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Research Article

Influence of Lightweight Foamed Concrete as Backfill Material on Stress and Deformation of Buttressed Earth-Retaining Wall

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Controlling settlement and earth pressure behind retaining wall in soft soil area are ongoing practical problems for the construction and operation of highway, which are mainly caused by the poor nature of soft soil. To reduce the pushing force on retaining wall and subgrade settlement, the authors propose the use of lightweight foamed concrete as subgrade filler behind the buttressed earth-retaining wall. However, the mechanical properties and deformation behavior of the buttressed earth-retaining wall remain unknown when lightweight foamed concrete is used as a backfill behind the wall. To solve this problem, a scale model of the subgrade filled with lightweight foamed concrete behind the buttressed earth-retaining wall is established to determine its stress and deformation characteristics under different factors. Lateral earth pressures and wall displacements at different elevations of the retaining wall model were monitored during the tests. Then, a series of orthogonal experiments are conducted to analyse and compare the effects of overload, density, and replacement thickness of lightweight foamed concrete on the earth pressure and displacement of this retaining wall. The results show that the size of earth pressures at the same position of retaining wall is affected by overload, density, and replacement thickness of lightweight foamed concrete, but its change of distribution form is only related to the replacement thickness of this backfill. Additionally, the primary-secondary relations of different factors' influence extent on the forces and deformation of the buttressed earth-retaining wall filled with lightweight foamed concrete as backfill are obtained by using range analysis method.

1. Introduction

With the new construction concept of "green, environmental protection and energy saving" actively advocated both at home and abroad in recent years, a large number of new materials and innovative technologies for infrastructure construction have been developed and applied in the practical engineering [1–3]. As a new type of lightweight material, lightweight foamed concrete has been widely valued and studied by many scholars and experts at home and abroad due to its advantages such as light weight, uprightness, high fluidity, good durability, convenient construction, and thermal insulation [4–9]. Besides, it has been gradually applied in various fields of civil engineering and achieved good engineering results, which has been vigorously promoted by the industry and widely recognized by the society [10–14]. Thus, the authors propose the use of lightweight foamed concrete as a filler behind the buttressed earth-retaining wall in Guangzhou-Foshan-Jiangmen Freeway of Guangdong province in China, which provides a new method to control subgrade settlement and reduce the pushing force on retaining wall (as shown in Figure 1).

Regarding the research on replacement technology of cast in situ lightweight foamed concrete, its constitution, physical properties, and engineering applications have been studied by Valore [15, 16], Rudnai [17], Taylor [18], and Short and Kinniburgh [19]. As foam concrete developed further, a series of experimental studies on modification of lightweight foamed concrete were carried out by adding different admixtures. For example, Jones and McCarthy

Figure 1: Use of lightweight foamed concrete as a filler behind buttressed earth-retaining wall.

[20] and Kearsley and Wainwright [21] suggested that using unprocessed, run-of-station, low-lime fly ash can significantly improve the performance of foamed lightweight concrete. Chandni and Anand [22] studied the effect of superplasticizer inclusion and the corresponding change in the water to solid ratio on compressive strength of foam concrete, and incorporation of PCE-based superplasticizer was observed to be effective in enhancing the strength of foam concrete. Wang et al. [23] found that the small amount (3 wt%) of crumb rubber can improve the waterproof performance of foamed concrete. Besides, as for the research on durability and microscopic properties of lightweight foamed concrete, Chung et al. [24] investigated the characteristics and properties of lightweight aggregate concrete and foamed concrete with the same density levels by using image analysis method; Kashani et al. [25] revealed the effect of recycled glass fines on mechanical and durability properties of concrete foam in comparison with traditional cementitious fines; Su et al. [26] analyzed the mechanical behavior of foamed concrete by a series of uniaxial and triaxial experiments; results indicated that foamed concrete demonstrates brittle failure under a uniaxial tension and small compression deformation for uniaxial loading. According to the above references, although a large number of experimental studies on lightweight foamed concrete have been carried out at home and abroad, it is mainly limited to experimental research on its physical and mechanical properties. There are few researches on the use of lightweight foamed concrete as a backfill behind the buttressed earth-retaining wall, and its force and deformation characteristics are still unclear, which need to be further studied.

On the other hand, relevant researches [27–29] show that factors affecting earth pressures and wall displacements of the retaining wall are as follows: overload, shape of retaining wall, the nature of the filled soil, and filled soil height. Taking into account the limitations of laboratory test conditions, three main influencing factors are considered in this paper, including overload, density of lightweight foamed concrete, and replacement depth of lightweight foamed concrete.

The overall objective of this study is to determine and compare the stress and deformation characteristics of buttressed earth-retaining wall backfilled with lightweight foamed concrete under different factors through the indoor model test. In addition, results of the model test can determine the primary and secondary relations of three factors' influence extent on the forces and deformation of this retaining wall through the range analysis, and the most suitable replacement thickness of lightweight foamed concrete behind buttressed earth-retaining wall can be also obtained by regression analysis, which can provide a reference in the practical engineering.

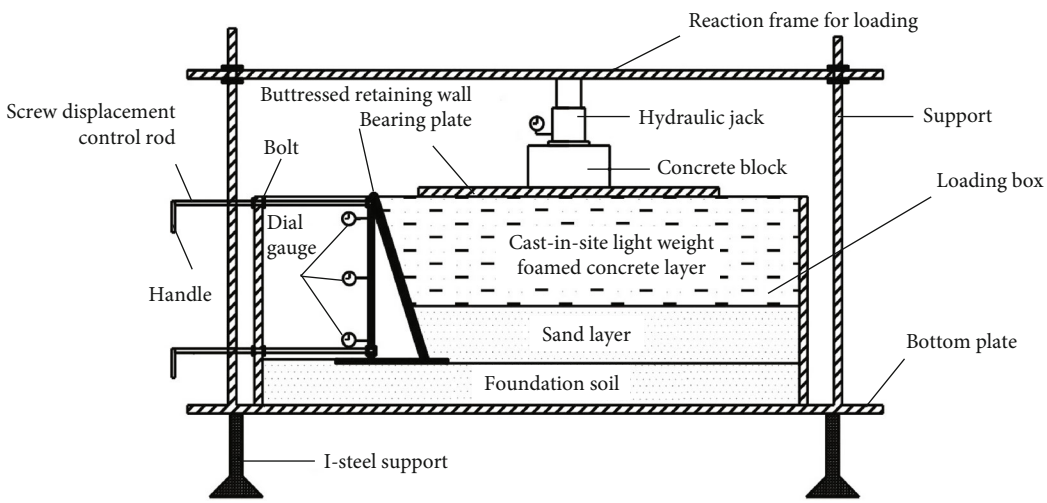
2. Experimental Procedure

2.1. Experimental Model Setup. In this paper, referring to the field structure size of Guangzhou-Foshan-Jiangmen Freeway of Guangdong province in China, a self-developed model box is used to carry out the model experiment with the reduced-scale of 25 : 1 (actual size : model size). The model box is mainly composed of the following parts: a loading box (backfill layer), a retaining wall, displacement control system of retaining wall, upper loading system, and measurement system (as shown in Figure 2).

