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# ADVANCED EXPERIMENTAL APPROACHES IN CONDUCTING DIRECT SHEAR TESTS FOR SOIL MECHANICS

BY

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**Abstract.** This study examines the impact of shearing direction on the soil shear strength using advanced direct shear testing. Cubic samples were tested in the vertical direction and parallelepiped samples in the horizontal. The hypothesis was that unlike the normal stress $\sigma_1$ in the case of the classic direct shear testing in horizontal shearing, where $\sigma_1=\sigma_3\neq0$ but $\sigma_2=0$; in the vertical shearing condition $\sigma_2\neq0$. Jaky's formula and Hooke's law used by Terzaghi were used in the determination of the $\sigma_2$. Jaky's formula emphasized frictional resistance using $\varphi$ from the results of the horizontal shearing, while Hooke's law accounted for elastic deformation using the Poisson's ratio. Results showed that cubic samples yielded higher cohesion and internal friction angles than parallelepipedic samples, with Jaky's formula often overestimating strength. Hooke's law provided more moderate and realistic values. These findings highlight the importance of shearing direction in evaluating slope stability, particularly in overconsolidated, collapsible soils, which can exhibit high strength followed by potential failure under loading. The study concludes that while cubic samples improve accuracy in slope stability

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assessments, careful model selection is essential to avoid overly conservative or excessive design parameters.

**Keywords:** direct shear test, shear strength parameters, soil mechanics, soil cohesion, internal friction angle.

## 1. Introduction

Shear strength is a critical property of cohesive soils which defines the soil's ability to resist maximum shear stress before failure. The determination of shear strength is essential for the safe design of foundations, slope stability analysis, and the construction of dams, embankments, retaining walls, and tunnels (Tiwari & Ajmera, 2023; Jiang, et al., 2020). Shear strength is primarily governed by the two fundamental parameters central to geotechnical engineering: cohesion ($c$) and internal friction angle ($\varphi$) (Terzaghi & Peck, 1948). Accurate determination of shear strength parameters helps in preventing structural failures, determining critical slip surfaces, and calculating the factor of safety required to ensure slope stability and consequently environmental sustainability (Isaev & Sharafutdinov, 2020; Axel, et al., 2023). In slope stability analysis, these parameters are necessary for evaluating the soil's shear strength and its ability to resist sliding along potential failure surfaces under gravitational and additional loading conditions (Budhu, 2010).

Laboratory techniques for measuring soil shear strength have evolved from the early Direct Shear Test to more sophisticated methods like the Triaxial Compression Test and Centrifuge Test. Other modern techniques like the Ring Shear and Bender Element Tests have further refined our understanding of soil's resistance to dynamic stress (Moon & Ku, 2016; White, 2020; ASTMD6467, 2021). The Direct Shear Test (DST) remains widely used for its simplicity and cost effectiveness. The concept of the direct shear test dates back to 1846 when Alexandre Collin developed the first apparatus for slope stability studies and was later refined by Arthur Casagrande in 1932 at Harvard University. The direct shear test is a simple test and its application supports cost efficiency and material optimization in construction (Imran, et al., 2023).

The DST assumes that failure occurs at a single point along a cylindrical surface based on the recommendation of the Swedish Geotechnical Commission (Svensson, 1925) as shown in Fig. 1.

