Review on the Research Progress and Future Trends of Slope Support Measures

Shuai Zhang[1], Lu Lu[2,*], Wei Liu[2], Kaiyin Li[2], Hao He[2], Liangsheng He[2]
[1]*Sichuan Chengnan Expressway Co., Ltd., Chengdu, China*
[2]*CCCC Highway Consultants Co., Ltd., Beijing, China*
**Corresponding Author*

Abstract: With the rapid development of infrastructure in China, the number of slopes created by excavations for roads, tunnels, and other engineering projects has been steadily increasing, accompanied by a rise in natural hazards induced by slope instability. Owing to the complex engineering geological conditions, slopes often require appropriate support measures after excavation to ensure operational stability. The strata typically comprise mudstone, sandstone, shale, or a combination thereof. The presence of soft rock significantly reduces the mechanical strength of the slope, rendering soft-rock slopes less stable compared to those composed of hard rock. Consequently, assessing the effectiveness of slope support measures is of critical importance. This paper presents a comprehensive review of domestic and international research on slope stabilization techniques, including prestressed anchor frameworks and anti-slide piles. The interactions between support structures and the surrounding geotechnical body are analyzed to provide a theoretical foundation for the design and optimization of future slope support measures.

Keywords: Slope; Support Measures; Stability; Structural–Geotechnical Interaction; Literature Review

1. Introduction

With the rapid economic development in China, infrastructure construction—including roads, bridges, and tunnels—has accelerated significantly. Numerous types of slope support structures have been implemented in these projects. A key challenge in slope support design is effectively balancing economic efficiency and safety. Proper slope reinforcement can substantially enhance stability while reducing the risk of deformation or landslides. Commonly employed slope support methods include prestressed anchor framework beams, anti-slide piles, soil nail walls, and retaining walls, either individually or in combination. This paper provides a concise review and analysis of slope support structures to inform the development and optimization of slope reinforcement systems.

2. Research Status and Development of Anchor Framework Beams

Anchor framework beams integrate the supporting function of a framework beam with the anchoring capacity of anchors. Anchors penetrate stable strata and interact with the surrounding geotechnical body to develop substantial anchoring force. Framework beams, arranged on the slope surface in a mesh-like configuration, interact synergistically with both anchors and the geotechnical body to reinforce the slope [1-3].

Fang et al. [4] analyzed the interaction between slopes and anchor framework beams, investigating how bedding orientation affects beam response. By introducing the concept of anchoring angle, they optimized relevant parameters using finite element analysis. Zhou and Zeng [5] suggested that for unstable soft-rock slopes, anchor spacing should be reduced and prestress levels moderately decreased; Figure 1 [5] illustrates the calculation section of a prestressed anchor. Zhu et al. [6] developed analytical solutions to study interactions between anchor framework beams and slope rock mass, evaluating their influence on internal forces. Field measurements were generally consistent with predictions from the Winkler elastic foundation model.

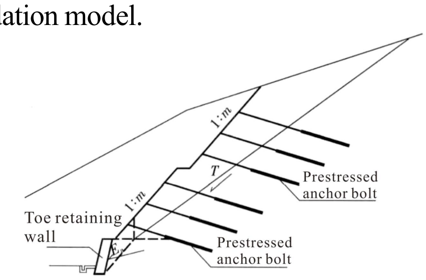


Figure 1. Schematic Diagram of the Calculation Section of the Prestressed Anchor

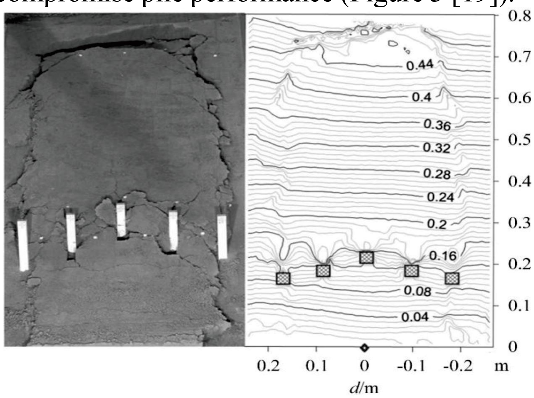
Yang and Zhao [7] conducted finite difference simulations to examine the effect of anchor framework beams on slope stability, finding that appropriate increases in anchoring inclination and length can significantly improve slope stability coefficients. Ye [8] analyzed the impact of removing anchor framework beams on red-bed soft-rock slopes, showing that potential slip surfaces gradually propagate toward the slope crest after excavation, with shear strain increments primarily in mudstone layers. The presence of anchor framework beams significantly enhances slope stability. Chang [9] evaluated the construction technology for prefabricated anchor framework beams, demonstrating its feasibility and effectiveness in improving slope stability while meeting construction requirements. Li [10] proposed a practical construction scheme for anchor framework beams and assessed its applicability.

