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Research and Application of Comprehensive Protection Technology for High-Fill Embankment Slope: A Case Study of an Urban Road in Hunan Province

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Abstract: This paper takes the high-slope project of a newly built urban road in Hunan Province as the research object and systematically analyzes its geological conditions, hydrological characteristics, and slope stability issues. In response to the characteristics of high fill slope height (9–17.3 m) and high safety level (Level I), a comprehensive treatment plan was proposed, incorporating "anchored pile-sheet retaining walls, slope ratio method, interception and drainage, and greening protection". The paper elaborates on the design of the support structure, construction techniques, quality control, and deformation monitoring, with a particular focus on discussing the collaborative working mechanism between prestressed anchor cables and anti-slide piles, the timing control of layered filling and anchor cable tensioning, as well as the information-based construction and emergency response mechanisms. Research indicates that this plan demonstrates good applicability and safety under complex geological conditions and limited slope relaxation, providing a technical reference for similar high-slope projects.

Keywords: High slope; Anchor-pulled pile sheet retaining wall; Prestressed anchor cable; Deformation monitoring; Construction control; Geological disaster prevention and control

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1. Introduction

With the acceleration of urbanization in China, road construction is gradually extending to hilly and mountainous areas, leading to an increasing number of high slope projects [1–3]. Due to their complex geological conditions, poor stability, and high construction risks, high slopes have become a focal point and challenge in geotechnical engineering [4]. Hunan Province, characterized by its predominantly hilly terrain, abundant rainfall, and frequent geological disasters, makes the management of high slopes particularly crucial. This paper takes a high slope of a newly built urban road in Hunan Province as a case study to systematically analyze its engineering geological conditions, support structure design, construction techniques, and monitoring and control methods, aiming to provide references for similar projects.

2. Project overview

This project involves a newly constructed secondary arterial road in Hunan Province, with a total length of 912.899 meters and a designed speed of 30 km/h. A high fill slope exists in the section from K0 + 030 to K0 + 208.940, with a slope height ranging from 9 to 17.3 meters. It is a soil slope with a safety class of Class I and a designed service life of 50 years. The northwestern side of the slope is designated as urban planning land, with limited conditions for slope grading, necessitating the adoption of strong support measures.

3. Engineering geological and hydrogeological conditions

3.1. Climate and topography

This area has a subtropical humid climate with abundant precipitation, an average annual rainfall of 1,391.7 mm, and a maximum annual rainfall of 1,957.6 mm (recorded in 1977). The average annual evaporation is 1,281.7 mm. The annual average temperature is 16 ℃, with an extreme maximum temperature reaching 40.2 ℃ (on July 4, 1971). The annual average sunshine duration is 1,563.5 hours, and the freezing period occurs in January and February, with an average of 29 freezing days. The longest recorded frost and snow period spans 25 days, and the extreme minimum temperature is -7.5 ℃ (on January 30, 1977). The prevailing wind is from the northeast, with an average annual wind speed of 1.1 m/s and a maximum wind speed also reaching 1.1 m/s (in August and September). The average annual humidity is 81% [5].

The terrain along the project route generally slopes downward from higher elevations on both sides to a lower elevation in the middle, with significant topographical variations. The landform type in this area is characterized by dissolution-erosion hills, and microtopographically, it belongs to the middle slopes of these hills. The vegetation is sparse, with only a small number of shrubs and a few economic forests present. The ground elevation ranges from 310.68 to 330.45 m, with slopes ranging from 10–30°.

3.2. Stratigraphic lithology

The site consists of, from top to bottom, plain fill, red clay, strongly weathered dolomite, and moderately weathered dolomite. Among these, the red clay is prone to softening when exposed to water and is classified as a special soil type. The strongly weathered dolomite is considered extremely soft rock, while the moderately weathered dolomite is classified as relatively hard rock.

3.3. Hydrogeology

On the northwest side of the site lies a small stream with low and highly variable water flow, showing pronounced seasonal variations. The highest flood level in this river section is 295.00 m, which has no impact on the slope.

The catchment area of the slope engineering zone is approximately 15,000 m^2, with a drainage slope ranging from 10 to 30 degrees and a drainage length of about 130 m. The mountain slope has sparse vegetation. Surface catchment water causes severe erosion to the slope, so it is essential to implement effective slope interception and drainage measures to prevent erosion. The groundwater at the site primarily consists of bedrock fissure water. Due to the site's high elevation, the groundwater is deeply buried, and no groundwater was observed within the surveyed depth range during the investigation.

