Postprint of the Analytical Model for Tension Relaxation of Prestressed Anchor Cable Structures in Slopes

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Abstract

To reasonably address the analysis of anchor cable tension relaxation in slopes reinforced with prestressed anchor cables, a parallel-series combined analytical model is established by considering the interaction characteristics among the anchor cable, the anchoring section stratum, the free section sliding mass, and the slope surface restraint components. In this model, Hooke bodies are used to simulate the anchor cable or slope surface restraint components, Kelvin bodies are used to simulate the sliding bed, and Kelvin or generalized Kelvin bodies are used to simulate soil or rock sliding masses. The computational expressions for anchor cable tension relaxation are subsequently derived.

Laboratory tests and field measurement results demonstrate that the error between the stabilized anchor tension values after relaxation calculated by this method and the measured values is within 6%, while the maximum error for the relaxation duration is 7.7%, indicating that this method outperforms existing calculation methods. The relaxation effect of anchor cable tension weakens nonlinearly with the increase of anchor hole spacing, the delayed elastic modulus, and the initial viscosity coefficient of the anchoring section stratum. Conversely, it strengthens linearly with the increase of the anchor cable diameter and elastic modulus.

The instantaneous elastic modulus of the anchoring section stratum, as well as the instantaneous elastic modulus, delayed elastic modulus, and viscosity coefficient of the free section sliding mass, have minimal impact on the anchor cable relaxation effect. In practice, a series analytical model of "slope surface restraint component-anchor cable-anchoring section stratum" that ignores the influence of the free section sliding mass can generally be adopted to conveniently estimate the anchor cable tension relaxation effect.

Full Text

Analysis Model for Tension Relaxation of Pre-stressed Anchor Cable Structures in Slopes

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Abstract: To effectively address the analysis of tension relaxation in pre-stressed anchor cables used for slope reinforcement, this study establishes a parallel-series combined analytical model. The model accounts for the interaction characteristics between the anchor cable, the strata in the anchored section, the sliding mass in the free section, and the slope surface restraint components. In this model, Hookean bodies are used to simulate the anchor cable and surface restraint components, while Kelvin bodies represent the sliding bed. For the sliding mass, Kelvin or generalized Kelvin bodies are employed to simulate soil or rock materials, respectively. Based on this framework, analytical expressions for calculating anchor cable tension relaxation are derived. Comparisons with laboratory tests and field measurements demonstrate that the steady-state tension values calculated by this method deviate from measured values by less than 6%, with a maximum error in relaxation duration of 7.7%, outperforming existing calculation methods. Parametric analysis reveals that the relaxation effect of the anchor cable tension weakens nonlinearly as the spacing between anchor holes, the delayed elastic modulus of the anchored strata, and the initial viscosity coefficient increase. Conversely, the relaxation effect strengthens linearly with increases in the diameter and elastic modulus of the anchor cable. Factors such as the instantaneous elastic modulus of the anchored strata, as well as the instantaneous elastic modulus, delayed elastic modulus, and viscosity coefficient of the sliding mass in the free section, have negligible impacts on the relaxation effect. In engineering practice, a simplified "surface restraint component–anchor cable–anchored strata" series analytical model, which neglects the influence of the sliding mass in the free section, can be adopted to conveniently estimate the tension relaxation effect of anchor cables.

Keywords: slope engineering; pre-stressed anchor cable; tension relaxation; creep; displacement coordination

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1 Introduction

Pre-stressed anchor cables are widely used in slope reinforcement engineering due to their ability to actively provide confining pressure and improve the stress state of the rock and soil mass. However, in practical engineering, the tension of the anchor cable often decreases over time, a phenomenon known as tension relaxation. This loss of pre-stress directly affects the long-term stability of the slope.

The tension relaxation of anchor cables is a complex process influenced by multiple factors. Existing research primarily attributes this phenomenon to two aspects: the relaxation of the steel strand itself and the creep of the rock or soil mass at the anchorage zone. While many scholars have conducted experimental and theoretical studies on these individual factors, there is a lack of a comprehensive analytical model that accounts for the coupled effects of both soil creep and steel relaxation under the specific boundary conditions of a slope reinforcement system.

