



# Study on the Stress and Deformation Coordination of Pile Foundation and Buttress Retaining Wall Combined Structure in High-Fill Areas of Mountainous Regions

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**Abstract.** This paper, based on an ongoing mountainous area high-fill embankment project, investigates the high-fill pile foundation and cantilever retaining wall composite support structure in loess gully regions. A numerical simulation method was employed to analyze the stress and deformation process of the composite support structure, revealing the characteristics of stress distribution and deformation patterns of the structure. The main research conclusions are as follows: under the action of earth pressure, significant stress concentration occurs at  $X=0.7\text{m}$  and  $X=5\text{m}$  along the  $X$ -direction of the bottom slab of the retaining wall. The cantilever retaining wall exhibits a tendency to tilt towards the fill side, with horizontal displacement and settlement showing a stratified distribution feature. Meanwhile, the contour line displacements are equal at the connection between the retaining wall and the pile foundation, indicating that the composite structure deforms coordinately under earth pressure as a whole.

**Keywords:** Pile foundation-Buttress retaining wall; Mechanical properties; Deformation coordination; Numerical simulation

## 1 Introduction

In recent years, with the gradual development of domestic transportation infrastructure, engineering projects are often carried out in mountainous regions with complex terrain and numerous ravines. To overcome the challenges of large topographic variations and steep slopes typical of such areas, the pile foundation-buttress retaining wall combined structure has been applied in similar projects. The pile foundation-buttress retaining wall is a novel type of embankment retaining structure. Compared to traditional spread foundations, the pile foundation saves 35% of materials and 70% of excavation volume<sup>[1]</sup>, significantly reducing construction costs, while the construction technology is reliable and the results are effective. As a result, many scholars have conducted in-

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depth research on pile foundation-buttress retaining walls. Xia Yebin<sup>[2]</sup> found that a three-row pile combined retaining wall is suitable for high-fill slopes, with soil pressure distribution changing according to displacement patterns. Terzaghi<sup>[3]</sup> pointed out the classical soil pressure theory, stating that soil pressure distribution follows the theoretical pattern only when the horizontal displacement of the wall is sufficiently large. Byung-Suk Park<sup>[4]</sup> and others revealed the impact of the geometric characteristics of the retaining wall on soil pressure. T. Ito<sup>[5]</sup> and Randolph<sup>[6]</sup> studied pile foundation design methods and the characteristics of ultimate lateral resistance. Liu Yuxin<sup>[7]</sup>, He Junlong<sup>[8]</sup>, and Ouyang Guobin<sup>[9]</sup> proposed a simplified method for the unit design of pile-buttress combined retaining walls, optimizing applicability. Kong Gang<sup>[10]</sup> analyzed the pile-soil-wall interaction and proposed anchor rod support measures. Ni Hongliang<sup>[11]</sup> studied the displacement-reducing characteristics of pile-supported beam retaining walls, and Wang Chao<sup>[12]</sup> proposed an optimization plan for pile-top buttress retaining walls, verifying the critical role of pile length and spacing in structural stability.

Currently, the pile foundation and cantilever retaining wall have been widely applied in engineering, but the theoretical research is relatively lagging. In the current design process, the upper retaining structure and the lower pile foundation are typically calculated separately, without fully considering the load-bearing characteristics of the structure as a whole under external loads. This paper establishes a three-dimensional finite element model using ABAQUS software to study the construction process of the high-fill project's composite support structure with pile foundations and cantilever retaining walls in loess gully regions. It reveals the stress distribution characteristics and deformation coordination patterns of the composite support structure under these special engineering geological conditions. This has important theoretical significance and practical engineering value for guiding the construction of support structures in high-fill projects in loess gully areas.

