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Experimental and Numerical Simulation Study on Artificial Hard Shell Model

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Abstract

At present, there is controversy over the selection of stress diffusion angle for artificial hard shell layers, which still draws on the stress diffusion theory of natural hard shell layers. The overall strength of the artificial hard shell layer formed by in-situ curing technology is much higher than that of the natural hard shell layer. Obviously, directly adopting the stress diffusion theory of double-layer foundation will inevitably underestimate the bearing capacity of artificial hard shell layers. Based on this, this article analyzes the effects of the thickness of the hard shell layer, elastic modulus, and filling height of the embankment on the stress diffusion angle. The results indicate that, firstly, increasing the thickness and elastic modulus of the hard shell layer is beneficial for stress diffusion; Secondly, the thickening of the artificial hard shell layer directly leads to a decrease in stress diffusion angle; On the contrary, increasing the elastic modulus gradually increases the stress diffusion angle and ultimately maintains around 30°. Finally, when the embankment height is increased from 100mm to 300mm, the stress diffusion angle of the artificial hard shell layer increases from 26.7° to 32.1°. In summary, the stress diffusion angle of the artificial hard shell layer is determined to be around 30°.

Keywords

Artificial Hard Shell Layer; Double Layer Foundation; Model Testing; Numerical Simulation; Stress Diffusion Angle.

1. Introduction

The dredged silt soft soil foundation in coastal provinces of China is difficult to meet the requirements of construction sites due to its high moisture content, high compressibility, and low shear strength [1-4]. The in-situ solidification technology is a green construction technology that uses a certain proportion of solidification agent [5-7], and under the action of a strong mixing head [8], it mixes with soft soil silt to form an artificial hard shell layer [9]. It does not require abandoned soil or borrowed soil, and can achieve the circular utilization of land resources [10]. Compared with traditional natural hard shell layers [11], the formation of artificial hard shell layers has higher compressive and shear strength, which can effectively improve the bearing capacity of the foundation.

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As early as 2007, Kuang and Hu [12] used mechanical calculation models to verify the feasibility of using artificial hard shells to treat soft foundations. Later, Chen, Y. [13], Gao, S. [14], and Wang, Y. [10] applied this technology to engineering practice, greatly improving the bearing capacity of the foundation. Fang H. Y [15], Mitchell and Gardner [16], and D.M. Milovic [17] conducted finite element numerical calculations, and from the generated images, it can be concluded that the hard shell layer has a significant stress diffusion effect on the soft soil layer stress [18-19]. This function is widely used in high-grade highway engineering, combined with rigid pile composite foundation [20-22], to replace the traditional reinforced cushion composite foundation with loose materials [22]. It can be seen that it is very important to study the stress diffusion effect of artificial hard shell layer and fully grasp its mechanism of action. Scholars [23] directly applied the stress diffusion angle of double layered foundation [25-26] given in the specification [24] as the basis to analyze the bearing performance of artificial hard shell layer double layered foundation, and the obtained bearing capacity value is relatively small compared to the actual value. Luo [27] obtained a stress diffusion angle of 8.28°~20.57°for the solidified hard shell layer of sludge during the layered reinforcement process of sludge and slag soil; The recommended values for the stress diffusion angle of the artificial hard shell layer are 28° to 45°, as stated in the Technical Guidelines for Design and Construction of in situ Solidification of Highway Embankments (Strong Mixing Method) [28].

In summary, it can be seen that there is currently controversy over the selection of stress diffusion angle for artificial hard shell layers. And it is unreasonable to directly apply the stress diffusion angle of the standard. Based on this, this article analyzes and studies the stress diffusion angle of artificial hard shell layers. By conducting model experiments and numerical simulations, the influence of the thickness and elastic modulus of the artificial hard shell layer, as well as the embankment filling height on the stress diffusion angle, is analyzed to further determine the reasonable value of the stress diffusion angle.

2. Model Test Content

The experimental plan is shown in Table 1. Obtain the distribution law of additional stress at the interface under different thicknesses of hard shell layers through plate load tests, and explore the changes in stress diffusion angle of hard shell layers under different working conditions.

