Design and Application of Pre-support for Bedding Cutting Slope Excavation

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Abstract

Bedding cutting slopes are controlled by the occurrence conditions of rock formations. Under the coupling effect of excavation unloading and environmental factors, they are prone to delayed instability, which has become a core bottleneck in mountain transportation infrastructure construction. Aiming at the problems such as lack of systematic standards for pre-support discrimination, poor design adaptability, and fragmented processes, this paper takes typical highway slopes as samples. Through on-site investigation, laboratory tests, numerical simulation, and engineering verification, it analyzes the core influencing factors of stability, and identifies 6 types of typical failure modes and their evolution laws. A three-level classification system is constructed, and a four-step closed-loop pre-support process is innovatively proposed, clarifying the support selection and parameter design methods. Verified by numerical simulation and case studies, 6 types of slopes such as gently to moderately inclined soft rock slopes require key discrimination. The combined support of anchor (cable) and grouting has the widest adaptability, which can improve the slope safety factor and save costs. The research results provide theoretical support and technical solutions for the safety of bedding slopes, and are of great significance for disaster prevention and mitigation in mountain transportation infrastructure.

Keywords

Bedding Cutting Slope; Pre-Support Design; Engineering Application.

1. Introduction

With the in-depth advancement of the transportation power strategy in the western mountainous areas, the number of bedding cutting slope excavation projects has surged. Such slopes account for 68% of the rocky slopes in the western mountainous areas. Due to the bedding inclination characteristics of rock formations, they are prone to disasters such as sliding and collapse after excavation, which restricts project safety. According to data from the China Geological Survey, the instability of layered slopes accounts for 63% of the total rocky disasters, and the economic loss caused by bedding landslides exceeds 70%. For example, the slope collapse at Section K28+320 of the Puxuan Expressway resulted in a 3-month construction delay and emergency rescue costs of 2.1 million yuan. The traditional "support after excavation" mode reduces the shear strength of rock mass by 30%, greatly increasing the support difficulty. Although pre-support technology can actively reinforce the slope, problems such as chaotic discrimination standards, poor design adaptability, and fragmented processes urgently need to be solved[1].

Domestic and foreign studies have formed basic methods such as the limit equilibrium method and UDEC simulation, but the systematic classification and closed-loop process for the complex geology in western China are still lacking. Taking typical highway slopes as samples, this paper analyzes the influencing factors of stability, identifies 6 types of failure modes, constructs a three-level classification system of "rock stratum dip angle - slope height - lithological combination", and proposes a closed-loop process of "classification - discrimination - design - verification". Combined with engineering case verification, it provides technical support for the safety of mountain slopes[2].

2. Stability Analysis of Bedding Cutting Slopes

2.1 Influencing Factors of Stability

The stability of bedding cutting slopes is controlled by the coupling of internal, external, and temporal factors. The weight of each factor varies significantly and they interact with each other, jointly determining the instability risk and failure characteristics of the slope. Through statistical analysis of 186 engineering samples, the influence weights of lithological combination and rock stratum dip angle among internal factors reach 35% and 28% respectively, the influence weight of groundwater among external factors is 22%, and the temporal factor accounts for 15%.

2.1.1 Internal Influencing Factors

Internal factors are the basic control conditions for slope stability, mainly including lithological combination, rock stratum dip angle, and geological structure, among which lithological combination and rock stratum dip angle are core indicators.

Lithological combination and rock stratum dip angle are the core control factors of stability. The cohesion c of soft rocks (mudstone, shale) is only 18-25 kPa, and the internal friction angle φ is 19-22°. In contrast, the c value of slightly weathered limestone reaches 180-220 kPa, and the φ value is 35-40°, whose shear strength is 3-5 times that of soft rocks. In slopes with thick hard rocks interbedded with soft rocks, soft rock interlayers are prone to form sliding surfaces; in the structure with hard rocks on the upper part and soft rocks on the lower part, the plastic flow of the underlying soft rocks will cause tension cracking of the upper hard rocks[3].

The matching relationship between the dip angle of rock stratum and the excavation slope angle directly triggers instability. When the rock stratum dip angle is 22° and the excavation slope angle is 30°, the sliding shear force increases by more than 60% compared with the case where the two angles are equal; when the included angle between the strike of the rock stratum and the slope surface is less than 30°, a through sliding surface is easily formed, and the instability risk increases sharply.

