

Research Article

Model Tests of Earth Pressure on Buried Rigid Pipes and Flexible Pipes underneath Expanded Polystyrene (EPS)

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To obtain the optimal load-reduction scheme and calculation method of earth pressure on the crown of the pipe, the load-reduction efficiency of rigid pipe and flexible pipe with different thicknesses and layers of expanded polystyrene (EPS) is investigated by model tests, and the law of load reduction is obtained by analyzing the earth pressure and the displacements of the filling around the pipe. The test results show that the earth pressure is obviously reduced with EPS laying on the crown of pipe, and the load-reduction efficiency is increased to be constant with increasing of EPS thickness. In the case that the summation thickness of EPS is constant, the load-reduction efficiency of EPS with two layers spread on the pipe is higher than that of one layer only. Compared with the rigid pipe, the load-reducing effect of flexible pipe is more significant. Based on the data obtained from the model tests, the nonlinear earth pressure calculation formula obtained from regression analysis is adopted, and the results from it are compared with the existing formula consequences of the earth pressure on the buried pipe. The results show that the earth pressure calculated by nonlinear earth pressure theory is on the brink of that tested in the field. The research results can provide references for selection of load-reduction measures and calculation of earth pressure on the crown of the pipe.

1. Introduction

With the fast development and expansion of modern cities, buried pipes have been extensively applied for transmission of various media such as water, gas, and petroleum. The underground pipe project is concealed, and its investment is huge; once the pipe is affected, it may cause huge economic loss and even the crisis of public safety. In recent years, the damage phenomenon of urban road surface of underground pipe is serious, especially the ruin of shallow buried pipeline, which greatly affects the smoothness and safety of urban traffic. In order to ensure the normal operation of pipelines, many scholars have studied the stress, deformation, settlement, and cracking of underground pipe [1–6].

In order to change the stress concentration phenomenon of earth pressure on crown of pipe and reduce earth pressure, artificial measures should be adopted. Firstly, the distribution of earth pressure along pipe can be adjusted by laying relieving slab to improve the overall stress state of the structure [7]. Meanwhile, laying geogrid and geocell can

reduce the settlement between the central soil prism and the lateral on the crown of the pipe and also can reduce the earth pressure on the pipe crown [8–12]. Furthermore, laying materials with compressibility much higher than filling soil around the pipe can greatly reduce the earth pressure on crown of the pipe, reduce the size and nonuniform settlement of the structure, and prevent the occurrence of cracking diseases [13, 14].

Marston first proposed lying compressible flexible material on crown of the culvert (pipe) for earth pressure load reduction and verified the feasibility of the method of pipe structure load reduction [15]. Later, Spangler conducted field experiments by placing an additional compressible inclusion above the buried pipe. The result implied that placing an additional compressible inclusion above the plane of equal settlement can reduce the relative settlement between the central soil prism and its adjacent soil, so as to reduce the frictional resistance on the central soil prism from lateral adjacent soil prisms [16]. Then, after more than five years of field tests and measurements, Sun et al. [17] found

that the geofoam can reduce the earth pressure of culvert crown by about 10%.

Expanded polystyrene (EPS) is a kind of foam plastic, because of its light weight, corrosion resistance, and good compression deformation performance, in the research subject has been favored by many scholars and has been widely used in practical engineering. Bartlett et al. [18] suggested that EPS placed as compressible material on the underground pipe to reduce the vertical load above the pipe. After that, Vaslestad and Sayd [19] have proved that the method of laying EPS on the crown of the culvert is stable through 25 years of long-term observation. Meguid and Ahmed used a flexible sensing technology to measure the earth pressure distribution on the pipe under static and cyclic load conditions, which also proved that laying EPS could reduce the vertical earth pressure on the crown of the pipe [20].

Obviously, EPS is a very useful load-reducing material. However, at present, the research on the earth pressure reduction at the crown of the pipe mostly stays on the parameters of EPS. For example, Zhang et al. [21], based on in situ load-reduction test of pipe, used EPS as a load-reduction material, tested the load-reduction characteristics of culvert crown earth pressure under different thickness of EPS. Li et al. [22] studied the influence of different moduli of EPS on earth pressure at pipe crown. Gao et al. [23] studied the influence of EPS widths on earth pressure of culvert crown. Dancygier and Yankelevsky [24] studied the optimum laying range of flexible packing on the crown of pipe. But all the above considerations are the laying of single-layer load-reducing materials.

Therefore, some scholars put forward the method of laying multilayer polymer or combined reinforcement on pipe roof to reduce the earth pressure. Zhao et al. [25] analyzed the field performance of soft subgrade reinforced by multilayer geogrids through field tests. The results showed that multilayer geogrids can effectively reinforce the soil and meet the compaction requirements of lining soil. Hegde et al. [26] studied the applicability of the combination of geogrid and geocell reinforcement system in protecting the buried pipe through laboratory test. The test showed that the crown earth pressure of pipe decreased by more than 50%, and the strain value decreased by more than 40%. Meanwhile, Mehrjardiaab et al. [27] discussed the effect of the combination of geocell and rubber reinforcement system on the strain of buried flexible pipe and the settlement of backfill. The test results showed that the settlement of backfill over pipe can be reduced by 70% and vertical diametral strain can be reduced by 47% when the combination of geocell and rubber reinforcement system was placed on the crown of pipe. The above proves the feasibility of laying multilayer load shedding material on the crown of pipe. In a word, laying multilayer load-reducing material on culvert crown is also a feasible method.

Laying EPS on the crown of pipe can reduce the settlement difference between central and lateral soil prism, and reducing the concentration of earth pressure on the crown of pipe is a feasible and effective load-reduction scheme. However, there are many papers on load reduction of single-

layer EPS on culvert crown, which does not consider the load-reduction effect of multilayer EPS and seldom use it in flexible pipe. In this paper, the load-reduction effects of shallow buried rigid pipe and flexible pipe under different thickness and layers of EPS are analyzed by laboratory model tests. Considering the arch effect on the crown of pipe, the nonlinear earth pressure calculation formula is obtained by regression analysis. And the reliability of the formula is verified by comparing with the current six classical calculation methods, which provides a reference for the design of pipe load reduction and the calculation of earth pressure.

2. Design of Experiment

2.1. Model Designs

2.1.1. Boundary Conditions. Regardless of the impact of the boundary of the earth pressure of the buried pipe, the pipe under such burying conditions is a buried pipe. Therefore, the left and right baffle of the test model box is 4 times the diameter of the pipe away from the pipe axis, which is used to simulate the trench slope far away from the pipe axis, as the boundary condition of this test.

2.1.2. Test Materials. This test mainly focuses on the variation of earth pressure around the pipe. Flexible pipe and rigid pipe are selected according to their mechanical properties. Usually, the deformation of pipe is larger than the settlement of soil above the pipe. The soil on both sides of the pipe will produce upward friction on the soil above it, which reduces the phenomenon of earth pressure concentration on the crown of the pipe. This kind of pipeline is called flexible pipe; conversely, it is called rigid pipe. Therefore, when choosing pipe material, the flexible pipe is simulated by the PVC pipe with larger deformation, and the rigid pipe is simulated by the steel pipe with smaller deformation. And the specifications are DN110 (wall thickness is 3.2 mm). The filling material is ISO standard sand, and its particle size distribution is given in Figure 1. The load-reducing material is EPS, and its compressible stress-strain curve of EPS is shown in Figure 2. The physical parameters of standard sand and EPS are given in Tables 1 and 2, respectively.

