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# Study on Arching Mechanism of Bridge Pile Foundation: Taking the Shiyangtai No.1 Bridge as an Example

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**Abstract:** The structure of a bridge has certain peculiarities, and its pile foundations are susceptible to uplift or settlement deformation due to various factors. This can result in bridge deck cracking, structural instability, tilting, and even irreversible damage, which significantly impacts the bridge's stability and driving safety. This study focuses on the Shiyangtai No.1 Bridge and aims to investigate the factors that cause abnormal rise and fall deformations of bridge pile foundations. The study combines macro and micro analysis, physical characteristic testing of the overlying soil under the bridge pile foundation, and numerical simulation of the bridge pile foundation in the goaf. The study discusses in-depth the formation mechanism of the abnormal uplift of some pile foundations of the Shiyangtai No.1 Bridge based on the analysis of the factors influencing the abnormal rise and fall deformation of the bridge pile foundations at home and abroad. The expansive soil beneath the pile foundation is weak, and the force generated by the water expansion is insufficient to cause the pile foundation to rise to 309 mm. The results indicate that the pile foundation of the bridge is not affected by the expansion characteristics of the overlying soil. The collapse of the goaf roof generates double lateral thrust from the accumulation body at the bottom of the goaf and the upper collapse arch. This causes staggered bending uplift of the sandstone soil layer, resulting in upward squeezing pressure that causes the bridge pile foundation to rise. Therefore, the coal mining area is the main factor influencing the abnormal uplift of the pile foundation of the Shiyangtai No.1 Bridge.

**Keywords:** bridge foundation uplift; expansive soil; the coal mining area; numerical simulation; genetic mechanism



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## 1. Introduction

The construction of expressways is of great importance in the development of traffic infrastructure worldwide. Bridges are an essential component of expressways, constituting a significant proportion. The operation of expressways commonly presents bridge engineering problems related to potential safety hazards caused by foundation deformation and bridge pile foundation deformation. This is due to the unique characteristics of the bridge structure, which is highly sensitive to topographic changes and geological activities. In practical engineering, bridges often pass through challenging geological areas, such as mountainous regions with complex geology, collapsible loess, and high-stress areas. These conditions can lead to various issues in bridge pile foundations during stable operation, resulting in permanent and irreversible deformation of the bridge structure, which endangers operational safety.

Research indicates that currently, many scholars are focusing on the study of settlement issues in bridge pile foundations. And the numerous studies carried out indicate that bad geological conditions (karst area [1–5], groundwater [6–9]), human engineering activities (foundation pit excavation [10–13], coal mining [14,15]), and other factors will affect the settlement and deformation of adjacent bridge pile foundation. However, there are few studies on the abnormal uplift of bridge pile foundation, and there is a lack of certain conclusions and theoretical basis. At present, the existing research results show that if the underground overburden in the bridge area has the rock and soil mass with expansion characteristics after encountering water, the expansion effect will lead to the uplift of the bridge pile foundation [16–18]. Under special conditions, the development of the mined-out area will also lead to the uplift of the foundation [19]. This is because the roof of the large-area mined-out zone collapses, and the lateral thrust generated by the collapse of the slab beam causes the underlying bedrock to move, resulting in the foundation rising [20]. In addition, the large-scale lifting of groundwater reduces the effective stress of the overlying soil under the pile foundation, and the buoyancy generated by groundwater causes the overlying soil to lose its load as a whole, eventually leading to the overall upward floating of the pier [21]. Qu et al. [22] analyzed the influencing factors of bridge pile foundation arch by using Plaxis 3D finite element software simulation, and concluded that ground stress is the main reason for bridge pile foundation arch. Zheng et al. [23] proposed a novel complex true triaxial static-dynamic combined loading method reflecting underground excavation damage and frequent intermittent disturbance failure and also proposed a new three-stage true triaxial coupled static and dynamic load test method to simulate the stress path of rock in the process of disturbance and failure after deep engineering excavation.

In summary, research on issues related to bridge pile foundations, both domestically and internationally, has predominantly concentrated on settlement aspects. However, there is a lack of research on the uplift of bridge pile foundations. Therefore, this study aims to investigate the cause mechanism of the uplift of the pile foundation of the Shiyangtai No.1. Based on an analysis of the factors that cause abnormal lifting and deformation of bridge pile foundations both domestically and internationally, measures should be taken to prevent continuous uplift of the pile foundation of the bridge and reduce the impact on traffic in the region. The cause mechanism of the abnormal uplift of the pile foundation of the Shiyangtai No. 1 Bridge is discussed in depth through macro and micro analysis of the core soil samples of the overlying soil under the pile foundation of the bridge, experimental study of the physical characteristics, and numerical simulation of the bridge pile foundation in the goaf. Through the research in this paper, it is hoped that the research on bridge pier issues can be enriched, so as to lay a foundation for preventing the continuous lifting and deformation of bridge pile foundations, analyzing the causes of diseases such as the arching of bridge pile foundations, and laying a foundation for subsequent bridge lifting and remediation technical measures. The paper also provides theoretical references for the uplift and deformation of bridge pile foundation and the safe construction of bridges in practical engineering.

## 2. Engineering Background

The Shiyangtai No.1 Bridge is an important part of the Wujing Expressway. It is located in the WeiJialou section of Hengshan District, Yulin City, Shaanxi Province. It was completed and opened to traffic in October 2007. Since 2016, the Shiyangtai No.1 Bridge has experienced abnormal deck alignment. That year, the bridge was monitored on-site. Through the analysis of the monitoring data, it was found that some bridge pile foundations of the Shiyangtai No.1 Bridge had been lifted to varying degrees. Using data from this monitoring, Figure 1 depicts a diagram of the change in height difference of pier No. 8 from 2016 to 2018. It can be seen that the maximum uplift of the bridge is located at the right of pier No. 8, and the deformation value reaches 309 mm.

Due to the uplift of the bridge pile foundation, the bridge pier is cracked and deformed, the bridge railing is damaged and destroyed, the bridge subgrade is cracked and linearly changed (Figure 2). The structural stability of the bridge and the safety of traffic are seriously affected. This not only hinders the development of social economy in the region, but also poses a great threat to people's personal safety and to property safety to a certain extent.

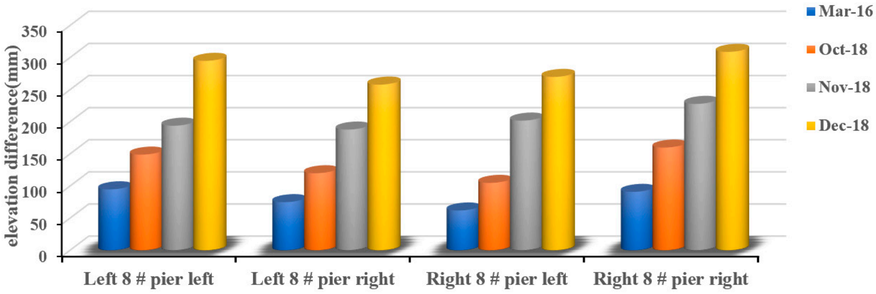



**Figure 1.** Variation of height difference of pier No. 8 of Shiyangtai No.1 Bridge.

(**a**) Bridge guardrail cracking

(**b**) Squeezed expansion joints

**Figure 2.** Bridge disease diagram of Shiyangtai No.1 Bridge.

## 3. Characteristics of Overlying Soil under Bridge Pile Foundation

According to the initial geological survey results of the Shiyangtai No.1 Bridge, it is found that the soil composition near the bridge site contains more soft clay, such as montmorillonite and illite, with strong hydrophilicity. Therefore, it can be concluded that the uplift of some pile foundations of the Shiyangtai No.1 Bridge may be related to the expansion characteristics of the soil in the overlying soil layer under the bridge foundation. Therefore, three geological boreholes were drilled near the anomaly of the No. 8 pier of the Shiyangtai No.1 Bridge, and the depth of each hole was approximately 15 m (the depth of the pile foundation is about 16 m). The specific locations of the drill holes are shown in Table 1 below. These holes were made to investigate the correlation between the basic characteristics of the rock and soil under the bridge pier and the uplift of the bridge pier.

**Table 1.** List of drilling location.

| Shiyangtai No.1 Bridge | Drilling Number | Drilling Position |
|---|---|---|
| Left line | No.1 borehole | 4.6 m on the left side of pier No. 8 |
| | No.2 borehole | Pier No. 8 small pile side 3 m |
| Right line | No.3 borehole | 3.4 m on the left side of pier No. 8 |

### *3.1. Macro and Micro Analysis of Rock and Soil Mass*

#### 3.1.1. Analysis of Rock and Soil Composition

The soil samples (as shown in Figure 3) were sent to the Xi'an Mineral Resources Supervision and Inspection Centre of the Ministry of Land and Resources for component analysis. It is found that the core soil samples in three boreholes near pier No. 8 of the Shiyangtai No.1 Bridge contain different proportions of montmorillonite. At the location of the ZK1 borehole, the content of montmorillonite is the largest, between 2% and 8%, and the maximum reaches 7.24%. The montmorillonite content of the other two core samples is around 3%, with a maximum of 4.71%. It can be judged that there are different proportions of clay minerals with strong hydrophilicity in the core soil samples of the overlying soil layer under the pile foundation of the Shiyangtai No.1 Bridge.

