction effect gradually increased during the 100 months after the completion of filling, after which the vertical earth pressure on the top of the culvert slowly increased and eventually stabilized, and the final vertical earth pressure on the top of the culvert was reduced by about 50% compared with that at the completion of filling.

(2) The vertical earth pressure of the soil column outside the plane of the culvert top increased gradually with time and gradually tended to be stable after 100 months. The creep of the EPS board caused an increase of about 40% in the horizontal earth pressure on the side walls of the box culvert. Therefore, the increase of horizontal earth pressure on the box culvert sidewall caused by the reduction of earth pressure on the culvert top under long-term load should be considered in the design. The foundation contact pressure also increased gradually and tended to be stable with the increase of time.

(3) The mechanical model of long-term stress characteristics of high-fill box culverts under EPS slab load reduction condition was established, and the theoretical formula for calculating the long-term earth pressure on the top of the box culvert was developed, it and was verified to be correct.

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