## 2 Project Overview

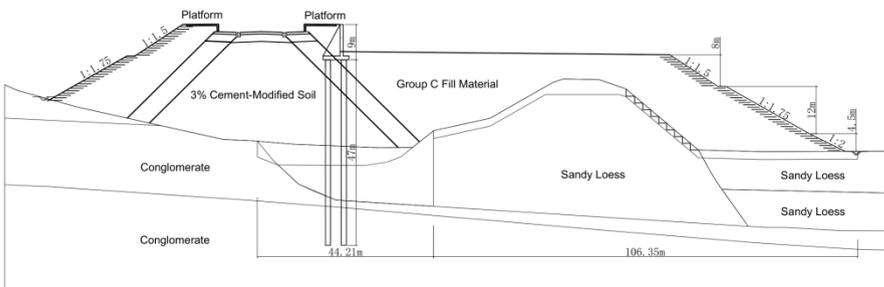


Fig. 1. Design Drawing of Section DK27+160

The paper is based on a practical engineering project, specifically a high-fill embankment station project in a mountainous area for a certain ongoing railway, with the alignment range from DK26+050.00 to DK28+100.00, and a total station length of 1733.01 meters. The station is located in a typical gully region of the Loess Plateau. The main

project content includes: gully modification, pile and diaphragm wall, slope protection, and foundation treatment. The fill height ranges from 1 to 29 meters, and the excavation depth ranges from 1 to 23 meters. The pile foundation-buttress retaining wall at the typical section of DK27+160 is selected as the research object for this paper, with the typical section design diagram shown in Figure 1.

### 3 Establishment of the Model

The numerical model adopts a 1:1 scale to simulate the actual engineering, including the slope height, retaining wall dimensions, and pile foundation dimensions. The soil constitutive relationship is modeled using the Mohr-Coulomb model, and both the pile foundation and retaining wall are simulated using a linear elastic theory model. C3D8 hexahedral elements are used for meshing the structure. The interaction between the structure and the soil is modeled using penalty-based contact, with normal contact defined as "hard contact" and the tangential friction coefficient set to 0.4. Boundary conditions: The left and right boundaries of the model are set with horizontal displacement constraints in the x-direction, the front and rear boundaries are set with horizontal displacement constraints in the z-direction, and the bottom boundary is fully constrained. In the calculation, the model first performs geostress equilibrium on the foundation soil before simulating three working conditions:

1. Working condition 1: Fill construction stage with 3 meters of fill
2. Working condition 2: Fill construction stage with 6 meters of fill
3. Working condition 3: Fill construction stage with 9 meters of fill

The physical and mechanical parameters of the soil in the numerical simulation are mainly based on parameters provided by laboratory tests and geotechnical investigation data. The mechanical parameters of the pile foundation-buttress retaining wall structure are determined based on empirical values and material properties, as shown in Table 1.

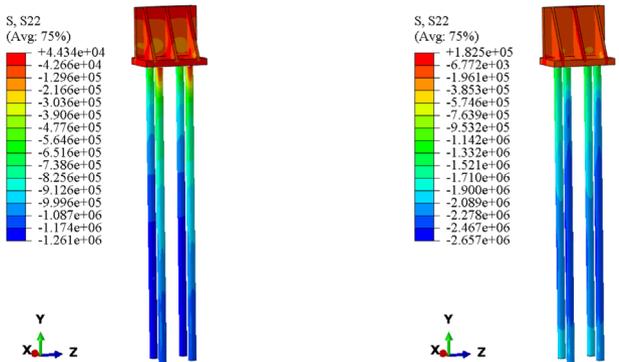
**Table 1.** Material Parameters for Model Soil Layers and Structure

Material	Density (kg/m <sup>3</sup> )	Elastic Modulus (N/m <sup>2</sup> )	Poisson's Ratio	Cohesion (pa)	Internal Friction Angle (°)
Loess	1800	50e <sup>6</sup>	0.28	23e <sup>3</sup>	23
Gravel Rock	2500	8e <sup>9</sup>	0.3	100e <sup>3</sup>	38
Graded Crushed Stone	1900	180e <sup>6</sup>	0.23	3000	40
5% Cement Modified Soil	2000	100e <sup>6</sup>	0.25	38e <sup>3</sup>	32
C45 Concrete	2400	33.5e <sup>9</sup>	0.2	—	—
Composite Foundation	2100	150e <sup>6</sup>	0.3	30e <sup>3</sup>	35
3% Cement Modified Soil	1940	80e <sup>6</sup>	0.2	35e <sup>3</sup>	35
Group C Fill Material	1860	120e <sup>6</sup>	0.26	40e <sup>3</sup>	32