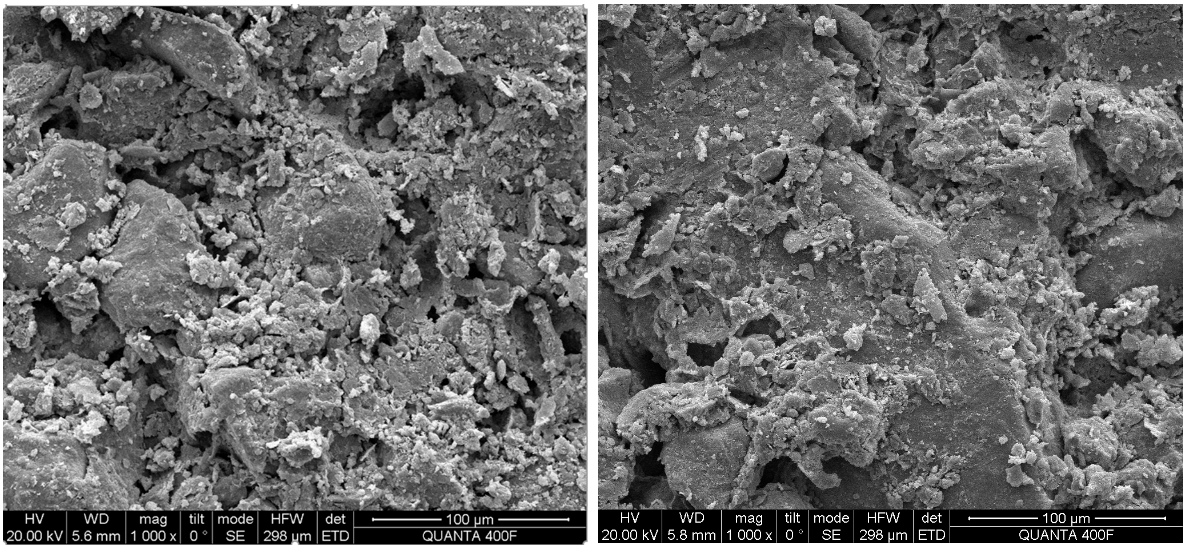
(**a**) ZK1 soil sample (**b**) ZK2 soil sample

(**c**) ZK3 soil sample

**Figure 3.** Drilling core soil samples. The Chinese characters in the figure only indicate the depth and type of rock samples, which has little influence on the research content of this paper.

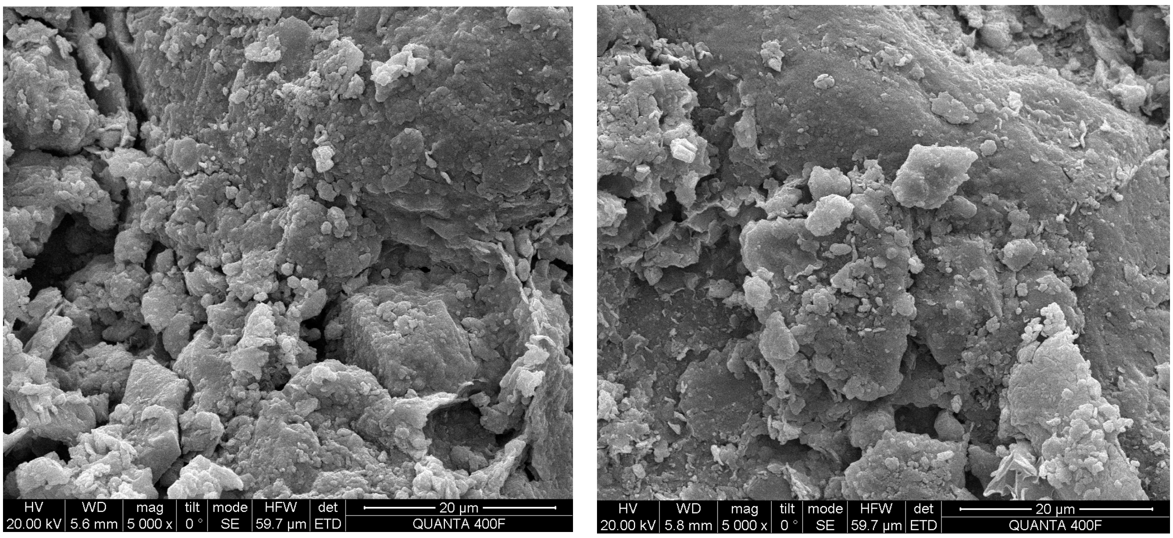
3.1.2. Micro Analysis of Rock and Soil Mass

The obtained rock and soil samples were subjected to SEM examination, and the core samples were placed in the oven for drying treatment for 2 h. The particle morphology of rock and soil before and after immersion was observed under the microscope at 1000 and 5000 times, and the changes of particle morphology of soil microstructure before and after immersion were observed, as shown in Figures 4 and 5 below.




(**a**) Before soaking (**b**) After soaking

**Figure 4.** Micro-particle morphology of soil samples before and after soaking (1000 times).



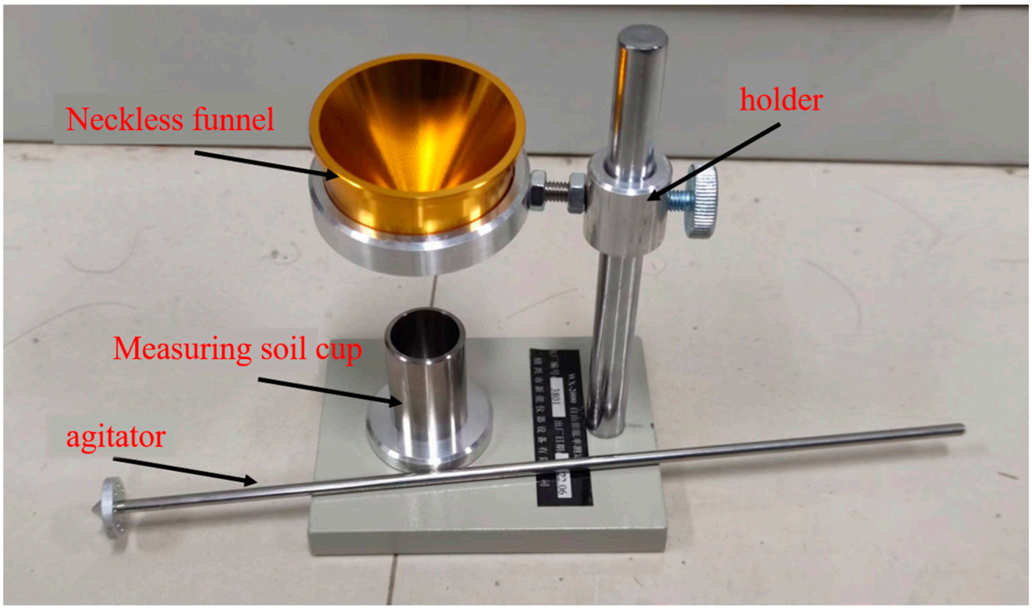

(**a**) Before soaking (**b**) After soaking

**Figure 5.** Micro-particle morphology of soil samples before and after soaking (5000 times).

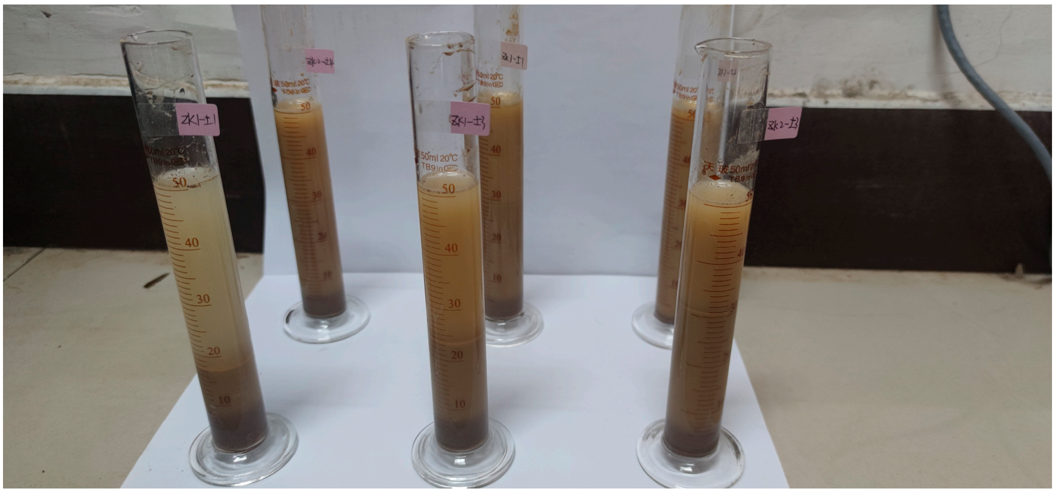
Figures 4 and 5 demonstrate that at 1000× and 5000× magnification, the soil sample exhibits large particle pores and irregular distribution. However, after being fully absorbed in water for 2 h, the soil expands and the pores between particles become smaller, resulting in a denser internal structure. It can be concluded that the rock and soil mass beneath the pier of Shiyangtai No.1 Bridge has a significant potential for expansion in the overlying soil layer.

