ADVANCED OPTIMISATION STRATEGIES FOR ROAD CONSTRUCTION IN OPEN PITS: AN APPROACH FOCUSING ON GEOTECHNICAL STABILITY

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Abstract. The construction and maintenance of mine roads are critical to ensuring the efficiency, safety, and cost-effectiveness of mining operations. This paper presents an advanced mathematical framework that integrates effective stress principles, dynamic loading conditions, soil anisotropy, non-linear behavior, and time-dependent changes to provide a comprehensive assessment of soil stability during the construction of these facilities.

By combining effective stress with the Mohr-Coulomb failure criterion, the framework accounts for both inherent soil properties and the influence of pore water pressure, leading to more precise shear strength calculations. The Modified Cam Clay model addresses soil anisotropy and nonlinear behavior, enhancing the prediction accuracy of soil responses under different loading conditions. Incorporating a dynamic factor (D_f) allows for realistic assessments of stress due to heavy machinery, improving the evaluation of long-term stability and safety.

Key words. Mine roads construction, Efficiency and safety, Non-linear behavior

УСЪВЪРШЕНСТВАНИ СТРАТЕГИИ ЗА ОПТИМИЗАЦИЯ ЗА СТРОИТЕЛСТВО НА ПЪТИЩА В ОТКРИТИ РУДНИЦИ: ПОДХОД С АКЦЕНТ ВЪРХУ ГЕОТЕХНИЧЕСКАТА СТАБИЛНОСТ

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Резюме. Изграждането и поддръжката на руднични пътища са от решаващо значение за осигуряване на ефективността, безопасността и рентабилността на минните операции. Настоящата работа представя усъвършенствана математическа рамка, която интегрира принципи на ефективното напрежение, условия на динамично натоварване, анизотропия на почвата, нелинейно поведение и зависими от времето промени, за да предостави цялостна оценка на стабилността на почвата при изграждането на такава инфраструктура.

Чрез комбиниране на ефективното напрежение с критерия на Мор-Кулом се отчитат както присъщите свойства на почвата, така и влиянието на водното налягане в порите, което води до по-прецизни изчисления на якостта на срязване. Модифицираният модел на Кам-Клей се свързва с анизотропията на почвата и нелинейното поведение, като повишава точността на прогнозиране на реакциите на почвата при различни условия на натоварване. Включването на динамичен фактор (D_f) позволява реалистични оценки на напреженията, дължащи се на тежки машини и подобрява оценката на дългосрочната стабилност и безопасност.

Ключови думи:

Introduction

Open mine road construction is a crucial element in the mining industry, playing a pivotal role in ensuring the efficient and safe transportation of heavy machinery, personnel, and extracted materials. The quality and durability of these roads directly impact operational efficiency, safety standards, and overall productivity. As mining operations continue to expand, there is a pressing need to develop and implement advanced optimisation strategies that can enhance the construction and maintenance of this essential infrastructure. This paper focuses on a single strategy: comprehensive geotechnical stability analysis, presenting new mathematical models to support this approach.

The geotechnical stability of open mine roads involves understanding and managing the complex interactions between soil and rock properties, loading conditions, and environmental factors. Traditional approaches to geotechnical analysis have relied on empirical methods and basic theoretical models, such as the effective stress principle and the Mohr-Coulomb failure criterion. While these methods provide a foundation, they often fall short in addressing the dynamic and time-dependent behaviours encountered in real-world mining scenarios.

To address these challenges, we propose an enhanced mathematical framework that integrates several advanced concepts:

1. Dynamic Loading Conditions: Mining operations involve significant dynamic loads from heavy machinery and equipment. Traditional static models do not adequately account for these effects. By incorporating a dynamic load factor (D_f), we can better predict the stresses and potential failure modes under operational conditions.
2. Soil Anisotropy and Nonlinear Behavior: Soils often exhibit anisotropic and non-linear behaviour, particularly under varying load conditions. Using advanced models, such as the Modified Cam Clay model, allows us to capture these complex behaviors more accurately.
3. Time-Dependent Behaviour (Creep and Consolidation): Soil properties and stability can change over time due to consolidation and creep. Traditional models often ignore these effects, leading to inaccurate long-term predictions. Our framework includes equations for primary consolidation and secondary creep, providing a more comprehensive analysis of long-term stability.
4. Integration of Effective Stress and Dynamic Factors: By combining the effective stress principle with dynamic loading conditions, we create a more robust model for evaluating the stability of mine roads. This integrated approach allows for more accurate predictions of failure under both static and dynamic conditions.

The novelty of this approach lies in its comprehensive integration of these advanced concepts into a single mathematical framework tailored specifically for open mine road construction. By leveraging numerical simulations and finite element methods (FEM), we can simulate stress distributions and deformations under various conditions, providing more reliable and actionable insights for road design and maintenance.

