

Geological Investigation and Slope Stability Analysis of the Archaeological Excavation Trench at the Zhouqiao Bridge Site and Bianhe Canal Ruins, Kaifeng

Wenjing Zhang¹, Haitao Yan^{1,*}, Yanhong Li¹, Qingwen Ma², Qizheng Xiang¹

¹Henan Provincial Institute of Cultural Heritage and Archaeology, Zhengzhou, 450000, China

²Zhengzhou University, Zhengzhou 450000, Zhengzhou, China

*Corresponding author's e-mail: yanhaitaopku@163.com

Abstract: Based on field investigations of the geological structure, stratigraphic lithology, and groundwater depth of the excavation trench slopes at the Zhouqiao bridge site and Bianhe canal ruins, Kaifeng, together with slope deformation monitoring data, the stability of the trench slope was studied by numerical simulation using the FLAC3D model. The results show that under the self-weight condition, the maximum displacement of the trench wall is 3.87 cm and the factor of safety (FOS) is 1.18, indicating a basically stable state; under the combined self-weight and earthquake condition, the maximum displacement reaches 7.23 cm and the FOS is 0.943, indicating an unstable state. These findings provide a data reference for the selection and implementation of reinforcement and protection measures for the slopes of archaeological excavation trenches.

Keywords: Grand Canal Cultural Belt; Zhouqiao bridge site; archaeological excavation trench; slope stability; reinforcement and protection.

1. Introduction

Kaifeng, an ancient capital on the bank of the Yellow River, has maintained a close relationship with water throughout its history. Once an important canal city possessing abundant canal cultural heritage, it is a vivid example of the interaction and symbiosis between the Grand Canal and the ancient cities along its course. In recent years, focusing on the construction of the Grand Canal Cultural Belt, Kaifeng has actively promoted the archaeological exploration and value investigation of the Grand Canal heritage within Dongjing, the capital of China's Northern Song Dynasty, laying a foundation for the adaptive reuse and public display of the canal heritage—work of outstanding academic value and practical significance.

Guided by the principle of "excavating, protecting, displaying, and researching simultaneously", the archaeological excavation of the Zhouqiao bridge site and adjacent Bianhe canal ruins in Kaifeng was officially launched in October 2018. With a total excavated area of 4,400 m², the excavation successively revealed the Bianhe canal channel, both banks of the channel, and the main body of the Zhouqiao bridge (Figure 1), and unearthed a large number of artifacts [1]. The bridge body and the canal ruins are important components of the Grand Canal heritage of Dongjing, the capital of China's Northern Song Dynasty, possessing extremely high historical, scientific, and social value, and the site was selected among China's top 10 archaeological discoveries in 2022.

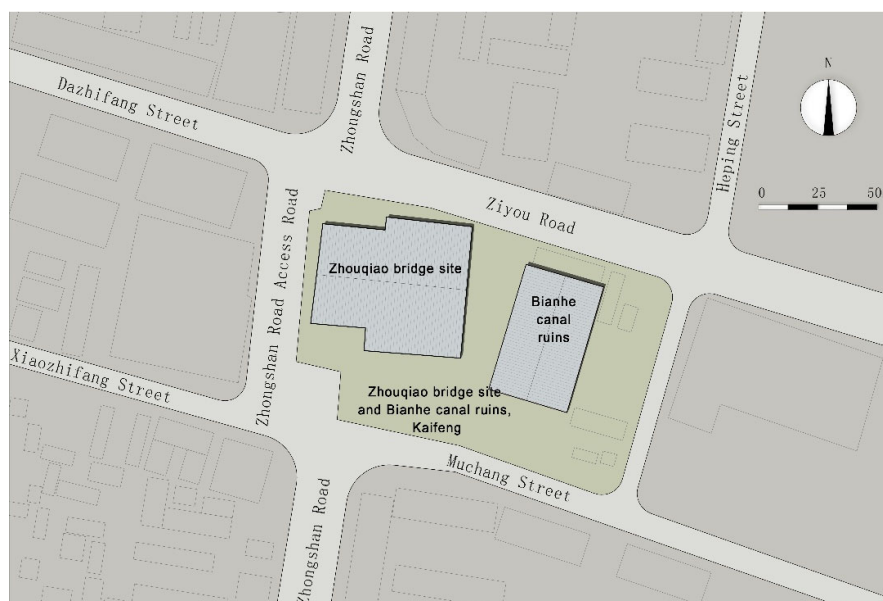


Figure 1. Urban location map of Zhouqiao bridge site and Bianhe canal ruins, Kaifeng

After the Zhouqiao bridge site and Bianhe canal ruins were excavated, their hosting environment (temperature, humidity, illumination, etc.) changed significantly. Affected by groundwater seepage, stress unloading, mechanical vibration, and other factors, the site soil has developed various types of deterioration, including weathering, cracking, collapse, structural instability, and biological weathering [2], among which the structural deterioration of the Bianhe canal ruins is particularly severe. The top of the excavation trench is approximately 50 m long in the north–south direction and 25 m wide in the east–west direction (Figure 2). Excavated in a stepped manner with seven terraces arranged vertically, the trench reaches a maximum exposed depth of 13.41 m, with a slope angle of approximately 48° (Figure 3), and it has been displayed in situ since the completion of excavation. Constrained by the early excavation conditions, the natural geology, the surrounding environment, and many other factors, the trench at the site is deeply excavated and steeply sloped, making the structural safety problems of the slope prominent and complex[3 - 5].