Table 1. Model test plan

Test	Thickness of hard shell layer (mm)	Soft soil layer thickness (mm)	Load plate size (mm)
Artificial hard shell layer double layer foundation with different thicknesses	60	700	100×100×10
	100	700	100×100×10
	140	700	100×100×10
	200	700	100×100×10

3. Test Materials and Equipment

The soft soil required for the model test is all taken from the dredged sludge at the "Oufei" in-situ solidification construction site in Wenzhou City, and its physical and mechanical properties are shown in Table 2. In this article, the artificial hard shell layer preparation process involves pouring the uniformly mixed solidified soil into the model box to make it fully contact with the soft soil layer. The pressure applied to the load plate is read by a manual digital hydraulic jack. Magnetic base digital dial indicators are installed on the left and right sides of the load plate, and the average of the degrees of the two dial indicators is taken as the settlement value, as shown in Figure 1. Use a strain gauge soil pressure box with consistent specifications to collect the stress magnitude in the soil. The collected data is obtained from the stress diffusion angle calculation formula [28]. The plate load experiment was conducted in accordance with the requirements of the "Code" [24].

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Table 2. Your table here and center

Moisture content (%)	Natural gravity (kN/m^3)	Void ratio	Cohesive force (kPa)	Internal friction angle (°)	Liquid limit (%)	Plastic limit (%)
75.24	14.81	2.85	7.32	6.78	37.91	25.70

Figure 1. Model test site loading and testing actual diagram

4. Test Results and Analysis

4.1 Analysis of Bearing and Deformation Characteristics of Artificial Hard Shell Double Layer Foundation

Figure 2 shows the load settlement (P-S) curves for different thicknesses. Due to the improvement of the internal physical and mechanical properties of the artificial hard shell layer formed through curing agent treatment, its load-bearing capacity has been greatly improved [20]. The variation pattern of each curve is the same: as the thickness of the hard shell layer increases, the ultimate bearing capacity of the foundation also increases, respectively 102kPa, 192kPa, 415kPa, 677kP, and the corresponding settlement values are 16mm, 23mm, 35mm, and 42mm. For every 40mm increase in thickness, the ultimate bearing capacity increased by 90kPa, 223kPa, and 262kPa, respectively. Therefore, increasing the thickness of the hard shell layer can effectively improve the ultimate bearing capacity of the foundation.

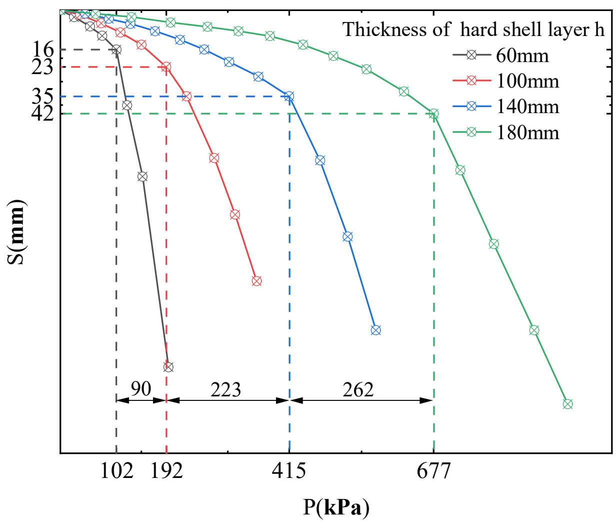

Figure 2. P-S curves under different thicknesses

Volume 10 Issue 1, 2024
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4.2 Stress Diffusion Law of Artificial Hard Shell Layer

Figure 3 shows the comparison of the vertical additional stress variation curve of the artificial hard shell layer along the depth with the classical Boussinesq elastic theory solution. From the figure, it can be seen that there is a certain difference between the measured values of the model experiment and the classical Boussinesq elastic theory solution, which is due to the existence of stress diffusion in the hard shell layer. Moreover, the vertical stress decreases with the increase of the thickness of the hard shell layer, reaching its minimum value at the bottom of the hard shell layer. When an external load of P=100kPa is applied to the surface of artificial hard shell layers with thickness h=60mm, 100mm, 140mm, and 180mm, the artificial hard shell layer can evenly distribute the upper load to the lower soil layer at a certain angle, reducing the vertical additional stress transmitted to the bottom of the hard shell layer to 18.04kPa, 16.08kPa, 14.25kPa, and 13.24kPa, respectively, with a reduction of 81.96%, 83.92%, 85.75%, and 86.76%, respectively. From the perspective of stress diffusion, increasing the thickness of the hard shell layer reduces the vertical additional stress inside the hard shell layer.