*3.2. Free Expansion Rate Test*

To determine the expansion potential of expansive soil in the overlying soil layer of Shiyangtai No.1 Bridge, we conducted a free expansion rate test on six groups of soil samples. Each group was taken from the highest montmorillonite content in each borehole coring soil. The free expansion rate tester (Figure 6a) was used to calculate the free expansion rate of the soil samples.




(**a**) Free expansion rate measuring instrument



(**b**) The measuring cylinder is stationary for 24 h

**Figure 6.** Free expansion rate test.

The volume change values of six groups of soil samples were measured by the free expansion rate test, and the free expansion rate of the overlying soil under the pier of Shiyangtai No.1 Bridge was obtained. Table 2 shows that the free expansion rate of the six groups of soil samples ranges from 20% to 60%, with an average of 44%. It should be noted that the loose degree of soil particles can affect the size of the free expansion rate and introduce test errors during the volume measurement process, leading to underestimation of the actual free expansion rate. Based on the free expansion rate test, it can be concluded that the expansive soil in the overlying soil layer under pier No. 8 of the Shiyangtai Bridge No.1 has a free expansion rate of approximately 50%. Therefore, it can be classified as weak expansive soil with low expansion potential.

**Table 2.** Free expansion rate test results.

| Drilling Number | Sample Number | Volumetric Change (mL) | Free Swelling Ratio (%) |
|---|---|---|---|
| ZK1 | ZK1-Soil sample 1 | 4.2 | 42 |
| | ZK1-Soil sample 2 | 5.3 | 53 |
| ZK2 | ZK2-Soil sample 1 | 2.5 | 25 |
| | ZK2-Soil sample 2 | 5.1 | 51 |
| ZK3 | ZK3-Soil sample 1 | 3.5 | 35 |
| | ZK3-Soil sample 2 | 5.7 | 57 |

### 3.3. Load Expansion Rate Test

The top layer of rock and soil with expansion characteristics will experience additional stress in its current state. When it expands in water, external stress will hinder its expansion potential. Therefore, the uniaxial consolidation instrument was used to determine the expansion potential of the expansive soil beneath pier No. 8 of the Shiyangtai No.1 Bridge under the conditions of self-weight load of the upper bridge and pile end load. The load expansion rate test instrument and samples are shown in Figure 7.

(**a**) Consolidator

(**b**) Expanded soil specimen

**Figure 7.** Load expansion rate test.

The load expansion rate test of 10 kPa constant axial pressure was applied to the core soil sample in the overlying soil layer near pier No. 8 of the selected Shiyangtai No.1 Bridge using the consolidation instrument. The deformation of the soil sample after soaking expansion was measured to obtain the expansion rate of the expansive soil in the overlying soil layer under constant load conditions. The specific test data is presented in Table 3.

**Table 3.** Load expansion rate test results list.

| Drilling Number | Sample Number | Initial Mass (g) | Initial Height (mm) | Sample Deformation (mm) | Load Expansion Rate (%) |
|---|---|---|---|---|---|
| ZK1 | ZK1-Soil sample 1 | 89.5 | 21.00 | 0.14 | 0.67 |
| | ZK1-Soil sample 2 | 85.5 | 21.00 | 0.20 | 0.95 |
| ZK2 | ZK2-Soil sample 1 | 83.6 | 20.00 | 0.06 | 0.30 |
| | ZK2-Soil sample 2 | 87.1 | 20.00 | 0.15 | 0.75 |
| ZK3 | ZK3-Soil sample 1 | 85.7 | 20.00 | 0.11 | 0.55 |
| | ZK3-Soil sample 2 | 82.6 | 21.00 | 0.23 | 1.09 |

Table 3 shows that the test soil samples exhibited varying degrees of deformation after full immersion. The six groups of soil samples in this test experienced deformation ranging from 0.06 mm to 0.23 mm under a constant load of 10 kPa axial compression, with the maximum deformation being 0.23 mm. The load expansion rate was calculated based on the maximum deformation of the sample under the most unfavorable conditions. Specifically, the sample's expansion deformation under 10 kPa axial compression reached 0.23 mm, resulting in an expansion rate of 1.09%. It is assumed that the 2 m stratum under pier No. 8 of Shiyangtai No.1 Bridge consists entirely of expansive rock and soil mass. Based on the ratio, the underground expansive soil only expands 23 mm when encountering water, which is significantly less than the expected 309 mm. Therefore, it can be concluded that the impact of expansive soil on the uplift deformation of certain piers of Shiyangtai No.1 Bridge is minimal.

## 4. Numerical Simulation of Pile Foundation in Goaf

Human engineering activities, such as coal mining, can have a significant impact on nearby structures. Specifically, in the case of the Shiyangtai No.1 Bridge located in Weijialou, Jingbian County, the bridge passes through the coal seam occurrence area, and the goaf formed by coal mine excavation poses a threat to the nearby bridge structure. The goaf left behind during coal mining can significantly impact the stability of bridge pile foundation structures. Therefore, it can be inferred that coal mining may be a primary factor contributing to the abnormal uplift of certain bridge pile foundations of the Shiyangtai No.1 Bridge. To investigate this, the FLAC3D software was used to simulate the impact of coal mine goaf on the bridge pile foundations.

### *4.1. Establish a Numerical Model*

Prior to modelling, an on-site investigation was conducted to plan the route scanning area of the Shiyangtai No.1 Bridge. Aerial photography of the bridge research area was then carried out using the DJI Jingling UAV to obtain multi-directional photos of the bridge area with centimeter-level accuracy. The software Photoscan was used to import the pictures and create an aerial three-dimensional geomorphological model of the Shiyangtai No.1 Bridge area, as shown in Figure 8.

However, this model cannot be used directly for numerical simulation calculations. Therefore, additional software is required for processing and transformation to make it suitable for numerical simulation. Figure 9 shows the processing flow. This map is shown in Figure 10.


**Figure 8.** UAV aerial photography three-dimensional map.

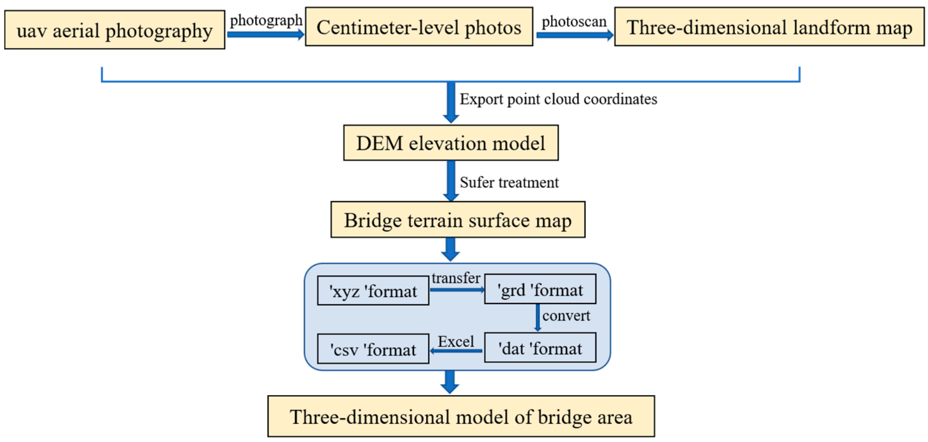



**Figure 9.** Flow chart of 3D model establishment.

The above steps generate a three-dimensional aerial model of the bridge and a three-dimensional topographic map of the study area of the Shiyangtai No.1 Bridge, which can be used for numerical simulation.