2.1.1. Buttressed Earth-Retaining Wall and Backfill Layer. Taking the size of the on-site buttressed earth-retaining wall structure as a reference prototype, the size of buttressed earth-retaining wall in model is designed with reduced-scale of 25 : 1 (actual size : model size) (as shown in Figure 3). Besides, the design sizes of the model box and the loading box are 150 cm × 50 cm × 40 cm (length × width × height) and 100 cm × 50 cm × 40 cm (length × width × height), respectively. In the loading box, the cast in situ lightweight foamed concrete layer and sand layer are presented as packing layers from top to bottom. The thicknesses of two packing layers behind the retaining wall can be adjusted according to the test requirements.

2.1.2. Sensors Distribution. In order to reveal the stress and deformation characteristics of buttressed earth-retaining wall backfilled with lightweight foamed concrete under different conditions, 17 earth pressure cells and 3 dial indicators were buried at different elevations of the retaining wall model to, respectively, monitor the lateral earth pressures and wall displacements during the tests.

LY-350 series strain type miniature earth pressure sensors were selected to measure lateral earth pressures of this retaining wall in the tests. Among them, 3 earth pressure cells were arranged at the bottom plate, numbered 1 through 3, and the distances from the edge of the wall toe plate are 4, 13, and 22 cm in order; 4 earth pressure cells were buried on the inside of vertical wall, numbered 4 through 7, and distances from the top of the wall are 5, 14, 23, and 32 cm in order; 5 earth pressure cells were arranged on the left side of the soil facing surface of buttress; its stress surface is vertical to the horizontal surface, numbered 8 through 12, and distances from the top of the wall are 6, 13, 20, 27, and 34 cm in order; 5 earth pressure cells were buried on the right side of the buttress sidewall, numbered 13 through 17, and distances from the top of the wall are 6, 13, 20, 27, and 34 cm, respectively. The detailed buried positions of the earth pressure cells are shown in Figure 4.



(a) Schematic diagram of the model box

(b) Real image of the model box

Figure 2: The test model box.

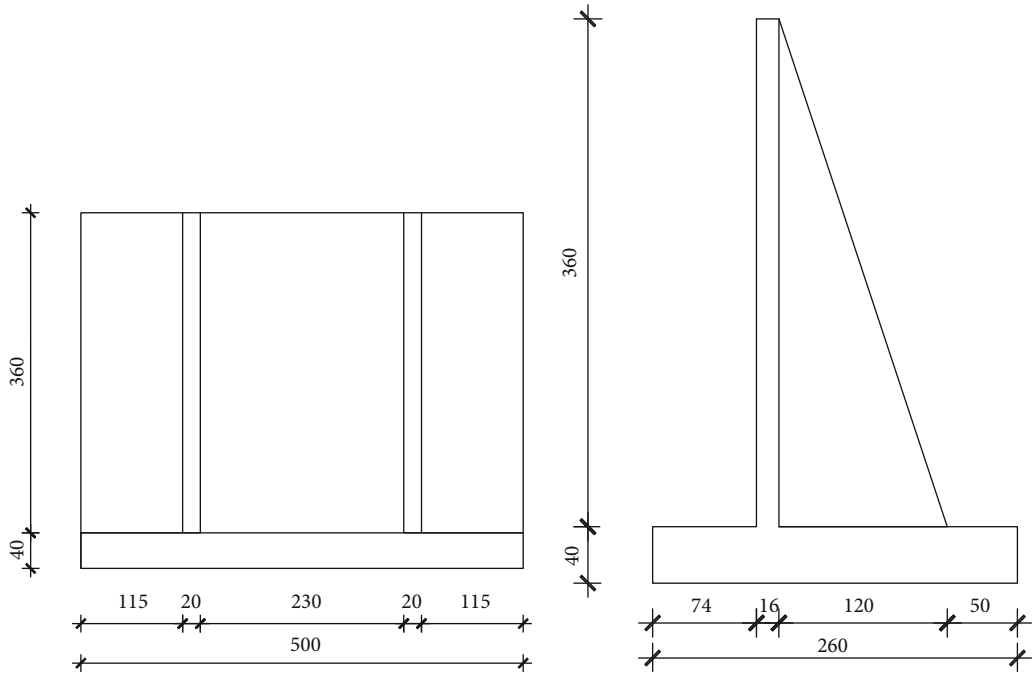
In addition, 3 dial indicators were selected to measure displacements of the retaining wall in model tests, which were, respectively, arranged at the positions of 2, 16, and 32 cm from the top of the wall (as shown in Figure 5).

2.1.3. Loading System and Data Acquisition System. The upper loading system in the model is mainly composed of reaction beam, a hydraulic jack, concrete block, steel load bearing plate, and support rod. In the tests, the hydraulic jack with precision pressure gauge was selected, which can directly apply the required load and make up pressure at any time. Furthermore, the load exerted by the jack can be evenly transmitted to packing layers because of the load bearing plate with sufficient rigidity. The experimental model is loaded by using the stage loading method, which is divided into three stages. The deformation of the retaining wall can be considered to be stable when the loading interval time of each stage is 1 h, and the readings of dial indicators and earth pressure cells corresponding to the level of load shall be recorded.

Based on the above loading system and sensor distribution, the dynamic data are gathered by a dynamic acquisition system during the loading process. The CM-1A-20 digital static strain gauge produced by Qinhuangdao Xinheng Electronic Technology Co., Ltd. was used as the collection device in the test. The connection of the earth pressure cells adopts the full bridge mode, and the measurement data collection is controlled by the computer (as shown in Figure 6).

2.2. Model Test Scheme. According to the above experimental model, limited by laboratory test conditions, the effects of three factors, including surface load, density of lightweight foamed concrete, and replacement thickness of lightweight foamed concrete, on the stress and deformation of buttressed earth-retaining wall backfilled with lightweight foamed concrete are considered in this paper.

With the support of Guangzhou-Foshan-Jiangmen Freeway, under vehicle loads, the uniform load at the top surface of lightweight foamed concrete subgrade is about 60.8 kPa according to local traffic volume and numerical calculations.



(a) Plane graph (b) Sectional drawing

Figure 3: Size of buttressed earth-retaining wall (unit: mm).

(a) Bottom plate (b) Inside of vertical wall (c) Soil facing surface of the buttress (d) Sidewall of the buttress

Figure 4: The distribution of earth pressure cells.

Figure 5: The distribution of dial indicators.

Figure 6: Data acquisition system.

In consideration of the three-stage loading method used in the model test, the overloads (concentrated load) of 14, 16, and 18 MPa at the top surface of lightweight foamed concrete layer behind the retaining wall are applied by controlling the loading system for interval 1 h, respectively. In fact, these overloads can be converted to the uniform loads of 61, 69.484 and 77.969 kPa by numerical calculations, which are consistent with the actual engineering.

Table 1: The single-factor orthogonal test scheme.