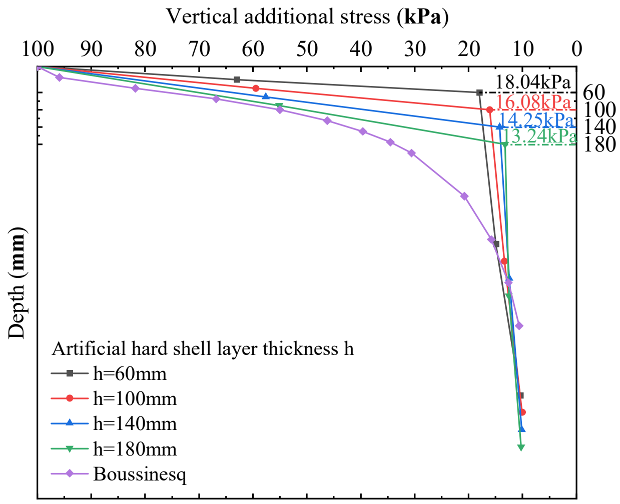

Figure 3. Comparison of measured values and elastic theoretical solutions for the distribution of vertical stress along depth

5. Finite Element Simulation and Verification

5.1 Introduction to Finite Element Model

Establish a two-dimensional model using ABAQUS. This article uses the quadrilateral structured grid technique (CPE4) when meshing the hard shell layer. Horizontal constraints are applied on both sides of the soil model, and fixed constraints are applied at the bottom. And carry out in-situ stress balance.

5.2 Model Parameters and Calculation Conditions

This article establishes an elastic-plastic model for a double-layer foundation, and its failure criterion is the Mohr Coulomb constitutive model. The numerical simulation material parameters in this simulation were obtained based on indoor experiments, as shown in Table 3.

Table 3. Physical and mechanical property indicators

Material	Elastic modulus (kPa)	Void ratio	Cohesive force (kPa)	Internal friction angle (°)	severe (g·cm^{-3})	Contact friction coefficient
Artificial hard shell layer	101297	0.26	311.28	53.01	1.88	0.9
Soft soil layer	530	0.34	7.04	7.38	1.51	0.9

Volume 10 Issue 1, 2024
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5.3 Verification of the Correctness of the Finite Element Model

To verify the correctness of the numerical analysis method in this article. Numerical simulation was conducted on the model test, and the relationship curve between the load and settlement of the artificial hard shell double-layer foundation (P-S curve) was compared and analyzed (Figure 4). Under uniform load, the displacement increases with the increase of load; When the ultimate bearing capacity is reached, a sudden change in displacement indicates that the foundation has been damaged. In summary, the results obtained from the established numerical analysis model are roughly the same as the model test results, and can be further used for practical simulation analysis.