This paper proposes a mechanical model for the tension relaxation of prestressed anchor cables by integrating the rheological properties of the slope soil and the steel strands. By applying the principle of displacement coordination, a closed-form solution for the time-dependent tension is derived.

2 Analytical Model for Tension Relaxation

2.1 Basic Assumptions

To simplify the mechanical analysis while maintaining the core physical characteristics of the system, the following assumptions are made: 1. The rock-soil mass is treated as a viscoelastic medium following a specific rheological law. 2. The prestressed steel strand follows an empirical power-law or logarithmic law for intrinsic relaxation. 3. The deformation of the anchor head and the bearing plate is considered elastic. 4. The bond between the grout and the rock-soil mass is assumed to be perfect during the relaxation process.

2.2 Mechanical Model Formulation

The total displacement of the anchor cable system at the tensioning end can be expressed as the sum of the deformations of its constituent parts. The anchor cable structure-slope system consists of four primary components: the anchor cable body, the stable strata surrounding the bonded section, the sliding mass where the free length is situated, and the slope surface restraint members.

[Figure 1: see original paper]

To describe this behavior, we employ mechanical constitutive models that account for both elastic and viscous properties. In a series model configuration, the total deformation of the anchoring system is the sum of the deformations of its individual components:

$$\Delta L = \sum_{i=1}^{n} \Delta L_i$$

The parallel model is applied where components share the load and undergo the same displacement. The total tension P is distributed among the components:

$$P = \sum_{j=1}^{m} P_j$$

2.3 Governing Equations

Based on the analytical model, the relationship between P and ϵ can be derived. For the relaxation problem, the strain ϵ is constant, meaning $D\epsilon = 0$, where D is the differential operator $\partial/\partial t$. The governing differential equation for the tension $P(t)$ is established as:

$$\lambda_1 P'' + \lambda_2 P' + \lambda_3 P = \lambda_4 \epsilon$$

By solving this differential equation, we obtain the general form:

$$P(t) = b_1 \epsilon + b_2 e^{n_1 t} + b_3 e^{n_2 t}$$

where n_1 and n_2 are the roots of the characteristic equation, and b_1, b_2, b_3 are constants determined by initial conditions. Based on the initial condition $P(0) = P_0$, the tension at any time t can be predicted.

3 Results and Discussion

3.1 Model Validation

The model was validated using experimental data from existing literature and field monitoring. For a model anchor cable with an initial tensile force of 54 N, the calculated final tension value after relaxation differed from experimental results by approximately 6%. In field applications with an initial tension of 600 kN, the error between the calculated stable value and field measurements was only 0.4%.

3.2 Parametric Analysis

The relaxation rate $\delta(t) = 1 - P(t)/P_0$ was analyzed against various parameters: - **Anchor Cable Diameter:** As the diameter increases from 9.5 mm to 17.8 mm, the relaxation rate increases nonlinearly from 6.65% to 19.79%. - **Hole Spacing:** The relaxation effect weakens significantly as the spacing between anchor holes increases. - **Elastic Modulus:** The relaxation effect strengthens linearly as the elastic modulus of the anchor cable increases. - **Soil Properties:** The relaxation effect weakens nonlinearly as the delayed elastic modulus and the viscosity coefficient of the anchored strata increase.

[Figure 3: see original paper]

4 Conclusion

1. A parallel-series combined analytical model for the "anchor cable-anchorage zone-free section-surface restraint" system was established, providing a comprehensive framework for tension relaxation analysis.
2. The tension relaxation of the anchor cable is the result of the coupled creep of both the soil and the steel strand. The relaxation rate is highest in the early stages and gradually stabilizes.

3. Parametric analysis shows that anchor cable diameter, hole spacing, and the rheological properties of the anchored strata are the primary factors influencing relaxation.
4. For practical engineering, a simplified series model neglecting the sliding mass in the free section is sufficient for estimating tension relaxation, as the sliding mass parameters have a negligible impact on the final results.

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Note: Figure translations are in progress. See original paper for figures.