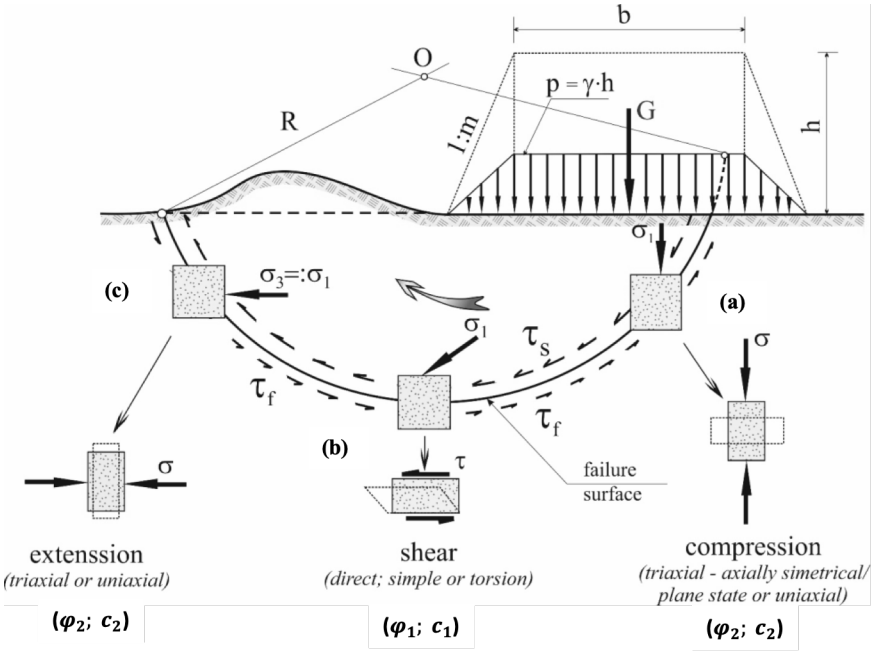



Fig. 1 – Types of soil stresses along a failure surface and appropriate tests for determining shear strength (Stanciu & Lungu, 2006).

At point (b) in the Fig. 1, upon which the classical DST is assumed, the normal stress $\sigma_1$ in the horizontal shearing, assumes that $\sigma_1=\sigma_3\neq 0$ but $\sigma_2=0$. This oversimplification can overlook the variability in shear resistance across different failure planes (Shiqing, et al., 2012; Buck, 2023). Fig. 2 shows the variability along the failure surface from the initiation and emergence points (a) and (c).

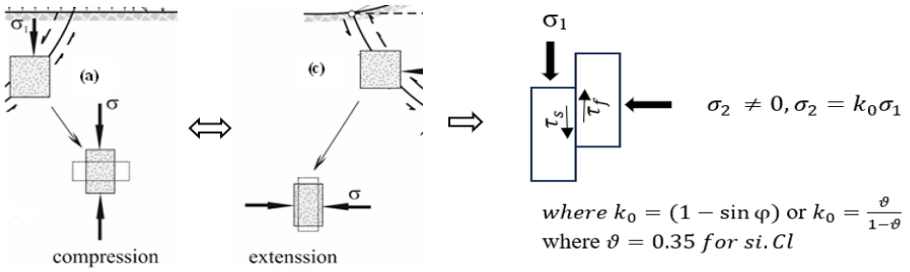



Fig. 2 – Variability along failure surface showing the forces at the initiation and emergence points.

At both the emergence and initiation points, $\sigma_2 \neq 0$ unlike at point (b) in Fig. 1 and therefore $\sigma_2$ has an impact on the shear strength parameters. The equation for the determination of $\sigma_2$ using the constants $k_0$ (coefficient of earth pressure at rest) can be seen in Fig. 2. Hence the shear stress at failure can be obtained from the two equations below:

$$\tau_{f2} = \sigma_1 (1 - \sin\varphi) \tan\varphi + c \quad (1)$$

$$\tau_{f2} = \sigma_1 \left[\frac{\vartheta}{1-\vartheta}\right] \tan\varphi + c \quad (2)$$

Equation (1) which uses Jaky, 1948 relationship ( $k_0 = 1 - \sin\varphi$ ), is commonly used in soils where $\varphi = \varphi_{cv}$. Thus, $\varphi_{cv}$ is constant-volume friction angle or the critical state friction angle. Collapsible soils do not usually behave like normally consolidated soils and hence do not deform at a constant volume because of their significant volumetric changes under stress. The inclusion of Terzaghi's relation with Hooke's law ($k_0 = \frac{\vartheta}{1-\vartheta}$) where $\vartheta$ is the Poisson's ratio in equation (2) makes analysis more relational. The typical Poisson's ratio for silty clay generally ranges from 0.3 to 0.4, but in practice the value 0.35 is used when site-specific data is unavailable.

This paper therefore analyzes the new data from cohesive soil samples using an innovative vertical shear testing method from the Romanian Patent RO 134239 (Stanciu, et al., 2020) taking into consideration $\sigma_2$ in the equations above and comparing it with standard direct shear tests to assess the variability of shear strength parameters along the failure surface and their implications for slope design and stability analysis.