In previous conservation practice, excavation trenches in such environments have mainly relied on backfilling

protection. Although this measure can quickly isolate the site from the external environment and slow the development of deterioration, it severely restricts the interpretation and display utilization of the site's value and is therefore unsuitable for important sites of outstanding value. As a key node of the Grand Canal heritage of Dongjing, the capital of China's Northern Song Dynasty, the Zhouqiao canal ruins are of outstanding value; it is therefore necessary to properly protect the site body, ensure the structural safety of the rock–soil mass of the trench, and continue the in-situ display mode. Accordingly, studying the structural stability of the trench slope of the canal ruins is highly specific and complex yet imperative, and constitutes the focus and difficulty of the entire conservation work. This study systematically analyzes the hosting environmental conditions of the Zhouqiao canal ruins area, including its geological structure, soil stratification, and groundwater dynamics; a two-year slope displacement monitoring campaign was carried out on the trench, and the displacement under different working conditions was numerically simulated, so as to investigate the stability characteristics of the trench structure and provide data support for subsequent conservation engineering.

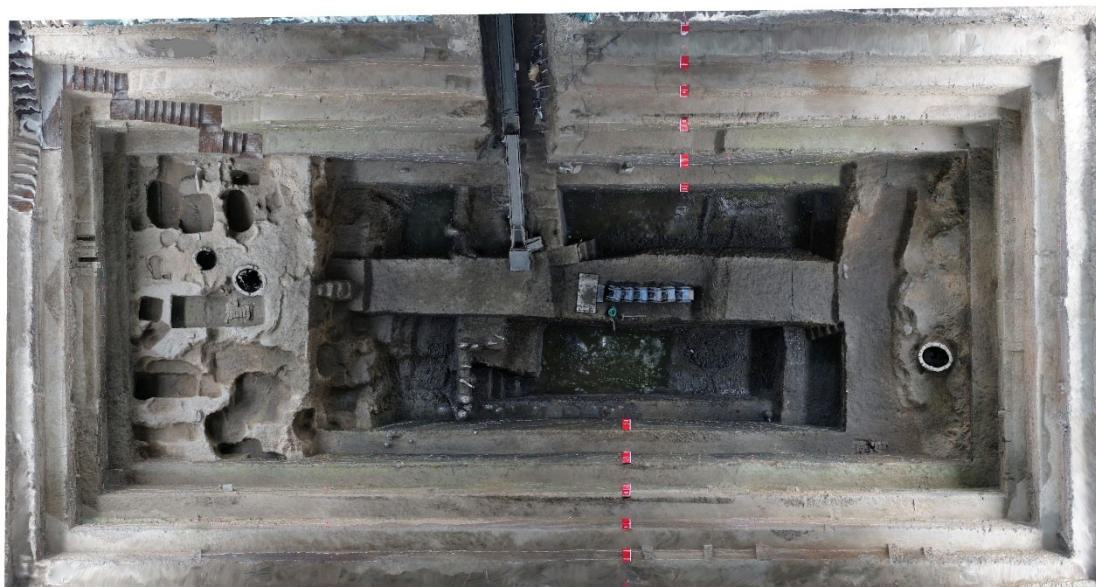


Figure 2. Top view of the excavation pit at the Bianhe canal ruins

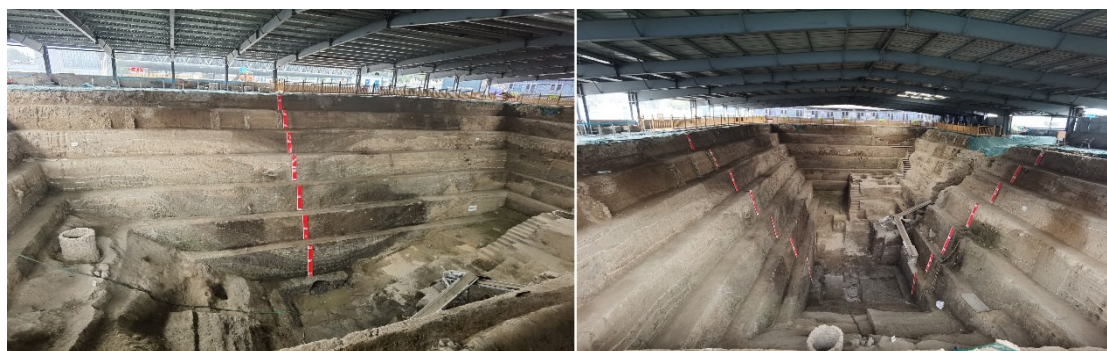


Figure 3. Internal view of the excavation pit at the Bianhe canal ruins

2. Site Preservation Environment

2.1. Geological Structure and Seismicity

Tectonically, the Bianhe canal ruins area of the Zhouqiao site belongs to the southern North China Block (SNCB),

