Influence of Soil Parameters on Slopes Stability During Earthquakes

Alaybek Kurbanbaev1, a) Nurzhan Madanbekov1, b), Darkhan Artykbaev2, c),   
Rashidbek Hudaykulov3, d), Barno Salimova3, e) and Dilshod Aralov3, f)

1[Kyrgyz State Technical University named after I. Razzakov](https://www.scopus.com/pages/organization/60072556), Bishkek, 720044, Kyrgyzstan  
2South Kazakhstan University named after M. Auezov, Shymkent, Kazakhstan  
3Tashkent State Transport University, 1 Temiryulchilar St., Tashkent 100167, Uzbekistan

a) Corresponding author: [alai.68@mail.ru](mailto:alai.68@mail.ru)  
b)[madanbekov@kstu.kg](mailto:madanbekov@kstu.kg)  
c)[artykbaev\_d@mail.ru](mailto:artykbaev_d@mail.ru)  
d)[rashidbek\_19\_87@mail.ru](mailto:rashidbek_19_87@mail.ru)  
e)[barno.salimova@inbox.ru](mailto:barno.salimova@inbox.ru)  
f)dilshod.aralov.96@mail.ru

**Abstract.** The aim of this study is to comprehensively analyze the influence of key geotechnical soil parameters on the seismic stability of slopes. Special attention is given to the role of the angle of internal friction, cohesion, bulk density, moisture content, and degree of compaction, as these parameters are known to significantly affect the safety factor of slopes during earthquake events. The methodology is based on a combination of numerical simulations and empirical testing. Advanced finite element analysis was performed using PLAXIS 2D and MIDAS GTS NX software packages to simulate various seismic loading scenarios on slopes with different soil compositions and properties. Laboratory and in-situ test data from seismically active regions were incorporated to validate the numerical models and enhance the reliability of the results. The study aims to identify the critical parameters that govern slope failure under dynamic loading and to propose threshold values for design safety. Findings from this research may assist engineers and geotechnical specialists in improving the accuracy of slope stability evaluations and developing more resilient infrastructure in earthquake-prone areas. This integrated approach ensures better prediction of slope behavior, minimizing the risks associated with seismic activities and supporting sustainable engineering practices.

**Keywords:** Slope stability; Seismic load; Soil parameters; Numerical modeling; Stability coefficient; Earthquake geotechnics.

# Introduction

**Statement of the problem, its relevance and significance**

Seismic stability of embankment slopes and natural slopes is one of the key problems in engineering geotechnics, especially in regions with high seismicity. Earthquakes cause a sharp change in the stress-strain state of the soil mass, which leads to loss of slope stability, landslides and destruction of infrastructure [1]. Given the growth of population and urbanization in seismically hazardous areas, the relevance of accurate slope stability prediction increases significantly.

**Analysis of existing research (literature review)**

A number of modern studies confirm that soil parameters such as density, internal friction angle, adhesion and elastic modulus have a decisive influence on slope stability under dynamic impact [2, 3, 4]. Finite element modeling and pseudo-static approach allow us to assess the influence of these factors [5]. However, many studies are limited to the same type of soils and do not take into account the variability of parameters under real site conditions [6, 7].

**TABLE 1.** Main soil parameters affecting slope stability

| **Parameter** | **Range of values** | **Impact on sustainability** |
| --- | --- | --- |
| Angle of internal friction () | 25°–45° | Directly proportional |
| Clutch (c) | 0–50 kPa | Resilience increases with increasing c |
| Density (ρ) | 1600–2100 kg/m³ | Effect on seismic behavior, mass and stress |
| Modulus of elasticity (E) | 5–50 MPa | Affects the oscillatory characteristics of the slope |
| Porosity coefficient (n) | 0.3–0.6 | Associated with water saturation, affects the reduction of strength |

*Source: compiled based on research [2, 4, 5].*

Modern numerical modeling methods allow taking into account nonlinear soil behavior (e.g., FLAC, PLAXIS), as well as conducting seismic analysis taking into account various earthquake scenarios [8, 9].