## 2. Apparatus, Materials and Methodology

### 2.1 New Shear Test Apparatus

The new shearing device is designed for direct shearing on a vertical plane using cubic soil samples (6cm x 6cm x 6cm). It consists of five main sub-assemblies which basically resembles the standard DST machine but has some key differences. The first sub-assembly, the lever group, applies axial force using weights and a vertical screw. The second involves the shear force application and measurement, utilizing a marked screw reducer, dynamometric rings, and a micro-comparator. The third sub-assembly, a uniquely designed shear box, facilitates vertical shearing. The fourth is the box support group, which includes tracks, support columns, and a micro-comparator for consolidation measurement. Finally, the fifth sub-assembly is a metal plate supporting all components, including a motor-driven system for regulating shearing speed.

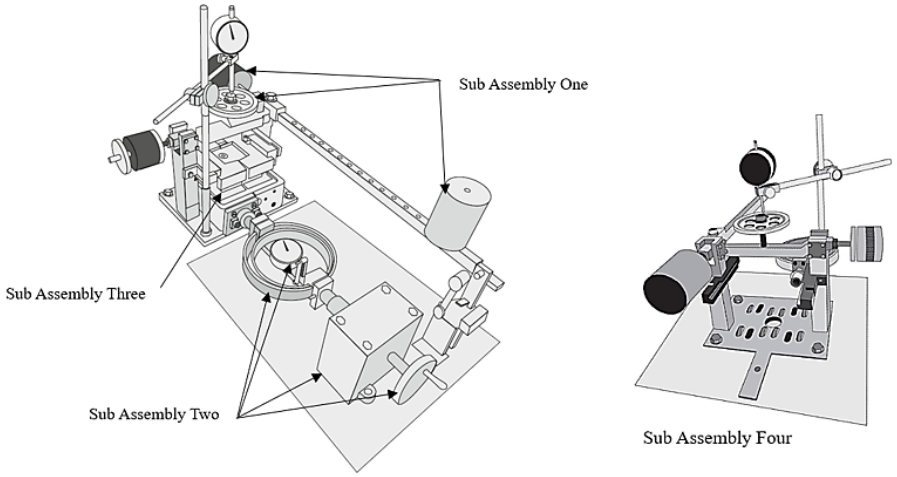



Fig. 3 – General layout of the New Shear Apparatus showing its sub-assemblies.

### 2.2 Soil Characterization

The soil used in this study was sampled from Copou in Iasi, Romania. It was classified as silty clay (si.Cl) according to STAS 1913/5-85. The Atterberg limits revealed a liquid limit of 36.49%, a plastic limit of 24.09%, and a plasticity index of 12.40%. This classification indicates that the soil has medium plasticity. The bulk unit weight ($\gamma_{bulk}$) was measured at 16.84kN/m$^3$, with a dry density ($\rho_d$) of 1.73g/cm3. The soil exhibited a degree of saturation ($S_r$) of 0.36 and a void ratio of 0.64, corresponding to a porosity of 38.9%. The optimum moisture content (OMC) was determined to be 14.93% during compaction tests.

### 2.3 Sample Preparation

Soil specimens were prepared by first oven-drying at 105ºC, followed by milling and sieving. Based on the determined dry density and OMC, the samples were mixed with water in airtight plastic bags to obtain a homogenous mixture and also to prevent moisture loss. The samples were then molded using the static compaction technique with a TriTech 50kN compressor. Two sample sizes were prepared: cubic (6cm x 6cm x 6cm) and parallelepiped (6cm x 6cm x 2cm). For the cubic samples, soil was compacted in three layers at a rate of 1.25mm/min to a final height of 6 cm. The parallelepiped samples were uniformly compacted at the same rate to a height of 2cm. After compaction, the samples were carefully extruded from the molds to prevent disturbance. Each size was tested under Unconsolidated Undrained (UU) and Consolidated Drained (CD) conditions. Six samples of each size were prepared, and shear strength parameters were recorded.

### 2.4 Testing Procedure

The testing procedure commenced with the assembly of the shear boxes for vertical and horizontal shearing. For vertical shearing, the two half-boxes were joined face-to-face, equipped with cutting knives, porous stones, and perforated ribbed plates. A cubic sample was inserted and pistons with bearings were placed to ensure consistent vertical load application (N/2 on each piston) throughout the process. The assembled box was positioned on tracks, with weights applied to balance vertical loads, and the shear force was then applied through sub-assembly two. For horizontal shearing, the lower half of the standard shear box was securely positioned on the base plate. The sample, flanked by porous stones and perforated plates, was carefully placed inside. After securing the loading cap and balancing vertical loads, the shear box was attached to the horizontal drive mechanism.