3.4. Seismic fortification intensity

According to the "Seismic Ground Motion Parameter Zonation Map of China" (GB18306-2015), the seismic fortification intensity in this area is 6 degrees, with the design earthquake group classified as Group I. The basic seismic acceleration for Class II sites is 0.05 g, and the characteristic period of the response spectrum for basic ground motion acceleration is 0.35 s. The site falls within a seismic fortification intensity zone of 6 degrees, with no liquefiable strata present. Therefore, the impact of liquefaction can be disregarded. Additionally, there is no weak soil, eliminating the need to consider seismic subsidence issues. The likelihood of landslides or collapses triggered by earthquakes is low, indicating good seismic stability of the rock and soil.

3.5. Unfavorable geology

The overburden of this line project consists of Quaternary soil layers, underlain by Cambrian dolomite with stable lithology and facies, indicating favorable engineering geological conditions.

4. Design of support structure

4.1. Design principles

A comprehensive support system integrating "anti-slide piles, retaining walls between piles, prestressed anchor cables, slope protection, and water interception and drainage" is adopted, taking into account stability, economy, and ecology.

4.2. Design of anti-slide piles

The piles have a diameter of 2 m, with a rectangular cross-section of 2 m × 2 m at the top. The pile length ranges from 13–27 m, with an embedded depth of ≥ 4 m into moderately weathered rock or an embedded length of ≥ 10 m. The pile shaft is constructed using C30 concrete, with a main reinforcement cover of 80 mm.

The retaining walls between piles are prefabricated components with a thickness of 0.4 m, width of 0.5 m, and length of 3.6 m, overlapping with adjacent anti-slide piles by 0.8 m on both sides.

4.3. Design of prestressed anchor cables

Each pile is equipped with 2 to 4 prestressed anchor cables, which consist of 12 strands of 15.2 high-strength, low-relaxation, double-layer PE-coated, unbonded prestressed steel strands with a standard tensile strength of 1860 MPa. The anchor hole diameter is 150 mm, and the inclination angle is 15°. The anchor cables are arranged at 2 m, 5 m, 8 m, and 11 m below the top elevation of the anti-slide piles, with the number of anchor cable channels determined based on the corresponding cantilever pile length.

4.4. Slope and drainage design

Above the pile top, a slope with a ratio of 1:1.5 and a height of 6 m is formed, protected by diamond-shaped grids and vegetation. Intercepting ditches and blind drainage ditches are provided, and the slope surface is covered with geogrids to enhance overall integrity.

4.5. Design of anchored pile sheet retaining wall

The larger value between the Coulomb earth pressure of the backfill behind the retaining wall and the landslide thrust is used for calculation. The values of calculation parameters for the backfill are as follows:

$$\gamma = 20\ \text{kN/m}^3,\ c = 10\text{kPa},\ \phi = 35°$$

5. Key construction techniques

5.1. Construction of anti-slide piles

5.1.1. Pre-construction preparation

Identify underground pipelines and develop relocation/protection plans; accurately set out and position, and construction can only commence after supervisor's review and approval.

5.1.2. Borehole formation and geological verification

The circular-square interface is located 2 m below the slope line; geological logging is required during drilling, and the pile length is dynamically adjusted: embedded in moderately weathered rock ≥ 4 m; if embedding is not possible, the pile length shall be ≥ 10 m.

5.1.3. Casing and pouring techniques

The steel casing is buried 2–4 m deep, with an inner diameter 20–40 cm larger than the pile diameter.

When the geological conditions are poor, mud wall protection + underwater pouring is adopted: the initial pouring depth of the tremie pipe shall be ≥ 500 mm; during pouring, the tremie pipe shall be buried 2–6 m deep; the pile top shall be over-poured by 0.5 m; and the sediment at the bottom of the hole shall be ≤ 50 mm.

5.1.4. Reinforcement and inspection

The reinforcement cage shall be protected against deformation, and guide pipes for anchor cables shall be pre-embedded; four acoustic detection pipes (compliant with JT/T 871-2013) shall be bound and extend 300 mm above the pile top.