specifically located in the central-southern part of the Kaifeng Depression of the Henan–Anhui fault block. Regional data [6 - 8] indicate that the Zhengzhou–Kaifeng fault zone is an important buried fault zone in the lower reaches of the Yellow River. This fault, the boundary-controlling fault on the southern margin of the Kaifeng Depression, is a regional

deep-seated fault superimposed by multi-phase active tectonics, controlling regional sedimentation and the development and evolution of the fault block. The fault zone starts from Zhengzhou in the west, passes eastward through Zhongmu County, Xinghuaying Town, and Kaifeng County, and extends northeastward, where it intersects the Xinxiang–Shangqiu fault (Fig. 4). The fault strikes approximately E–W and dips to the north, with the dip angle gradually flattening from shallow to deep, making it a listric normal fault. The fault zone consists of multiple subordinate near-E–W faults,

which from west to east are the Shangjie fault, Xushui fault, Zhongmu fault, North Zhongmu fault, and Kaifeng fault. The region surrounding the site is segmented by active faults, uplifts, and depressions, resulting in a relatively complex regional geological structure, and the near-field area possesses the tectonic conditions for moderate-to-strong earthquakes. These geological characteristics necessitate consideration of the potential influence of seismic action in the structural stability assessment of the site.

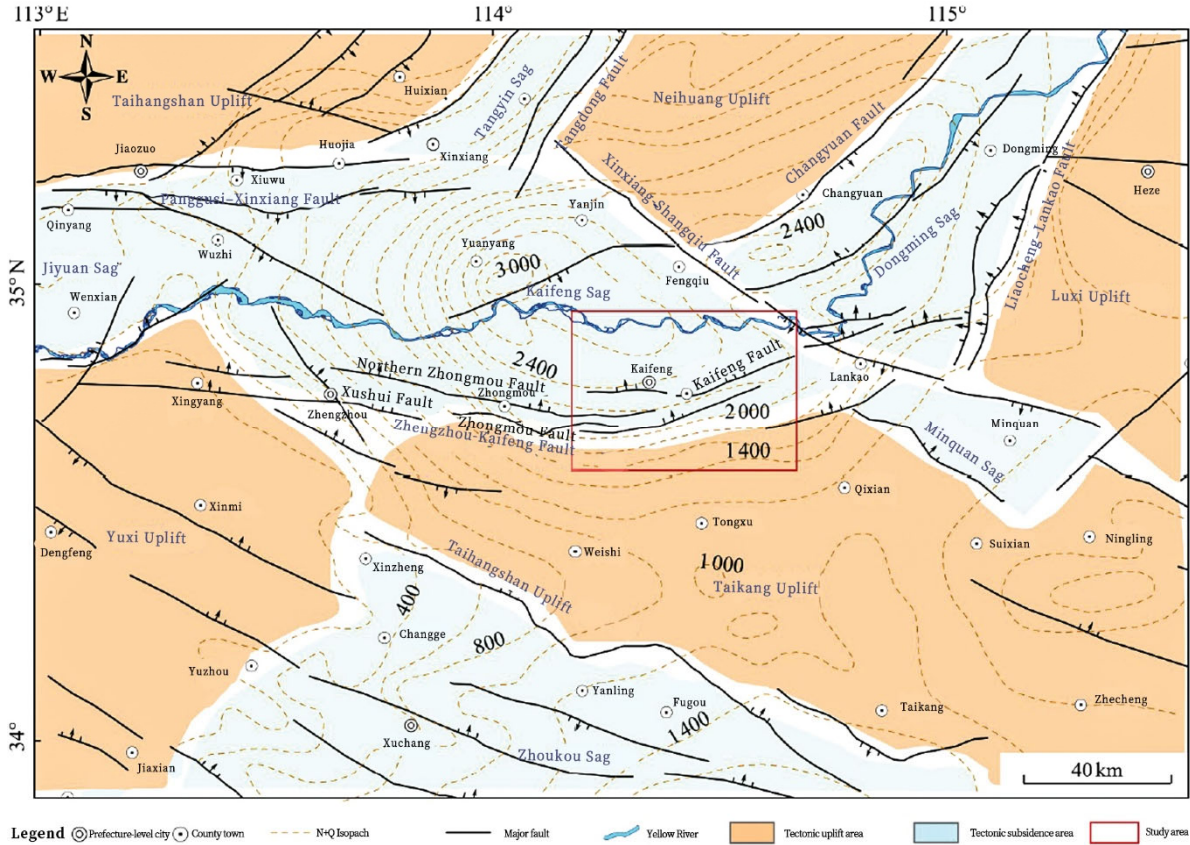


Figure 4. Regional Geological Structure Map of the Site Area

2.2. Stratigraphy and Lithological Characteristics

According to the geological investigation, the soil within the investigation depth of the Bianhe canal ruins area can be divided into five engineering geological units (Fig. 5), which differ significantly in genesis, particle composition, density, water content, inclusions, and uniformity. Layers ①–③ are recently deposited soils accumulated since the Holocene (Q4) cultural period, dominated by miscellaneous fill and silt, slightly dense and slightly moist, and mixed with abundant construction debris such as broken bricks and stones. The soil structure is loose and heterogeneous; surface water readily infiltrates and induces uneven settlement; transverse tensile cracks easily develop at the top of the trench wall; and local spalling or collapse readily occurs at the boundaries of the mixed debris. Layer ②, located in the middle-upper part of the trench wall, locally develops thin layers or lenses of soft-plastic silty clay with low shear strength, which soften upon contact with water and readily induce interlayer sliding. Layer ③, located in the middle-lower part of the trench wall, is thick (5.90 m on average) and wet, with continuously deteriorating shear strength; extreme rainfall or a rise in the