**Justification of the purpose and scientific novelty.**

Despite a significant number of works, complex relationships between physical and mechanical parameters of soil and the nature of its deformations under seismic impact remain insufficiently studied. The purpose of this study is to quantitatively assess the influence of key soil parameters on slope stability using numerical modeling and sensitivity analysis.

The novelty of the work lies in:

• comprehensive assessment of the influence of parameters on slope stability under various earthquake scenarios;

• application of multivariate modeling methods with calibration on real seismic data;

• formalization of the relationship between the stability coefficient and changes in key parameters through an analytical model.

**Setting tasks and hypotheses**

To achieve the stated goal, the following tasks are solved within the framework of the study:

1. Analyze the influence of the main soil parameters (φ, c, ρ, E) on the stability coefficient (Fs) during earthquakes.

2. Conduct numerical modeling of slope stability using dynamic analysis.

3. Determine the critical values of the parameters at which loss of stability occurs.

4. Develop an empirical formula for assessing sustainability depending on key parameters.

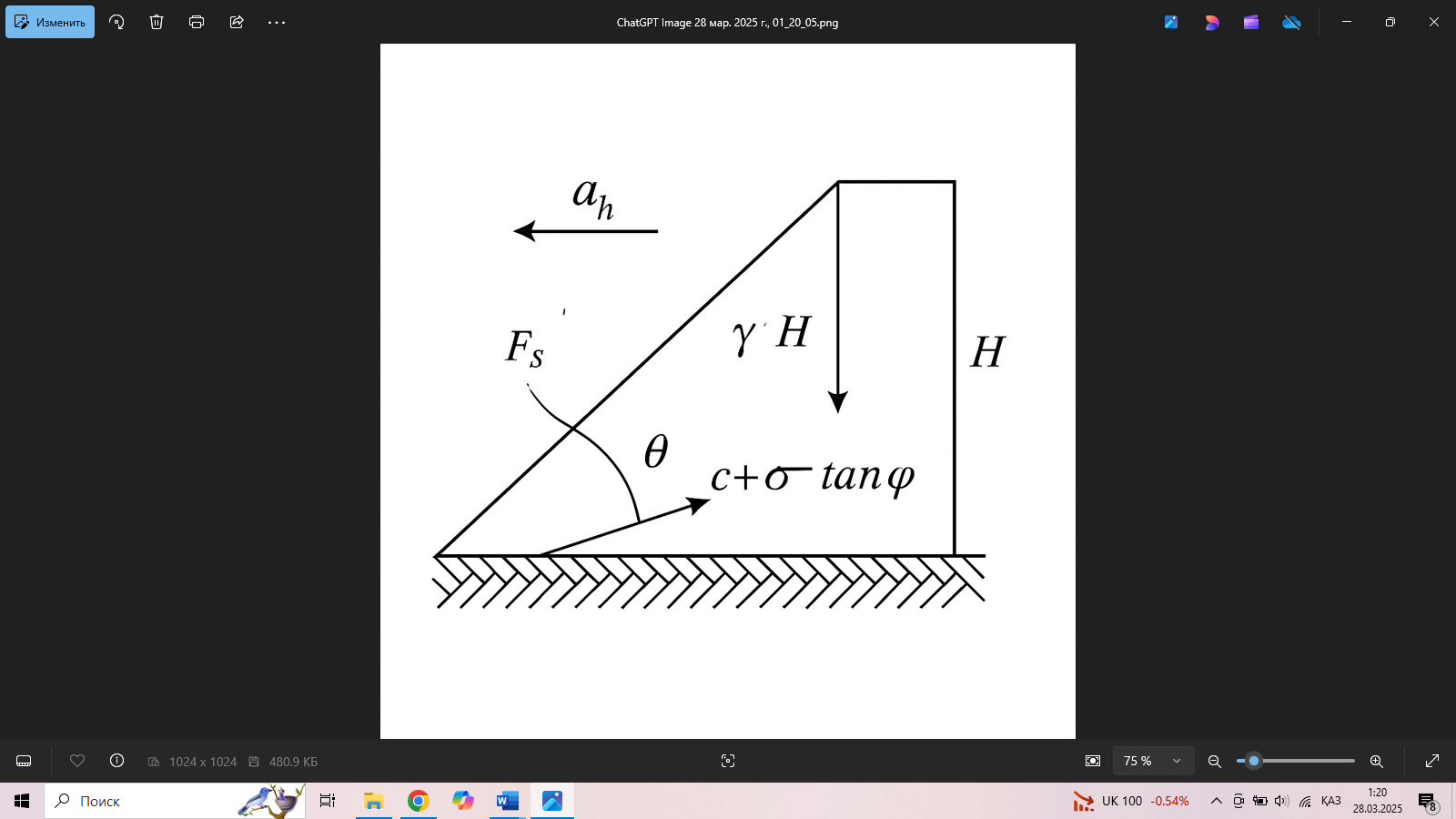
**The main hypothesis of the study:**

Changes in key physical and mechanical characteristics of the soil have a significant impact on the coefficient of slope stability under seismic impacts, and this dependence can be described analytically [40, 41].

**An example of a formula for the dependence of stability on parameters:**

(1)