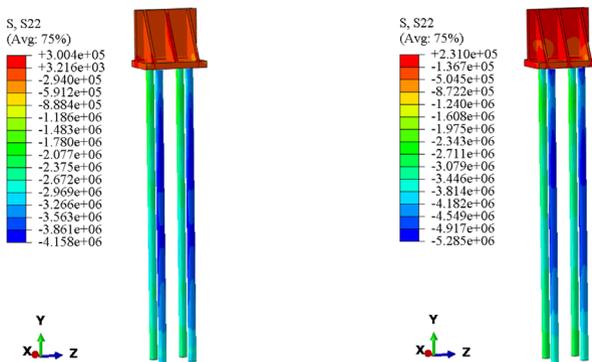
## 4 Analysis of the Simulation Results of the Pile-Slab Retaining Wall Structure System

### 4.1 Stress Distribution Characteristics of the Structural System

As shown in Figure 2(a), when the pile foundation-buttress retaining wall combined structure is subjected to its own gravity load, the vertical stress on the buttress retaining wall is positive, while the vertical stress on the pile foundation is negative. The stress on the outer rows of piles is greater than that on the inner rows of piles, and stress concentration occurs at the four piles under the bottom slab of the retaining wall. The buttress retaining wall resists settlement through the upward support force provided by both the foundation soil and the pile foundation, while the pile foundation bears downward stress. The shift of the pile foundation's center of gravity causes stress concentration, with the maximum vertical compressive stress reaching 0.53 MPa.



(a) Stage of retaining wall self-weight action. (b) The construction stage with 3 meters of fill



(c) The construction stage with 6 meters of fill (d) The construction stage with 9 meters of fill

**Fig. 2.** Vertical stress contour map of the pile foundation-buttress retaining wall under different working conditions

As shown in Figures 2(b) to 2(c), as the soil pressure increases, the stress concentration on the buttress retaining wall intensifies. The maximum vertical stress increases to 1.687 MPa, and the outward tilting of the retaining wall towards the outer piles decreases, while the stress concentration on the inner rows of piles increases. The vertical stress on the rock-embedded piles increases and presents a "circular arc" distribution, forming a compression zone and a tension zone. Initially, the piles resist the load through their own strength, and as the load increases, the rock-embedded piles achieve anti-sliding effects through the stability provided by the embedded rock layer.

As shown in Figure 3, during the fill construction process, the stress on the bottom slab of the retaining wall increases with the increase in soil pressure behind the wall, with more significant changes on the left side compared to the right. Upon completion of Working Condition 1, the stress on the bottom slab along the X-direction shows a trend of first increasing, then decreasing, and then increasing again. Stress concentrations of 1.3 MPa and 1.09 MPa occur at  $X = 0.7$  m and  $X = 5$  m, respectively. As the soil pressure increases, the vertical compressive stress at the bottom of the retaining wall further increases at these two locations, and the magnitude of the increase expands. This is due to the soil pressure causing the center of gravity of the retaining wall to shift toward the fill side, transferring most of the load to the heel slab, which results in a concentration of vertical compressive stress. When the soil pressure exceeds the critical value, the heel slab may experience compressive failure, potentially leading to the overturning of the retaining wall. This failure mechanism should be carefully considered in the design.

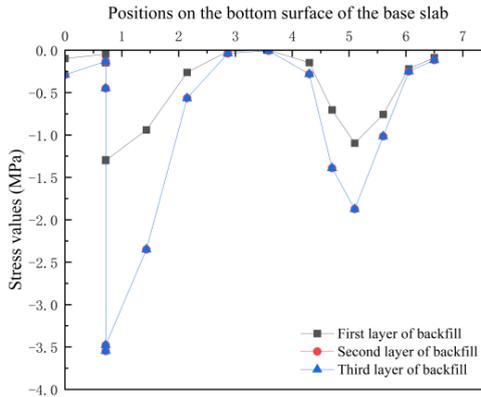


Fig. 3. The distribution curve of normal stress along the X-axis direction on the bottom slab

