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SLOPE STABILITY ASSESSMENT USING UAV-DERIVED DATA AND NUMERICAL MODELING WITH CONSIDERATION OF SOIL GEOMECHANICAL PROPERTIES

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Abstract
This article presents a comprehensive approach to assessing the stability of excavation pit slopes in seismically active regions, based on the integration of remote sensing data using unmanned aerial vehicles (UAVs) and numerical modeling using the limit equilibrium method.

The study focused on a pit up to 60 m deep, located in a zone of increased seismic activity in the Kyrgyz Republic. A high-precision digital elevation model was generated using aerial photography with a Phantom 4 RTK UAV, which was used to develop a geomechanical calculation model.

The stability calculation was performed using the Morgenstern-Price method, taking into account the physical and mechanical properties of the soils and pseudo-static seismic impact. The slope stability coefficient was assessed, potential slip surfaces were identified, and the most dangerous deformation zones were determined.

It was shown that taking seismic impact into account significantly reduces the stability coefficient and requires adjustments to the slope design parameters. The proposed approach improves the reliability of slope geomechanical assessments and can be used in engineering and geological surveys and design in complex geodynamic conditions.

Keywords: geomechanics, slope stability, UAV, digital terrain model, SLOPE/W, Morgenstern–Price method, seismic loading

ОЦЕНКА УСТОЙЧИВОСТИ СКЛОНОВ С ИСПОЛЬЗОВАНИЕМ ДАННЫХ БПЛА И ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ С УЧЕТОМ ГЕОМЕХАНИЧЕСКИХ ХАРАКТЕРИСТИК ГРУНТОВ

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Аннотация
В статье представлен комплексный подход к оценке устойчивости откосов котлованов в сейсмоактивных регионах, основанный на интеграции данных дистанционного зондирования с использованием беспилотных летательных аппаратов (БПЛА) и численного моделирования методом предельного равновесия.

В качестве объекта исследования рассмотрен котлован глубиной до 60 м, расположенный в зоне повышенной сейсмической активности Кыргызской Республики. На основе аэрофотосъёмки с применением БПЛА Phantom 4 RTK сформирована высокоточная цифровая модель рельефа, использованная при построении геомеханической расчетной схемы.

Расчёт устойчивости выполнен методом Моргенштерна–Прайса с учетом физико-механических характеристик грунтов и псевдостатического сейсмического воздействия. Проведена оценка коэффициента устойчивости откосов, выявлены потенциальные поверхности скольжения и определены наиболее опасные зоны деформаций.

Показано, что учет сейсмического воздействия приводит к существенному снижению коэффициента устойчивости и требует корректировки проектных параметров откосов. Предложенный подход обеспечивает повышение достоверности оценки геомеханического состояния склонов и может быть использован при инженерно-геологических изысканиях и проектировании в сложных геодинамических условиях.

Ключевые слова: геомеханика, устойчивость откосов, БПЛА, цифровая модель рельефа, SLOPE/W, метод Моргенштерна–Прайса, сейсмическое воздействие.

1. Introduction

The Kyrgyz Republic is characterized by high seismic activity caused by the interaction between the Indian and Eurasian lithospheric plates. This interaction leads to the formation of a highly stressed state of the Earth's crust and the occurrence of earthquakes with intensities up to 9 on the MSK-64 scale, which significantly affects the stability of engineering structures and natural slopes.

Slope stability is determined by a combination of geological, hydrogeological, and technogenic factors, including soil physical and mechanical properties, slope geometry, and external loads. Seismic effects are of particular importance, as they lead to stress redistribution and reduction of soil strength parameters [1].

Modern slope stability assessment methods include limit equilibrium methods and numerical approaches based on continuum mechanics. Among them, limit equilibrium methods implemented in software such as GeoStudio SLOPE/W remain widely used due to their ability to account for complex slope geometry and soil heterogeneity [2].

In recent years, significant attention has been given to integrating remote sensing data, particularly UAV-based photogrammetry, with geomechanical modeling. UAV applications allow rapid acquisition of high-resolution digital terrain models, significantly improving the accuracy of geometric representations used in stability analysis [3].

Despite this progress, the combined consideration of high-resolution UAV-derived geometry and seismic effects in the stability assessment of deep excavations remains insufficiently studied [4].