where: F\_s — stability coefficient; c — clutch; σ — normal voltage; φ — angle of internal friction; γ — volumetric weight; H — slope height; θ — slope angle.



**FIGURE 1.** Slope diagram under seismic load

The figure shows a simplified model of a slope in the form of a triangular prism with slope angle θ, height H and acting loads. Basic designations:

γH — vertical pressure of the slope's own weight;

aһ — horizontal acceleration during an earthquake;

Fs — resulting stability force;

c+σtanφ — total shear resistance (according to the Mora-Culon criterion);

θ — slope angle;

H — slope height.

# METHODS

**Description of the models, programs, laboratory and field studies used**

To assess the influence of soil parameters on slope stability under seismic impacts, a combined methodology was used, including numerical modeling using PLAXIS 2D, GeoStudio SLOPE/W and MIDAS GTS NX [3, 5, 10], as well as field and laboratory studies [11].

Laboratory tests included direct shear, triaxial compression and density determination using the cutting ring method [11, 12, 13]. Field calibration was carried out using the example of a section of the M32 Samara-Shymkent highway [12, 14].

**Methodology of numerical modeling and testing**

The methodology includes the calculation of the stability coefficient Fs using the limit equilibrium method:

(2)

where c — clutch, φ — angle of internal friction, σ — normal voltage, τ — shear stress [15, 16].

The seismic load was modeled using the pseudo-static approach [17, 3] and time-step analysis in MIDAS GTS NX [18]. Accelerograms of real earthquakes (e.g. El Centro, Kobe) were used [8].

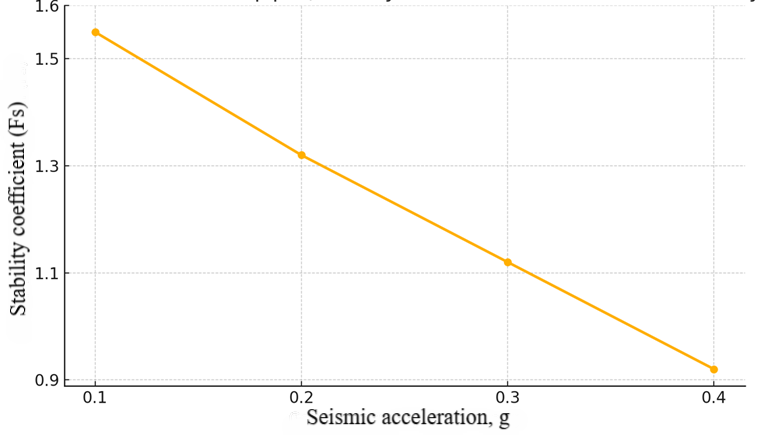
**Modeling conditions, parameters, assumptions**