2.1.3. Model Loading. Static load is applied by means of stress control and step compression. The concentrated load is transformed into a uniformly distributed load and transmitted to the filling soil through the bearing plate (steel plate with a length of 790 mm \times width of 400 mm \times thickness of 14 mm). The loading force of the model is determined according to the height of the simulated fill, and the height of 50 cm above is simulated through the stacking weight on the bearing plate. The weight has three specifications of 5 kg, 10 kg, and 20 kg, and the weight to be loaded to simulate different filling height is shown in Table 3.

Figure 3(a) shows that the geometry of the model box was 800 mm length \times 400 mm wide \times 500 mm height. In order to observe the deformation of the pipe and the

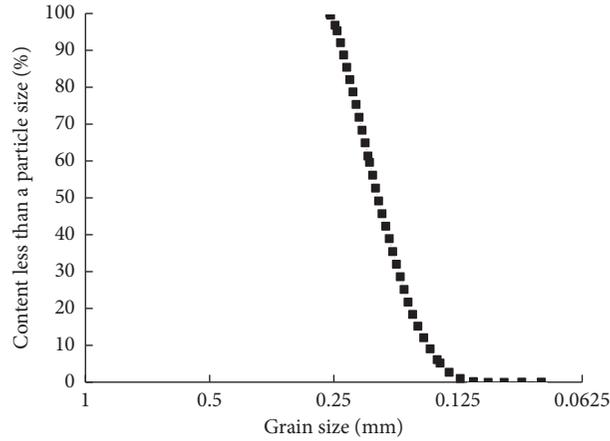


FIGURE 1: Gradation curve.

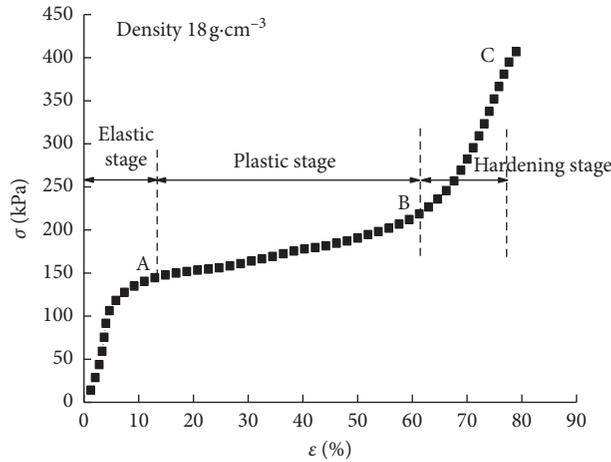


FIGURE 2: Compressible stress-strain curve of EPS.

TABLE 1: Parameters of sand.

Maximum dry density ($\text{g}\cdot\text{cm}^{-3}$)	Minimum dry density ($\text{g}\cdot\text{cm}^{-3}$)	Internal friction angle ($^{\circ}$)	Degree of compaction (%)	Water content (%)
1.70	1.65	30	95	8

TABLE 2: Parameters of EPS.

Density ($\text{kg}\cdot\text{m}^{-3}$)	Modulus of proportion (MPa)	Modulus of elasticity (MPa)	Yield modulus (MPa)
18	2.22	1.40	0.04

TABLE 3: The applied load on the model filling height.

Load weight (kg)	0	55	110	165	275
Height of backfill (cm)	50	60	70	80	90

settlement of the embankment in the test, the tempered glass with thickness 30 mm is used on the four sides of the model box, and the corner steel ribs are added to reduce the deformation of the model box during loading. In order to decrease the effect of friction between tempered glass and standard sand, lubricating grease was plastered to the inner

surface of tempered glass before the backfill of sand. The earth pressure cell is a strain type miniature earth pressure sensor with a diameter of 3.0 cm and range of 0.08 MPa.

2.2. Test Schemes. Figure 3(b) shows the circular pipe with the outer diameter $D = 110$ mm was embedded in the model box, the 4 cm thickness standard sand is laid on the bottom as a pad, and the EPS with a width of 165 mm ($1.5D$) was laid on the pipe crown [28]. In order to restore the actual situation to the greatest extent, a model similar to the actual

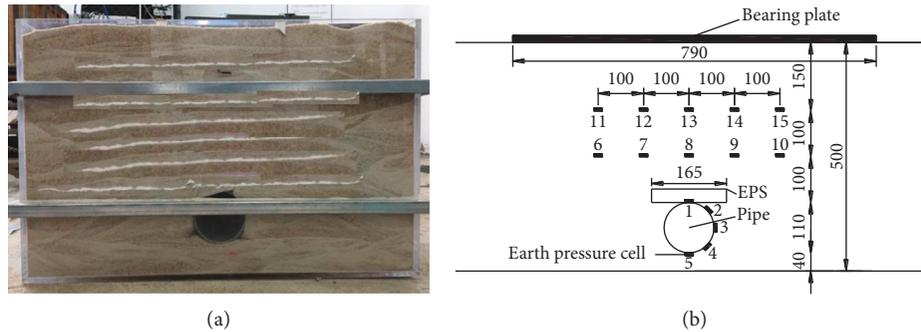


FIGURE 3: Model test box (unit: mm).

situation is adopted to carry out the test under various schemes. The thickness of EPS is also corresponding to the pipe size according to the actual situation. The miniature earth pressure cells, No. 6 to No. 10, are installed at a symmetric equidistance of 100 mm in the level 100 mm above the crown of the pipe, and earth pressure cells No. 11 to No. 15 are installed at an equidistance of 100 mm in the level of 200 mm above the crown of the pipe. The earth pressure cells on each floor are vertically spaced 100 mm and arranged symmetrically along the pipe axis. Additionally, by using epoxy resin, the No. 1 to No. 5 earth pressure cells are fixed on the surface perpendicular to the diameter of the pipe, and the vertical earth pressure on the surface of the pipe is measured. Before embedding, the earth pressure cells should be placed in the same environment as the measured temperature for half an hour. On the other hand, the initial frequency is measured by a frequency measuring instrument, and the recorded value is balanced to zero.

Table 4 lists the scheme of laying EPS of different thicknesses and different layers on the crown of pipe in the test and the tests of rigid pipe and flexible pipe under diverse conditions. It represents the practical scenario.

3. Test Results and Analysis

3.1. Influence of EPS Thickness. Figure 4 shows the earth pressure on the crown of the pipe in scheme 1 to scheme 5 measured by No. 8 earth pressure cell. Figure 5 indicates the relationship between the thickness of the EPS and the load-reduction rate of the earth pressure at the crown of the pipe.