The through weak interlayer in geological structure is a "fatal defect" for slope instability. The cohesion c of such interlayers is less than 20 kPa, the internal friction angle φ is less than 20°, and the shear strength is extremely low. A bedding slope in Chongqing contains a 0.5m-thick argillaceous weak interlayer. Before excavation, the safety factor was 1.2; after excavation, the mechanical parameters of the interlayer decreased sharply, the safety factor dropped to 0.92, and finally sliding instability occurred. The development degree of joints and fissures also affects stability. Dense joints cut the rock mass into blocks, destroying the integrity of the rock mass and reducing the overall bearing capacity[4].

2.1.2 External Influencing Factors

External factors are the inducing conditions for slope instability, mainly including groundwater, excavation disturbance, and seismic action, among which groundwater is the most active inducing factor.

Groundwater is the most active inducing factor for instability. A 1m rise in groundwater level can reduce the c and φ values of rock mass by 30%-50% and increase the sliding force by 20%. The collapse at Section K28+320 of the Puxuan Expressway was caused by a 2.3m rise in groundwater level due to heavy rain. When the charge per hole in blasting excavation exceeds 0.5kg, the vibration wave will form a relaxation zone within 10-15m of the slope surface. The instability risk of bedding excavation is 40% higher than that of cross-bedding excavation. Under the action of magnitude 7 earthquake, the safety factor of the slope needs to be increased by an additional 0.15-0.20, which is clearly stipulated in the Technical Code for Building Slope Engineering (GB50330-2013).

Excavation disturbance is the main man-made inducing factor for slope instability. The vibration wave generated by blasting excavation will lead to the expansion of rock mass structural planes. Tests show that when the charge per hole exceeds 0.5kg, the peak velocity of the vibration wave reaches 0.3-0.5 cm/s, which can expand the rock mass fissures by 0.5mm and form a relaxation zone within 10-15m of the slope surface, significantly reducing the rock mass strength. The excavation method also affects stability; bedding excavation easily damages the integrity of the rock stratum, and the instability risk is more than 40% higher than that of cross-bedding excavation.

Seismic action changes the stress state of the slope through inertial force. Under the action of magnitude 7 earthquake, the safety factor of the slope needs to be increased by an additional 0.2 to ensure stability, which is clearly required in the Technical Code for Building Slope Engineering (GB50330-2013). The vibration caused by the earthquake will also aggravate the expansion of rock mass fissures, reduce the shear strength of the weak interlayer, and induce delayed instability.

2.1.3 Temporal Influencing Factors

Temporal factors are mainly reflected in the long-term effects of rock mass creep attenuation and environmental erosion. Soft rock has significant creep characteristics. Under long-term load, the deformation of the rock mass increases continuously with time, and finally reaches the critical state of failure. The instability delay period of gently inclined soft rock slopes can be up to 6 months. The initial deformation is small, which easily leads to the delay of support decision-making due to the illusion of "initial stability"[5].

The long-term effect of environmental erosion also reduces the rock mass performance. Rainwater scouring intensifies the weathering of the slope surface rock mass, and the long-term immersion of groundwater continuously softens the weak interlayer. These factors together lead to the gradual decrease of slope stability over time.

2.2 Analysis of Typical Failure Modes

Based on the statistical analysis of 127 unstable slope projects, the failure mode of bedding cutting slopes is closely related to the rock stratum dip angle and lithological combination. A total of 6 types of typical failure modes are identified, and the distribution ratio and engineering characteristics of each mode are significantly different[6]. Among them, the sliding-tension cracking type accounts for the highest proportion (32%); the plastic flow-tension cracking type and the wedge sliding type account for 21% and 18% respectively; the sliding-bending type, sliding-compression shear-out type, and sliding-splitting type account for relatively low proportions, which are 13%, 10%, and 6% respectively. The systematic analysis of the formation conditions, typical lithology, and stability characteristics of various failure modes provides targeted basis for pre-support design, as shown in Table 1.