groundwater level will further aggravate softening deformation. Layers ④–⑤ are general sedimentary soils deposited before the Holocene (Q4) cultural period, dominated by silt, silty clay, and fine sand, slightly dense to medium dense, and very wet. This zone has long been eroded by groundwater (water table elevation 64.16–65.25 m), forming a controlling interface for slope toe failure. Layer ④ has a high clay particle content and poor permeability, readily causing perched water in the overlying layer; Layer ⑤ has a high sand content and good permeability, and the repeated rise and fall of the groundwater level induces cyclic seepage within the slope, so the soil is prone to leaching erosion, which may lead to internal erosion or piping[9 -12].

The investigation shows that the trench slope in the site area is a layered heterogeneous structure, with engineering deterioration showing obvious layer-specific differentiation, and the layer interfaces are zones of abrupt change in mechanical properties and zones of weakness. Layers ② and ③ are the key strata controlling the overall stability, while the interface between Layers ④ and ⑤ dominates the failure mode at the trench toe.

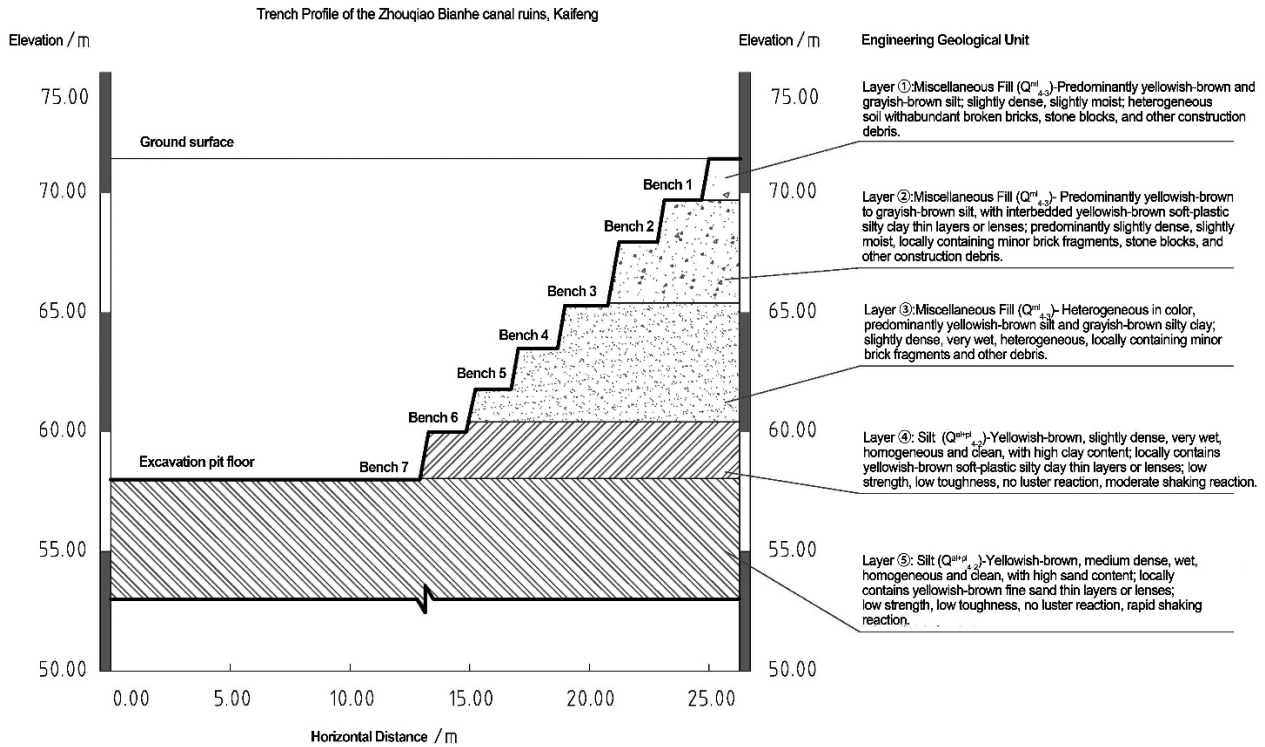


Figure 5. Geological Stratification Profile

2.3. Groundwater Conditions

The groundwater table in the Bianhe canal ruins area of the Zhouqiao site remains stable year-round at a depth of 6.4–7.4 m (absolute elevation of 64.16–65.25 m), and rises in summer to a depth of about 5.5 m (absolute elevation of 65.91 m). Groundwater is mainly recharged by atmospheric precipitation and the lateral runoff of surface water, shows significant seasonal fluctuations, and belongs to phreatic pore water in Quaternary loose rocks. The bottom of the trench has long been eroded by groundwater, which is closely related to the hydraulic action at the interface of Layers ④–⑤. According to the Code for Investigation of Geotechnical Engineering (GB50021-2001) (2009 edition), the environmental type of this site is Class II[13]. The fluctuation of the groundwater table exerts a periodic influence on soil strength and slope stability and is a key external factor inducing deterioration.