Figure 4 shows that when the filling height is 90 cm, the crown earth pressure of the pipe in scheme 1 to scheme 5 is 35.18 kPa, 33.37 kPa, 31.58 kPa, 27.18 kPa, and 25.70 kPa, respectively. The earth pressure is decreased by 5.14%, 10.23%, 22.74%, and 26.95% after EPS of 1 cm to 4 cm placed on the crown of the pipe, respectively. In addition, the earth pressure on the crown of the pipe is increasing nonlinearly with the increase of the backfill height, and the pressure on the crown of the pipe is greater than the weight of the overburden of the backfill (i.e., the linear theory; the crown stress of the pipe is γH , H is the height of the soil prism on the crown of the pipe). However, with the increase of the thickness of the EPS on the crown of the pipe, the measured earth pressure on the crown of the pipe is closer to the weight of the overburden of the backfill.

Figure 5 shows that with the increase of the thickness of the EPS, the load-reduction efficiency of the crown earth pressure increases in a nonlinear form, and the load-reduction efficiency of the EPS of 2 cm thickness is significantly higher than that of 1 cm. When the thickness of the EPS exceeds 3 cm, the load-reduction rate begins to weaken obviously and tends to be stable. When the thickness of EPS is 4 cm, and the filling height $H = 50$ cm, 60 cm, 70 cm, 80 cm, and 90 cm, the load-reduction rate of earth pressure on the crown of the pipe trends to 34.12%, 27.18%, 25.74%, 24.90%, and 23.95%, respectively. It indicates that under the condition of low filling height, the load-reduction effect of EPS is greater, but with the increase of filling height, the load-reduction effect starts to decrease.

According to the above analysis, the earth pressure on the crown of the pipe presents a nonlinear increasing trend with the increase of filling height, and all of the monitored pressure is greater than the linear theoretical value. On the one hand, the gravity stress on the crown of the pipe increases with the increase of the height of the fill (the gravity stress is the intergranular stress transmitted between the soil particles at the contact points, neglecting the effect of friction and cohesion between the particles, and the existence of the frictional force and cohesion is the reason for the nonlinear growth of the pressure of the crown of the pipe with the height of the backfill). On the other hand, with the increase of the height of the backfill, the differential settlement will be produced between the central soil prism and the lateral on the crown of the pipe. The stiffness of the rigid pipe is greater than the surrounding soil, and the settlement of the pipe side backfill is greater than that of the crown of the pipe. That is, the settlement difference between the central and lateral soil prisms is $\Delta_1 < 0$ (as shown in Figure 4); thus a sliding surface will be produced on the crown of the pipe underneath the plane of equal settlement. The friction force on both sides of the sliding surface will cause stress concentration on the crown of the pipe, and the earth pressure on the crown of the pipe is generally higher than the linear theoretical value. The settlement difference between central and lateral soil prism is reduced by the compression deformation of the EPS. When the compression volume increases rapidly and enters the hardening stage, the volume of the compression deformation is small, and the load-reduction effect starts to weaken. Therefore, the load-reduction effect will decline as

TABLE 4: Test programs.

Scheme	Pipe material	Load-reducing material	Thickness of EPS, C (cm)	Layer spacing of EPS, Z (cm)	Number of EPS layers, N	EPS width, B (cm)
1	Steel pipe	—	—	—	0	—
2	Steel pipe	EPS	1	—	1	16.5
3	Steel pipe	EPS	2	—	1	16.5
4	Steel pipe	EPS	3	—	1	16.5
5	Steel pipe	EPS	4	—	1	16.5
6	Steel pipe	EPS	2	5	2	16.5
7	PVC pipe	—	—	—	0	—
8	PVC pipe	EPS	1	—	1	16.5
9	PVC pipe	EPS	2	—	1	16.5
10	PVC pipe	EPS	3	—	1	16.5
11	PVC pipe	EPS	4	—	1	16.5

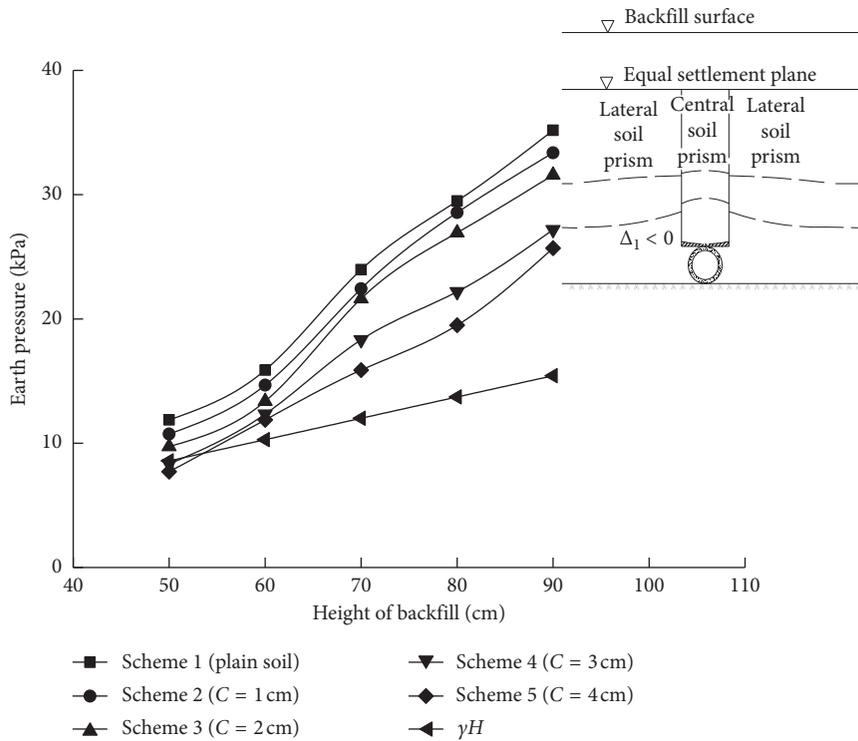


FIGURE 4: Pressure on crown of pipe vs. height change of filling soil.

the height of the fill reaches a certain degree. For EPS with a thickness of 1 cm to 4 cm, although the thickness difference is quite large, it can be seen from Figure 5 that the load-reduction effect begins to stabilize from 3 cm. Therefore, the thickness of EPS is more suitable between 3 cm and 4 cm.

By laying EPS to increase the settlement of backfill on the crown of pipe and reduce the differential settlement between the central and lateral soil prisms, the concentrated stress on the crown of the pipe can be transferred. Figure 6 shows the earth pressure on the pipe crown measured by No. 6 to No. 10 earth pressure cells at the height of 90 cm backfill height. Figure 7 shows the vertical earth pressure on the surface of the pipe measured by No. 1 to No. 5 earth pressure cells when the thickness of the EPS is 4 cm.