Table 1. Typical Failure Modes and Characteristics of Stratum-Parallel Roadcut Slopes

Failure Mode	**Core Conditions**	**Typical Lithology**	**Stability Characteristics**	**Engineering Identification**
Sliding-tension cracking	Rock stratum dip angle 5-35°, excavation slope angle > rock stratum dip angle	Soft rock, alternating hard and soft rock	F_s < 1.0, developed tension cracks at the trailing edge, uniform sliding along the rock layer	Fissures parallel to the rock layer appear on the slope surface, and tension cracks exist at the trailing edge
Plastic flow-tension cracking	Rock stratum dip angle 5-20°, double-layer structure with hard rock on top and soft rock below	Limestone interbedded with mudstone, sandstone interbedded with shale	F_s = 0.85-1.0, plastic flow of underlying soft rock, tension cracking of upper part	Bulging at the slope toe, vertical cracks in the upper hard rock
Sliding-bending	Rock stratum dip angle 36-65°, excavation slope angle ≈ rock stratum dip angle	Shale, schist, phyllite	F_s = 0.9-1.05, rock stratum bends and breaks like a "cantilever beam"	Arc bending of rock stratum on the slope surface, accompanied by shear cracks
Sliding-compression shear-out	Rock stratum dip angle 36-65°, gently inclined joints at the slope toe	Thick hard rock interbedded with soft rock, granite interbedded with schist	F_s < 0.95, compression cracking at the slope toe, sudden shear-out	Dense shear cracks at the slope toe, sudden displacement change
Wedge sliding	Included angle between rock stratum strike and slope surface < 30°, cut by two sets of structural planes	Various lithologies	Sudden F_s < 0.95, concealed initial displacement, sudden sliding failure	Rock mass cut into wedges, slight local displacement
Sliding-splitting	Rock stratum dip angle 66-90°, containing weak interlayers	Phyllite, slate, gneiss	F_s = 0.8-1.0, sliding-splitting along the interlayer accompanied by rotation	Rotational cracks on the slope surface, sliding traces at the interlayer

Note: The data in the table is based on the measured statistics of 8 typical construction sites such as the Yuhuai Railway and Puxuan Expressway. The safety factor is calculated by the Bishop method, which is suitable for circular sliding surfaces and bedding sliding surfaces, and the calculation accuracy meets the engineering requirements.

2.3 Evolution Law of Failure Modes

The evolution of bedding slope failure modes is divided into three stages: incubation, development, and failure. The evolution period of the sliding-tension cracking type (32%) and plastic flow-tension cracking type (21%) is 1-3 months. Micro-cracks appear on the slope surface in the initial stage, and the cracks expand rapidly in the development stage; the period of the sliding-compression shear-out type and wedge sliding type (18%) is only a few days to a few weeks, which is prone to sudden instability; the period of the sliding-bending type (13%) and sliding-splitting type (6%) is 2-4 weeks, accompanied by rock stratum deformation[7].

Lithology determines the evolution basis, and the evolution of soft rock slopes is faster; groundwater shortens the period by 30%-50%, while blasting excavation directly triggers the transition from the incubation stage to the development stage. Therefore, pre-support should be implemented in the incubation stage.

The evolution of failure modes is controlled by the coupling of multiple factors. Lithological combination determines the basic characteristics of evolution: the evolution rate of soft rock slopes is faster, while that of hard rock slopes is relatively slow; groundwater accelerates the evolution process, and the rise of groundwater level can shorten the evolution period by 30%-50%; excavation disturbance is the key triggering factor for evolution, and blasting excavation can directly cause the failure mode to enter the development stage from the incubation stage. Clarifying the evolution law of failure modes can provide a basis for the selection of pre-support timing. Pre-support should be implemented in the incubation stage of evolution to effectively prevent the mode from developing to the failure stage.

3. Pre-support Discrimination Classification System and Technical Process

3.1 Construction of Three-level Classification System

Following the principles of "engineering practicality, support relevance, and clear criteria", combined with the statistical analysis of 186 engineering samples, a three-level classification system with rock stratum dip angle, slope height, and lithological combination as core indicators is constructed. This system accurately reflects the stability characteristics and pre-support needs of different slopes through a progressive classification method, providing a basis for subsequent discrimination and design.

The first-level classification indicator is the rock stratum dip angle, which controls the direction of excavation unloading and sliding tendency, and is the core of the classification system. According to the dip angle of the rock stratum, the bedding cutting slope is divided into three categories: gently to moderately inclined (5-35°), steeply inclined (36-65°), and ultra-steeply inclined (66-90°)[8]. Gently to moderately inclined slopes are prone to sliding failure along the rock layer; steeply inclined slopes are prone to bending and shear-out failure; ultra-steeply inclined slopes mainly experience sliding-splitting failure.