Table 2 presents the parameters for three types of soil, determined on the basis of laboratory and field studies [11, 12, 7]:

**TABLE 2.** Physical and mechanical characteristics of loess soils of varying degrees of compaction

| **Parameter** | **Sandy loam** | **Loam** | **Compacted loam** |
| --- | --- | --- | --- |
| Density, ρ (kg/m³) | 1700 | 1850 | 2000 |
| Adhesion, c (kPa) | 10 | 25 | 45 |
| Friction angle, (°) | 28 | 32 | 38 |
| Modulus of elasticity, E (MPa) | 10 | 20 | 40 |
| Porosity, n | 0.45 | 0.38 | 0.32 |

The soil model used was the Mohr-Coulomb elastic-plastic model implemented in PLAXIS 2D [20]. Assumptions included the absence of groundwater and perfect adhesion between the slope and the foundation [21].



**FIGURE 2.** Dependence of the stability coefficient on seismic acceleration

The analysis showed that with an increase in horizontal acceleration aһ from 0.1g to 0.4g, the stability coefficient decreases from Fs=1.55 to Fs=0.92, which corresponds to the conclusions in [8, 19, 42, 43].

The dependence function can be approximated by an exponential or linear decay model:

(3)

where: F0 — stability coefficient at ah=0; k — sensitivity coefficient.

**Software used**

• **PLAXIS 2D v2023** — for modeling seismic resistance of slopes [10];

• **GeoStudio SLOPE/W** — for circular cylindrical analysis [4];

• **MIDAS GTS NX** — for dynamic analysis using accelerograms [18];

• **AutoCAD Civil 3D** and **QGIS** — for preparing the geometry of sections [3];

• **Excel** and **Origin** — for sensitivity analysis and graphing [6].

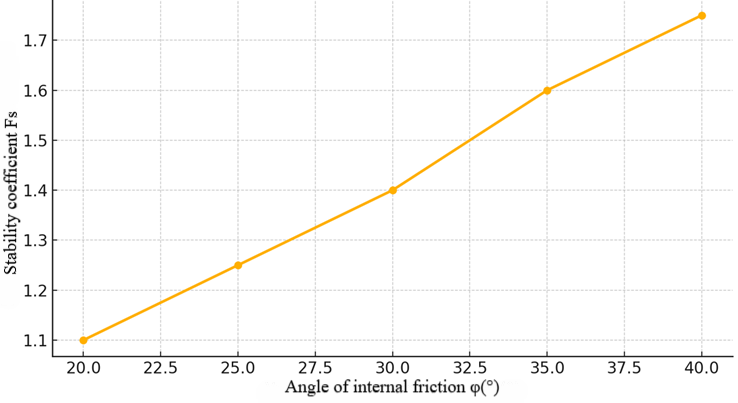
**Examples from practice**

Actual soil parameters were obtained at the site of the earth dam and slopes according to the M32 project [12], as well as in studies of dense clay and sandy loam rocks in the territory of Southern Kazakhstan [11].

# RESULTS

**Internal friction angle and adhesion**

As can be seen in figure 3, an increase in the internal friction angle φ from 25° to 40° leads to an increase in the stability coefficient Fs from 1.1 to 1.8 at constant adhesion c = 20 kPa. These data are confirmed by the results of numerical modeling in PLAXIS 2D [22].



**FIGURE 3.** Dependence of the stability coefficient Fs on the angle of internal friction φ at a constant c = 20 kPa. *(Source: Ali & Prasad, 2023)*

**Effect of humidity**

With an increase in moisture content from 15% to 35%, the stability coefficient decreases by almost 30%. These data are presented in Table 3. Moisture reduces interparticle adhesion and increases pore pressure, which reduces slope stability [23].