Test number	Overload (MPa)	Density of lightweight foamed concrete (kg/m^3)	Replacement thickness of lightweight foamed concrete (m)	Single factor
1-1	14	700	0.28	Overload
1-2	16	700	0.28	
1-3	18	700	0.28	
1-4	14	600	0.28	Density of lightweight foamed concrete
1-5	14	700	0.28	
1-6	14	800	0.28	
1-7	14	700	0.22	Replacement thickness of lightweight foamed concrete
1-8	14	700	0.28	
1-9	14	700	0.40	

Table 2: The multiple-factor orthogonal test scheme.

Test number	Overload (MPa)	Density of lightweight foamed concrete (kg/m^3)	Replacement thickness of lightweight foamed concrete (m)
2-1	14	600	0.22
2-2	14	700	0.28
2-3	14	800	0.40
2-4	16	600	0.28
2-5	16	700	0.40
2-6	16	800	0.22
2-7	18	600	0.40
2-8	18	700	0.22
2-9	18	800	0.28

As for the selection of density of lightweight foamed concrete in tests, the foamed lightweight concrete paste with density of 600, 700, and 800 kg/m^3 are used to cast the lightweight foamed concrete layer referring to the cast-in-place lightweight foamed concrete density of 700 kg/m^3 in actual engineering. In addition, according to the height of the buttressed retaining wall model, the replacement thicknesses of lightweight foamed concrete layer of 0.22, 0.28, and 0.40 m are selected to carry out the tests, and the corresponding thicknesses of the sand layer are 0.18, 0.12, and 0 m.

In order to more accurately reveal the force and deformation characteristics of the buttressed earth-retaining wall backfilled with lightweight foamed concrete, the influence laws of the changing single factor on the resultant earth pressure and the point of resultant force of retaining wall were studied first by means of single-factor orthogonal test. And then, using range analysis method, the primary and secondary relations of the influence extent of each factor on the forces and deformation of this retaining wall were analyzed by the multiple-factor orthogonal test.

The single-factor orthogonal test scheme is shown in Table 1, and the multiple-factor orthogonal test scheme is shown in Table 2.

2.3. Materials, Mixture Proportion, and Properties. As a new type of artificial lightweight cement material, lightweight foamed concrete is firstly prepared by the physical method from the foaming agent into the foam, then the foam is mixed into the cement slurry which has been stirred evenly in a certain proportion, and finally, hardened by physical and mechanical effects. The preparation process of lightweight foamed concrete is shown in Figure 7.

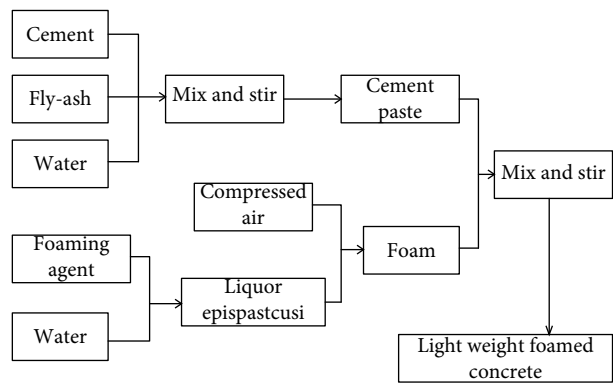


Figure 7: Preparation process of lightweight foamed concrete.

In this paper, lightweight foamed concrete is produced under a controlled percentage of OPC (42.5), water, and foaming agent without adding aggregate or modifiers. On the basis of the Chinese *Technical Specification for Design and Construction of Cast-In-Situ Lightweight Foamed Concrete Subgrade* (*TJG F10 01-2011*) [30] and results of previous tests [31, 32], the most suitable water/solid ratio of lightweight foamed concrete under this condition is 1 : 2.0 by comparison of performances; the mix proportions of lightweight foamed concrete with target densities of 600, 700, and 800 kg/m^3 are shown in Table 3. According to the Chinese *Technical Specification for Design and Construction of Cast-In-Situ Lightweight Foamed Concrete Subgrade* (*TJG F10 01-2011*) [30] and the Chinese *Test Methods of Soils for Highway Engineering* (*JTG E40-2020*) [33], the main performance indexes of lightweight foamed concrete and sand are measured in Tables 4 and 5, respectively.

As can be seen from the results in Table 4, with the increase of the target density of lightweight foamed concrete, the moist unit weight, compressive strength, flexural strength, and CBR of lightweight foamed concrete increase gradually, but its flow value and water absorption rate

Table 3: The mix proportions of lightweight foamed concrete.

Water/solid ratio	Density of lightweight foamed concrete (kg/m^3)	Density of cement (kg/m^3)	Density of foam (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)
1 : 2.0	600	3069	40.27	381.6	190.8	27.6
1 : 2.0	700	3069	40.27	449.8	224.9	25.3
1 : 2.0	800	3069	40.27	518.0	259.0	23.0

Table 4: The performance indexes of lightweight foamed concrete.

Density of lightweight foamed concrete (kg/m^3)	Flow value (mm)	Moist unit weight (kN/m^3)	Compressive strength (28 days) (MPa)	Flexural strength (28 days) (MPa)	Water absorption (%)	CBR (%)
600	186	5.08	0.99	0.34	23.5	12.5
700	178	5.74	1.45	0.47	21.7	15.6
800	170	6.48	1.86	0.63	20.1	18.9

Table 5: The performance indexes of sand.

Density (kg/m^3)	Moisture content (%)	Nonuniform coefficient	Curvature coefficient	Elasticity modulus (MPa)	Poisson ratio	Cohesion (kPa)	Internal friction angle (°)
1613	1.12	5.33	1.28	15.0	0.35	0	35.8

decrease gradually. According to the *Technical Specification for Design and Construction of Cast-In-Place Lightweight Foamed Concrete Subgrade* (*TJG F10 01-2011*) [30], the main performance indexes of lightweight foamed concrete in Table 4 meet the relevant requirements, which indicates that lightweight foamed concrete can be used as filler for the model.

In addition, results in Table 5 reveal that the nonuniform coefficient of sand is greater than 5 and that its curvature coefficient is between 1 and 3. This indicates that sand is well graded and can therefore be used as filler for the model.