In summary, the Zhouqiao canal ruins area features a complex geological structure, distinctly layered and inhomogeneous soil stratification, and significant seasonal groundwater fluctuations, which together constitute the unique and complex hosting environment of the Bianhe canal ruins area. The natural environment, superimposed on the "deep" and "steep" characteristics of the free face of the archaeological excavation trench, complicates the mechanical behavior of the rock–soil mass of the trench and makes the risks to structural safety and slope stability prominent. Therefore, the subsequent design of conservation and display-utilization engineering at the site must be strictly based on detailed geomechanical model analysis, so as to ensure the safety and stability of the archaeological trench structure.

3. Displacement Monitoring and Data Analysis

3.1. Monitoring Scheme

Given the relatively complex geological structure of the site area and its engineering geological characteristics of "deep excavation, steep slope, and large area", a displacement monitoring network was deployed in key areas of the site to accurately characterize the deformation evolution of the trench slope. Specially installed cement piles on the site served as reference points, and characteristic points on the trench walls (at the tops of the surrounding trench walls) were selected as the monitoring objects. A total station was used to conduct surveys at monthly intervals and record displacement data[14 - 15]. A two-year displacement monitoring campaign was carried out beginning in early 2019, with data collected monthly, yielding 22 sets of valid data (Table 1); the maximum value of each month's monitoring data was selected for analysis.

3.2. Selection of Numerical Analysis Method

The excavation trench at the Bianhe canal ruins of the Zhouqiao site constitutes a continuum, heterogeneous slope problem characterized by a large volume, distinct stratification, and abrupt changes in mechanical properties at the interlayer interfaces. Among the numerical methods commonly used in rock and soil mechanics, the Discrete Element Method (DEM) is suitable for simulating the large-displacement problems of discontinuous media during instability; Discontinuous Deformation Analysis (DDA) focuses on high-precision kinematic solutions of block systems; the Numerical Manifold Method (NMM) realizes the full-process simulation of material behavior from continuous to discontinuous deformation through unified cover functions; and the Lagrangian method, based on the

three core computational principles of the discrete formulation, the explicit finite difference method, and the dynamic relaxation method, allows the element mesh to deform along with the material as it yields or undergoes plastic flow, making it suitable for simulating progressive failure, instability, and large deformation [16 - 18]. Its representative software, FLAC3D (Fast Lagrangian Analysis

of Continua in 3 Dimensions), is widely used in geotechnical engineering and geological hazard simulation [19 -20]. After comparison, the Lagrangian method best matches the hosting environment characteristics of the trench at the Zhouqiao canal ruins and was therefore adopted as the core analysis method in this study.

Table 1. Displacement monitoring data of the pit wall at the Zhouqiao Bianhe canal ruins

ID	Date	Monthly Max. Displacement (mm)	Cumulative Displacement (mm)
1	2019.3	0	0
2	2019.4	0.4	0.4
3	2019.5	0.9	1.3
4	2019.6	1.7	3
5	2019.7	2.0	5
6	2019.8	2.9	7.9
7	2019.9	3.1	11
8	2019.10	3.7	14.7
9	2019.11	3.3	18
10	2019.12	4.3	22.3
11	2020.1	5.1	27.4
12	2020.2	6.1	33.5
13	2020.3	6.7	40.2
14	2020.4	7.5	47.7
15	2020.5	7.1	54.8
16	2020.6	7.2	62
17	2020.7	7.7	69.7
18	2020.8	7.8	77.5
19	2020.9	7.4	84.9
20	2020.10	7.2	92.1
21	2020.11	7.6	99.7
22	2020.12	7.0	106.7

3.3. Calculation Model and Parameter Selection

The Mohr-Coulomb elastic-perfectly plastic model was adopted in this computation, as it can adequately describe the yielding and failure behavior of soil. Given the complexity and diversity of the factors affecting the actual slope at the site, the following basic assumptions were made to simplify the modeling and analysis: (1) the soil is regarded as a homogeneous, isotropic, elastic-plastic material; (2) the local influence of the inclusions within the trench on the mechanical parameters of the soil is neglected; and (3) groundwater and seepage effects are not considered.

A typical profile of the trench wall at the Bianhe canal ruins

was selected for the stability calculation and analysis. As the site is large in scale, AutoCAD and ANSYS were used to establish the numerical computational model of the slope and to perform mesh generation, and FLAC3D was used to conduct a quasi-three-dimensional simulation. The model coordinate system is defined as follows: the x-axis is horizontal, positive from the trench wall toward the outside; the y-axis is vertical, positive upward; and the z-axis is horizontal and longitudinal, positive toward the outside. The established model profile is shown in Fig. 6. The model is 20 m long in the x direction, 1 m in the y direction, and 17.5 m in the z direction.