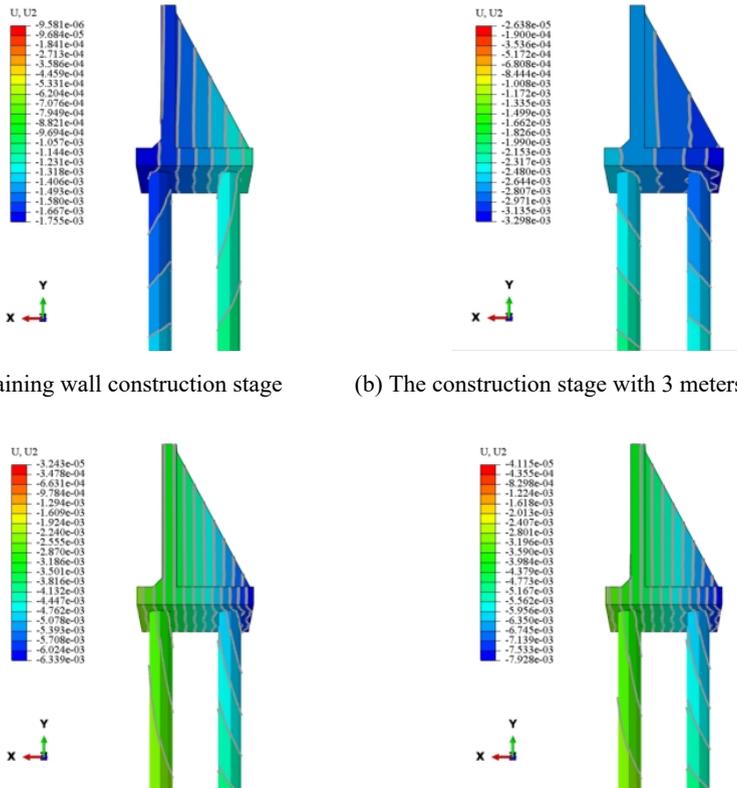
#### 4.2 The Deformation Coordination Process of the Pile Foundation-Buttress Retaining Wall Combined Structure

Figure 4(a) shows that the pile foundation-buttress retaining wall combined structure, under the action of gravity load only, is in its initial state. The vertical displacement of the buttress retaining wall shows a strip-like distribution, with the maximum settlement of -1.755 mm and the minimum of -1.231 mm, resulting in a settlement difference of

0.524 mm, indicating slight uneven settlement. The vertical displacement deformation of the buttress retaining wall and the rock-embedded piles is consistent. Since the rock-embedded piles need to support the inclined retaining wall, the vertical displacement shows a sloped layer distribution.

Figure 4(b) shows that after the fill construction, the vertical displacement distribution becomes sparser compared to the initial state. The maximum settlement on the fill side is -3.298 mm, while the settlement on the backfill side is -2.644 mm, with a settlement difference increasing by 0.1 mm. This indicates that the soil pressure has balanced the initial uneven settlement, and the settlement of the inner row piles is greater than that of the outer row piles, resulting in a change in the stress state.

Figures 4(c) to 4(d) show that as the soil pressure increases, the vertical displacement of the pile foundation-buttress retaining wall combined structure gradually increases and tilts toward the fill side.



(a) Retaining wall construction stage

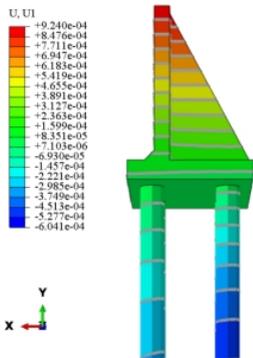
(b) The construction stage with 3 meters of fill

(c) The construction stage with 6 meters of fill

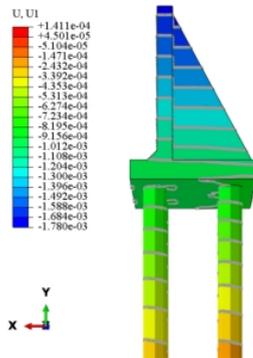
(d) The construction stage with 9 meters of fill

**Fig. 4.** Vertical displacement contour maps of the pile foundation-buttress retaining wall under different working conditions