The aim of this study is to develop and validate a comprehensive approach to slope stability assessment based on the integration of UAV photogrammetry and numerical modeling using the Morgenstern–Price method with consideration of seismic loading.

In addition, this study provides a quantitative comparison of slope stability under different seismic acceleration scenarios (0.2g and 0.346g), which allows identification of critical stability thresholds for deep excavations.

2. Study Area and Engineering-Geological Conditions

The study area is a deep excavation with a depth of 55–60 m located near an urban area. The ground surface elevation ranges from 938 to 940 m.

The geological structure of the site includes:

– fill soils (up to 1.5 m thick) composed mainly of gravel material;

– underlying coarse-grained soils (gravels) with sandy filler (20–25%);

– boulder content up to 10–15%, with sizes reaching 250–300 mm.

The soils are characterized by low moisture content and high density and consist mainly of fragments of igneous and metamorphic rocks.

Seismic conditions correspond to:

– the influence zone of the Issyk-Ata fault;

– soil category 1B;

– peak ground acceleration:

– ag=0.346g

– The region experiences regular seismic events with intensities of 6–7, significantly affecting slope stability.

3. Methodology

3.1. Digital Terrain Model Generation

The geometric model of the slope was developed using UAV-based aerial photogrammetry (Phantom 4 RTK). Image processing was performed using Agisoft Metashape [5], resulting in a point cloud, digital terrain model (DTM), and orthophoto.

RTK technology provided centimeter-level positioning accuracy, meeting modern engineering survey requirements [6].

The shear strength of soils is described using the Mohr–Coulomb failure criterion:

$$\tau = c + \sigma' \, tg\varphi$$

Pseudo-static seismic force

Seismic loading is introduced as a horizontal inertial force:

$$F_h = k_h \cdot W$$

Where k_h is the seismic coefficient and W is the weight of the sliding mass.

The factor of safety (FS) is defined as:

$$FS = \frac{\text{resisting forcesdriving forces}}{\text{driving forcesresisting forces}}$$

3.2. Geomechanical Model

Slope stability analysis was conducted using GeoStudio SLOPE/W.

The following assumptions were adopted:

– soils are considered isotropic;

– strength is described by the Mohr–Coulomb criterion;

– plane strain conditions are assumed.

Soil properties:

– unit weight: $\gamma = 2.26$ t/m^3

– cohesion: c = 30 kPa

– friction angle: $\varphi = 37°$

Figure 1 – Aerial view of the study area (excavation) based on Google Earth data.