Figure 6 shows that the earth pressure of No. 8 at the central axis of the pipe is the largest, and the earth pressure

measured by scheme 1 to scheme 5 is 35.18 kPa, 33.37 kPa, 30.58 kPa, 28.23 kPa, and 24.70 kPa, respectively, showing a trend of decreasing. The earth pressure measured by No. 7 on the side of pipe is 17.56 kPa, 18.23 kPa, 19.99 kPa, 20.99 kPa, and 21.67 kPa, respectively, showing a trend of increasing. In order to clarify the influence of the stiffness difference between the pipe and the fill on the surrounding stress, the distribution law of earth pressure in the same plane with symmetrical axis about 20 cm is explored. In this area, the earth pressure decreases with the increase of the distance from the pipe axis, and the earth pressures of No. 7 and No. 9 (10 cm from the pipe axis) reach the maximum values. It can be seen that the earth pressure on the crown decreases with the increase of the thickness of the EPS, but the horizontal earth pressure at the distance of 10 cm (about 1D) increases with the increase of the thickness of the EPS,

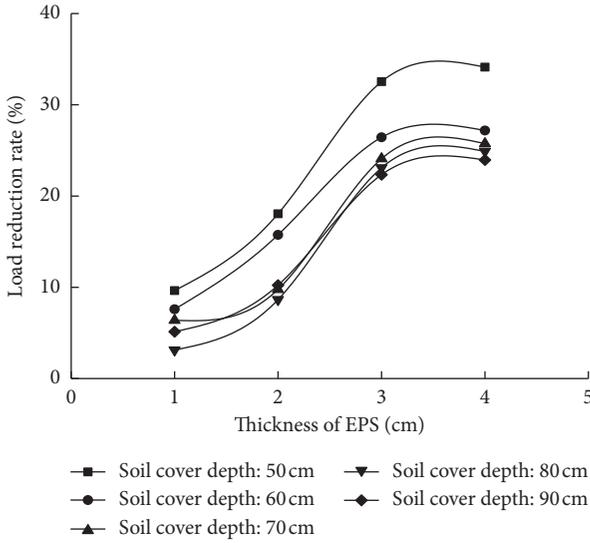


FIGURE 5: Load-reduction rate of EPS in different soil cover depths.

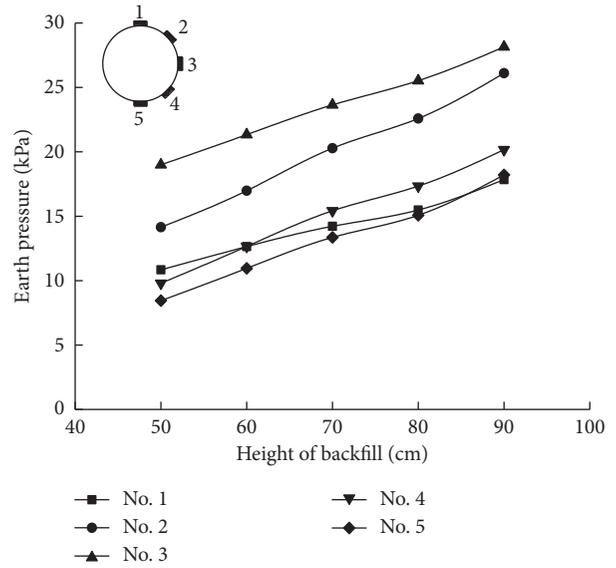


FIGURE 7: Pressure variation of No. 1–5 pressure cells with filling height.

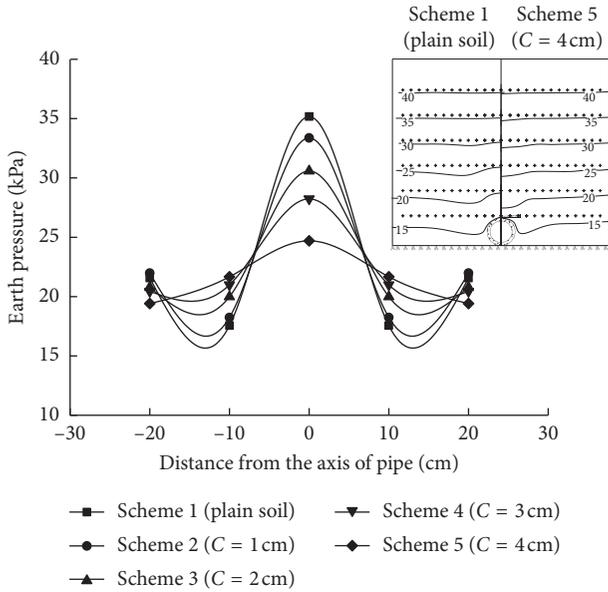


FIGURE 6: Distribution of vertical earth pressure above the pipe.

indicating that the EPS laid on the crown of the pipe can transfer the earth pressure on the crown to both sides of the pipe.

Figure 7 shows that the measured earth pressure increases with the increase of the filling height. When the height of backfill is 90 cm, the vertical earth pressure on the surface of the pipe measured by No. 1 to No. 5 earth pressure cells is 17.84 kPa, 26.11 kPa, 28.15 kPa, 20.15 kPa, and 18.21 kPa, respectively, and the earth pressure measured by No. 3 is the greatest. It can be concluded that the concentration of horizontal earth pressure on both sides of pipe is remarkable when the thickness of EPS is 4 cm.

The test results demonstrate that the earth pressure on the crown of the pipe decreases and the earth pressure on the side of the pipe increases with the increase of the thickness of

EPS. The main reason is that the EPS of a certain great thickness has a large compressible deformation, which reduces the differential settlement between the central and lateral soil prisms (as shown in Figure 6); thus, the friction force between the soil prisms is reduced. Therefore, the earth pressure on the crown of the pipe decreases and the earth pressure at the sides of the pipe increases. In conclusion, as the thickness of EPS increases, the earth pressure on the crown of the pipe will reduce, but the earth pressure at the side of the pipe will increase.

3.2. Influence of EPS Layer Number. Figure 8 shows the earth pressure on the crown of the pipe in scheme 1, scheme 5, and scheme 6 measured by No. 8 earth pressure cell. Figure 9 displays the relationship between the load-reduction rate of single-layer and two-layer EPS with the change of filling height.

Figure 8 shows that when the filling height on the pipe is 90 cm, the earth pressure on the pipe in schemes 1, scheme 5, and scheme 6 is 35.18 kPa, 26.70 kPa, and 24.03 kPa, respectively. In terms of the overall tendency, the earth pressure in scheme 6 is the smallest, while that in scheme 1 is the highest. Compared with those without EPS, under the same total thickness of EPS, the single-layer and two-layer EPS decreased by 24.10% and 31.69%, respectively. The load-reduction effect of two-layer EPS was 7.59% more than that of single-layer EPS. It can be seen that the load-reduction efficiency of the EPS of double 2 cm thickness on the crown of the pipe is better than that of the EPS of a single 4 cm thickness.

It can be seen from Figure 9 that when the filling height is 50 cm, the load-reduction rates of single-layer and two-layer EPS is 21.99% and 17.71%, respectively. The load-reduction efficiency of single-layer EPS is greater. In this condition, the filling load is small, and the load-reduction effect of two-

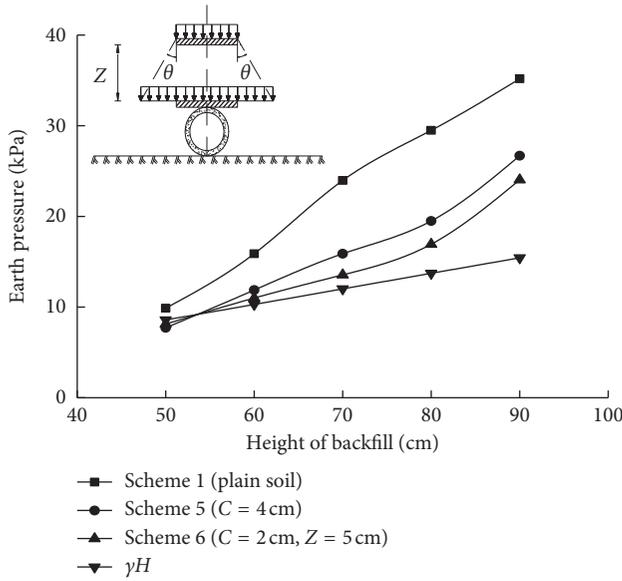


FIGURE 8: Pressure on crown of pipe vs. filling height.

layer EPS is not fully played. With the increase of filling height, the load-reduction effect of two layers EPS becomes to exceed that of single-layer EPS, and the load-reduction efficiency is stable on them.