Figure 10 illustrates the process of generating a three-dimensional terrain model of the bridge study area. First, the terrain surface map is obtained. Then, the 'csv' format data, which is convenient for Rhino recognition, is used to generate point cloud data through its text processing function. Finally, the embedded surface function is employed to establish the three-dimensional terrain model. The curve extrusion command is used to create a three-dimensional numerical simulation model entity with a bottom surface. To conduct more refined research due to the large range of aerial photography, certain areas of the bridge, such as the left and right line No. 8 and No. 9 bridge pile foundations, were selected for numerical simulation research by cutting. The numerical simulation research area is shown in Figure 11a. Based on the stratigraphic data, the physical stratum in the study area is divided. A three-dimensional solid grid is obtained by dividing the area using a griddle. The model size is 160 m × 80 m × 90 m (length × width × height). The three-dimensional solid grid file is exported using the griddle, which can be identified by FLAC3D to generate the numerical simulation model, as shown in Figure 11b.

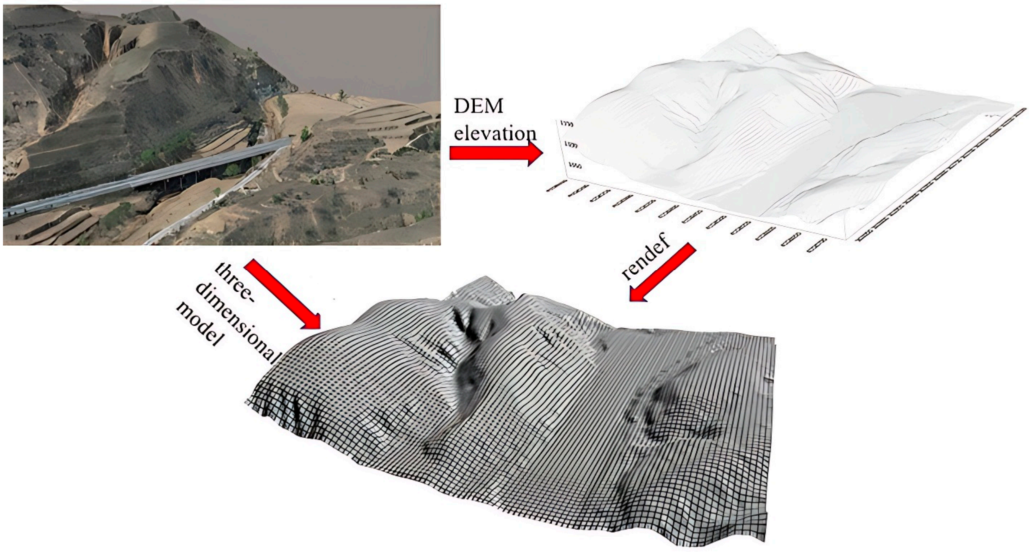
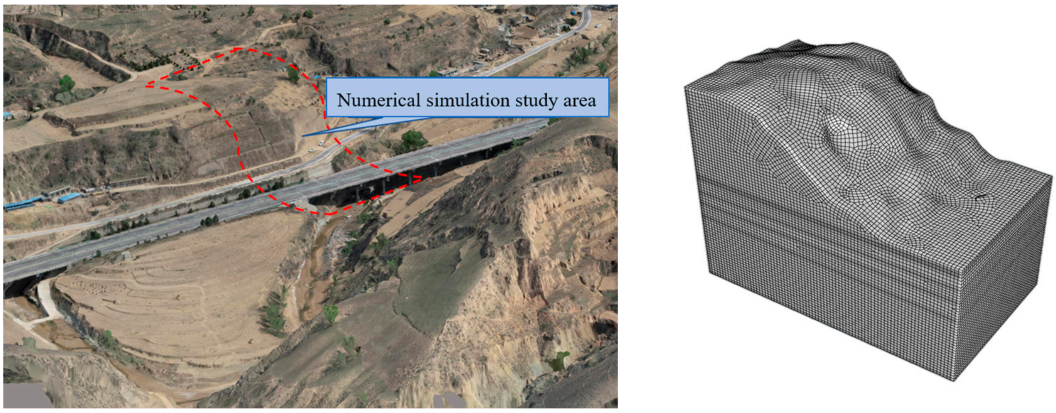



**Figure 10.** Three-dimensional surface of bridge area.




(**a**) Numerical simulation study area (**b**) Model meshing

**Figure 11.** Calculation model of study area.

### *4.2. Model Parameters and Boundary Conditions*

#### 4.2.1. Constitutive Model and Parameters

Based on geological survey and drilling data, the strata from top to bottom consist of surface pebble soil, loess, strongly weathered siltstone, moderately weathered siltstone, and sandstone. The stratigraphic structure has been simplified according to actual data. The rock and soil mass are considered special elastic–plastic materials that follow the Mohr–Coulomb criterion. The physical and mechanical parameters of the rock and soil mass in the study area were obtained through laboratory tests and field experience. These parameters are presented in Table 4 below:

**Table 4.** Model rock and soil parameters table.

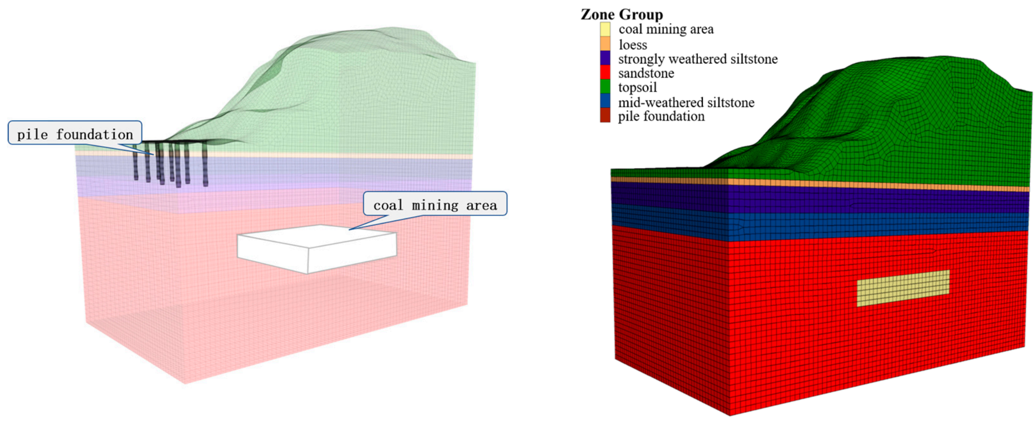
| Soil Horizon | Gravity $\gamma$/(kN·m$^3$) | Elastic Modulus *E*/MPa | Poisson $\mu$ | Cohesion *c*/kPa | Friction $\varphi$/(°) |
|---|---|---|---|---|---|
| Topsoil | 16 | 30 | 0.35 | 22 | 32 |
| Loess | 15 | 16 | 0.30 | 35 | 20 |
| Strongly weathered Siltstone | 20 | 5200 | 0.30 | 120 | 25 |
| Mid-weathered Siltstone | 23 | 5800 | 0.25 | 305 | 29 |
| Sandstone | 24 | 6350 | 0.25 | 350 | 30 |

The numerical simulation area of the Shiyangtai No.1 Bridge comprises eight bridge pile foundations numbered 7, 8, 9, and 10. The pile foundations are arranged with a diameter of 1.8 m, a single row spacing of 20 m, and a convergence of 10 m between the left and right lines. The pile length is 16 m, and C40 concrete was cast in situ. The main materials used for the bridge pile foundation of the No.1 Yangtai Bridge are concrete and steel structures. The properties and material parameters of concrete and steel are quite different. However, in practical engineering, the concrete composition in the bridge pile foundation structure is much larger than that of steel. The bridge goaf simulation aims to analyze the displacement deformation and stress distribution of the bridge pile foundation structure. Therefore, in the numerical simulation process, the bridge pile foundation structure can be considered a homogeneous solid element. Thus, to balance the effect of the steel bar, the elastic modulus of the concrete can be suitably increased in the parameter selection. For simulating the bridge pile foundation, the linear elastic model was chosen. Table 5 presents the material parameters of the bridge pile foundation.

**Table 5.** Pile foundation material parameter table.

| Name | Grade of Concrete | Gravity $\gamma/(\text{kN}\cdot\text{m}^3)$ | Poisson $\mu$ | Elastic Modulus $E$ |
|---|---|---|---|---|
| Pile foundation | C40 | 25 | 0.2 | $3.25 \times 10^4$ |

The goaf of the coal mine is located in the underground area of piers 7 and 8. The Yangtai No.1 Bridge is situated in the Hengshan District of Yulin City. After investigating over 20 township coal mines in the Hengshan District of Yulin City, it was found that the coal seams in the mining area are shallow, with most being over 100 m, and the overlying strata are thin, with a minimum of 10 m. If the goaf is buried deep enough, it does not affect the foundation of the bridge piles. Thus, the goaf's buried depth is limited to approximately 70 m, with an impact range encompassing piers 7 and 8. This makes the goaf suitable for pier uplift. Figure 12a displays the goaf's layout diagram.