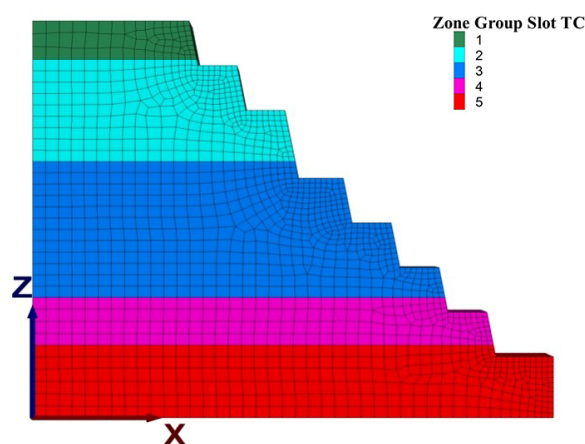


Figure 6. Calculation model profile of the Bianhe canal ruins pit wall

(1) Case I: Self-Weight Condition

The material property parameters required for the FLAC3D computation mainly include elastic deformation parameters and strength parameters, and the material density must also be input when gravity is considered. In general, a material in the elastic stage adopts an isotropic elastic model, described jointly by the bulk modulus (K) and the shear modulus (G), which can be converted from the elastic modulus (E) and Poisson's ratio (μ) as follows:

$$K = \frac{E}{3(1 - 2\mu)} \quad (3)$$

$$G = \frac{E}{2(1 + \mu)} \quad (4)$$

The basic physico-mechanical parameters of the soil were obtained through field drilling, sampling, and laboratory tests, and were comprehensively determined in combination with previous data, investigation data, and engineering experience analogy. The physico-mechanical parameters of each soil layer in the computational model under the self-weight condition are listed in Table 2.

Table 2. Calculation parameters for the pit slope model.

Layer	Thickness (m)	Natural Density (kg/m ³)	Elastic Modulus (MPa)	Poisson's Ratio	Bulk Modulus (MPa)	Shear Modulus (MPa)
1	1.5	1840	19.98	0.44	55.5	6.94
2	4.5	1610	26.22	0.42	54.63	9.23
3	5.9	1570	22.77	0.3	18.98	8.76
4	2.1	1610	26.22	0.42	54.63	9.23
5	3.2	1940	22.77	0.3	18.98	8.76

The simulation results show that under the self-weight condition, the FOS of the trench wall slope is $1.18 > 1.0$, indicating a basically stable state. The maximum displacement of the slope is 3.87 cm, located in the middle-lower part of the slope, which is consistent with the observed deformation characteristics. The potential sliding

surface is arc-shaped, distributed within the soil mass and cutting across multiple layers. The soil above this surface is mainly subjected to tensile stress and is prone to tensile failure, and local stress concentration may produce cracks. The soil near the sliding surface is mainly controlled by shear stress, and shear failure predominates.

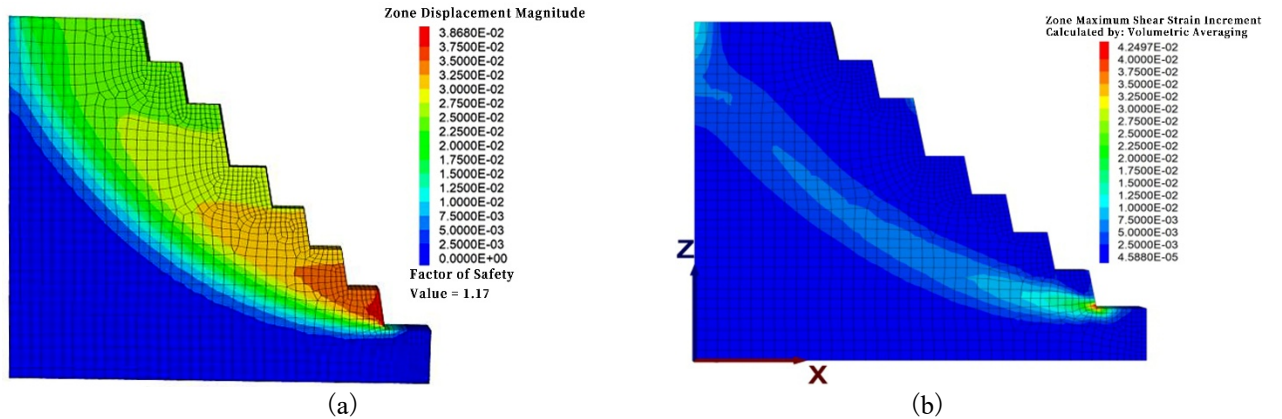


Figure 7. Contours of (a) displacement and (b) strain increment for the pit wall profile under Case I (self-weight) conditions

(2) Case II: Coupled Self-Weight + Seismic Condition

Under the combined self-weight and earthquake condition, the seismic action was simplified using the pseudo-static method: the seismic action was equivalently treated as unidirectional horizontal and vertical accelerations applied at the centroid of the potential sliding mass, with the acceleration direction set to the direction most unfavorable to slope stability. The specific calculation formulas are as follows:

$$F_{hi} = a_w W_i a_i \quad (5)$$

$$F_{vi} = F_{hi} / 3 \quad (6)$$

$$a_w = a_h \xi / g \quad (7)$$

(where F_{hi} and F_{vi} are the horizontal and vertical seismic forces acting on the potential sliding mass, respectively; a_w is the seismic coefficient; W_i is the weight of the potential sliding mass; a_i is the dynamic distribution coefficient; a_h is the design horizontal peak acceleration; ξ is the reduction factor; and g is the gravitational acceleration.)