5.1.5. Formwork and scaffolding

The formwork must be checked for strength, rigidity, and stability; a specialized plan must be prepared for scaffolding, with the verticality of upright poles being ≤ ± 75 mm.

5.2. Installation of retaining plate

5.2.1. Prefabrication and installation conditions

Prefabrication can be carried out in a factory or on-site, with lifting holes/drainage holes reserved; installation can only proceed after the strength of the anti-slide piles meets the standard.

5.2.2. Installation process

Excavate a trench between piles à compact crushed stones à place the retaining plate; the bottom of the plate should penetrate into the stable slope by ≥ 0.5 m; overlap with the pile by ≥ 800 mm, with the joint surface brushed with hot asphalt and lined with geotextile; pay attention to the installation direction to prevent breakage.

5.3. Filling of subgrade soil behind the wall

5.3.1. Base treatment

Clear vegetation, excavate steps on steep slopes (width > 2 m, inward slope > 4%); the degree of compaction of the foundation should be ≥ 85%.

5.3.2. Filling material and compaction

Prefer graded crushed stone soil with a particle size < 150 mm; a 0.5 m inverted filter layer (gravel/graded crushed stone) should be provided behind the retaining plate; fill in layers (each layer ≤ 30 cm), with a degree of compaction ≥ 94% (porosity of crushed stone soil ≤ 20%); large machinery was prohibited from rolling within 2 m behind the wall, and manual compaction should be used instead.

5.3.3. Drainage and reinforcement

Install blind drainage ditches (6 m long, inclined upwards at 10°, with a vertical spacing of 2 m); lay bidirectional geogrids (GSGS 80-80) at the interface between old and new soil: extend the laying to 4 m above the pile top, with a layer spacing of ≤ 1 m; ensure a longitudinal overlap width of ≥ 30 cm, which can be disconnected at anchor cable locations; secure with U-shaped nails (spacing 1.5 m × 1.5 m).

5.4. Anchor cable construction

5.4.1. Procedure

Drilling à Anchor Cable Fabrication à Hole Cleaning and Cable Insertion à Full-Hole Grouting à Tensioning and Locking à Anchor Sealing and Protection.

5.4.2. Drilling and anchor cable fabrication

Drill with casing, with a hole position deviation of ≤ ± 100 mm and an inclination deviation of ≤ 2%; the anchored section should penetrate into moderately weathered rock by ≥ 5 m; the anchor cable consists of unbonded steel strands (12 bundles of ϕ 15.2), with the PE sheath stripped and grease removed from the anchored section.

5.4.3. Grouting

Use cement paste (P • O 52.5, with a water-cement ratio of 0.42), with a strength of ≥ 40 MPa; ensure grout returns from the hole bottom, with a pressure of ≥ 0.5 MPa.

5.4.4. Tensioning and locking (Core process)

(1) Timing
When filling reaches 2m above the anchor cable elevation.

(2) Sequence
Perform cyclic and phased tensioning: first tensioning to 50% of the locking force; second tensioning to 100% of the locking force (after completion of upper layer filling).

(3) Control
Dual control of tensioning force and elongation value; work must be stopped for inspection if the error is within ± 5% to 10%.

(4) Safety
Supervised by designated personnel to prevent clip ejection, wire breakage, etc.

5.4.5. Anchor sealing and quality control

After tensioning, seal the holes and perform grouting; apply oil to exposed steel strands for corrosion protection. One set of test cubes (70.7 mm cubes) shall be reserved for every 30 anchor cables.

5.5. Backfilling construction of the platform in front of the piles

After the lowest row of anchor cables for piles A22# to A27# are locked, backfill and compact the area in front of piles A18# to A29# in layers. After completion, harden the area within 4 meters in front of the piles and set a 2% outward-sloping transverse slope.

5.6. Slope protection construction

The topmost retaining slab and the intercepting ditch at the top of the pile shall be cast in one piece, with drainage pipes embedded. Above the pile top, fill and compact according to the slope ratio à trim the slope à set out and excavate the foundation trench for the grid beam à pour concrete. After the grid beam reaches the required strength, backfill with 15 cm of planting soil, sow grass seeds, and plant shrubs.