(**a**) Goaf layout map (**b**) Numerical simulation model diagram

**Figure 12.** Goaf model and grid division.

However, it is impossible to obtain the influence range, specific structure, and subsidence state of the goaf in the overlying soil of the Shiyangtai Bridge No.1 due to economic and technical limitations. Therefore, the size of the goaf could only be considered under ideal conditions in the modeling process. To verify the influence of the coal mine goaf on the bridge pile foundation, a simplified goaf model was used. The goaf's simplified model is a cuboid measuring 50 m × 50 m × 10 m (length × width × height). Figure 12b below shows the numerical simulation model of the goaf's impact on the pile foundation.

#### 4.2.2. Boundary Conditions

To prevent discrepancies between numerical simulation displacement deformation results and the actual project caused by boundary condition setting errors, it is necessary to limit the model's boundary conditions based on the actual situation during the modeling and analysis process. Based on the actual displacement and deformation of the bridge pile foundation in the goaf of the Shiyangtai No.1 Bridge, the following boundary conditions have been established for the numerical simulation model:

(1) The upper part of the pile foundation and its soil surface are free surfaces and are not limited.
(2) The bottom surface of the model is constrained in the X, Y, and Z directions and is fixed in its support.
(3) Constraints have been set on both sides of the X direction of the model.
(4) The model's front side in the Y direction is unconstrained, while the rear side is constrained.

### *4.3. Analysis of Simulation Results*

Following the excavation of a coal mine goaf, the surrounding rock and soil mass undergoes significant stress disturbance, leading to the redistribution of stress. This results in what is known as the secondary stress field. It is important to note that coal mining and the remaining goaf can have an impact on the adjacent bridge pile foundation. For a visual representation of the stress and displacement fields in the vertical direction of the coal mine goaf on the bridge pile foundation, please refer to Figures 13 and 14 below.

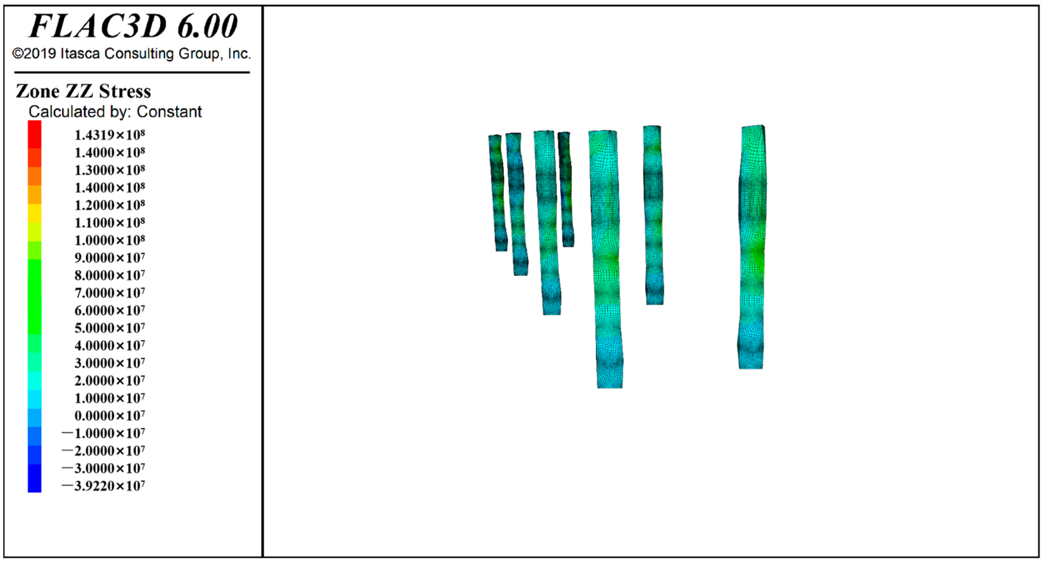



**Figure 13.** Stress field of pile foundation after coal mining.

Figure 13 shows the stress results of the bridge pile foundation. It is evident that coal mining causes a redistribution of stress in the soil, significantly affecting the pile foundation. The stress in the pile foundation is concentrated mainly in the middle and upper parts, with a maximum of 143 MPa in the vertical upward direction. The upward tensile stress on the pile foundation is caused by the extrusion effect of coal mine goaf on the rock and soil mass, which generates shear stress. The compressive stress is the smallest at the contact point between the pile foundation and the rock and soil. Based on the simulation results presented in Figure 14, the vertical displacement of the bridge pile foundation decreases progressively from top to bottom. This indicates that the pile foundation has been uplifted, with a maximum uplift displacement of 255 mm. This value is consistent with the actual monitoring of the elevation of pier No. 8 of the Shiyangtai No.1 Bridge. It can be concluded that the abnormal uplift of some pile foundations of the Shiyangtai No.1 Bridge is mainly caused by the influence of coal mine goaf, as the amplitude change of 309 mm is almost the same.

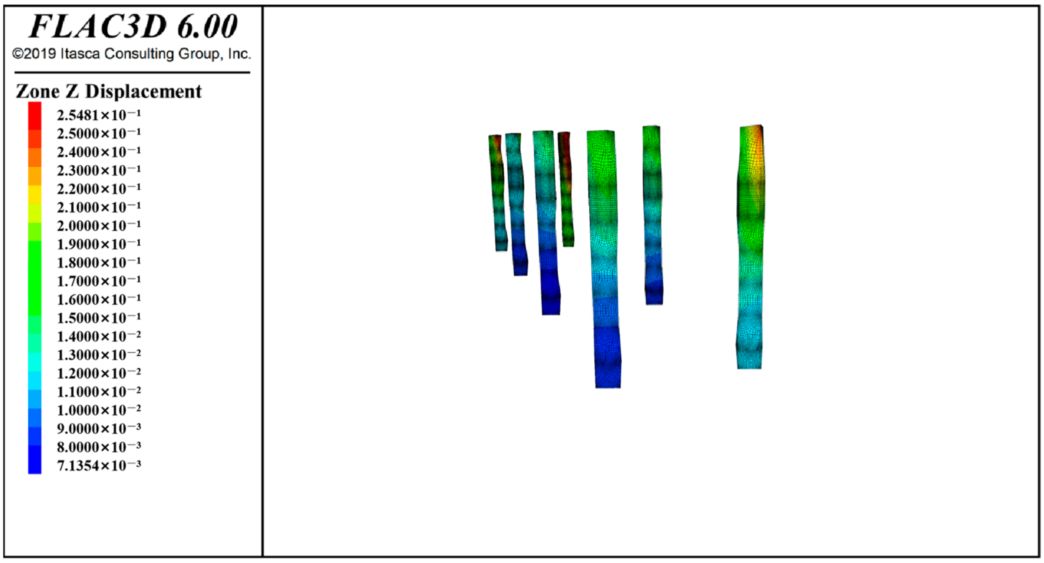



**Figure 14.** Displacement field of pile foundation after coal mining.

*4.4. Mechanism Analysis of Goaf Affecting Pile Foundation Uplift*

The numerical simulation results indicate that the goaf has a similar influence on the bridge pile foundation as the actual monitoring value. Based on the goaf, the uplift mechanism of the bridge pile foundation is analysed. Figures 15–19 show the horizontal stress diagram of the rock and soil mass, which includes the section analysis of the bottom and top of the goaf, below the pile foundation, and in the middle of the pile foundation.

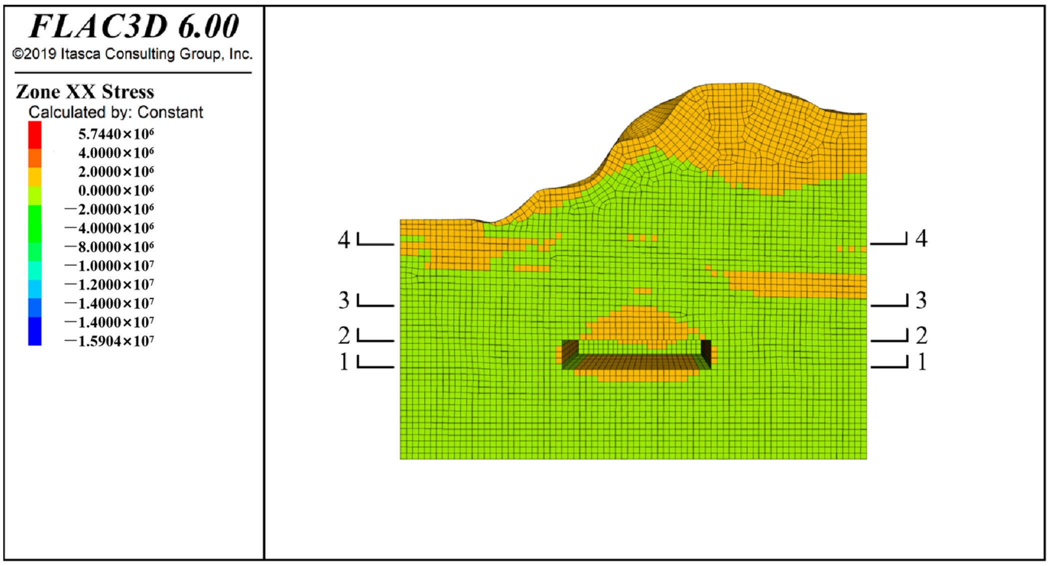



**Figure 15.** Horizontal stress diagram after coal mining. 1-1 indicates the cross section.

Figures 16 and 17 illustrate the horizontal stress diagram of the bottom and top sections of the goaf. The stress in the direction of the bridge pile foundation is evident in both areas, with a maximum value of 1.2 MPa. Stress in this area is generated towards the bridge pile foundation. This occurs after the roof of the goaf loses its bearing capacity and collapses, causing the rock and soil mass in the upper loose area to collapse. As a result, the soil accumulates at the bottom and top of the goaf.