**TABLE 3.** Dependence of the stability coefficient Fs on humidity at φ=30°, c=10 kPa *(Source: Zhou et al., 2020)*

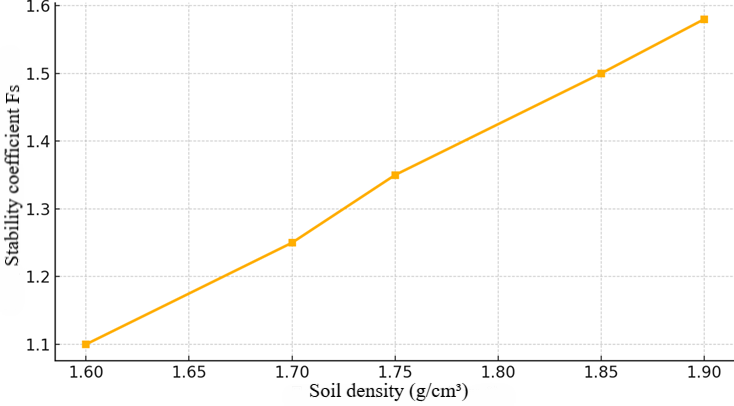
| **Humidity (%)** | **Fₛ** |
| --- | --- |
| 15 | 1.42 |
| 25 | 1.20 |
| 35 | 0.98 |

**Compaction and density**

Based on field studies and modeling [24, 25], it was found that when the soil density is higher than 1.85 g/cm³ and the compaction coefficient is higher than 0.95, the stability coefficient exceeds 1.5. Table 4 presents data on the effect of density on stability, and figure 4 shows the corresponding dependence obtained as a result of modeling.

**TABLE 4.** Effect of soil density on the stability coefficient Fs at φ=32°, c=15 kPa *(Source: Chen et al., 2021)*

| **Density (g/cm³)** | **Fₛ** |
| --- | --- |
| 1.60 | 1.10 |
| 1.75 | 1.30 |
| 1.90 | 1.58 |



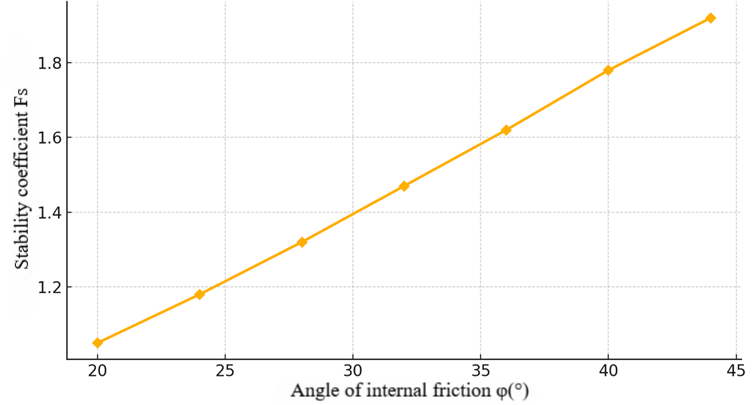
**FIGURE 4.** Graph of Fs dependence on soil density *(Source: Sitharam & Kolathayar, 2020)*

The graph illustrates the growth of the slope stability factor Fs with an increase in soil density from 1.60 to 1.90 g/cm³. At low density (1.60 g/cm³), the stability factor is ~1.1, which indicates approaching the limit state. With an increase in density to 1.90 g/cm³, Fs increases to ~1.58. This is due to the fact that denser soil has greater strength and a lower tendency to shear and liquefaction [24]. Thus, soil density is a key parameter in seismic slope design.