6. Construction quality inspection

6.1. Pile body quality inspection

The quality of the pile body is fundamental to whether the anti-slide piles can perform their designed functions. In this project, non-destructive testing of all anti-slide piles is conducted using the sonic transmission method and the low-strain reflected wave method. The sonic transmission method can effectively identify the uniformity, continuity, and defect locations of the concrete in the pile body; the low-strain method is suitable for quickly evaluating the integrity and length of the pile body. For piles with detected abnormalities or those randomly selected based on a certain proportion, the core drilling method is employed for verification. Core drilling inspection allows for a direct assessment of the pile's concrete strength, the thickness of sediment at the pile bottom (with a control value ≤ 50 mm), and the lithology of the bearing stratum at the pile tip, making it the most direct means of evaluating pile quality. Additionally, a steel bar detector is used to re-inspect the position, spacing, quantity, and protective layer thickness of the steel reinforcement cage, ensuring that the steel reinforcement work meets design requirements.

6.2. Inspection of prestressed anchor cables

Prestressed anchor cables serve as crucial load-transferring components in anchored support systems, with their pullout resistance directly affecting overall stability. Prior to construction, basic tests are conducted in typical strata, with each group comprising no fewer than three cables, to verify the rationality of design parameters and construction techniques. During construction, anchor cables are randomly selected at a rate of 3–5% for acceptance tests to check whether their tensioning and locking values meet the design requirement of 1000 kN. Furthermore, the strength of the grouting mixture is tested through reserved specimens to ensure it is not less than 40 MPa.

6.3. Acceptance of concealed works

Concealed works, such as the installation of steel reinforcement cages, anchor cable drilling, blind drains behind walls, and the laying of geogrids, must undergo acceptance inspections before being covered. Only after passing the acceptance inspection can the next construction phase proceed, and complete visual and written records must be maintained to ensure quality traceability.

6.4. Basis for acceptance criteria

All construction quality acceptance shall strictly adhere to the "Technical Specification for Construction of Highway Subgrades" (JTG/T 3610-2019) and the "Quality Acceptance Standard for Construction of Building Slope Engineering" (GB/T 51351-2019) to ensure that both the project entity and its documentation comply with regulations simultaneously.

7. Deformation and settlement monitoring system

7.1. Monitoring content and methods

(1) Pile top displacement and settlement monitoring

Real-time monitoring of horizontal and vertical displacements at the pile top shall be conducted using precision leveling instruments or total stations (with accuracy ≤ ± 0.5 mm).

(2) Soil layer horizontal displacement monitoring

By embedding inclinometers, monitor displacements at different depths within the backfill behind the wall to identify potential slip surfaces.

(3) Anchor cable tension monitoring

Install steel string pressure sensors on no less than 10% of the total anchor cables, with a focus on monitoring the upper anchor cables that bear greater loads.

(4) Crack observation in backfill behind the wall

Conduct manual inspections to record the emergence, development, and closure of cracks.

7.2. Monitoring frequency and control standards

The monitoring frequency shall be dynamically adjusted according to the construction phase, as detailed in **Table 1**.

Table 1. Monitoring frequency and control standards

Monitoring item	Monitoring frequency	Control standard
Pile top horizontal and vertical displacement	At least once daily during subgrade filling; every 3–7 days after filling completion	Displacement ≤ 30 mm; Horizontal displacement rate ≤ 2 mm/day
Soil layered horizontal displacement	Every 3–7 days after filling reaches the pile top	—
Anchor cable tension	At least once daily during filling; every 3–7 days after filling completion; once monthly during operation period (monitoring duration ≥ 2 years)	≤ 1500 kN
Cracks in backfill soil	At least twice daily during filling; once every two days after filling completion	No cracks

Note: When the measured values change dramatically, the monitoring frequency should be increased. In emergency situations, it is imperative to immediately report to the construction, design, and supervision parties and take corresponding measures to address the issue.

7.3. Early warning and feedback mechanism

(1) When the measured value is less than 0.7 times the monitoring value, it is in a safe state;

(2) When the measured value reaches 0.7 to 0.9 times the monitoring value, it is in a critical state;

(3) When the measured value exceeds 0.9 times the monitoring value, it is in a dangerous state.

During the monitoring process, if the situation is safe, monitoring should continue according to the original plan, and a monitoring report should be provided before the next monitoring. If the situation reaches a critical or dangerous state, or if the measured horizontal displacement rate of the pile top exceeds 2 mm/d for three consecutive days, the monitoring frequency should be increased, and an alarm should be raised promptly. Monitoring results should be submitted on the same day, and a written engineering contact letter should be issued to notify Party A, the design, supervision, and construction parties.