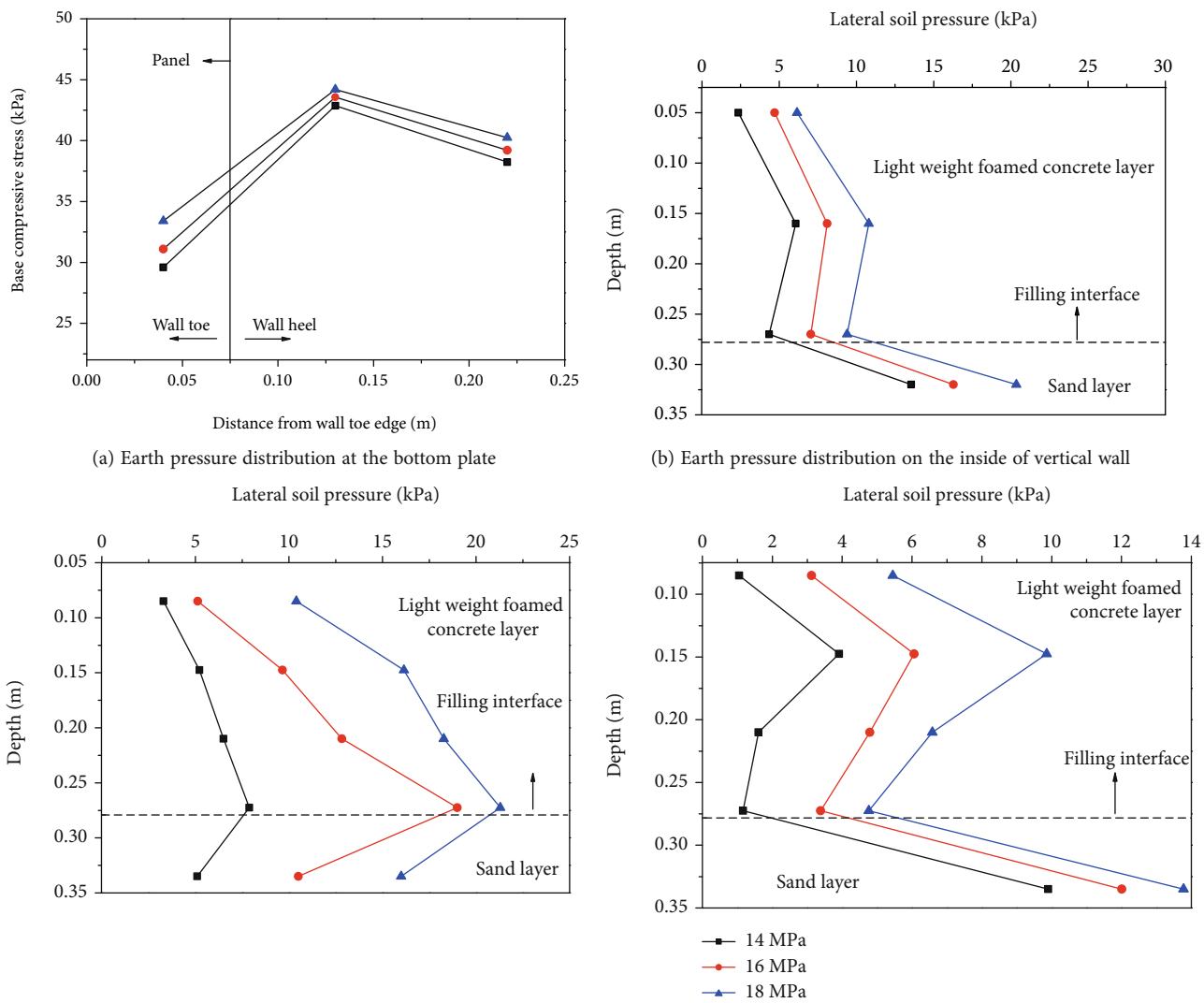
3. Results and Discussion

3.1. Results of the Single-Factor Orthogonal Test. Firstly, based on the single-factor orthogonal test scheme in Table 1, the effects of overload, density of lightweight foamed concrete, and replacement thicknesses of lightweight foamed concrete on the stress and deformation characteristics of buttressed earth-retaining wall backfilled with lightweight foamed concrete are analyzed and discussed, respectively, in this section of the paper.

3.1.1. Effects of Overload. According to the orthogonal test scheme in Table 1, the overloads of 14, 16, and 18 MPa were applied to the surface of backfill in order by using a jack on the premise of keeping the density and the replacement depth of lightweight foamed concrete unchanged.

The effects of different overload on the lateral earth pressures and wall displacements at different elevations of the retaining wall model filled with lightweight foamed concrete are presented in Figure 8, which shows that the overload has a great influence on the earth pressure of retaining wall filled with lightweight foamed concrete; the earth pressure at the same position increases with the increase of the overload, but it does not change the distribution laws of earth pressure at the same position of retaining wall. This effect is due to the larger of overload on the surface of the lightweight foamed concrete, the greater of compression force between the backfill and the retaining wall, which is reflected in the greater earth pressure of the retaining wall.

Compared with the size and distribution shape of earth pressure at different positions of the retaining wall in Figure 8, it can be seen that under the same overload, the size and distribution shape of earth pressure vary with the different positions of the retaining wall. As for the distribution shape of earth pressure under the same overload, the base compressive stress is not distributed in the triangle or trapezoid, but in a convex shape of "large in the middle and small on both sides", which indicates that there is a peak point of base compressive stress in the middle of the bottom plate. However, the earth pressure presents an "R" distribution shape along the height of the wall both on the inside of vertical wall and sidewall of the buttress. That is, the earth pressure increases first and then decreases along the lightweight foamed concrete layer depth, but the earth pressure suddenly increases along sand layer depth, showing a linear growth, which may be caused by the too large difference between the gravity of two filling layers. In the calculation of earth pressure, the gravity of filler is an important factor affecting the size of earth pressure, and the earth pressure increases with the increase of the gravity of fill. The density of sand is about 2.5 times as severe as that of lightweight foamed concrete, so the earth pressure in this two filling



(a) Earth pressure distribution at the bottom plate

(b) Earth pressure distribution on the inside of vertical wall

(c) Earth pressure distribution on the soil facing surface of the buttress

(d) Earth pressure distribution on sidewall of the buttress

Figure 8: Earth pressure distributions of retaining wall under different overloads.

layers presents an "R" distribution as a whole. Furthermore, the earth pressure on the soil facing surface of the buttress presents a "D" distribution shape along the height of the wall, that is, the earth pressure increases gradually with the increase of wall depth and reaches the maximum value at the junction of two filling layers, but the earth pressure in sand layer decreases rapidly, which may be due to the tensile stress at the root of buttress.

On the other hand, the magnitudes of lateral earth pressures vary with positions of retaining wall under the same overload. Taking the overload of 14 MPa as an example, it can be seen from Figure 8 that the maximum earth pressure on the inside of vertical wall and the soil facing surface of the buttress are 6.10 and 7.88 kPa, respectively, while the earth pressures on sidewall of the buttress are obviously smaller, with the maximum value of 3.95 kPa. The reason is that the sidewall of the buttress is not smooth, which leads to the soil arch effect between two buttresses in the horizontal direction. Due to the existence of these soil arches, most of the lateral earth pressures behind the wall are transmitted to the buttresses, which causes the earth pressure on the buttresses greater than that on sidewall of the buttress, reducing the lateral pressure on the retaining wall panels.

Figure 9 shows the displacement changes of retaining wall backfilled with lightweight foamed concrete along the height of the wall under different overload, "-" in Figure 9 indicates that the retaining wall moves away from the filling direction, and "-" in the following text is the same meaning, so it is not described in the following text.