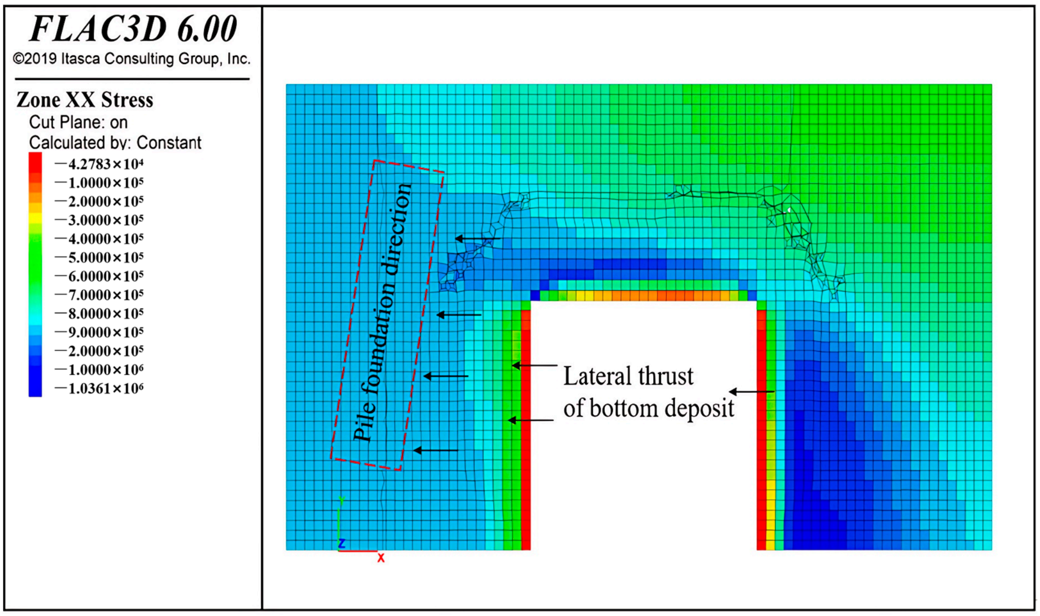



**Figure 16.** 1-1 horizontal stress diagram.

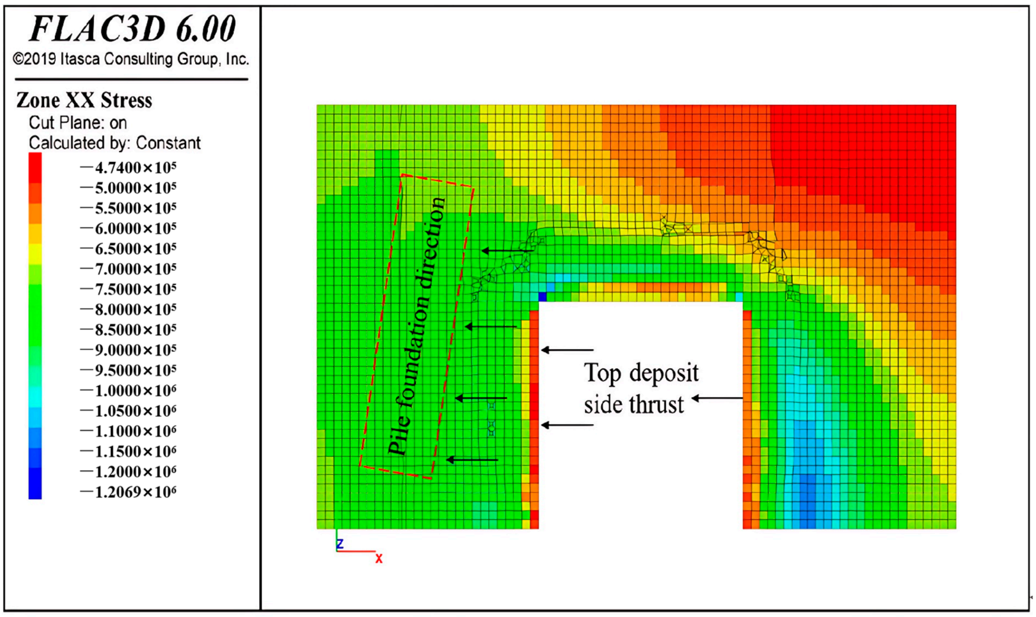



**Figure 17.** 2-2 horizontal stress diagram.

Based on Figure 18, it is evident that the stress in the direction of the bridge pile foundation is only produced in the top area of the goaf, reaching 5 MPa, which is higher than the stress at the bottom and top sections of the goaf. This is due to the formation of an arched cavity structure after the collapse of the rock and soil mass in the loose area of the upper part of the goaf. The stress is redistributed under the influence of the self-weight of the upper rock and soil mass. The arched cavity structure's vault experiences self-weight stress from the upper rock and soil mass, resulting in stress on the arch foot facing the bridge pile foundation.

The stress in the rock and soil mass directly above the goaf and around the bridge pile foundation can be determined from the horizontal stress of the section of the bridge pile foundation in Figure 19. The maximum stress value is 3.38 MPa, which is less than the side thrust of the collapse arch of the 3-3 section but greater than the side thrust of the accumulation body of the 2-2 section. After the upper roof of the goaf failed and collapsed, the rock stratum moved and deformed. This caused stress and deformation which extended to the area surrounding the goaf. The lateral thrust generated by the accumulation body and the collapse arch, combined with the lateral thrust generated by the deformation, caused stress release. This occurred when the lateral thrust value propagated to the surface and the soil around the pile foundation, which was offset by a part. Under double lateral thrust, sandstone soil layers may experience interlayer dislocation, resulting in uplift and deformation. This process will continue until a new stress balance is achieved in the rock stratum.