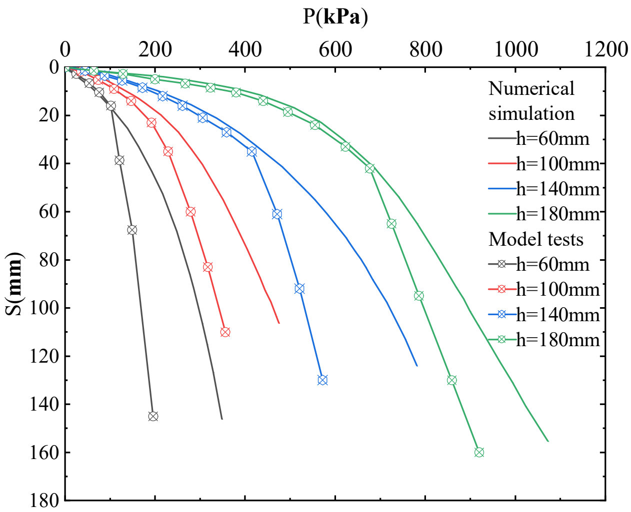

Figure 4. Comparison between numerical simulation results and model test results

6. Analysis of the Influence of Geometric Parameters

6.1 The Effect of Hard Shell Layer Thickness on the Stress Diffusion Angle of Artificial Hard Shell Layer

Figure 5 shows the effect of the thickness of the hard shell layer on the stress diffusion angle of the artificial hard shell layer. The vertical additional stress in the foundation varies with depth under a uniform load of 100kPa and different hard shell layer thicknesses (with a load width of 100mm). The variation pattern is the same as the conclusion obtained from model experiments: the vertical stress decreases with the increase of the thickness of the hard shell layer (at the same depth), but when the thickness reaches 260mm, the diffusion of vertical stress reaches 84.79%. When the thickness of the hard shell layer is greater than 180mm, the vertical additional stress at the bottom of the hard shell layer is close to overlapping, that is, it is transmitted to the soft soil layer at a vertical stress of 15kPa at the bottom of the hard shell layer. Undoubtedly, increasing the thickness of the hard shell layer enhances the stress diffusion of vertical additional stress, which is consistent with the results obtained from model experiments. Convert and plot the stress diffusion angle change curve shown in Figure 6 through the formula. It is not difficult to see from the curve variation pattern that increasing the thickness of the hard shell layer reduces its stress diffusion angle. When the thickness of the hard shell layer is 60mm~180mm, the stress diffusion angle decreases from 44.52° to 23.44°, and the decrease in stress diffusion angle is most significant. That is, the thickness of the hard shell layer increases at a rate of 40mm/time, and the average decrease in stress diffusion angle is 5.27°; When the thickness is greater than 180mm, the amplitude of change in stress diffusion angle decreases. Through analysis, it can be concluded that an increase in thickness can improve the bearing capacity of the foundation, but an excessively thick hard shell layer can weaken the stress diffusion effect.

 Volume 10 Issue 1, 2024
DOI: 10.6919/ICJE.202401_10(1).0030

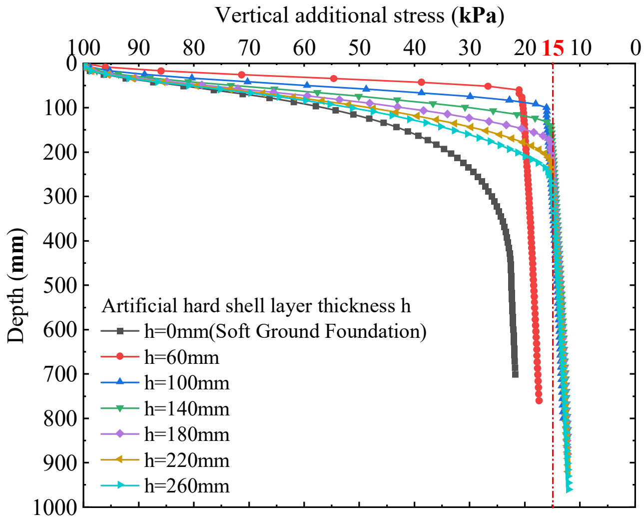

Figure 5. Vertical additional stress variation curve with different thicknesses

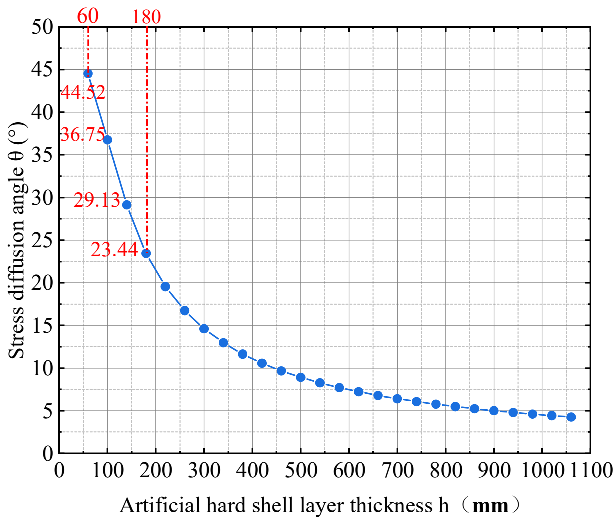

Figure 6. The variation law of stress diffusion angle under different thicknesses of hard shell layers