As seen from Figure 9, the wall displacements at the same depth increases gradually in the process of continuous loading, and the increase of the displacement at the top of the wall is larger than that at the bottom of the wall, which shows that the overload has a greater impact on the displacement at the top of the wall. From the results shown in Figure 9, the displacement change laws of the retaining wall are basically similar under different overload conditions, that is, the horizontal displacement of the retaining wall

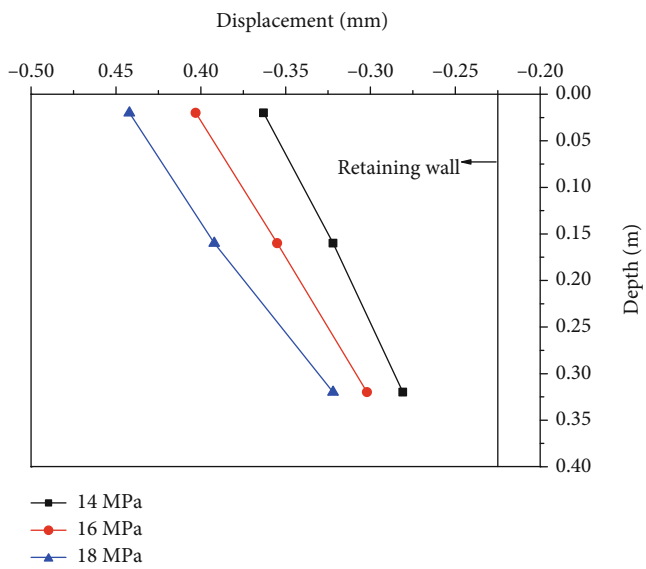


Figure 9: Displacement changes of retaining wall under different overloads.

decreases linearly with the increase of the retaining wall depth. The horizontal displacement at the top of the wall is larger than that at the bottom, which illustrates that the retaining wall not only rotates around the bottom of the wall but also moves away from the soil behind the wall. Therefore, it indicates that the displacement mode of the retaining wall backfilled with lightweight foamed concrete is an "RBT" mode in the actual project.

3.1.2. Effects of the Density of Lightweight Foamed Concrete. In this study, lightweight foamed concrete with the target density of 600, 700, and 800 kg/m^3 is used as the backfill behind the buttressed earth-retaining wall. Under the condition of overload and lightweight foamed concrete replacement thickness unchanged, the test results for earth pressure distribution law of retaining wall under different densities of lightweight foamed concrete are shown in Figure 10.

Compared with the test results in Figures 8 and 10, it can be seen that there are no significant differences in the distribution shapes of earth pressure at different positions of the retaining wall under the effect of overload or the density of lightweight foamed concrete. In other words, similar to the distribution shapes of earth pressure in Figure 8, Figure 10 shows that the base compressive stress is still distributed in a convex shape of "large in the middle and small on both sides", and the earth pressure on the soil facing surface of the buttress still presents a "D" shape distribution along the height of the wall, and the earth pressure still presents an "R" distribution along the height of the wall both on the inside of vertical wall and sidewall of the buttress.

However, by contrasting the maximum values of lateral earth pressure at each location of retaining wall in Figures 8 and 10, it can be found that two factors have different effects on the magnitude of lateral earth pressure of retaining wall backfilled with lightweight foamed concrete. Obviously, the magnitudes of lateral earth pressure at the same location under the effect of overload are greater than that under the effect of lightweight foamed concrete density. Therefore, it can be concluded that overload has a greater effect on the force performance of the retaining wall backfilled with lightweight foamed concrete, compared to the effect of density of lightweight foamed concrete.

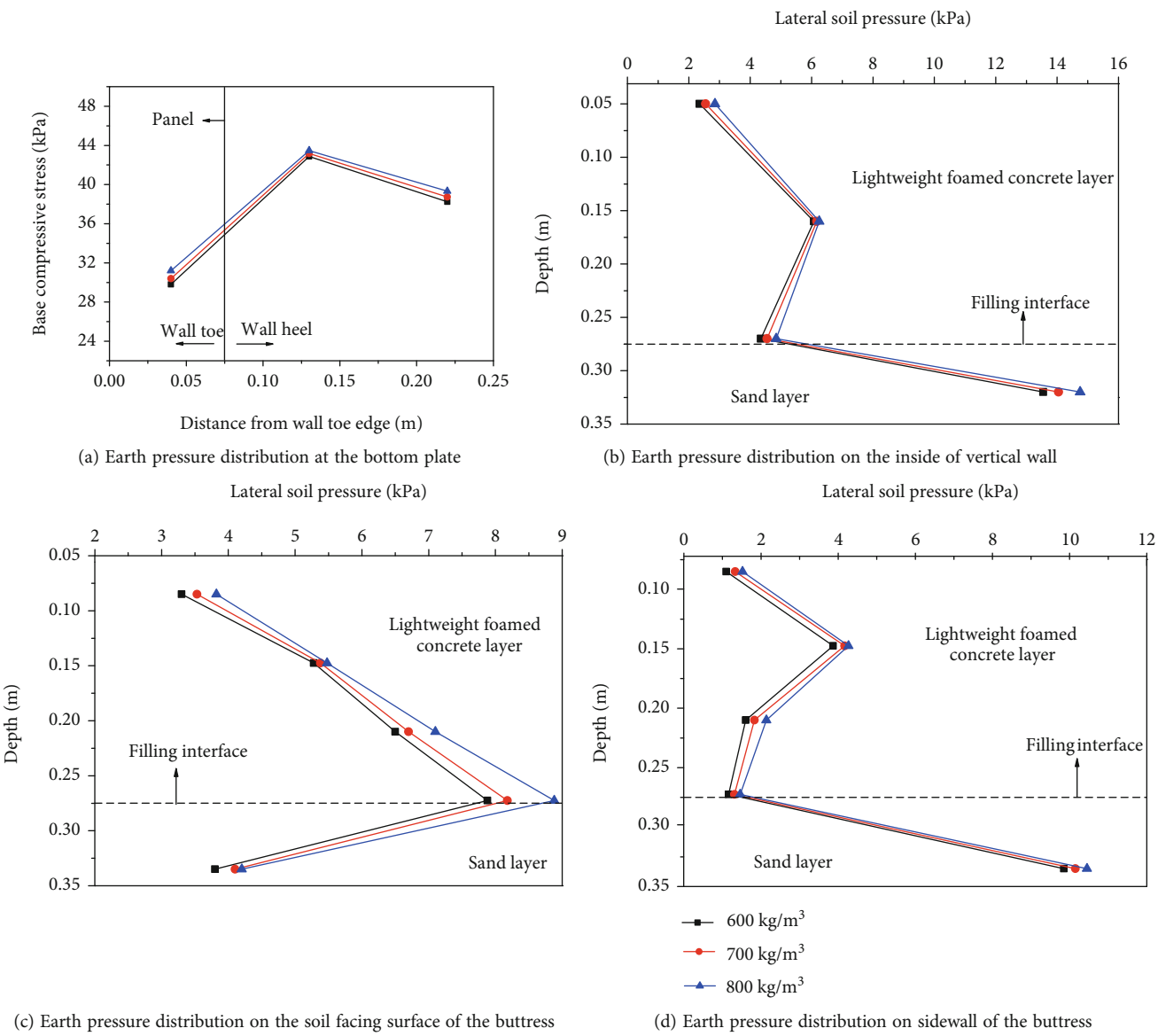
Furthermore, the results in Figure 10 show that the earth pressure at the same position increases with the increase of the density of lightweight foamed concrete, but it does not change the distribution laws of earth pressure at the same position of retaining wall, which is similar to the effects of overload. Therefore, it can be concluded that both of two factors can only change the magnitude of the earth pressure of this retaining wall, but cannot change its distribution shapes.