The second-level classification indicator is the slope height, which reflects the excavation unloading intensity and stress distribution characteristics. Slopes are divided into two categories: medium-high slopes (≥8m) and low slopes (<8m). Medium-high slopes require bench excavation due to large excavation depth and high unloading intensity, with a wide range of stress redistribution and great difficulty in stability control; low slopes have low excavation unloading intensity, can be excavated with one-time slope release, and have relatively good stability.

The third-level classification indicator is the lithological combination, which determines the anti-sliding foundation capacity of the slope and is a direct reflection of the pre-support demand. According to the characteristics of lithological combination, it is divided into five categories: hard rock, soft rock, thick hard rock interbedded with soft rock, alternating hard and soft rock, and double-layer structure with hard rock on top and soft rock below. The mechanical properties and failure modes of various lithological combinations are significantly different, which directly determine the necessity of pre-support and the selection of measures.

3.2 Establishment of Pre-support Discrimination Criteria

Based on the three-level classification system, combined with the calculation results of the limit equilibrium method and engineering experience, the preliminary discrimination criteria for pre-support of bedding cutting slopes are established. The discrimination criteria adopt two-level discrimination results: "√" (needing further verification) and "×" (no support required). Slopes marked with "√" need further verification through the limit equilibrium method or UDEC numerical simulation, and pre-support must be implemented when the safety factor $F_s < 1.15$; slopes marked with "×" have a safety factor $F_s \geq 1.3$, with good stability, and no pre-support is required. The accuracy rate of this discrimination criterion has been verified by engineering to reach 90%, which can effectively guide the pre-support decision-making[9].

Combined with the three-level classification system and the calculation results of the safety factor, the preliminary discrimination criteria for pre-support are established, as shown in Table 2, clarifying the pre-support needs of slopes in different classifications. It can be seen from the table that among the gently to moderately inclined slopes, except for the hard rock type, the medium-high slopes and low slopes of other lithological combinations need further verification; among the steeply inclined and ultra-steeply inclined slopes, only the soft rock type needs further verification, and other lithological combinations have good stability and do not require support. This law is consistent with the analysis results of failure modes. Gently to moderately inclined soft rock slopes have the highest instability risk and are the key objects of pre-support.

Table 2. Preliminary discrimination table for pre support of layered road cut slopes

First-level Classification (Rock Stratum Dip Angle)	**Second-level Classification (Slope Height)**	**Third-level Classification (Lithological Combination)**	**Preliminary Pre-support Discrimination**
Gently to moderately inclined (5-35°)	Medium-high slope (≥8m)	Hard rock	×
		Soft rock	√
		Thick hard rock interbedded with soft rock	√
		Alternating hard and soft rock	√
		Double-layer structure with hard rock on top and soft rock below	√
	Low slope (<8m)	Hard rock	×
		Soft rock	√
		Thick hard rock interbedded with soft rock	√
		Alternating hard and soft rock	√
		Double-layer structure with hard rock on top and soft rock below	√
Steeply inclined (36-65°)	Medium-high slope (≥8m)	Hard rock	×
		Soft rock	√
		Thick hard rock interbedded with soft rock	×
		Alternating hard and soft rock	×

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		Double-layer structure with hard rock on top and soft rock below	×
	Low slope (<8m)	Hard rock	×
		Soft rock	√
		Thick hard rock interbedded with soft rock	×
		Alternating hard and soft rock	×
		Double-layer structure with hard rock on top and soft rock below	×
Ultra-steeply inclined (66-90°)	Medium-high slope (≥8m)	Hard rock	×
		Soft rock	√
		Thick hard rock interbedded with soft rock	×
		Alternating hard and soft rock	×
		Double-layer structure with hard rock on top and soft rock below	×
	Low slope (<8m)	Hard rock	×
		Soft rock	√
		Thick hard rock interbedded with soft rock	×
		Alternating hard and soft rock	×
		Double-layer structure with hard rock on top and soft rock below	×

Note: "√" indicates the need for verification by the limit equilibrium method or UDEC numerical simulation (pre-support is mandatory when $F_s < 1.15$); "×" indicates $F_s \geq 1.3$, and no support is required.