Traditionally, anchor framework beams have been cast in situ. However, construction methods are progressively evolving toward prefabrication, intelligent construction, and diversified applications. Advancements in construction technology, as well as innovations in materials, have enabled anchor framework beams to play an increasingly important role in slope protection. Nevertheless, structural materials undergo strength degradation over time. Further research is needed to explore how advanced construction techniques can mitigate such deterioration. While studies have examined interactions between anchor framework beams and slopes at micro- and macro-scales, additional work is required in areas such as multi-field coupling, integration of diverse analytical approaches for data-driven modeling, and intelligent control of slope support systems using artificial intelligence.

3. Research Status and Development of Anti-Slide Piles

Anti-slide piles were first introduced in China in the 1950s for slope stabilization. Due to their effective resistance against sliding, they have been widely applied in landslide mitigation, motivating numerous studies [11-13] on their reinforcement mechanisms. Xie et al. [14] examined the interaction between anti-slide piles and the surrounding geotechnical body, proposing two mechanical models that elucidate the relationship between pile bearing capacity and horizontal displacement at the pile top, thereby providing a theoretical basis for design. Zhang et al. [15] conducted model tests on micro-piles combined with connecting beams, demonstrating that piles along the sliding direction reach plastic yielding first, and their elastic-stage deformation has the most significant impact on slope stability.

Jiang et al. [16] performed experimental model tests under various pile arrangements and reported that arched pile layouts reduce tensile cracks at the rear slope edge and enhance cooperative soil effects, thereby improving slope stability (Figure 2 [16]).Wei et al. [17] applied the strength reduction finite element method to optimize anti-slide pile layouts, concluding that placing piles near the central region of a slope maximizes stability improvement. Increasing pile density was found to be more effective than enlarging pile diameter. Hu et al. [18] investigated rainfall effects on anti-slide pile reinforcement, showing that surface erosion initially reduces the strength of shallow slope layers, and subsequent infiltration affects deeper strata. In this context, pile tops restrict displacement and improve overall stability. Chen et al. [19] studied the influence of pile anchorage length on homogeneous slope stability, demonstrating that deeper anchorage enhances anti-slide capacity. Deviations from the optimal anchorage depth alter stress distribution and may compromise pile performance (Figure 3 [19]).

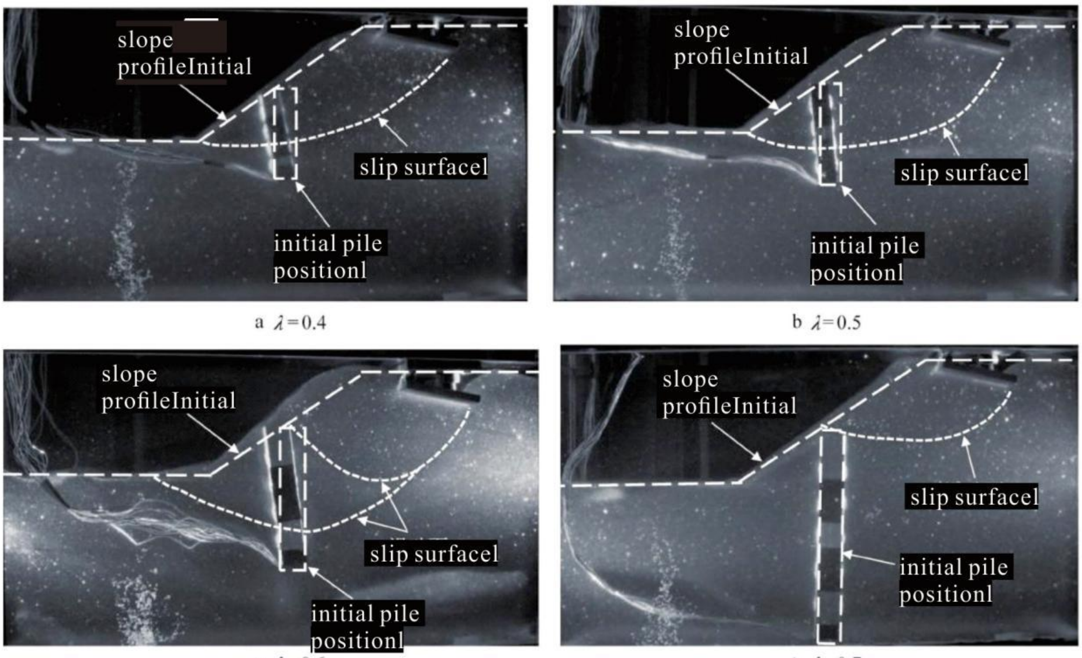


(a) Arching pattern of the slope surface soil

(b) Displacement field of the slope surface with arched pile arrangement

Figure 2. Slope Surface Displacement under Arched Pile Arrangement

The study of slope stability reinforced by anti-slide piles has evolved from traditional macroscopic and empirical analyses to multi-scale, refined approaches. Research on multi-scenario coupling effects—such as progressive deformations induced by prolonged rainfall or repeated seismic events—remains limited. Integrating monitoring technologies and artificial intelligence into analyses is essential for evaluating the evolution of pile performance over the full service life of slopes, thereby providing a theoretical basis for disaster prevention and mitigation.