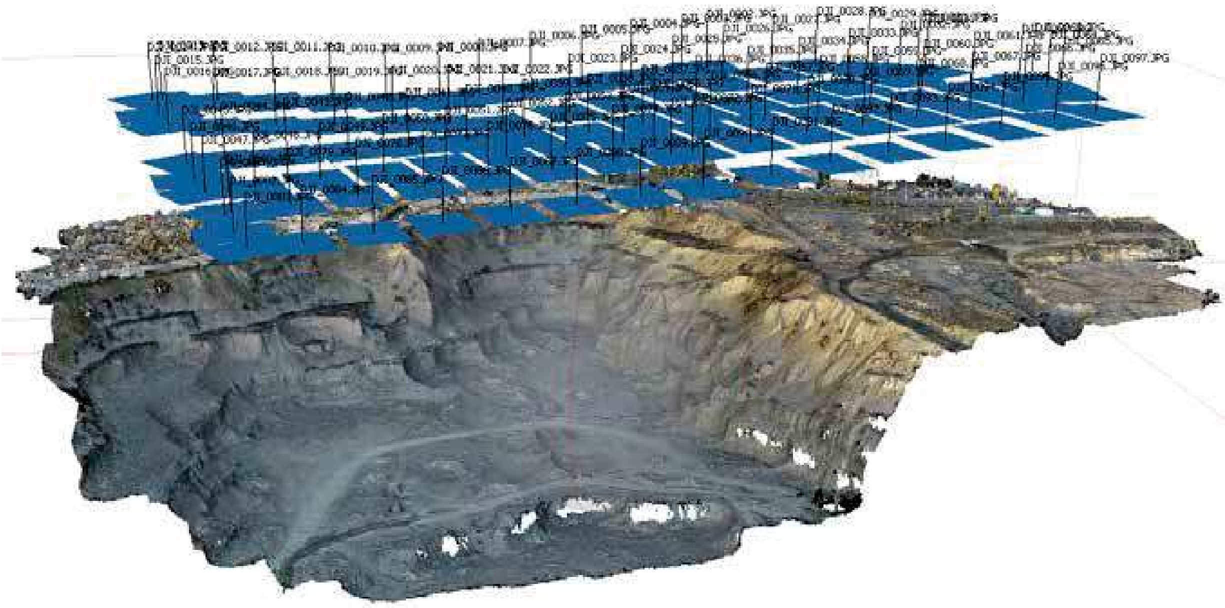

Figure 2 – Three-dimensional digital terrain model of the study area (excavation fragment) generated from UAV-based aerial photogrammetry data.

Cross-sections (1–5) were extracted from the orthophoto and used for numerical analysis.

3.3. Seismic Loading

Seismic loading was considered using the pseudo-static approach:

$$k_h = \frac{a_g}{g}$$

where (ag = 0.346g).

3.4. Stability Analysis Method

Slope stability was evaluated using the Morgenstern–Price method [8], which satisfies both force and moment equilibrium conditions.

The factor of safety (FS) is defined as the ratio of resisting forces to driving forces:

$$FS = \frac{\Sigma(cl + N \cdot tan\varphi)}{\Sigma^{T}}$$

4. Results

According to commonly accepted geotechnical criteria, slope stability can be classified as follows:

– FS > 1.3 — stable condition

– FS = 1.1–1.3 — marginally stable

– FS < 1.0 — unstable

Based on the obtained results, sections 3, 4, and 5 under seismic loading conditions exhibit FS values below 1.0, indicating a high probability of slope failure. This behavior is attributed to increased slope height, unfavorable geometry, and reduced shear strength at the interface between fill and natural soils.

The results indicate a nonlinear relationship between seismic acceleration and slope stability. A relatively small increase in seismic coefficient results in a disproportionate reduction in the factor of safety, which highlights the sensitivity of steep slopes to dynamic loading.

Slope stability analyses of the excavation (Figure 3), performed using the Morgenstern–Price method, allowed determination of the factors of safety for various calculation scenarios across five cross-sections, including both static conditions and seismic loading [10–12].

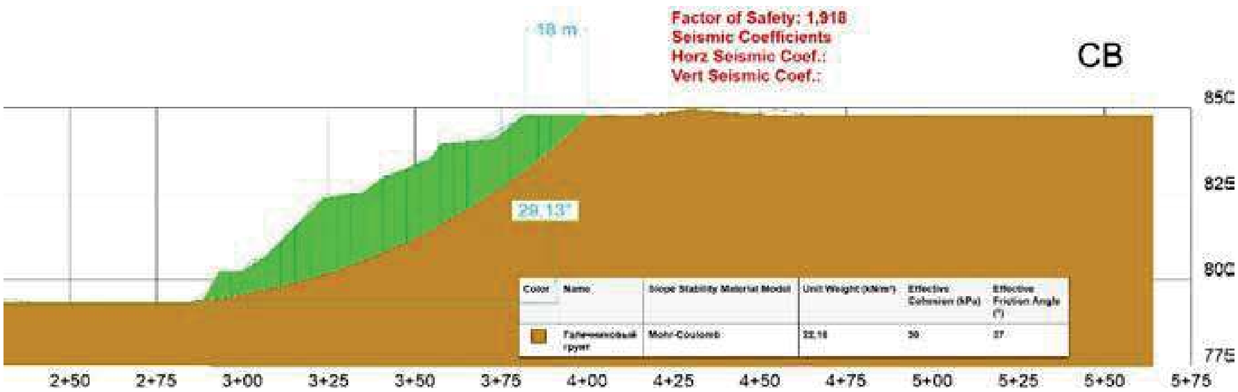

Figure 3 – Results of slope stability analysis of the excavation under various loading conditions.

The analysis results are presented in Table 1.

Considering the relative reduction in stability:

$$\Delta K = \frac{K_y - K_{yc}}{K_y} \cdot 100\% = \%$$

where:

— factor of safety under initial (natural) conditions;

FS (g) — factor of safety under seismic loading (0.2g–0.346g);

— reduction in stability, %.

where:

FS is the factor of safety under initial (static) conditions;

FS (g) is the factor of safety under seismic loading (0.2g–0.346g);

Δ FS is the percentage reduction in stability.