The above test results show that when the backfill is high, under the condition that the total thickness of EPS is the same, the load-reduction efficiency of two layers of EPS is greater than that of one layer. The probable reason is that the soil particles contact each other to transfer stress, and the stress is spread layer by layer. When the crown of the pipe is overlaid two layers of EPS, the upper layer of EPS increases the stress diffusion angle (as shown in Figure 8) and enlarges the area of stress transfer downward and thus increases the pressed area on the crown plane of the pipe and reduces the earth pressure. The advantage of this method is that there is a definite space between the two layers of EPS. After the stress dispersion of the upper EPS, the load transferred to the lower EPS is obviously reduced, and the effect of load reduction is played in advance.

Figure 10 shows the variations of earth pressure measured by No. 6 to No. 10 earth pressure cells with the thickness of EPS underneath the backfill of 90 cm height. The horizontal earth pressure measured by No. 3 earth pressure cell with the change of the filling height is illustrated in Figure 11.

It can be seen from Figure 10 that the measured earth pressure from No. 8 earth pressure cell at the axial line of the pipe crown is the greatest, and the measured earth pressure in scheme 1, scheme 5, and scheme 6 is 35.18 kPa, 26.70 kPa, and 24.03 kPa, respectively, representing a decreasing trend. The earth pressure measured by No. 7 earth pressure cell at the pipe side is 17.56 kPa, 20.06 kPa, and 21.67 kPa, respectively, representing an increasing trend. As a whole, the earth pressure on the crown of the pipe is decreasing, and the earth pressure on the pipe side is increasing.

Figure 11 shows the horizontal earth pressure corresponding to scheme 1, scheme 5, and scheme 6 is 23.80 kPa, 28.15 kPa, and 29.69 kPa, respectively, at the filling height of 90 cm. Compared with those without EPS, under the same

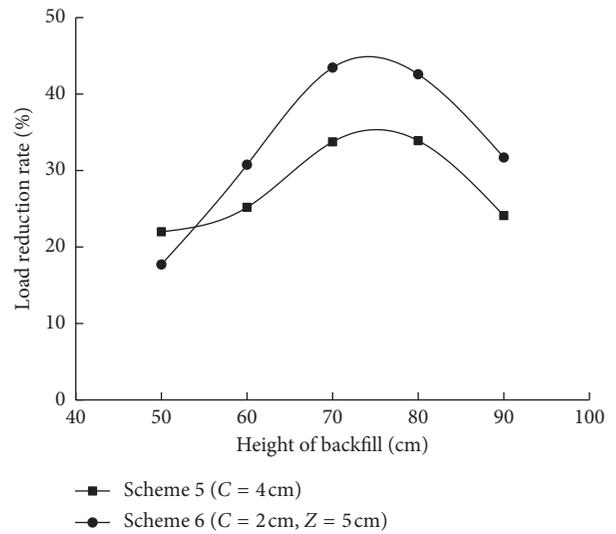


FIGURE 9: Load-reduction rate of different layers of EPS vs. filling height.

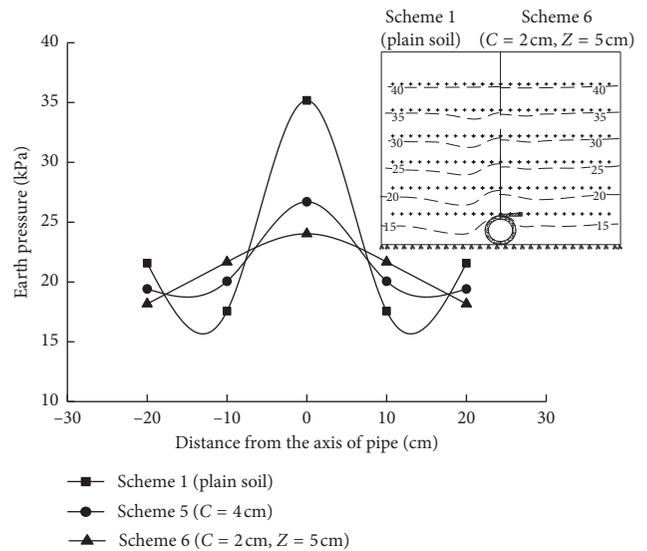


FIGURE 10: Distribution of vertical earth pressure above the pipe.

total thickness of EPS, the single-layer and two layers EPS increased by 24.10% and 31.69%, respectively. After two layers of EPS were laid on crown of the pipe, the horizontal earth pressure on the pipe side was 6.47% more than that of single-layer EPS. It can be seen that the horizontal earth pressure increased with the increase of the filling height and increase the number of EPS layer.

The above test results show that the load-reduction effect of two layers of EPS on the crown of pipe is better than that of single-layer, but at the same time, the increase of horizontal earth pressure measured in the pipe is more obvious. On the one hand, the deformation of the two-layer EPS is more sufficient than that of the single-layer EPS, thus the differential settlement is better reduced by two-layer EPS, (as shown in Figure 10), so the concentration degree of earth pressure on

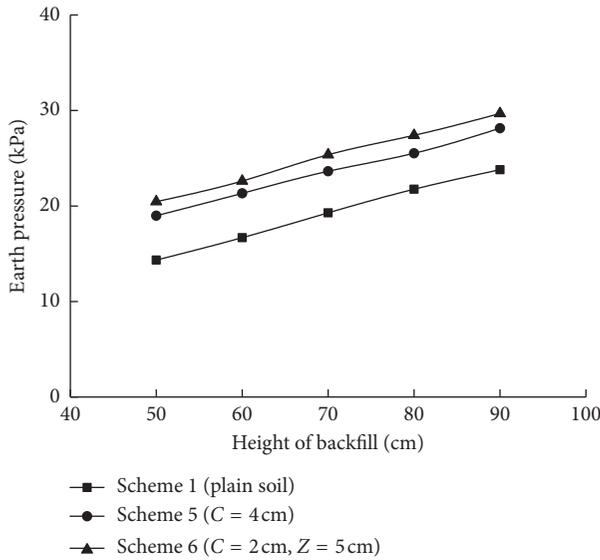


FIGURE 11: Pressure of No. 3 earth pressure cell with filling height.

the crown of pipe decreases, and the concentration degree of earth pressure on both sides increases. On the other hand, the stress dispersion angle is enlarged by the first layer of EPS in the process of downward stress transfer, which expands the scope of downward stress transmission. The stress on crown of the pipe is transferred to the adjacent sides in progress, so the vertical earth pressure on both sides of the pipe is increased, and the horizontal earth pressure of the pipe is increased too. In conclusion, the load-reduction effect of vertical earth pressure on culvert crown is the best after two layers of EPS with a thickness of 2 cm are laid on the culvert crown, but the increase of vertical earth pressure and horizontal earth pressure on the culvert side is also the most obvious.