Based on the above calculations, the deformation of the trench wall at the Bianhe canal ruins under the combined self-weight and earthquake condition was obtained, as shown in Fig. 8.

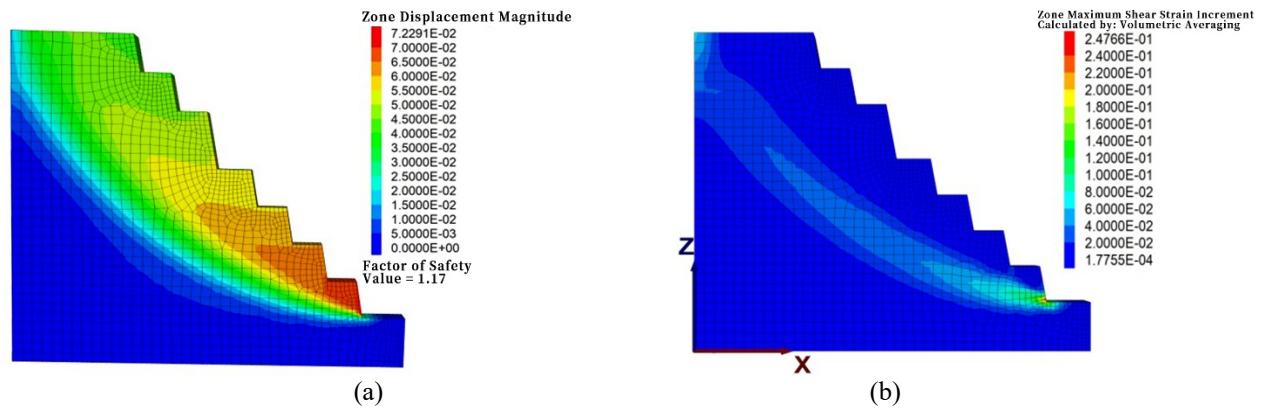


Figure 8. Contours of (a) displacement and (b) strain increment for the pit wall profile under Case II (self-weight + seismic) conditions

Analysis of the displacement contour maps and the numerical simulation results of the trench wall shows that under Case II, the displacement of the trench wall slope at the Bianhe canal ruins is 7.23 cm, and the FOS is $0.943 < 1.0$, indicating that the trench slope is in an unstable state.

4. Conclusions

Two years of continuous displacement monitoring revealed persistent lateral displacement at the top of the trench slope, totaling 106.7 mm. The rate was relatively high in the early stage and later stabilized at a high level (7.0–7.8 mm/month), indicating that the slope has developed a cumulative deformation trend under long-term loading, with no attenuation of the deformation rate; the slope is in a state of non-convergent creep, and its stability will face significant risk in the event of extreme rainfall or continued groundwater erosion of the foundation. The numerical simulation results further show that the maximum displacement of the slope under the natural condition is 3.87 cm, with an FOS of 1.18, indicating a basically stable state, whereas under the combined self-weight and earthquake condition, the maximum displacement increases to 7.23 cm, with an FOS of 0.943, indicating an unstable state. Although inclusions such as bricks, tiles, and plant fibers within the trench wall enhance the integrity of the soil to a certain extent, the bottom has long been eroded by groundwater, with stress concentration, and remains a structurally weak zone where major disasters such as landslides or collapse are likely to occur under seismic action.

The structural deterioration of the trench slope is the combined manifestation of a multi-layer heterogeneous soil mass under environmental factors (rainfall and groundwater) and dynamic loads (earthquakes, engineering activities, etc.). The loose and heterogeneous structure of the shallow miscellaneous fill, the potential sliding of the middle soft-plastic interlayer, the strength softening of the high-moisture layer, and the abrupt changes in the forces at the interlayer interfaces together constitute the internal conditions for slope instability. It is recommended that, in subsequent conservation engineering, a real-time monitoring and early-warning system be established promptly for the trench structure at the site, focusing on abrupt slope displacement and changes in hydrological conditions; that waterproofing, drainage, and local reinforcement works be implemented at the bottom of the trench wall; that strength improvement and drainage dewatering be carried out for

Layers ② and ③; and that waterproofing and seepage cutoff be implemented at the interface of Layers ④–⑤, so as to reduce groundwater erosion, disperse the concentrated stress at the slope toe, and improve the overall stability of the trench structure.

It should be noted that necessary simplifications were made in the model construction regarding soil homogeneity, the inclusions within the trench soil, and groundwater seepage; the results therefore mainly reflect the macroscopic mechanical behavior under the preset typical working conditions. Future research-oriented conservation work should further integrate multi-source monitoring data with dynamic simulation, deeply analyze the spatiotemporal evolution mechanism of slope deformation, and provide quantitative support and reference for the structural protection and risk control of excavation trenches at sites under similar geological conditions, thereby promoting the scientific and precise development of heritage conservation.

Acknowledgment

This work was supported by the Henan Province Key Research and Development and Promotion Special Project (Science and Technology Research) under Grant No. 222102320216.