Both shear boxes were subjected to controlled shearing using a motorized mechanism, with readings taken from the micro-comparators. For the UU test, shearing was performed at 1.0mm/min without prior consolidation. In the CD test, samples were allowed to consolidate under vertical loads for 24 hours before being sheared at 0.1mm/min. After testing three cubic and three parallelepiped samples under different vertical stresses (100kPa, 200kPa, and 300kPa), the resulting shear stress values were used to plot Coulomb's failure envelope, allowing for the determination of shear strength parameters (φ and c) for each test condition

## 3. Results

### 3.1 Shear Strength Parameters

The direct shear tests conducted on the prepared soil samples provided the shear strength parameters; cohesion (c) and the internal friction angle (φ). The results for both type of samples and their type of tests from the Mohr Coulomb envelopes are in the Table 1.

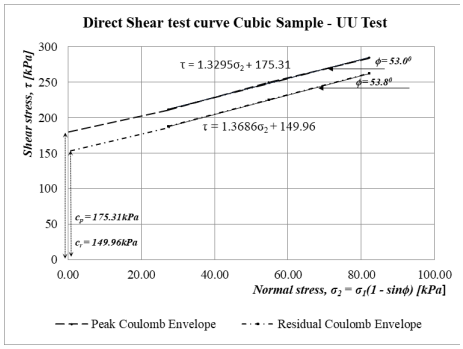
**Table 1**

*Tabulated Results of Internal friction angle and cohesion for peak and residual shear strength of soil under different testing conditions and formula*

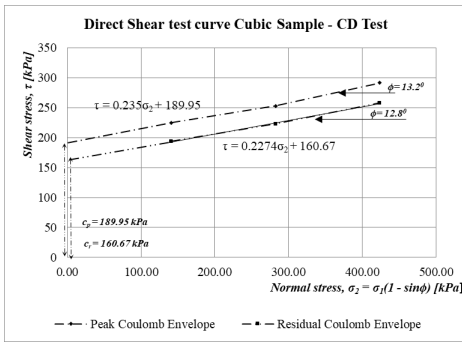
| Type of Test Results | | Parallelepiped sample | Cubic sample *Jaky's formula* | Cubic sample *Hooke's law* |
|---|---|---|---|---|
| Unconsolidated Undrained (UU) Test | Peak (φ) [deg(º)] | 32.2 | 53.0 | 34.1 |
| | Residual (φ) [deg(º)] | 28.9 | 53.8 | 34.8 |
| | Peak (c) [kPa] | 49.41 | 175.31 | 175.31 |

| | | | | |
|---|---|---|---|---|
| | Residual (c) [kPa] | 38.72 | 149.96 | 149.96 |
| Consolidated Drained (CD) Test | Peak (φ) [deg(º)] | 28.7 | 13.2 | 31.7 |
| | Residual (φ) [deg(º)] | 27.0 | 12.8 | 30.8 |
| | Peak (c) [kPa] | 72.64 | 189.95 | 189.95 |
| | Residual (c) [kPa] | 57.52 | 160.67 | 160.67 |

The results from both UU and CD tests highlight the influence of sample geometry and shearing conditions on these parameters. It also shows the significant differences in the internal friction angles when the two different relationships are used. The Mohr Coulomb failure envelopes for the different cases are shown in Fig. 4, Fig. 5 and Fig. 6.

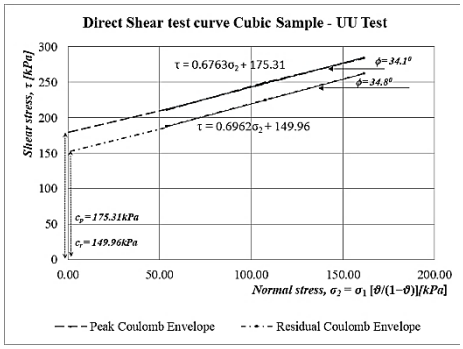



a)

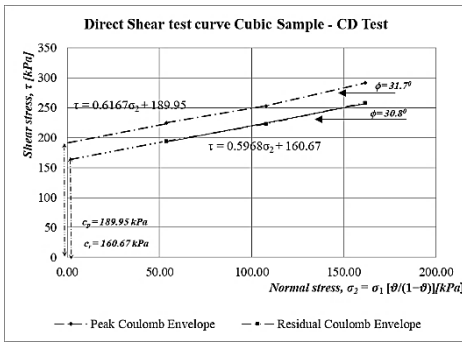



b)

Fig. 4 – Mohr Coulomb failure envelope for the Cubic Samples using Jaky's formula (a) UU condition (b) CD condition.