3.3. Influence of Rigid Pipe and Flexible Pipe. The earth pressure on the crown of the pipe measured by earth pressure cell No. 8 in scheme 1 and schemes 7 to 11 is shown in Figure 12. Figure 13 shows the variation of load-reduction rate of the earth pressure with the EPS thickness of rigid pipe and flexible pipe.

Figure 12 shows that the pressure on the crown of the pipe increases nonlinearly with the increases of the filling height. When the filling height is 90 cm, the earth pressure on the crown in scheme 1 and schemes 7 to 11 is 35.18 kPa, 25.98 kPa, 23.56 kPa, 20.56 kPa, 14.55 kPa, and 11.84 kPa, respectively. It can be seen that the flexible pipe itself has a 26.15% load-reduction rate compared to the rigid pipe, and the EPS on the crown of the flexible pipe can also play the role of load reduction, and the effect increases with the increase of the thickness. When the thickness of the EPS is 3 cm, the measured earth pressure on pipe crown is less than the linear theoretical value, and the load-reduction rate is 58.64%; in this condition, the load-reduction effect is remarkable. When the thickness of laying EPS is 4 cm, the load-reduction rate reaches 66.34%; in this condition, the load-reduction effect is the greatest.

It can be seen from Figure 13 that when the thickness of EPS is in the range of 2 cm to 3 cm, the load-reduction effect

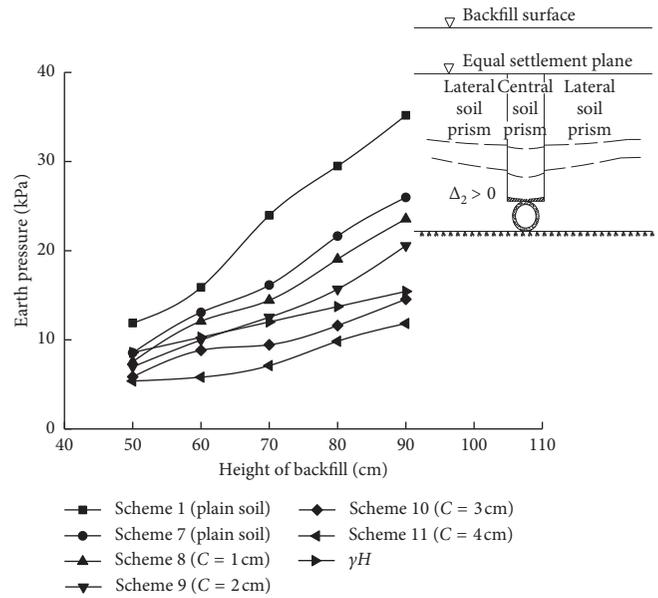


FIGURE 12: Crown earth pressure vs. the filling height.

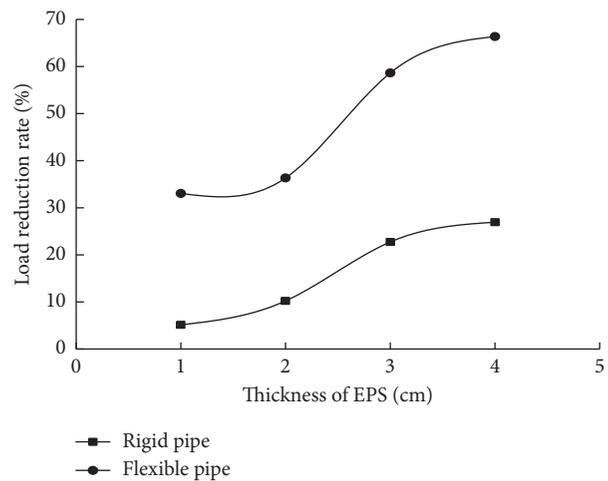


FIGURE 13: Crown earth pressure vs. filling height.

of flexible pipe and rigid pipe changes significantly. When the thickness of EPS is 3 cm to 4 cm, the effect of load reduction gradually becomes stable. For example, when the thickness of EPS is 4 cm, the load-reduction rate corresponding to rigid pipe and flexible pipe is 26.95% and 66.34%, respectively. The load-reduction rate of flexible pipe is 39.39% higher, so the load-reduction effect is more obvious.

The analysis shows that the flexible pipe has a certain deformation capacity, which can reduce the differential settlement between central and lateral soil prisms and the stress concentration on the crown of the pipe. Therefore, compared with rigid pipe, the deformation of flexible pipe contributes a certain load-reduction capacity. The settlement of the soil prism on crown of flexible pipe can be further increased through the compression deformation of EPS with different thickness. As shown in Figure 12, when the thickness of the EPS exceeds 3 cm, the differential settlement between the central and lateral soil prisms on the pipe crown is $\Delta_2 > 0$, and

the earth pressure on pipe crown is smaller than the weight of the overburden. On the other hand, EPS installed can not only increase the bearing capacity of flexible pipe, but also protect the pipe from stress concentration and excessive deformation.

The variation of earth pressure measured by the earth pressure cells of No. 6 to No. 10 with the filling height of 90 cm on the crown of the pipe is illustrated in Figure 14. Figure 15 shows the horizontal earth pressure on the side of pipe in schemes 1, 7, and 11 measured by No. 3 earth pressure cell.

Figure 14 shows the earth pressure at the central axis of the pipe crown decrease with the increase of the thickness of the EPS. The earth pressure measured by No. 7 earth pressure cell (10 cm from the axis) is 26.97 kPa, 27.52 kPa, 27.88 kPa, 28.79 kPa, and 29.54 kPa, respectively, which increase with the increase of the thickness of the EPS. Compared with those without EPS, when the thickness of EPS is 1 cm, 2 cm, 3 cm, and 4 cm, the vertical earth pressure on pipe side increases by 2.04%, 3.37%, 6.75%, and 9.23%, respectively, showing an increasing trend. And the vertical earth pressure at 10 cm away from the axis of the flexible pipe is greater than that of the vertical earth pressure at the pipe crown, which proves that the flexible pipe itself has a good load-reducing capacity.

As saw from Figure 15, when the filling height is 90 cm, the horizontal earth pressure at the pipe side in schemes 1 and 7–11 is 22.28 kPa, 26.21 kPa, 27.92 kPa, 29.24 kPa, 30.58 kPa, and 32.15 kPa, respectively. Compared with schemes 1, the pipe horizontal earth pressure of schemes 7–11 increased by 17.66%, 25.34%, 31.25%, 37.26%, and 44.29%, respectively. It can be seen that the horizontal earth pressure of flexible pipe is greater than that of rigid pipe, and the horizontal earth pressure of pipe increases with the increase of EPS thickness.