6.2 The Influence of Elastic Modulus on the Stress Diffusion Law of Artificial Hard Shell Layer

Figure 7 shows the vertical stress variation curve under different elastic moduli (thickness 140mm). By increasing the elastic modulus, the vertical stress will decrease and reach the minimum value at the bottom of the hard shell layer. When the thickness of the hard shell layer is less than 140mm, the vertical stress at the same depth decreases with the increase of the elastic modulus of the hard shell layer. When the elastic modulus is 300Mpa, the vertical stress decreases by up to 85.5%. By plotting the stress diffusion angle change curve, as shown in Figure 8. The curve variation pattern verifies that the direct reason why the reduction of vertical additional stress is no longer significant after the elastic modulus increases to a certain range is that the stress diffusion effect reaches a critical state. The stress diffusion angle remains around 30° as the elastic modulus increases. In the stress diffusion angle curve, it can be found that when the elastic modulus is less than 100Mpa, the change in stress diffusion angle is most significant, with an increase in the multiple of the elastic modulus, and the average change in stress diffusion angle remains around 4.25°. It can be seen that increasing the elastic modulus of the hard shell layer can increase its stress diffusion angle. When the stress diffusion angle reaches around 30°, the diffusion effect of additional stress in the foundation can be fully utilized.

Volume 10 Issue 1, 2024
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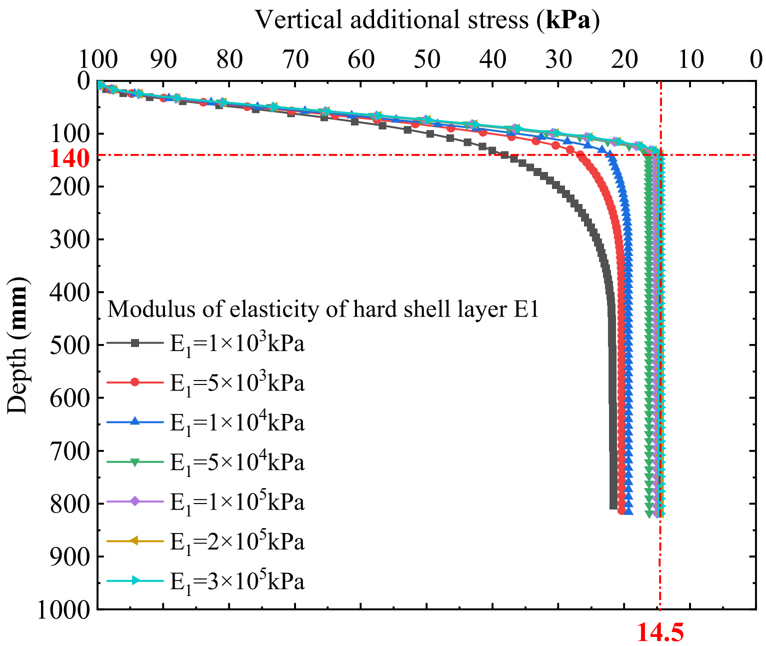

Figure 7. Vertical stress variation under different elastic moduli of hard shell layers

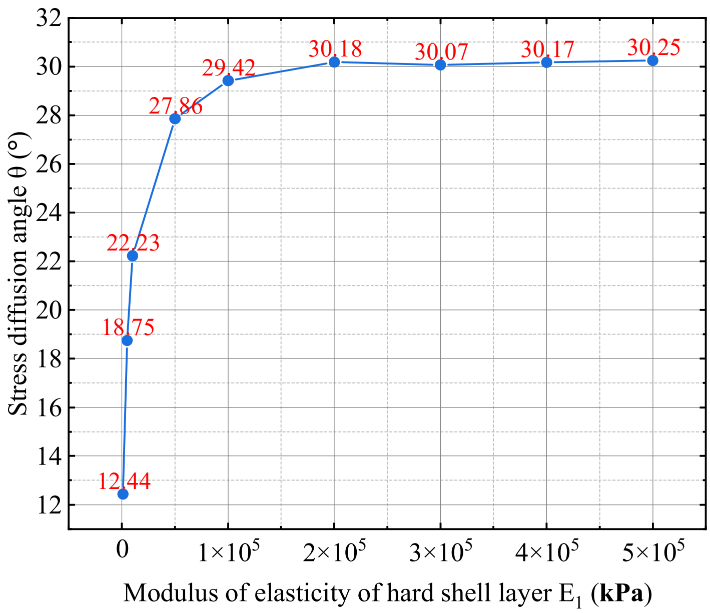

Figure 8. Changes in stress diffusion angle under different elastic moduli of hard shell layers