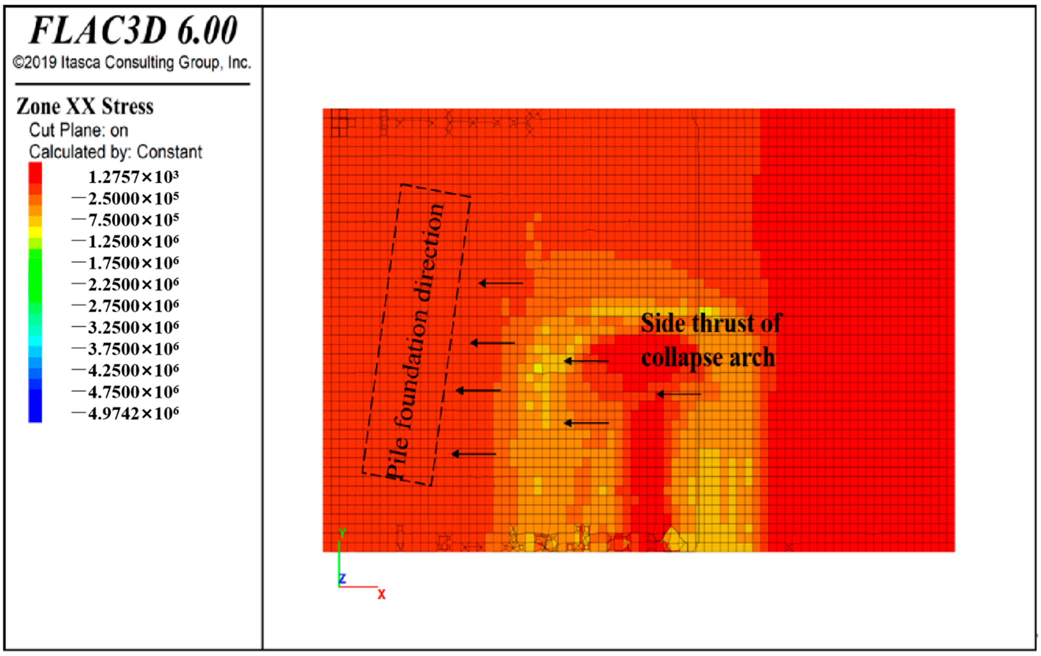



**Figure 18.** 3-3 horizontal stress diagram.

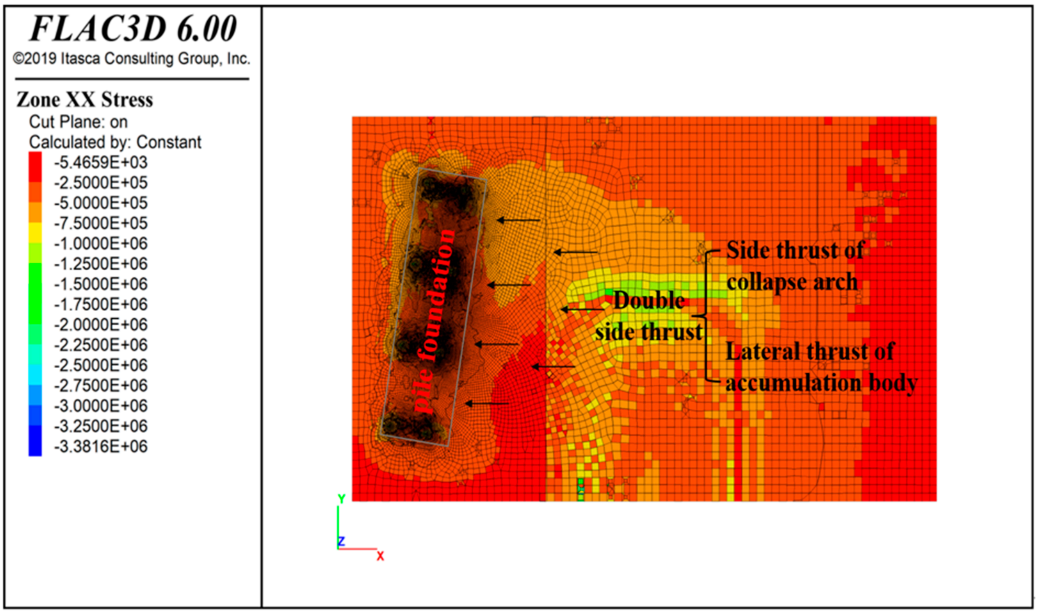



**Figure 19.** 4-4 horizontal stress diagram.

The analysis in Figures 20–23 examines the vertical stress of the rock and soil mass in relation to the bridge pile foundation's upward movement caused by the squeezing pressure from the double lateral thrust.

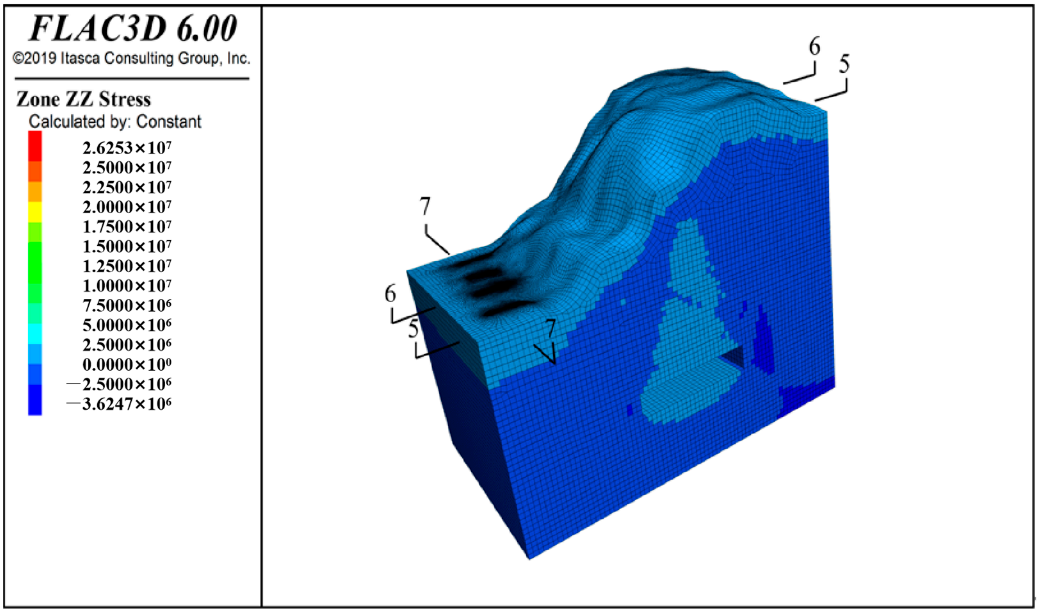



**Figure 20.** Vertical stress diagram after coal mining. 5-5, 6-6, and 7-7 indicate the profile direction.

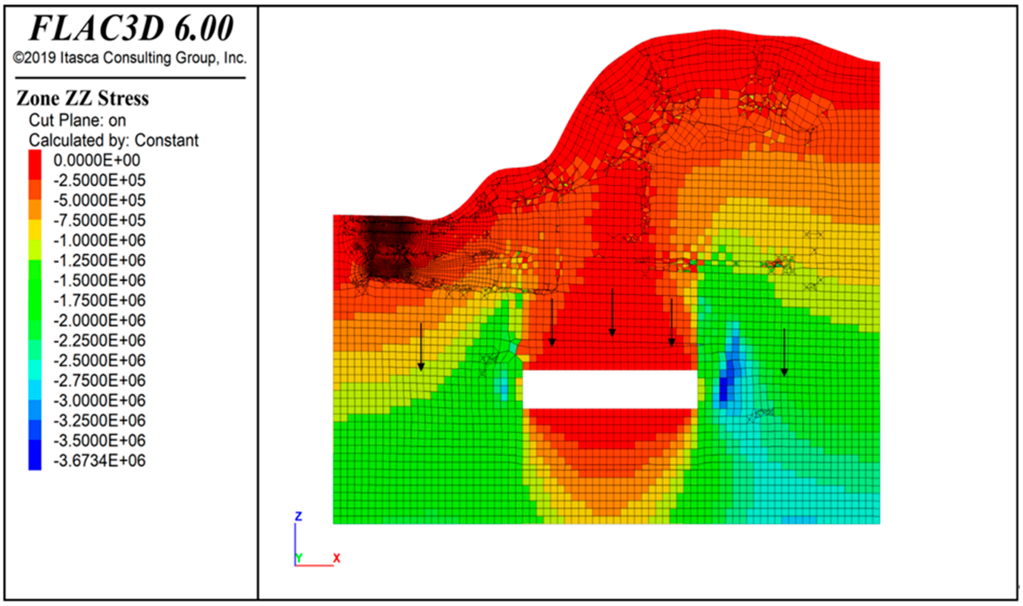



**Figure 21.** 5-5 vertical stress diagram (X-Z). The arrows in the figure represent the gravity of the overlying soil. The white part in the figure is the part of simulated underground goaf.

Figure 21 shows that the goaf and pier edge section experience vertical downward compressive stress, with a maximum of 3.67 MPa. This is due to the collapse of the goaf roof at the edge position, which causes the soil to collapse downward under the influence of the surrounding upper rock's self-weight. Based on the vertical plane stress diagrams in Figures 22 and 23, it is evident that the vertical upward stress is below the bridge pile foundation and the bottom pile end soil, with a maximum stress of 2.5 MPa. The upward extrusion pressure is caused by the interlayer dislocation of the sandstone strata due to the double lateral thrust generated by the deposit and collapse arch. The maximum load on the upper part of the pier is 3618 kN, and the stress area of the pile pier is 2.54 $m^2$. The maximum stress value calculated for the pier is 1.42 MPa, which is lower than the vertical upward extrusion force of 2.5 MPa. This can cause the pier to lift up to 30 cm.