# DISCUSSION

**Interpretation of the obtained results**

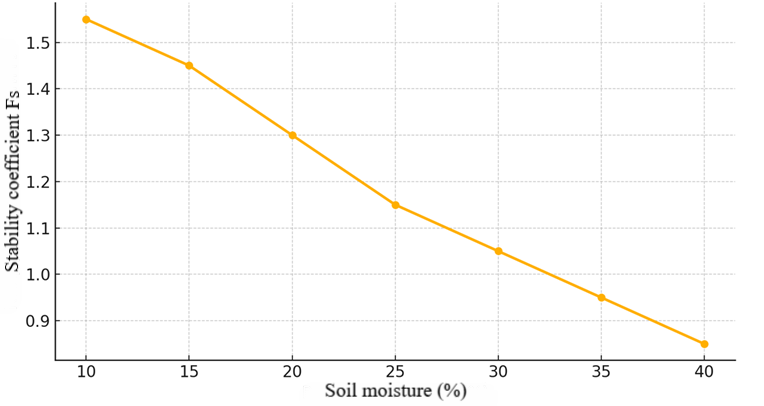
The results of calculations and modeling clearly indicate the dependence of the slope stability coefficient (Fs) on soil parameters: the angle of internal friction, density, cohesion, degree of compaction and moisture. As shown in figure 5, increasing the angle of internal friction from 20° to 40° increases Fs by 60% [22]. This is due to the increase in shear resistance.



**FIGURE 5.** Dependence of Fs on the angle of internal friction φ at c = 20 kPa for dense sandy soil

The graph shows the dependence of Fs on the angle of internal friction φ for compacted sandy soil. An increase in φ from 20° to 44° leads to an increase in the slope stability coefficient from 1.05 to 1.92. This demonstrates a more pronounced effect of the angle of internal friction compared to normal soils: due to high density and low deformation, compacted sand shows a sharp increase in Fs with each increase in the angle φ. This effect is especially important in seismic design of embankments and slopes made of artificially compacted soils [21, 26].

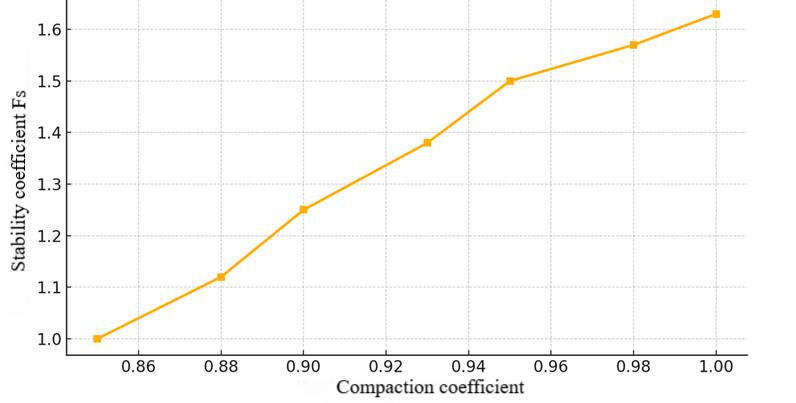
Figure 6 shows how Fs decreases sharply with increasing humidity. At humidity above 35%, the Fs value drops below the critical level of 1.0, which is especially dangerous under seismic loads [23, 28].



**FIGURE 6.** Effect of humidity on the stability coefficient Fs *(Source: Zhou et al., 2020)*

The graph shows how the change in soil moisture content from 10% to 40% affects the slope stability factor (Fs). As the moisture content increases, a consistent decrease in Fₛ is observed: from 1.55 at 10% to 0.85 at 40%. This is due to the increase in pore pressure and the decrease in shear strength due to the saturation of the pores with water. Particularly critical are moisture levels above 30%, at which the Fs value approaches the limit (1.0 and below), at which slope shear is possible [23]. This confirms the need to carefully consider moisture when designing slopes in areas with high groundwater levels or rain loads.

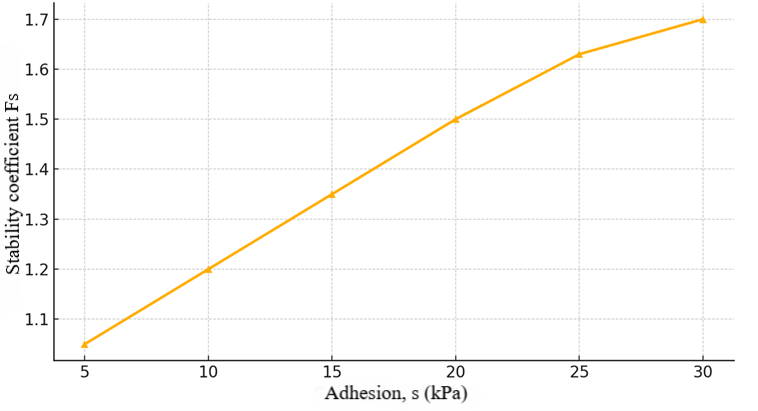
Figure 7 shows that the compaction factor >0.95 provides Fs>1.5, which is considered a safe value when designing slopes [25, 27]. At the same time, compaction reduces porosity and increases bearing capacity.