6.3 The Influence of Embankment Filling Height on the Stress Diffusion Law of Artificial Hard Shell Layer

Figure 9 shows the vertical stress variation curve inside the hard shell layer at the embankment height. The stress diffusion inside the artificial hard shell layer increases with the increase of embankment filling height. When the height of the embankment reaches 100mm, the vertical stress curve becomes steeper. Continuing to increase the height of the embankment, the vertical stress curve gradually flattens out. Indicates that the height of embankment filling affects the internal stress diffusion of the artificial hard shell layer. Convert the vertical stress inside the artificial hard shell layer into the stress diffusion angle, and draw the stress diffusion angle curve as shown in Figure 10. The stress diffusion angle inside the artificial hard shell layer increases with the increase of embankment filling height. When the embankment height is between 100mm and 300mm, the stress diffusion angle of the artificial hard shell layer increases from 26.7° to 32.1°.

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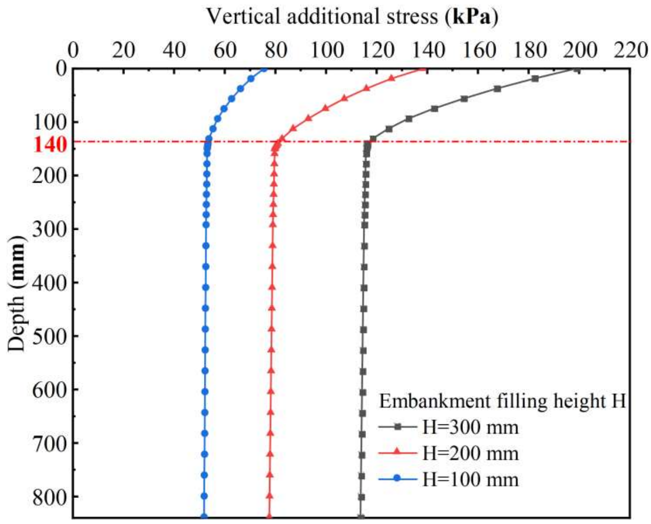

Figure 9. Changes in stress diffusion angle under different elastic moduli of hard shell layers

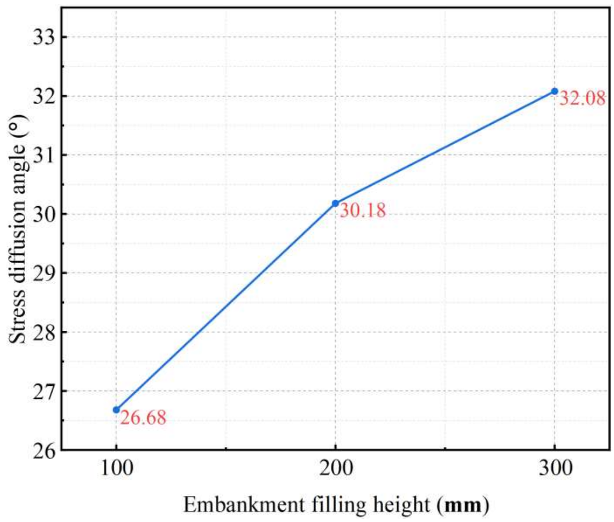

Figure 10. Changes in stress diffusion angle under different elastic moduli of hard shell layers

7. Conclusion

1) An increase in thickness can reduce vertical stress. When the thickness exceeds 180mm, the stress diffusion within the artificial hard shell layer weakens, and the vertical additional stress curve approaches overlap. However, the stress diffusion angle decreases with the increase of the thickness of the hard shell layer, and finally tends to stabilize.

2) Increasing the elastic modulus also reduces the vertical stress inside the hard shell layer, and its stress diffusion effect is equivalent to the thickness of the hard shell layer. Increasing the elastic modulus of the hard shell layer gradually increases the stress diffusion angle and ultimately maintains it at around 30°.

3) The increase in embankment filling height can enhance the stress diffusion effect inside the hard shell layer, and the stress diffusion angle increases from 26.7° to 32.1°.

4) In engineering applications, the recommended value for the stress diffusion angle of the artificial hard shell layer is around 30°, which can effectively exert the internal stress diffusion effect of the hard shell layer.

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