8. Major construction hazards

The construction of high slopes is a high-risk operation prone to safety accidents due to the complexity of terrain and geological and hydrological conditions, as well as the relatively low quality of personnel involved. Through a comprehensive analysis of factors such as personnel, machinery, materials, methods, and environment, the following four hazards that may cause personal injury or property damage have been identified and confirmed:

(1) Mechanical injury

During mechanical operation, accidental mechanical failures or violations of operating procedures may result in personal injury or mechanical damage.

(2) Hole collapse injury

During the construction of anti-slide piles, from the excavation of pile holes to before sealing them, the failure to properly protect or waterproof the hole openings can easily lead to pile hole collapse, resulting in personal injury.

(3) Electric shock injury

If the outer edge of the project does not maintain a safe distance from external high-voltage power lines, electrical equipment lacks neutral or ground protection, protective equipment fails, high voltage is used for mobile or lighting purposes, or electrical equipment is used and operated in violation of regulations, personal injury or damage may occur.

(4) Formwork and scaffolding collapse injury

The construction of the cantilever section of anti-slide piles involves scaffolding and formwork engineering. If safety precautions are not taken during the construction process, the collapse of formwork and scaffolding can easily cause personal or mechanical injury or damage.

(5) Collapse and landslides

Improper construction methods, improper use of machinery, or construction during thunderstorm seasons during roadbed filling can easily lead to slope collapse and landslides, causing personal or mechanical injury or damage.

(6) Pipeline damage

Failure to ascertain pipeline locations before construction and causing pipeline damage during construction can easily deteriorate the construction environment and may also result in property damage and personal injury.

During the construction process, it is necessary to strengthen the prevention of the aforementioned major hazards to ensure construction safety.

9. Emergency measures

Slope support shall adhere to information-based construction, with corresponding treatment measures taken based on on-site conditions. Strengthen deformation monitoring, arrange dedicated personnel for 24-hour duty to observe deformation around the slope, promptly report any abnormalities, and initiate emergency measures.

9.1. Abnormal deformation at the pile top

Due to the complex construction process of the tension-anchor pile-sheet retaining wall structure, if abnormal deformation occurs in the pile during the filling and anchor cable tensioning processes, construction should be immediately halted, the cause should be investigated, remedial measures should be taken, and relevant parties such as the supervision and design units should be promptly notified to develop countermeasures.

9.2. Abnormal deformation at the slope crest

Given the complex geological conditions of the slope, if there are signs of slope instability during construction or phenomena such as cracks and abnormal settlement occur in the surrounding roads and flood interception ditches, construction should be immediately stopped. Timely measures should be taken to prevent rainwater scouring and infiltration, and relevant parties such as the supervision and design units should be promptly notified to develop countermeasures.

9.3. Severe rainwater scouring on the slope surface

Due to inadequate and untimely slope protection, rainwater severely scours the slope surface. Before the onset of heavy rain, the entire slope surface should be promptly covered with impermeable materials such as plastic sheeting, and the slope crest should be compacted with soil to prevent rainwater infiltration.

10. Conclusions and recommendations

For high-fill slopes under complex geological conditions, the comprehensive support system of an anchored pile-sheet retaining wall is technically feasible and safe and reliable. The key to construction lies in controlling the timing of layered filling and anchor cable tensioning, which effectively coordinates deformation. An information-based monitoring and early warning system is an important means of achieving dynamic design and risk management and control. Long-term maintenance and management are essential for ensuring the sustained stability of the slope.

Disclosure statement

The authors declare no conflict of interest.

References

[1] GB 50330, 2013, Technical Code for Building Slope Engineering. Beijing: China Architecture and Building Press.

[2] CECS 22, 2005, Technical Specification for Ground Anchors. Beijing: China Association for Engineering Construction Standardization.

[3] JTG/T 3610, 2019, Technical Specification for Construction of Highway Subgrades. Beijing: Ministry of Transport of the People's Republic of China.

[4] Zhang J, Li W, 2018, Theoretical Design and Engineering Practice of High Slope Support Structures. Beijing: China Architecture and Building Press.

[5] Hunan Provincial Meteorological Bureau, 2017, Compilation of Climatic Data in Hunan Province (1971–2016).