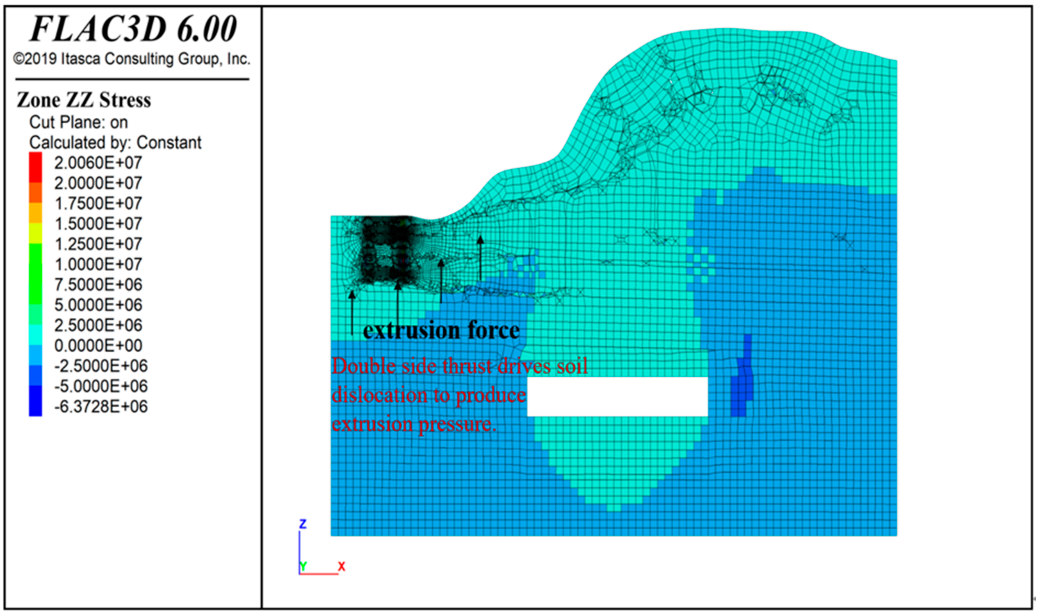



**Figure 22.** 6-6 vertical stress diagram (X-Z).

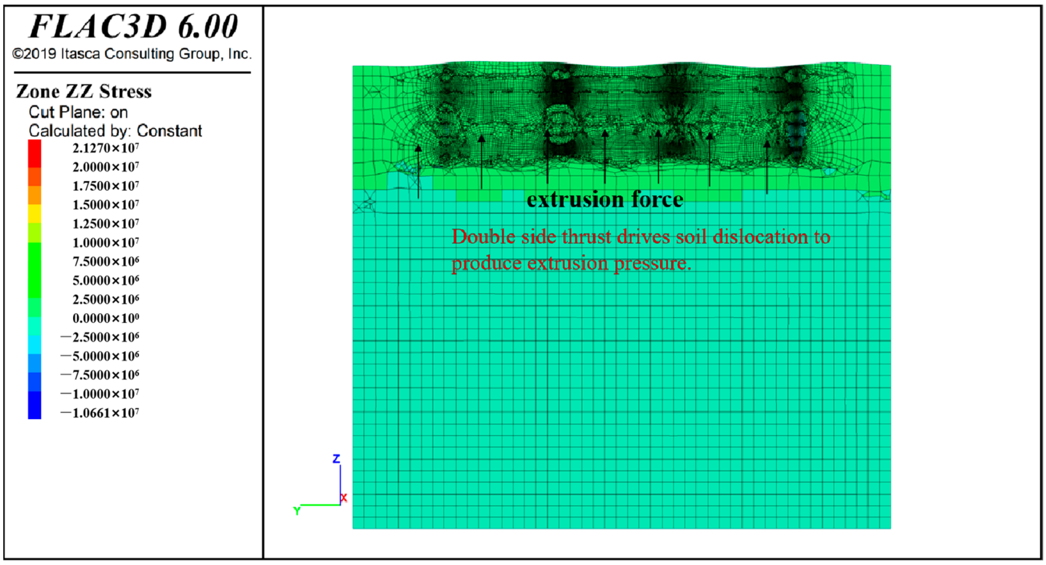



**Figure 23.** 7-7 vertical stress diagram (Y-Z).

In summary, the uplift of some pile foundations of the Shiyangtai No.1 Bridge is mainly caused by the influence of the coal mine goaf. The goaf left over by coal mining has evolved over time, causing the upper roof of the goaf to lose its bearing capacity, leading to collapse and deformation. Due to the gravitational pull of the surrounding rock on the upper mountain, loose rock and soil in the upper area collapse and fall to the bottom of the goaf, resulting in side thrust on the accumulation body facing the direction of the bridge pile foundation. The collapse of the loose zone causes the overlying rock and soil mass to bend into a stress arch, forming an arch-shaped cavity structure known as a collapse arch. The structure of the rock layer in the vault can be seen as a composite arch plate beam structure that supports the weight of the surrounding rock of the upper mountain. The roof of the plate beam arch bears the weight of the surrounding rock of the mountain and sinks, causing the arch foot part to produce the collapse arch side thrust facing the bridge pile foundation. The stratum of the study area consists of layered sandstone and siltstone. The lateral thrust of the accumulation body and the double lateral thrust of the collapse arch cause interlayer dislocation of the soil layer. This leads to dislocation bending uplift between the soil, resulting in a vertical upward extrusion force. The displacement and deformation of the bridge pile foundation and the rock and soil mass will continue to develop until the rock strata in the goaf reach a new stress balance. The abnormal uplift of the pile foundation and the bridge pile foundation occurs due to this phenomenon. Figure 24 shows a schematic diagram of the abnormal uplift mechanism of some pile foundations of the Shiyangtai No.1 Bridge affected by the goaf.

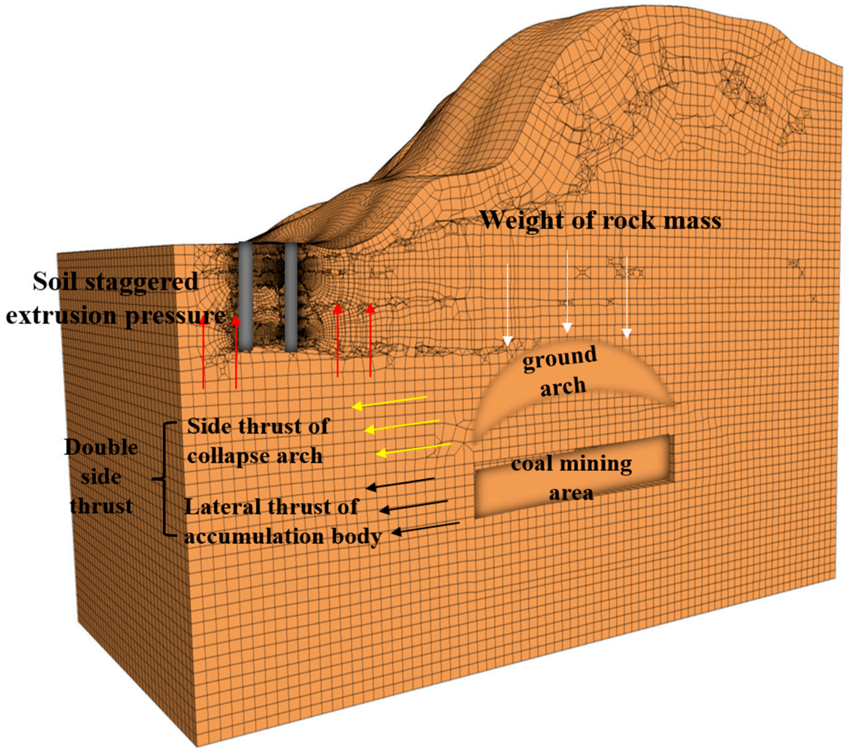



**Figure 24.** Schematic diagram of pile foundation uplift mechanism.

## 5. Conclusions

This paper examines the Shiyangtai No.1 Bridge of the Wujing Expressway as the research object. The study analyses the influence of numerical simulation of the bridge pile foundation in the goaf through macro and micro analysis of the core soil samples of the overlying soil drilling under the bridge pile foundation and the experimental study of physical characteristics. The mechanism behind the abnormal uplift phenomenon observed in some pile foundations of the Shiyangtai No.1 Bridge are discussed in depth. The following are the main conclusions:

(1) The soil layer beneath the pier contains weak expansive soil, with a maximum free expansion rate of 57%. Under ideal conditions, the axial compression is calculated in the same proportion. After the soil sample expands in water, it cannot generate enough force to cause the bridge pile foundation to rise upward.

(2) This study conducts a numerical simulation to determine the degree of influence of FLAC3D on the pile foundation in the goaf. The results indicate that the pile foundation experiences uplift after coal mining, with a maximum uplift displacement of 255 mm. This value is comparable to the 309 mm uplift amplitude of pier No. 8 of the bridge in the actual monitoring. Therefore, it can be concluded that the goaf is the primary cause of the abnormal uplift of some pile foundations of the Shiyangtai No.1 Bridge.

(3) The analysis of the pile foundation uplift mechanism revealed that the roof of the coal mine goaf collapsed and deformed due to the loss of its bearing capacity. The self-weight of the surrounding rock of the upper mountain caused a double lateral thrust of the accumulation body and the collapse arch. This led to interlayer dislocation

of the sandstone soil layer and vertical upward extrusion pressure. The maximum pressure reached 2.5 MPa, which was 1.42 MPa higher than the initial stress value of the pier. This can cause abnormal uplift of the soil around the pile foundation and the bridge pile foundation.

(4) According to previous studies [18], there are two ways to alleviate the uplift deformation of pile foundations: one is stress relief, that is, to eliminate or weaken the side thrust on the pile foundation caused by the collapse of the goaf and to cut off the propagation path of the side thrust. The second is to increase the resistance and increase the anti-slip resistance between the pile foundation and the rock and soil layer, so as to control the displacement amount and displacement rate of the key parts.

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**Conflicts of Interest:** Lian-Hua Wang was employed by the company China Railway 23rd Bureau Group Corporation Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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