In conclusion, the variation of horizontal earth pressure on the side of flexible pipe is similar to that of the rigid pipe, which increases with the increase of filling height and load-reduction efficiency. From Figure 14, it can be seen that in the case of without load-reduction measures, the settlement of lateral soil prism is greater than that of central soil prism. After placing 4 cm thick EPS, the settlement of pipe crown fill is greater than that of pipe side fill (as shown in Figures 12 and 14). At this point, the friction on both sides of the sliding surface concentrates on the soil on both sides of the pipe, which causes the vertical earth pressure on the pipe side to be greater than that on the crown of the pipe and causes the horizontal earth pressure on the pipe to increase obviously. In summary, while the vertical earth pressure on the crown of the pipe reduces, the increase of horizontal earth pressure on the side of the pipe should not be neglected.

4. Calculation Method of Earth Pressure

4.1. Current Calculation Formulae of Earth Pressure on Pipe

(1) *Terzaghi's Underground Cavern Method (TUCM)* [29]. Terzaghi regards stratum rock mass as a loose body with certain cohesion. It is assumed that the rock mass at the crown of the cavern will gradually sink after excavation, which will cause stress transmission to form the pressure of

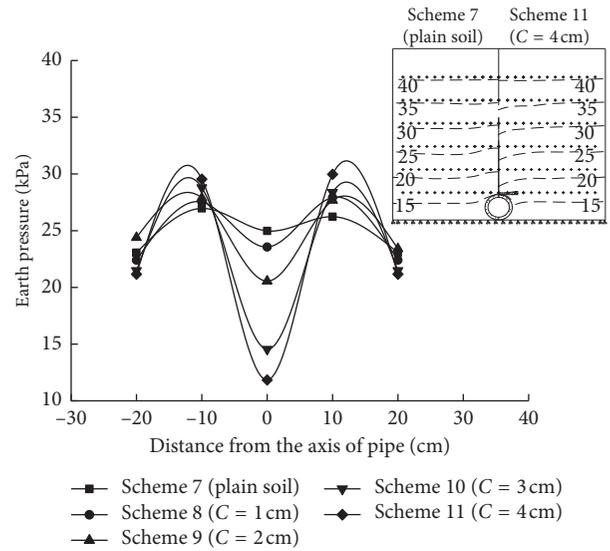


FIGURE 14: Distribution of vertical earth pressure above the pipe.

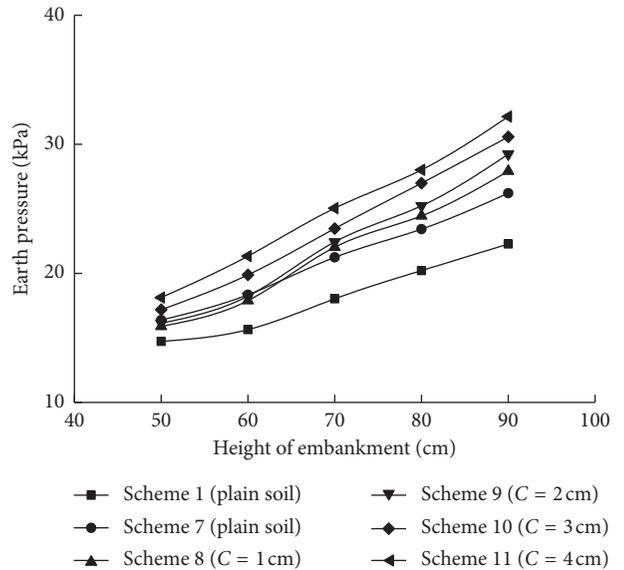


FIGURE 15: Pressure of No. 3 load cells with filling height.

the cavern. Based on the hypothesis of Terzaghi's underground cavern method, the earth pressure acting on the cavern is as follows:

$$\sigma_v = \frac{B_1 \gamma - c}{K \tan \varphi} \left(1 - e^{-((K \tan \varphi H)/B_1)} \right) + q e^{-((K \tan \varphi H)/B_1)}, \quad (1)$$

where K is the lateral pressure coefficient; φ is the internal friction angle of soil; c is the cohesion of soil; γ is the unit weight of soil; H is the overlying soil thickness on crown of pipe; q is the upper load on backfill; and B_1 is the width of the loose zone.

(2) *Marston's Earth Pressure Method (MEPM)* [30]. Marston's earth pressure method is based on the limit equilibrium method of bulk materials. Because of the uneven settlement of surrounding fill caused by the existence of pipe,

the earth pressure concentrates on the crown of pipe. The settlement of the soil layer on the crown plane of pipe is the largest; the pipe crown gradually decreases upward, and it decreases to zero at a certain height H_e of the filling on the crown of pipe. That is to say, a plane of equal settlement is formed. The calculation formula based on the plane of equal settlement is as follows.

When $H < H_e$,

$$\sigma_v = \frac{\gamma D}{2fk} [e^{2fkH/D} - 1]. \quad (2)$$

When $H > H_e$,

$$\sigma_v = \frac{\gamma D}{2fk} [e^{2fkH/D} - 1] + \gamma(H - H_e)e^{2fkH_e/D}, \quad (3)$$

where D is pipe diameter; γ is the unit weight of soil; H is the overlying soil thickness on the crown of pipe; H_e is equal level height; $f = \tan \varphi$; and k is active earth pressure coefficient, $k = \tan 2(45^\circ - \varphi/2)$.

(3) *Gu Anquan Formula (GAF)* [31]. Gu Anquan regards pipe as strip foundation and filling as infinite elastic solid and assumes that the stress distribution in pipe crown filling is similar to that in semi-infinite homogeneous linear deformation body. By calculating the additional earth pressure on the pipe crown by the settlement difference, the formula of calculating the vertical earth pressure on the pipe crown is obtained as follows:

$$\sigma_v = \gamma H \left[1 + \frac{(1 + h/2H)hE}{\omega_c B(1 - \mu^2)E_h} \eta \right], \quad (4)$$

where h is the height of pipe protruding ground; E_h is the deformation modulus of the backfill in height of h on both sides of the pipe; μ is Poisson's ratio on the crown of the pipe; ω_c is a coefficient related to the ratio of the length to width of a rigid pipe; and η is the shape influence coefficient of pipe cross section.

(4) *China General Code for Design of Highway Bridges and Culverts (CGCDHBC)* [32]. The earth pressure on pipe crown is calculated by soil column method, and the formula is as follows:

$$\sigma_v = \gamma H. \quad (5)$$

(5) *China Fundamental Code for Design on Railway Bridges and Culverts (CFCDRBC)* [33]. The earth pressure on pipe crown is calculated by concentrated coefficient method, and the formula is as follows:

$$\sigma_v = k\gamma H, \quad (6)$$

where k is determined by looking up the table according to H/D .

(6) *AASHTO Standard Specifications for Highway Bridges (AASHTO)* [34]. AASHTO points out that the effect of soil-structure interaction depends on the type of pipe and the compactness of the fills on both sides. For the positive-

buried pipe, the formula for calculating the earth pressure on the pipe crown is as follows:

$$\begin{aligned} \sigma_v &= F_e \gamma H, \\ F_e &= 1 + 0.2 \frac{H}{B_c}, \end{aligned} \quad (7)$$

where B_c is the outer diameter of the pipe and F_e is the interaction coefficient between soil and structure of buried pipe.