Table 1 – Factor of Safety for Different Sections

Section	Static FS	FS (0.2g)	FS (0.346g)
1	2.192	1.466	1.222
2	1.918	1.314	1.101
3	1.489	1.049	0.891
4	1.454	1.041	0.882
5	1.496	1.066	0.889

The factor of safety ranges:

static conditions: FS = 1.496–2.192

moderate seismic conditions (0.2g): FS = 1.066–1.466

peak seismic conditions (0.346g): FS = 0.882–1.222

A significant reduction in the factor of safety is observed, amounting to 30–34% under average seismic acceleration and reaching approximately 40% under peak seismic acceleration.

4.3. Slip Surface Analysis

During the analysis, critical safety conditions were identified, corresponding to the most unfavorable slope performance scenarios, namely:

– the formation of potential slip surfaces passing through weakened zones of the soil mass;

– the influence of additional loads applied at the crest of the excavation;

– the consideration of seismic loading.

Seismic loading was accounted for using a pseudo-static approach based on regulatory parameters for the territory of the Kyrgyz Republic in accordance with SN KR 20-02:2024. Two levels of seismic loading were considered: a design acceleration of 0.2g, corresponding to an intensity of 6–7 on the MSK-64 scale, and a peak acceleration of 0.346g, representing extreme conditions.

The modeling results demonstrate a consistent decrease in the factor of safety with increasing seismic loading. At 0.2g, the slope remains in a serviceable condition but approaches the limit equilibrium state. Under the influence of 0.346g, the slope transitions into a high-risk instability zone, which justifies the need for additional engineering measures and the implementation of monitoring systems.

4.4. Seismic Effect

Seismic loading results in:

– reduction of normal stresses;
– increase in driving forces;
– redistribution of stresses.

Spatial variability analysis

The analysis reveals significant spatial variability of slope stability. While sections 1 and 2 remain relatively stable even under seismic loading, sections 3–5 demonstrate critical behavior due to their geometric configuration and soil conditions. This indicates that slope instability is controlled not only by global parameters but also by local structural features.

5. Discussion

A comprehensive approach to slope stability assessment of a deep excavation is based on the integration of high-resolution digital geometry obtained using UAV-based aerial photogrammetry and verified geotechnical parameters (internal friction angle φ, cohesion c, and unit weight γ), determined from engineering-geological investigations, with stability analysis performed using the Morgenstern–Price method.

Seismic loading was considered within a pseudo-static framework with acceleration levels of 0.2g (corresponding to 6–7 intensity on the MSK-64 scale) and 0.346g.

The proposed approach integrates three interrelated levels of analysis:

– Information level — generation of a detailed digital terrain model based on UAV data, accounting for real geometric features of the slope (irregularities, benches, crest configuration);

– Analytical–predictive level — slope stability modeling under varying seismic loads (0.2g and 0.346g), enabling assessment of slope behavior under different loading scenarios;

– Engineering-geological level — application of physical and mechanical soil properties obtained from laboratory and field investigations.

The results of a comparative analysis of three calculation scenarios (static conditions and seismic loading at 0.2g and 0.346g) demonstrate a consistent decrease in the factor of safety with increasing inertial loading. Under 0.2g loading, corresponding to the design seismic level, the slope approaches a limit equilibrium state, which justifies the need for continuous monitoring.

With an increase in acceleration to 0.346g (⩾9 intensity on the MSK-64 scale), a critical slip surface develops, and at an excavation depth of 55–60 m, the slope transitions into an unstable condition. The obtained results confirm the governing role of seismic loading and substantiate the necessity of implementing engineering measures to ensure the required level of stability.

6. Conclusions

1. It has been established that the factors of safety for the slope cross-sections are as follows:

– under natural (static) conditions: FS = 1.454–2.192;
– under seismic loading of 0.2g: FS decreases to 1.041–1.466;
– under seismic loading of 0.346g: FS decreases to 0.882–1.222.

2. The inclusion of seismic loading results in a reduction in slope stability by 30–40%, confirming the significant influence of seismic accelerations on slope stability.
3. The obtained results can be applied in the design and assessment of slope stability in seismically active regions.

3. The obtained results can be effectively applied in the design and stability assessment of slopes in seismically active regions, particularly for identifying critical conditions and justifying engineering mitigation measures.

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