3.3 Four-step Closed-loop Technical Process of "Classification - Discrimination - Design - Verification"

Based on the three-level classification system and pre-support discrimination criteria, a four-step closed-loop pre-support technical process of "classification - discrimination - design - verification" is innovatively proposed, realizing the full-process control from investigation to verification, and ensuring the scientificity and effectiveness of pre-support design. Each link of the process is closely connected: the previous link provides a basis for the next link, and the next link verifies the rationality of the previous link, forming a closed-loop management.

3.3.1 Detailed Investigation and Classification

Detailed investigation is the basis of the technical process. Geological data and rock mass mechanical parameters of the slope are obtained through drilling investigation, geophysical testing, in-situ testing and other methods. The drilling investigation interval is controlled at 10-15m, and the depth needs to penetrate the potential sliding surface and enter the stable rock formation by 3-5m; geological radar and acoustic wave testing are used for geophysical analysis to identify weak interlayers and joint distributions; mechanical parameters such as cohesion c and internal friction angle φ of rock mass and sliding surface are obtained through on-site shear tests and laboratory tests. According to the investigation results, the slope is classified according to the three-level classification system to clarify the type characteristics of the slope.

3.3.2 Stability Discrimination

According to the slope classification and preliminary discrimination results, slopes marked with "√" need dual verification through the Bishop method and UDEC numerical simulation. The Bishop method considers the interaction between slices and has calculation accuracy meeting engineering needs; the UDEC discrete element method can accurately simulate the deformation of layered rock mass, with parameters obtained from laboratory tests, and the boundary conditions set as fixed at the bottom and constrained at the sides.

Research by Zhang Yongxing et al. shows that the combination of the two methods can increase the discrimination accuracy to 92%, which is much higher than 75% of a single method. Through the analysis of stress field and displacement field, the potential sliding surface and unstable area can be accurately located, providing quantitative basis for design[9].

3.3.3 Pre-support Design

According to the discrimination results, pre-support design is carried out for different types of slopes, following the principle of "one plan for one type of slope" to ensure design adaptability. Pre-support measures are divided into two categories: strong support and light support. Strong support measures focus on anchors (cables) and anti-slide piles, which are suitable for slopes with extremely poor stability and large sliding force; light support measures focus on micro-pile groups and grouting reinforcement, which are suitable for slopes with poor stability that need to retain rock mass integrity.

Anchor (cable) support restrains slope deformation through the mechanism of "force transfer at the bonding section - anti-pulling at the anchoring section". Four φ32 threaded steel anchors are commonly used, and the length is determined according to the slope height and potential sliding surface depth, usually ≥15m. The prestress value is 50-100kN, and the spacing is 3-5m. Anti-slide piles are suitable for medium-high slopes with large sliding force, and the depth embedded in the stable rock formation is not less than 1/3 of the pile length. The pile length is 20-30m, the cross-sectional size is 2m×3m, and C30 concrete is used for pouring.

Micro-pile groups improve the overall stability of the slope by forming a composite skeleton. The pile diameter is 150-300mm, the spacing is 1-2m, C30 concrete is used, and the pile length needs to penetrate the potential sliding surface. Grouting reinforcement achieves the reinforcement effect by filling rock mass fissures and improving the mechanical properties of rock mass. Cement-sodium silicate double-liquid slurry is used, with a grouting pressure of 1.5-2MPa, which can increase the cohesion c and internal friction angle φ of the rock mass by 30%.

The adaptability of various pre-support measures is different. The combined support of anchor (cable) and grouting has the widest adaptability, which is suitable for most slopes requiring support such as gently to moderately inclined soft rock slopes and thick hard rock slopes interbedded with soft rock; the combined support of micro-pile groups and grouting is suitable for steeply inclined soft rock slopes; anti-slide pile support is suitable for ultra-steeply inclined slopes and large landslides with large sliding force.

3.3.4 Design Verification

After the design is completed, verification is required through UDEC numerical simulation and on-site monitoring. Numerical simulation analyzes the safety factor of the slope after support to ensure $F_s \geq 1.15$; on-site monitoring arranges displacement monitoring points and stress monitoring points. Displacement monitoring uses total stations and displacement meters, with a monitoring frequency of once a day during the construction period and once a week during the operation period. When the displacement rate is less than 0.1mm/d for 3 consecutive days, the slope is considered stable. The combination of simulation verification and on-site monitoring ensures the effectiveness of the pre-support design.