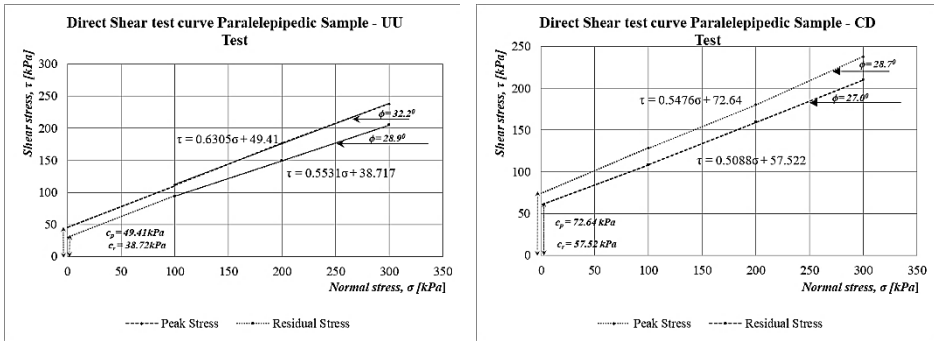



a)




b)

Fig. 5 – Mohr Coulomb failure envelope for the Cubic Samples using Hooke's law (a) UU condition (b) CD condition.




a) b)

Fig. 6 – Mohr Coulomb failure envelope for the Parallelepiped Samples (a) UU condition (b) CD condition.

### 3.2 Comparison of Unconsolidated Undrained (UU) and Consolidated Undrained (CU) Test Results

The analysis of shear strength results for cubic and parallelepiped samples shows distinct differences in internal friction angle (φ) and cohesion (*c*). In UU tests, cubic samples using Jaky's formula exhibit significantly higher peak and residual friction angles (53.0° and 53.8°) compared to parallelepiped samples (32.2° and 28.9°), with cohesion values also notably higher (175.31kPa as against 49.41kPa peak). Hooke's law moderates these results for cubic samples, showing more realistic peak and residual friction angles (34.1° and 34.8º) with unchanged cohesion values.

For the CD tests, cubic samples again show higher cohesion values (189.95kPa peak, 160.67kPa residual) compared to parallelepiped samples (72.64kPa peak, 57.52kPa residual), reflecting enhanced shear strength due to consolidation. However, Jaky's formula for cubic samples results in notably lower friction angles (13.2° peak, 12.8° residual), compared to Hooke's law, which yields values more aligned with expectations (31.7° peak, 30.8° residual).

The results demonstrate that cubic samples consistently yield higher shear strength parameters than parallelepiped samples, particularly in cohesion. Jaky's formula often produces higher friction angle particularly in the undrained conditions but relatively low friction angles in the drained condition. On the other hand, Terzaghi's application of the Hooke's law used provides more moderate and realistic results

## 4. Discussion

The results from both Unconsolidated Undrained (UU) and Consolidated Drained (CD) tests demonstrate the significant impact of sample geometry and testing methodology on soil shear strength parameters. Notably, cubic samples

exhibit higher cohesion and internal friction angles, particularly when analyzed using Jaky's formula. This observation aligns with previous research, such as that by Casagrande, 1936, which highlights the influence of boundary effects and stress distribution on shear strength testing. The tendency of Jaky's formula to overestimate peak and residual friction angles, especially in undrained conditions where pore pressure is significant, underscores the limitations of this approach.

In contrast, the results derived from Hooke's law for cubic samples, particularly in CD tests, are more moderate and consistent with findings from Terzaghi (1943) and Lade (2010), who investigated the effects of consolidation on soil behavior. By incorporating the Poisson ratio, Hooke's law provides a more accurate representation of soil behavior, accounting for elastic deformation and stress redistribution during shearing. The observed higher cohesion values in cubic samples, particularly after consolidation, support the principle that denser soils or those subjected to prolonged consolidation exhibit increased resistance to shearing forces. This understanding is crucial for slope stability and foundation design, as consolidated soils are generally more reliable due to their enhanced strength parameters.