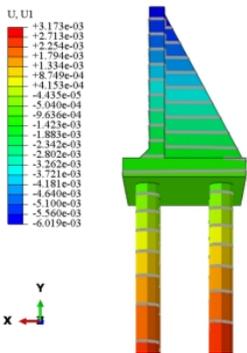
Figures 5 and 6 show the horizontal displacement characteristics of the pile foundation-buttrss retaining wall system under different working conditions, which exhibit a horizontal layered distribution. When the combined structure is subjected only to gravity loads, the horizontal displacement at the top of the buttress retaining wall is greater than at the bottom, with a slight displacement toward the toe slab. The horizontal displacement at the top of the rock-embedded piles is smaller than at the middle, and the displacement is directed toward the fill side. As the soil pressure increases, the horizontal displacement of the buttress retaining wall shifts from the wall crest direction to the wall back direction, while the rock-embedded piles displace toward the wall back. Upon completion of Working Condition 3, the maximum horizontal displacement at the top of the buttress retaining wall is 5.327 mm, and the maximum horizontal displacement of the rock-embedded pile occurs 12.5 meters from the pile top, with a value of 5.062 mm, resulting in a maximum horizontal displacement difference of 10.389 mm.



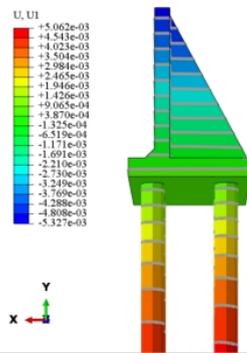
(a) Retaining wall construction stage



(b) First backfill layer construction



(c) Second backfill layer construction



(d) Third backfill layer construction

**Fig. 5.** Horizontal contour displacement map of the pile foundation-counterfort retaining wall under different conditions.

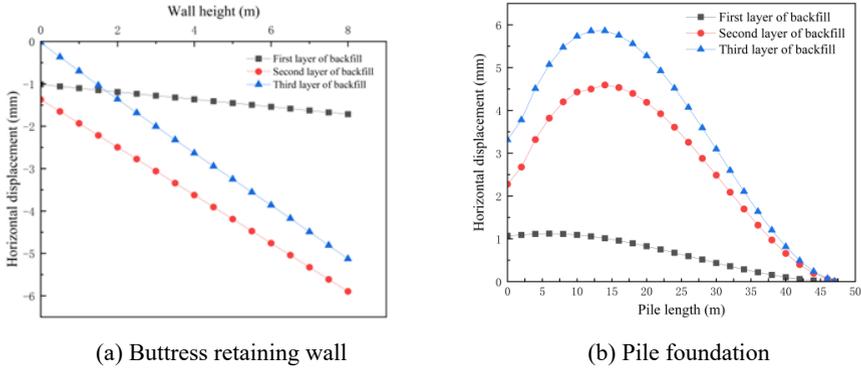


Fig. 6. Horizontal displacement variation curves of the pile foundation and retaining wall under different working conditions

### 5 Conclusion

A three-dimensional finite element model of the pile foundation-buttrass retaining wall was established using ABAQUS software to analyze the stress and deformation coordination process under three construction conditions. The following conclusions were drawn:

(1) Under the action of soil pressure, the stress concentration in the retaining wall increases, with the vertical stress reaching a maximum of 1.687 MPa. The stress concentration in the inner rows of piles also increases. The stress on the bottom slab of the retaining wall increases with the soil pressure, particularly at  $X = 0.7$  m and  $X = 5$  m, where significant stress concentrations occur. The soil pressure causes the center of gravity of the retaining wall to shift toward the fill side, leading to an increase in vertical compressive stress, which may cause compressive failure of the heel slab and lead to the overturning of the retaining wall. This stress concentration and failure mechanism should be carefully considered in the design.

(2) Under the action of earth pressure, the cantilever retaining wall exhibits a tendency to tilt towards the fill side. The horizontal displacement and settlement of the composite structure show a stratified distribution characteristic. At the connection between the retaining wall and the pile foundation, the contour line displacements are equal, indicating that the composite structure deforms coordinately under earth pressure as a whole. The maximum horizontal displacement of the cantilever retaining wall occurs at the top of the wall, measuring 5.327 mm, while the maximum horizontal displacement of the rock-socketed pile occurs 12.5 m below the pile top, measuring 5.062 mm. Overall, the increase in earth pressure significantly affects the vertical and horizontal displacements of the structure.

Therefore, during design, special attention should be paid to the locations where the composite support structure experiences maximum horizontal displacement and settlement. Consideration can be given to using anchor rod support or other measures for combined support to ensure the overall stability of the composite structure.

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