Comprehensive Geotechnical Stability Analysis

A detailed site investigation is crucial to understanding the geotechnical properties of the soil and rock in the mining area. This involves the following:

Geotechnical investigations begin with conducting surveys and sampling to collect data on soil composition, rock properties, and groundwater conditions. This information forms the foundation of any geotechnical analysis and is critical for understanding the site-specific challenges that might affect road stability. The next step involves performing laboratory tests to determine essential soil parameters such as cohesion (c), internal friction angle (ϕ), and unit weight (γ). These parameters are crucial for assessing the shear strength and compressibility of the soil. Additionally, field tests, like Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT), are employed to obtain in-situ soil strength parameters, providing a more accurate representation of the soil's behavior under actual field conditions.

To evaluate the stability of open mine roads, we use established mathematical models that incorporate effective stress, dynamic loading conditions, soil anisotropy, non-linear behaviour, and time-dependent changes.

Effective Stress Principle:

The effective stress principle is fundamental in soil mechanics and plays a vital role in determining soil strength. The effective stress (σ') is defined as the difference between total stress (σ) and pore water pressure (u) (Lade & Boer, 1997):

$$\sigma' = \sigma - u \tag{1}$$

This equation indicates that the soil’s ability to resist deformation and failure is directly influenced by the pore water pressure. Higher pore water pressures can reduce the effective stress, leading to potential instability.

Mohr-Coulomb Failure Criterion:

The Mohr-Coulomb failure criterion is used to describe the failure condition of soils under shear stress. It combines the effects of cohesion and internal friction angle to define the shear strength (τ) of the soil (Heyman, 1972; Labuz and Zang, 2012):

$$\tau = c + \sigma' \tan\phi = c + (\sigma - u)\, tan\, \phi \tag{2}$$

Anisotropy and Non-Linear Soil Behaviour:

Soils often exhibit anisotropic and non-linear behaviour, particularly under varying load conditions. The Modified Cam Clay model is an advanced soil model that accounts for this complex behaviour. The yield function for this model is given by Foriero et al. (2015):

$$F = \frac{q^2}{M^2} + p(p - p_c), \tag{3}$$

where:

q is Deviatoric stress,
M - Slope of the critical state line,
p - Mean effective stress,
p_c - Preconsolidation pressure.

This equation provides a more accurate representation of the soil’s response to different loading conditions, considering both anisotropic and non-linear properties.

Dynamic Loading Conditions:

In mining operations, roads are subjected to dynamic loads from heavy machinery. These dynamic loads can significantly impact the stress distribution within the soil. To account for this, a dynamic factor (D_f) is introduced into the stress calculations (Kansake et al., 2023):

$$\sigma_d = \sigma . D_f, \tag{4}$$

where σ_d is the dynamic stress.

The dynamic Factor of Safety (FoS) can then be expressed as:

$$FoS_d = \frac{\tau}{\sigma_d} = \frac{c + (\sigma - u)\, tan\, \phi}{\sigma . D_f} \tag{5}$$

This equation helps in assessing the stability of the road under operational conditions by incorporating the effects of dynamic loading.

Time-Dependent Behaviour (Creep and Consolidation):

Soil properties and stability can change over time due to consolidation and creep. This time-dependent behaviour is crucial for long-term stability analysis.

Primary Consolidation:

The settlement due to primary consolidation is given by:

$$S_c = \frac{H . \Delta\sigma'}{E_S} . \log\left(\frac{\sigma' + \Delta\sigma'}{\sigma'}\right), \tag{6}$$

where:

S_c is settlement due to consolidation,
H - Thickness of the compressible layer,
$\Delta\sigma'$ - Change in effective stress,
E_S is consolidation modulus.

Secondary Creep:

The strain due to secondary creep is given by:

$$\epsilon_c = \alpha_c . \log\left(\frac{t}{t_0}\right), \tag{7}$$

where:

ϵ_c is Creep strain,
α_c - Creep coefficient,
t - Time,
t_0 is reference time.

These equations provide a framework for predicting long-term changes in soil properties and their impact on road stability.

Conclusion

This paper presents a mathematical framework for the geotechnical stability analysis of open mine roads by integrating effective stress principles, dynamic loading conditions, soil anisotropy, non-linear behaviour, and time-dependent changes.

The effective stress principle, combined with the Mohr-Coulomb failure criterion, allows for precise calculations of shear strength, accounting for variations in pore water pressure. The Modified Cam Clay model addresses the limitations of traditional isotropic assumptions by considering the anisotropic and non-linear behavior of soils. This leads to more accurate predictions of soil response under different loading conditions and better identification of potential failure mechanisms.

Incorporating dynamic loading conditions through a dynamic factor (D_f) provides a realistic assessment of stresses from heavy machinery operations. The dynamic Factor of Safety (FoS) model enhances the prediction of failures under operational conditions. Additionally, modeling time-dependent behaviour, such as primary consolidation and secondary creep, offers a framework for evaluating long-term changes in soil properties and their impact on road stability.

The proposed framework marks an improvement over traditional methods by offering a detailed and accurate understanding of soil behaviour. This leads to safer and more efficient designs for open mine roads, enhancing operational efficiency and safety. Future research can refine these models further and explore new factors that may impact soil stability, ensuring continued advancements in the field of geotechnical engineering for mining operations.

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