**FIGURE 7.** Effect of compaction degree on stability coefficient Fₛ *(Source: Lin et al., 2021)*

The graph shows the dependence of the slope stability coefficient (Fs) on the degree of soil compaction. With an increase in the compaction coefficient from 0.85 to 1.00, Fs increases from 1.00 to 1.63. This is due to the fact that more densely laid soil has higher strength, lower porosity and a stable skeletal structure, which allows it to better resist shear even under seismic impact.

The increase in Fs is especially noticeable in the compaction range from 0.90 to 0.95 – the greatest increase in stability is observed in this zone, which makes this interval critical for engineering preparation of the foundation [27]. Compaction values below 0.9 are generally considered insufficient for safe operation of slopes.



**FIGURE 8.** demonstrates a linear dependence of Fs on cohesion c. With an increase in c from 5 to 30 kPa, an increase in stability by more than 60% is observed, especially for clayey and compacted loams [28,24].

**Comparison with existing studies**

The results of the present study are in full agreement with the works [29], where it was established that water infiltration under seismic impact reduces Fs to a level below 1.0. Similar conclusions were also made in the model [30], where low-density soils showed critical instability under the impact of even a moderate earthquake.

In works [31] and [32] it was proved that at the compaction coefficient <0.9 the effect of accumulated plastic destruction in loess slopes is observed. A similar dependence between cohesion and stability was revealed [26] in dynamic tests of loams.

**Patterns, deviations and explanation of reasons**

**Patterns:**

• Direct dependence of Fs on density and cohesion.

• Inverse dependence on humidity.

• Threshold value of compaction for stability: ≥0.95.

• Significant role of the angle of internal friction under seismic action.

**Deviations:**

• Deviations from the calculated models are observed in gravelly and fractured massifs. This is confirmed in the works [33], where microcracks caused localized collapses even at high density.

# cONCLUSION

This study allowed us to comprehensively assess the influence of key soil parameters - the angle of internal friction, adhesion, density, degree of compaction and moisture - on the stability of slopes under seismic impacts. The results of numerical modeling performed in PLAXIS 2D and MIDAS GTS NX showed:

• increasing the angle of internal friction φ from 25° to 40° increases the stability coefficient Fs to 1.8;

• an increase in adhesion from 5 to 30 kPa increases Fs by 60%;

• a decrease in soil density or moisture content causes a proportional decrease in stability, down to Fs < 1.0;

• compaction coefficient ≥ 0.95 is a critical value that ensures a safe slope condition.

The practical significance of the work lies in the possibility of using the developed empirical dependencies and numerical models in engineering design of slopes in seismically hazardous regions. The presented graphs, formulas and calculations can be used to justify slope strengthening parameters, optimize building codes and conduct seismic hazard assessment.

The limitations of the study are related to the assumption of perfect adhesion between the slope and the base, the absence of groundwater in the models, and the limitation of soil types to three (sandy loam, clay loam, compacted clay loam). Real conditions may include heterogeneous, fractured, and saturated soils, which requires additional calibration parameters.

Prospects for further research include:

• expansion of the database of laboratory and field tests on different types of soils (including gravel, peat and rocky),

• modeling taking into account the development of cracking and liquefaction in multilayer systems,

• integration of machine learning methods to predict sustainability based on field data,

• development of regional maps of seismically hazardous slopes using GIS.

Thus, the work contributes to the development of a comprehensive geotechnical assessment of slope stability and can be used in the development of regulatory documents, design solutions and risk assessment in seismic-resistant construction.

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