The displacement changes of retaining wall backfilled with lightweight foamed concrete along the height of the wall under different densities of lightweight foamed concrete are shown in Figure 11.

As shown in Figures 9 and 11, the displacement of this retaining wall is less affected by the density of the lightweight foamed concrete compared to the effect of overload, but the horizontal displacement change laws of the retaining wall caused by these two factors are similar. Under the condition that the density of lightweight foamed concrete remains the same, the displacement of the retaining wall decreases linearly with the increase of the filling depth. However, as the density of lightweight foamed concrete increases, the displacement of wall at the same depth would increase slightly. According to the test results in Figures 9 and 11, it is worth noting that the displacement of the retaining wall is small when lightweight foamed concrete is used to as the backfill behind the retaining wall, which is far less than the displacement required to active earth pressure under normal filling (0.004H, H is the height of retaining wall). The reason is that the lightweight foamed concrete has good self-standing after curing, and it has almost no pushing force on the retaining wall after curing. Therefore, using lightweight foamed concrete as the backfill behind the retaining wall can significantly reduce the deformation of the retaining wall in the actual engineering.

3.1.3. Effects of the Replacement Thickness of Lightweight Foamed Concrete. Based on the height of the buttressed earth-retaining wall model, lightweight foamed concrete with the target replacement thickness of 0.22, 0.28, and 0.40 m is used to cast the lightweight foam concrete layer behind the retaining wall, while the corresponding thicknesses of the sand layer are 0.18, 0.12, and 0 m, respectively. Under the premise of keeping overload and the density of lightweight foamed concrete unchanged, the effects of the replacement thickness of lightweight foamed concrete on the earth pressure at different positions of retaining wall are presented in Figure 12.

Different from the effects of overload and density of lightweight foamed concrete, it can be clearly seen from Figure 12, both the sizes of the earth pressure of the retaining wall and its distribution laws have changed significantly,



(a) Earth pressure distribution at the bottom plate

(b) Earth pressure distribution on the inside of vertical wall

(c) Earth pressure distribution on the soil facing surface of the buttress

(d) Earth pressure distribution on sidewall of the buttress

Figure 10: Earth pressure distributions of retaining wall under different densities of lightweight foamed concrete.

when using different replacement thicknesses of lightweight foamed concrete as the backfill in the model tests. The base compressive stress is still distributed in a convex shape of "large in the middle and small on both sides", and it gradually decreases with the increase of the replacement depth of lightweight foamed concrete since the density of lightweight foamed concrete is about 1/3 of the general filling.

As for earth pressure distributions on the inside of vertical wall or on the sidewall of the buttress, three different replacement thicknesses of lightweight foamed concrete correspond to three different earth pressure distribution characteristics of retaining wall. When the replacement thickness is 0.28 m (the part backfill behind the wall is lightweight foamed concrete), the earth pressure still presents an "R" distribution shape, which is consistent with the previous distribution rule under the same conditions. When the thickness of replacement is 0.22 m, the earth pressures presents firstly increases and then decreases, but this does not represent the distribution rule of earth pressure in this case, since only two earth pressure sensors are buried in the lightweight foamed concrete layer with target thickness of 0.22 m in model, and the distribution law of earth pressure was determined by at least three sensors. However, with the increase of thickness, when the replacement thickness of lightweight foamed concrete is 0.40 m (the filling soil behind the wall is all lightweight foamed concrete), the earth pressure presents a "D" distribution shape, the lateral earth pressure near the bottom of the retaining wall decreases gradually, and the back bending appeared, which may be caused by the restraint of the bottom plate of the retaining wall.

Furthermore, as for the earth pressure distribution on the soil facing surface of the buttress, the lateral earth

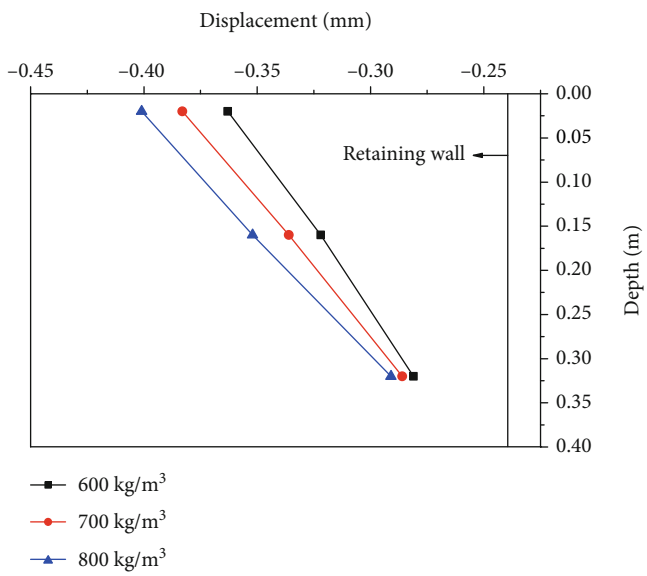


Figure 11: Displacement changes of retaining wall under different densities of lightweight foamed concrete.

pressure of the retaining wall is distributed as a "D" distribution shape along the depth of the wall when partially filled with foamed light soil, which is consistent with the previous distribution rule under the same conditions. However, the earth pressure distribution increased approximately linearly when all filled with lightweight foamed concrete, which means that the backfill is all filled with lightweight foamed concrete layer, and there is no difference in density between fillers.

To sum up, it can be concluded that the replacement thickness of lightweight foamed concrete has a great impact on the stress characteristics of this retaining walls. Therefore, it is very important to choose the suitable replacement thickness of lightweight foamed concrete as backfill in the actual engineering.

Figure 13 shows the effects of the replacement thickness of lightweight foamed concrete on the displacement of retaining wall. It can be seen from Figure 13 that the displacement of the retaining wall decreases approximately linearly as the depth of the retaining wall increases, which indicates that the displacement at the top of the retaining wall is the largest and the displacement at the bottom of the retaining wall is the smallest. Besides, with the increase of the replacement thickness of lightweight foamed concrete, the displacement of retaining wall at the same point decreases gradually, which indicates that increasing the replacement thickness of lightweight foamed concrete within a certain range is conducive to improving the stability of retaining wall.

3.1.4. Establishment of Regression Equations. In order to further reveal the relationships between the size of the resultant earth pressure, the point of resultant force of retaining wall, and above three factors, taking the earth pressure on the inside of vertical wall as an example, the resultant earth pressure and the point of resultant force of retaining wall are, respectively, fitted with different influencing factors based on the above test results. The corresponding fitting equations are established in Table 6, which provide references in the practical engineering.

According to the results in Table 6, it is very convenient to obtain the resultant earth pressure and the points of resultant force of this retaining wall model through the above fitting equations, and corresponding indexes in practical engineering can be converted by the scale of 25 : 1 (actual size : model size).

On the other hand, through the above fitting equations in Table 6 and the scale of 25 : 1 (actual size : model size), we can deduce the appropriate construction parameters or design parameters of the foamed lightweight earth as the backfill behind the retaining wall in actual engineering, which has a significant guiding value for the construction and design of similar projects.