References

- [1] Zhou, R. S. (2023). Excavation of the Zhouqiao Bridge and the adjacent Bian River site in Kaifeng. *Dazhong Kaogu* (Popular Archaeology), (8), 28–36. (in Chinese).
- [2] Zhang, W. J., Li, Y. H., & Yan, H. T. (2025). A preliminary analysis of deterioration types and causes in archaeological excavation units under heavy-rainfall conditions. *Wenwu Tiandi* (World of Antiquity), (11), 59–63. (in Chinese).
- [3] Bekele, A., & Tsegaye, G. (2025). Engineering geological characterization and slope stability analysis of soils along the Blue Nile Basin road section, northwestern Ethiopia. *Indian Geotechnical Journal*, 55(5), 3077–3101. <https://doi.org/10.1007/s40098-024-01106-1>
- [4] Bhardwaj, H., & Thakur, M. (2025). Slope stability analysis of the Mandi Landslide, Mandi, Himachal Pradesh, India. *Discover Geoscience*, 3, 146. <https://doi.org/10.1007/s44288-025-00258-8>
- [5] Wang, J., Zhang, W., Yin, H., Wang, Y., Han, J., & Chen, J. (2025). Stability analysis of a high-steep slope based on multi-scale structural geological model and 3D fracture

- p connectivity.
- Landslides*
- , 22(9), 3081–3094.
- <https://doi.org/10.1007/s10346-025-02541-8>
- [6] Yan, Z. P. (2009). Control function of geologic structure to the stability of elevated section of the lower Yellow River. *Yellow River*, 31(7), 16–17, 19. (in Chinese).
- [7] Wang, Z. S., & Ma, X. Q. (2018). The activity characteristics of Zhengzhou-Kaifeng Fault during Kainozoic. *Seismology and Geology*, 40(3), 511–522. <https://doi.org/10.3969/j.issn.0253-4967.2018.03.001> (in Chinese with English abstract).
- [8] Song, J. J., Tian, X. F., Wang, S. J., et al. (2021). Research progress of geological structure in the South North China and adjacent areas. *Progress in Geophysics*, 36(3), 940–952. (in Chinese with English abstract).
- [9] Liu, C. H., Chen, C. X., Feng, X. T., & Xiao, G. F. (2005). Effect of groundwater on stability of slopes at reservoir bank. *Rock and Soil Mechanics*, 26(3), 419–422. (in Chinese with English abstract).
- [10] Guo, J., Cao, H., Li, M., Zhang, W., & Wang, J. (2026). Stability analysis of residual soil slope with partially buried solitary rock block under rainfall conditions. *Journal of Mountain Science*, 23(4), 1758–1771. <https://doi.org/10.1007/s11629-025-9802-1>
- [11] Liu, F., Dong, Z., & Khayatnezhad, M. (2026). Parametric assessment of rainfall-related slope stability through SRM modeling and orthogonal experimental design: insights from the Zhuqudong slope, China. *Scientific Reports*, 16, 13091. <https://doi.org/10.1038/s41598-026-43289-y>
- [12] Belete, D., Chala, E. T., Jilo, N. Z., & Garo, T. (2025). Engineering geological investigation of the Katar Dam foundation and abutment slope stability analysis, southeast Ethiopia. *Indian Geotechnical Journal*, 55(3), 1563–1593. <https://doi.org/10.1007/s40098-024-01033-1>
- [13] Ministry of Construction of the People's Republic of China. (2009). GB 50021-2001, Code for investigation of geotechnical engineering (2009 edition). China Architecture & Building Press. (in Chinese).
- [14] Dong, W. W., Zhu, H. H., Sun, Y. J., & Shi, B. (2016). Current status and new progress on slope deformation monitoring technologies. *Journal of Engineering Geology*, 24(6), 1088–1095. (in Chinese with English abstract).
- [15] Harandizadeh, H., Jahed Armaghani, D., & Amiri, A. (2026). Application of integrated machine learning and digital twins for real-time monitoring and slope stability analysis. *Transportation Infrastructure Geotechnology*, 13, 162. <https://doi.org/10.1007/s40515-026-00925-4>
- [16] Griffiths, D. V., & Lane, P. A. (1999). Slope stability analysis by finite elements. *Géotechnique*, 49(3), 387–403. <https://doi.org/10.1680/geot.1999.49.3.387>
- [17] Matsui, T., & San, K. C. (1992). Finite element slope stability analysis by shear strength reduction technique. *Soils and Foundations*, 32(1), 59–70. <https://doi.org/10.3208/sandf1972.32.59>
- [18] Dawson, E. M., Roth, W. H., & Drescher, A. (1999). Slope stability analysis by strength reduction. *Géotechnique*, 49(6), 835–840. <https://doi.org/10.1680/geot.1999.49.6.835>
- [19] Wang, J., Zhang, W., Chen, D., Yin, H., & Chen, J. (2026). Multi-scale structural geological model and quantification of stability evaluation for a high-steep fractured rock slope. *Journal of Earth Science*, 37(2), 703–721. <https://doi.org/10.1007/s12583-023-1953-9>
- [20] Kou, X. D., Zhou, W. Y., & Yang, R. Q. (2001). Stability analysis of the high slopes of Three Gorges ship lock using FLAC-3D. *Chinese Journal of Rock Mechanics and Engineering*, 20(1), 6–10. (in Chinese with English abstract).