4. Engineering Case Verification

To verify the feasibility and effectiveness of the pre-support classification system and technical process proposed in this paper, two typical bedding cutting slope projects, namely the Daluhe Section of the Yuhuai Railway and the K28+320 Section of the Puxuan Expressway, are selected for case verification, and a comprehensive analysis is carried out from the aspects of design process, implementation effect, and economic benefits.

4.1 Case 1

4.1.1 Project Overview

The slope at the Daluhe Section of the Yuhuai Railway is a 23m-high medium-high slope with gently inclined (22°) silty shale, which belongs to the type of "gently to moderately inclined - medium-high slope - soft rock" in the three-level classification system. The rock mass density is 2.4g/cm³, the saturated compressive strength is 12MPa, the cohesion c of the rock layer is 25kPa, and the internal friction angle φ is 19°. The construction plan is "8m bedding clearing → two-level 7.5m cross-bedding excavation". The excavation area is located in the mountainous river valley area, with well-developed groundwater, and the maximum historical rainfall reaches 180mm/day.

4.1.2 Pre-support Scheme

According to the technical process of this paper, the slope is first classified and discriminated: it belongs to the type of gently to moderately inclined medium-high slope with soft rock, and the preliminary pre-support discrimination is "√"; the safety factor F_s after excavation calculated by the Bishop method is 0.96, which is less than 1.15, so pre-support is required; UDEC numerical simulation shows that the F_s is 2.35 (stable) after the first layer of clearing, and it is in a critical state before the second layer of excavation. After excavation, a relaxation zone is formed within 10-15m of the slope surface, and the displacement rate reaches 2.5mm/d, which is prone to sliding-tension cracking failure.

Based on the discrimination results, a combined support scheme of "anchor + grouting" is adopted: 4 rows of φ32 threaded steel anchors are arranged, with a length of 15m, a spacing of 5m, and a prestress of 80kN. The anchors are embedded in the stable rock formation by 5m; cement-sodium silicate double-liquid slurry is used for grouting, with a grouting pressure of 1.8MPa, a water-cement ratio of 1:1, and the grouting hole spacing is 3m, with a depth of 12m, covering the entire relaxation zone. The construction sequence is "grouting reinforcement → anchor installation → prestress tensioning → excavation" to ensure that pre-support is carried out first.

4.1.3 Implementation Effect Analysis

UDEC numerical simulation after support shows that the slope safety factor increases to 1.15-1.28, meeting the stability requirements. 12 displacement monitoring points are arranged on site. The maximum displacement during the construction period is 4.2cm, and the displacement rate gradually decreases to 0.08mm/d; the cumulative displacement during 2 years of operation is less than 1cm, and the slope is in a stable state.

Economic benefit analysis shows that the total cost of this pre-support scheme is 860,000 yuan. If the traditional "support after excavation" mode is adopted, the emergency support cost after sliding instability is expected to reach 1.43 million yuan. The pre-support scheme saves 40% of the cost compared with the traditional mode, and avoids construction delay, ensuring the on-schedule opening of the railway.

4.2 Case 2

4.2.1 Project Overview

The slope at Section K28+320 of the Puxuan Expressway is a 75.2m-high steeply inclined (36°) slope with shale interbedded with limestone. The thickness of the strongly weathered zone is 12m, which belongs to the type of "steeply inclined - medium-high slope - soft rock" in the three-level classification system. The saturated compressive strength of the rock mass is 8MPa, the cohesion c of the rock layer is 22kPa, and the internal friction angle φ is 18°.

The original design adopted the scheme of "10m bench excavation + support after excavation" without pre-support. During the fourth-level excavation (40m depth), a 28,000m³ wedge sliding occurred suddenly, resulting in 3 construction workers injured, direct economic loss of 2.1 million yuan, and a 3-month construction delay.

4.2.2 Optimization Scheme

The slope is reclassified and discriminated based on the technical system of this paper: it belongs to the type of steeply inclined medium-high slope with soft rock, and the preliminary pre-support discrimination is "√"; the safety factor F_s after excavation in the original design calculated by the Bishop method is 0.92. UDEC simulation shows that the stress concentration at the slope toe is serious, which is prone to sliding-compression shear-out failure.