a $\lambda=0.4$ b $\lambda=0.5$

a $\lambda=0.6$ b $\lambda=0.7$

Figure 3. Anti-slide Performance of Slopes under Different Anchorage Lengths

4. Conclusions

This paper reviews and analyzes the reinforcement effects and interaction mechanisms of anchor framework beams and anti-slide piles on slopes. Current research has expanded beyond traditional investigations of support structure–slope interaction, moving toward studies of multi-factor interaction mechanisms. Future research should increasingly integrate artificial intelligence and related technologies to provide visual, efficient, and precise guidance for slope disaster prevention and mitigation engineering.

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References

[1] Shi K, Wu X, Liu Z, et al. Coupled calculation model for anchoring force loss in a slope reinforced by a frame beam and anchor cables. Engineering Geology, 2019, 260: 105245.

[2] Zhang J, Li F, Zeng L, et al. Numerical simulation of the moisture migration of unsaturated clay embankments in southern China considering stress state. Bulletin of Engineering Geology and the Environment, 2021, 80(1): 11-24.

[3] Yang G, Zhong Z, Zhang Y, et al. Optimal design of anchor cables for slope reinforcement based on stress and displacement fields. Journal of Rock Mechanics and Geotechnical Engineering, 2015, 7(4): 411-420.

[4] Fang L, Duan L, Duan J, et al. Study on the interaction between isotropic rock slopes and prestressed anchor frame beams. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(1): 135-143.

[5] Zhou H, Zeng Z. Application analysis of prestressed anchor framework beams for slope reinforcement. Journal of Railway Engineering, 2013(3): 16-18, 85.

[6] Zhu D, Yan E, Song K. Interaction mechanism between lattice beams and slope rock mass and field experimental study. Chinese Journal of Rock Mechanics and Engineering, 2009, 28(z1): 2947-2953.

[7] Yang L, Zhao Y. Optimization of slope support schemes based on FLAC3D. Heilongjiang Science, 2024, 15(2): 51-55.

[8] Ye K. Stability study of the secondary excavation process of nearly horizontal red-bed slopes on the Chengnan Expressway [Doctoral dissertation]. Chengdu University of Technology, 2023.

[9] Chang Y. Application of prefabricated anchor framework beams in embankment slope protection. Traffic World, 2025(13): 57-59.

[10] Li D. Study on the protective technology of prefabricated anchor framework beams for embankment slopes. Shanxi Architecture,

2024, 50(1): 124-127, 142.

[11]Song Y, Hong W, Woo K. Behavior and analysis of stabilizing piles installed in a cut slope during heavy rainfall. Engineering Geology, 2012, 129-130: 56-67.

[12]Zhang Z, Xu Q, Chen J, et al. Geotechnical properties of a transparent glass sand saturated with a blend of mineral oils. Arabian Journal of Geosciences, 2017, 10(24): 534.

[13]Li C, Wu J, Tang H, et al. Model testing of the response of stabilizing piles in landslides with upper hard and lower weak bedrock. Engineering Geology, 2016, 204: 65-76.

[14]Xie H, Chen Z, Zhou H, et al. Preliminary study of a two-body mechanical model based on the interaction between engineering body and geological body. Chinese Journal of Rock Mechanics and Engineering, 2005, 24(9): 1457-1464.

[15]Zhang Y, Lei G, Yang W, et al. Experimental study on anti-slide mechanism of micro stabilizing pile–beam composite structure. Railway Architecture, 2022, 62(12): 162-166.

[16]Jiang T, Lei J, Wang R, et al. Model test study on the reinforcement effect of anti-slide piles under different pile arrangements. Journal of Applied Foundation and Engineering Science, 2019, 27(2): 404-417.

[17]Wei L, Yang C, Gao C. Optimization of anti-slide piles based on three-dimensional strength reduction finite element method. Chinese Journal of Geotechnical Engineering, 2005, 27(11): 1350-1352.

[18]Hu Q, Wang H, Zhou Y, et al. Influence of rainfall on slope stability reinforced by anti-slide piles. Journal of Hubei University of Technology, 2022, 37(4): 75-80.

[19]Chen J, Guo X, Tian D, et al. Influence of anti-slide pile anchorage length on sliding surfaces and anti-slide capacity of homogeneous slopes. Journal of Tongji University (Natural Science Edition), 2022, 50(1): 42-49.