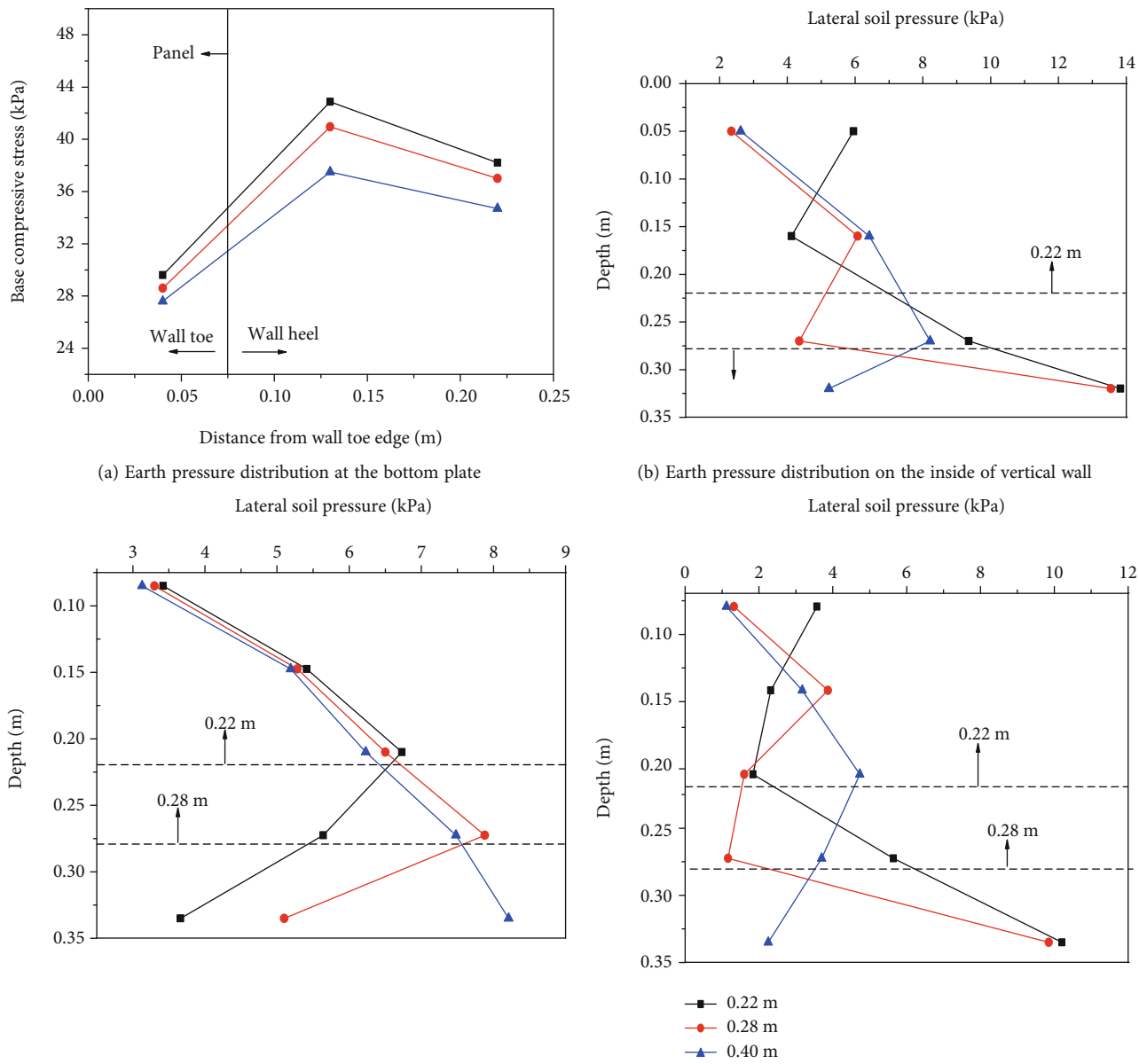
For example, as the conclusion mentioned previously, the replacement thickness of lightweight foamed concrete has great effects on the stress and deformation characteristics of retaining wall, which illustrates that choosing the suitable replacement thickness of lightweight foamed concrete as backfill is the key in the actual engineering. The suitable replacement thickness of lightweight foamed concrete layer behind the wall can be determined by the fitting equation in Table 6. According to the earth pressure theory of retaining wall, the smaller the earth pressure value is, the better the stability of retaining wall is. Therefore, combined with the fitting equation (No. 5) in Table 6, taking the size of the resultant earth pressure of the retaining wall as the control standard, when the replacement thickness of the lightweight foamed concrete in the model test is 0.346 m, the size of the resultant earth pressure of the retaining wall is the smallest. Then, through the scale ratio of 25 : 1 (actual size : model size), it can be calculated that the suitable replacement thickness of lightweight foamed concrete behind the buttressed earth-retaining wall in the supporting project is about 8.7 m.

3.2. Results of the Multiple-Factor Orthogonal Test. Through the analysis of the above single-factor test results, the lateral earth pressure distribution and deformation characteristics of the buttressed earth-retaining wall backfilled with lightweight foamed concrete under single factor are obtained. In order to further study the comprehensive influence of multiple factors on the stress and deformation characteristics of this retaining wall, taking the earth pressure on the inside of vertical wall as an example, the primary and secondary relations of three factors' influence extent on the forces and deformation of the retaining wall backfilled with lightweight foamed concrete are analyzed by using range analysis method.

The range of each factor is calculated by Equation (1):

$$R = \max\{K_{ij}\} - \min\{K_{ij}\}. \quad (1)$$

According to multiple-factor orthogonal test scheme in Table 2, the corresponding resultant earth pressure and the points of resultant force of retaining wall were calculated



(a) Earth pressure distribution at the bottom plate

(b) Earth pressure distribution on the inside of vertical wall

(c) Earth pressure distribution on the soil facing surface of the buttress

(d) Earth pressure distribution on sidewall of the buttress

Figure 12: Earth pressure distributions of retaining wall under different replacement thicknesses of lightweight foamed concrete.

by the model tests, and the range analysis method was used to analyze the test results under multiple factors (as shown in Tables 7 and 8).

As can be seen from Tables 7 and 8, the resultant earth pressure and the point of resultant force would change when the level of any influencing factor changes, and the degree of change varies significantly with different influencing factors. In addition, three influencing factors, including overload, density of lightweight foamed concrete, and replacement thickness of lightweight foamed concrete, maintain a mutually independent and mutually restrictive relationship in the process of affecting the stress and deformation characteristics of retaining wall backfilled with lightweight foamed concrete.

According to the results in Table 7, the sequence of three factors' range for resultant earth pressure of the retaining wall is as follows: $R_1 = 1.071566666 > R_3 = 0.478883333 > R_2 = 0.2799$. In other words, it can be concluded that the primary and secondary relation of three factors' influence extent on the mechanical characteristics of the retaining wall filled with lightweight foamed concrete is as follows: overload>density of lightweight foamed concrete>replacement thickness of lightweight foamed concrete.