Overconsolidated soils, such as loess and residual soils, display complex behavior characterized by high strength and stiffness, followed by potential collapse upon wetting or loading (Assallay, et al., 1997; Dijkstra, 1995). The overestimation of friction angles by Jaky's formula may lead to overly conservative assessments of slope stability in these soils, resulting in unnecessary design measures or the rejection of viable sites. Conversely, Hooke's law offers a more realistic estimate of strength parameters along failure surfaces by accounting for consolidation effects and stress redistribution during shearing. This approach aids in identifying critical failure surfaces and optimizing slope design (Lade, 2010; Terzaghi, 1943).

The significant discrepancy in friction angle values between Jaky's and Hooke's formulations highlights the importance of selecting appropriate soil behavior models in geotechnical design. As noted by Duncan & Wright (2005), overly simplified models like Jaky's can lead to conservative or excessive design parameters, particularly under undrained conditions. While Jaky's formula may serve as a useful tool for estimating initial peak strengths, its propensity to overestimate internal friction angles can result in unrealistic stability margins in practical applications. In contrast, Hooke's law provides a more sophisticated, elasticity-based model that considers soil-structure interaction, making it a robust alternative for high-level geotechnical analysis where precision is essential.

## 5. Conclusion

1. The cubic samples exhibited higher shear strength parameters than parallelepipedic samples which underscores the significant influence of sample geometry on soil behavior under shear stress.

2. The higher cohesion values observed in cubic samples, particularly post-consolidation, align with the principle that denser soils or those subjected to prolonged consolidation exhibit greater resistance to shearing forces, a critical consideration for slope stability and foundation design.

3. Jaky's formula tends to overestimate friction angles, leading to conservative assessments of slope stability in overconsolidated collapsible soils which can result in unnecessary design measures or the rejection of viable sites.

4. Hooke's law, which incorporates the Poisson ratio, provides a more realistic representation of soil behavior by accounting for elastic deformation and stress redistribution during shearing, offering better estimates of strength parameters along failure surfaces in slope stability analyses.

5. The significant discrepancy in friction angle values between Jaky's and Hooke's formulations emphasizes the need for careful selection of soil behavior models in geotechnical design, particularly when analyzing overly consolidated or collapsible soils, as variability along the failure surface can critically affect slope stability.

6. The findings from this study have practical implications for geotechnical engineering, particularly in ensuring the safety and stability of structures built on or within silty clay soils.

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## METODE EXPERIMENTALE AVANSATE PENTRU ÎNCERCĂRI DE FORFECARE DIRECTĂ ÎN MECANICA PĂMÂNTURILOR

Acest studiu examinează impactul direcției de forfecare asupra rezistenței la forfecare a pământului folosind o testare avansată de forfecare directă. Probe de formă cubică au fost testate pe direcție verticală și probele de formă paralelipipedică pe direcție orizontală. Ipoteza a fost că, tensiunea normală $\sigma_1$ în cazul forfecării directe în plan orizontal, unde $\sigma_1=\sigma_3\neq0$ dar $\sigma_2=0$ în cazul forfecării în plan vertical $\sigma_2\neq0$ spre deosebire de cazul anterior, pentru estimarea valorii folosindu-se formula lui Jaky și legea lui Hooke. Formula lui Jaky a evidențiat rezistența la forfecare datorată frecării utilizând unghiul de frecare interioară φ, obținut din rezultatele forfecării în plan orizontal, în timp ce legea lui Hooke a luat în considerare deformațiile elastice prin intermediul coeficientului lui Poisson. Rezultatele au arătat că probele de formă cubică au prezentat o coeziune și un unghi de frecare interioară mai ridicate decât la cele paralelipipedice, formula lui Jaky supraestimând adesea rezistența. Legea lui Hooke a oferit valori mai moderate și mai realiste. Aceste constatări subliniază importanța direcției de forfecare în evaluarea stabilității versanților, în special în cazul pământurilor supraconsolidate și colapsibile, care pot manifesta o rezistență ridicată urmată de potențiale cedări sub sarcină. Studiul concluzionează că, deși probele de formă cubică îmbunătățesc acuratețea evaluărilor privind stabilitatea versanților, selecția atentă a modelului este esențială pentru a evita parametrii de proiectare excesiv de conservatori sau supraestimați.