The optimized design scheme adopts the combined support of "water control + micro-pile group + anchor lattice beam": a 0.6m×0.8m intercepting ditch is arranged at the top of the slope, and φ50mm drainage holes are arranged on the slope surface, with a depth of 6m and a spacing of 2m, effectively reducing the groundwater level; φ200mm micro-piles are arranged along the bedding, using C30 concrete, with a length of 12m, a spacing of 1.5m, and embedded in the stable rock formation by 4m; anchor lattice beams are arranged on the slope surface, with anchors of 8m in length, a spacing of 2m, a prestress of 50kN, and the cross-sectional size of the lattice beam is 0.4m×0.4m.

4.2.3 Implementation Effect Analysis

UDEC simulation after the implementation of the optimized scheme shows that the slope safety factor is ≥1.2, meeting the stability requirements. On-site monitoring shows that the maximum displacement is 2.8cm, and the displacement rate is stable below 0.05mm/d, with the slope in a stable state.

Economic benefit analysis shows that the additional cost of the optimized scheme is 1.2 million yuan, which is 15% higher than the total cost of the original design, but it avoids the instability risk and ensures the on-schedule completion of the project. Without optimization, the subsequent emergency rescue and treatment cost is expected to reach 3.5 million yuan. The optimized scheme indirectly saves 2.3 million yuan in costs, with significant economic and social benefits.

4.3 Case Verification Conclusion

Verification by two engineering cases shows that the three-level classification system proposed in this paper can accurately reflect the stability characteristics of the slope, and the accuracy rate of the pre-support discrimination criteria reaches 90%; the "classification - discrimination - design - verification" technical process can effectively guide the pre-support design, ensuring the scientificity and adaptability of the design scheme; schemes such as the combined support of anchor (cable) and grouting, and the combined support of micro-pile group and anchor lattice beam can significantly improve the slope stability, keeping the safety factor stable above 1.15; the pre-support technology saves 30% of the cost compared with the traditional mode, with significant economic benefits and important engineering promotion value.

5. Conclusion

Taking typical highway bedding cutting slope projects as research samples, this paper systematically carries out research on pre-support design and application through the combination of on-site investigation, laboratory tests, numerical simulation, and engineering verification. The main conclusions are as follows:

(1) The core influencing factors of the stability of bedding cutting slopes are clarified. Among internal factors, lithological combination (weight 35%) and rock stratum dip angle (weight 28%) are the basic control conditions; among external factors, groundwater (weight 22%) is the most active inducing factor; temporal factors (weight 15%) are reflected in rock mass creep attenuation. The combination of soft rock, gently to moderately inclined angle, and high groundwater level is prone to cause slope instability.

(2) Six types of typical failure modes and their evolution laws are identified. The sliding-tension cracking type accounts for the highest proportion (32%), mainly occurring in gently to moderately inclined soft rock slopes; the plastic flow-tension cracking type (21%) and wedge sliding type (18%) are the next; the sliding-bending type, sliding-compression shear-out type, and sliding-splitting type account for relatively low proportions. The evolution period and characteristics of various modes are significantly different, providing a basis for the selection of pre-support timing.

(3) A three-level classification system of "rock stratum dip angle - slope height - lithological combination" is constructed, and scientific pre-support discrimination criteria are established. The system reflects the slope characteristics in a progressive manner, with a discrimination accuracy rate of 90%, and identifies 6 types of slopes that need key discrimination, such as gently to moderately inclined soft rock slopes and gently to moderately inclined thick hard rock slopes interbedded with soft rock, providing a basis for pre-support decision-making.

(4) A four-step closed-loop pre-support technical process of "classification - discrimination - design - verification" is proposed, and the pre-support adaptability standards for various slopes are clarified. The combined support of anchor (cable) and grouting has the widest adaptability, which can increase the slope safety factor by 0.2-0.3; UDEC numerical simulation can accurately locate the unstable time step of excavation, providing a quantitative basis for design.

(5) Engineering case verification shows that the pre-support technology can stably increase the slope safety factor to more than 1.12, and save 30% of the cost compared with the traditional post-excavation emergency support, significantly improving the engineering safety and economy.

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