On the other hand, it can be seen from the results in Table 8 that the sequence of three factors' range for point of resultant force is as follows: $R_3 = 0.04031722 > R_2 = 0.022143565 > R_1 = 0.018589099$. Therefore, the primary and secondary relation of three factors' influence

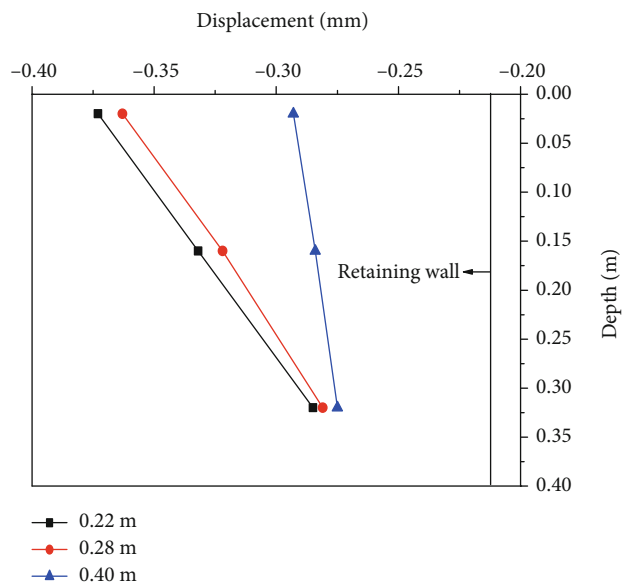


Figure 13: Displacement changes of retaining wall under different replacement thicknesses of lightweight foamed concrete.

Table 6: Regression equations with different factors.

Number	Dependent variable	Independent variable	Fixed parameter	Regression equation
1	y_1	x_1	$x_2 = 700,\ x_3 = 0.28$	$y_1 = 0.00507{x_1}^2 - 0.59728x_1 + 19.38062$
2	y_2			$y_2 = 0.0059{x_1}^2 - 0.034x_1 + 0.2361$
3	y_1	x_2	$x_1 = 14,\ x_3 = 0.28$	$y_1 = 0.00074x_2 + 1.37618$
4	y_2			$y_2 = -0.0005{x_2}^2 + 0.002x_2 + 0.1924$
5	y_1	x_3	$x_1 = 14,\ x_2 = 700$	$y_1 = 35.33565{x_3}^2 - 24.43032x_3 + 5.89528$
6	y_2			$y_2 = 0.0147{x_3}^2 - 0.0549x_3 + 0.1706$

Table 7: Results of resultant earth pressure by multiple-factor orthogonal tests.

Test number	Overload (MPa)	Density of lightweight foamed concrete (kg/m^3)	Replacement thickness of lightweight foamed concrete (m)	Resultant earth pressure (kPa)
2-1	14	600	0.22	2.23085
2-2	14	700	0.28	1.8886
2-3	14	800	0.40	1.8707
2-4	16	600	0.28	2.574295
2-5	16	700	0.40	2.31385
2-6	16	800	0.22	2.84595
2-7	18	600	0.40	2.59685
2-8	18	700	0.22	3.14125
2-9	18	800	0.28	3.46675
η_{j1}	1.996716667	2.467331667	2.73935	—
η_{j2}	2.578031667	2.4479	2.643215	—
η_{j3}	3.068283333	2.7278	2.260466667	—
R_j	1.071566666	0.2799	0.478883333	—

Table 8: Results of the point of resultant force by multiple-factor orthogonal tests.

Test number	Overload (MPa)	Density of lightweight foamed concrete (kg/m^3)	Replacement thickness of lightweight foamed concrete (m)	Point of resultant force (m)
2-1	14	600	0.22	0.130380918
2-2	14	700	0.28	0.193842579
2-3	14	800	0.40	0.141944335
2-4	16	600	0.28	0.191728314
2-5	16	700	0.40	0.141691374
2-6	16	800	0.22	0.13069862
2-7	18	600	0.40	0.144787266
2-8	18	700	0.22	0.134576483
2-9	18	800	0.28	0.131036786
α_{j1}	0.155389277	0.155632166	0.13188534	—
α_{j2}	0.154706103	0.156703479	0.17220256	—
α_{j3}	0.136800178	0.134559914	0.142807658	—
R_j	0.018589099	0.022143565	0.04031722	—

extent on the point of resultant force of the retaining wall filled with lightweight foamed concrete is as follows: replacement thickness of lightweight foamed concrete>density of lightweight foamed concrete>overload.

4. Conclusion

In this paper, a scale experimental model in which the backfill behind the buttressed earth-retaining wall is filled with lightweight foamed concrete is established to study its force and deformation characteristics under different factors. Based on the experimental results and numerical calculation study of this investigation, the following findings can be drawn:

(i) The size and distribution characteristics of earth pressure vary with the different positions of the retaining wall backfilled with lightweight foamed concrete under different factors

(ii) There are similarities and differences in the mechanical characteristics of the buttressed earth-retaining wall backfilled with lightweight foamed concrete under different influence factors by model tests: both of two factors (overload and density of lightweight foamed concrete) can only change the size of earth pressure of this retaining wall and cannot change its distribution laws; but both the size and the distribution form of earth pressure of this retaining wall have changed under the influence of different replacement thicknesses of lightweight foamed concrete

(iii) There are good linear relationships between the displacement of the retaining wall filled with lightweight foamed concrete and each factor: the horizontal displacement of the retaining wall increases with the increase of overload or the density of the lightweight foamed concrete, while it decreases with the increase of the replacement thickness of lightweight foamed concrete

(iv) Through regression analysis, the regression equations of the resultant earth pressure and the point of resultant force of this retaining wall under each single factor are obtained, which determined that the suitable replacement thickness of lightweight foamed concrete behind the buttressed earth-retaining wall in the supporting project is about 8.7 m

(v) Through the range analysis method, it is concluded that the primary-secondary relation of three factors' influence extent on the resultant earth pressure of the retaining wall backfilled with lightweight foamed concrete is as follows: overload > density of lightweight foamed concrete > replacement thickness of lightweight foamed concrete, while the primary-secondary relation of three factors' influence extent on the point of resultant force of this retaining wall is as follows: replacement thickness of lightweight foamed concrete > density of lightweight foamed concrete > overload

Abbreviations

i: Orthogonal test level
j: Number of orthogonal test factors
K_{ij}: Sum of factor j test results at level i
x_1: Overload
x_2: Density of lightweight foamed concrete
x_3: Replacement thickness of lightweight foamed concrete
y_1: Resultant earth pressure
y_2: Point of resultant force
η_{jk}: Average value of final resultant earth pressure when the index of the column j is at the level k ($k = 1, 2, 3$)
R_j: Range of the index of the column j, defined as $R_j = \max\ \{\eta_{jk}\} - \min\ \{\eta_{jk}\}$, ($k = 1, 2, 3$)
α_{jk}: Average value of final point of resultant force when the index of the column j is at the level k ($k = 1, 2, 3$)
R_j: Range of the index of the column j, defined as $R_j = \max\ \{\alpha_{jk}\} - \min\ \{\alpha_{jk}\}$, ($k = 1, 2, 3$).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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