4.2. *Nonlinear Regression Analysis.* According to the model tests results, the pressure on the crown of the pipe presents a nonlinear change with the increase of the filling height, which is caused by the load transition inside the backfill on the crown of the pipe. Considering the influence of load transition on pipe, the following nonlinear earth pressure calculation formula of pipe is proposed, and the undetermined coefficients in the formula are determined by the nonlinear regression analysis of the data measured by model tests [35]:

$$\sigma_v = \xi \gamma H^n, \quad (8)$$

where ξ and n are regression coefficients; γ is the weight of soil; and H is overlying soil thickness on the pipe. Using the data collected from the test, the nonlinear earth pressure calculation formula of the pipe is obtained as follows.

According to the tested results of scheme 1, the formula of regression earth pressure is

$$\sigma_{v1} = 2.669\gamma H^{1.9613} (H \leq 0.9 \text{ m}, R^2 = 0.9890). \quad (9)$$

According to the tested results of scheme 1 to scheme 5, the formula of regression earth pressure of rigid pipe is

$$\sigma_{v2} = k_1 \gamma H^{k_2} (H \leq 0.9 \text{ m}, R^2 = 0.9151), \quad (10)$$

where k_1 and k_2 are coefficients related to the thickness of EPS, whose values can be approximated to $k_1 = -405.14t^2 - 3.8303t + 2.6258$, $k_2 = -311.93t^2 + 14.206t + 1.9125$, t is the thickness of EPS.

According to the tested results of scheme 7 to scheme 11, the formula of regression earth pressure on flexible pipe is

$$\sigma_{v3} = k_3 \gamma H^{k_4} (H \leq 0.9 \text{ m}, R^2 = 0.8799), \quad (11)$$

where $k_5 = -140.17t^2 - 24.307t + 1.9210$ and $k_6 = -226.79t^2 - 4.5176t + 1.9009$.

The correlation index is as follows:

$$R^2 = \frac{\sum_{i=1}^n (\sigma_i - \bar{\sigma}_i)^2 - \sum_{i=1}^n (\sigma_i - \hat{\sigma}_i)^2}{\sum_{i=1}^n (\sigma_i - \bar{\sigma}_i)^2}. \quad (12)$$

4.3. *Comparison of Theoretical Calculation Results and Test Results.* Figure 16 shows the comparison between the measured data of the model tests and the calculation results of the above seven earth pressure calculations.

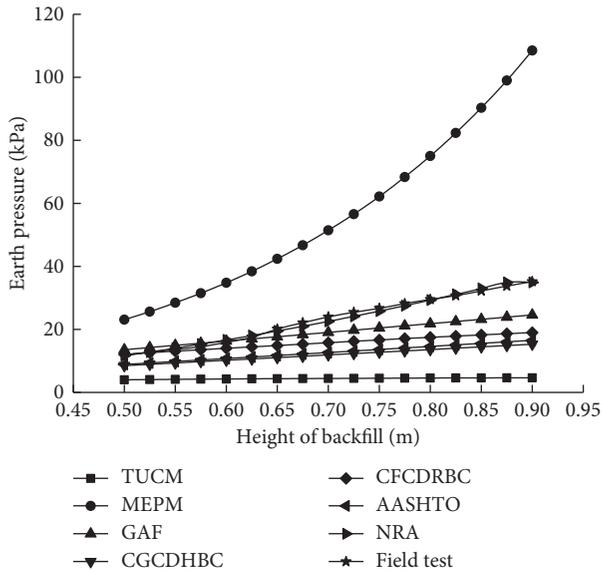


FIGURE 16: Comparison of earth pressure on crown of the pipe.

According to the comparison, when the backfill on a buried pipe reaches a certain height, the earth pressure on the crown of the pipe is obviously less than the measured earth pressure, which is calculated by Terzaghi's method, Gu Anquan formula, and CGCDHBC and CFCDRBC methods. Among them, Terzaghi's underground cavern theory underestimated the pressure and coefficient as compared with the field data. When the filling reaches a certain height, the pressure will no longer be transmitted downward, and the calculated earth pressure is minimal. Gu Anquan formula is based on the elastic theory, assuming that the pipe is a bar foundation, and the earth pressure is calculated by the settlement of the fill, but the calculation results are only closer to the measured value only when the height of the fill is large. The experience coefficient method is adopted in the CFCDRBC methods in China and the AASHTO methods in the United States. But the pressure of the pipe crown soil is obviously less than the measured earth pressure value calculated by the CFCDRBC methods, it is unsafe. And the pressure of the pipe crown soil of the AASHTO methods will increase with the height of the fill, it is not economic. Marston's formula needs to take into account the problem of the plane of equal settlement, and when the filling height is greater than that of it, the pressure on the crown of the pipe will be much larger than the measured value as the filling height increases. Here in, the nonlinear earth pressure calculation formula obtained by regression analysis of the test data are closest to the measured values of the earth pressure on the crown of pipe, which can better reflect the change process of the pressure of the crown of the pipe.

5. Conclusions

In this paper, model tests and theoretical analysis were employed to study the earth pressure on rigid pipe and flexible pipe underneath EPS, and the following conclusions can be drawn:

- (1) The instrument of EPS on the crown of the pipe can play a significant role in reducing load, and with the increase of the thickness of EPS, the efficiency of load reduction firstly increases and then tends to be constant. The load-reduction effect of two layers EPS on the crown of the pipe is better than that of single-layer EPS with the same total thickness.
- (2) Compared with rigid pipe, flexible pipes themselves play a role in reducing load, so when the filling height is low, the use of flexible pipe can play a valuable role in load reduction. When the height of the fill is high, placing the EPS on the flexible pipe can reduce the pressure on the crown of the pipe and increase the bearing capacity of the pipe effectively, therefore guarantee the safety of the flexible pipe in practical engineering.
- (3) The settlement difference between central and lateral soil prisms can be reduced by laying flexible filler on the crown of the pipe or replacing the flexible pipe, so that the concentrated stress on the crown of the pipe can be transferred to the adjacent soil mass, and the vertical earth pressure on the side of the pipe can be increased, and the horizontal earth pressure on the pipe can also be increased. Therefore, while considering the load reduction of the vertical soil pressure on the crown of the pipe, the effect on the horizontal soil pressure of the pipe cannot be ignored.
- (4) According to the model tests data, the nonlinear earth pressure formula is fitted by regression analysis and compared with the contemporary earth pressure calculation formulae of pipe. It is indicated that the calculation formula of nonlinear earth pressure is closer to the measured value.

Finally, the formula for calculating the nonlinear earth pressure proposed in this paper is simple in form and highly correlated with engineering practice. And it has an important reference value for calculating the earth pressure of pipe under different conditions. In addition, Chen et al. [35] also used a similar nonlinear earth pressure regression equation, and the results validated the feasibility of the method. At the same time, the nonlinear earth pressure calculation formula proposed in this paper also has some limitations. Just as the formula does not support the calculation of earth pressure under different stiffness of pipes for the time being, the regression equation related to the stiffness of pipes can be obtained through the new working condition, which reflects the flexibility and applicability of the formula.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request, and the readers can access the data supporting the conclusions of the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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