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Optimization of shear strength parameters of deposited clastic sediments via crack shape

D. Božić
Geomatriks, Ljubovija, Serbia
danijelabozic1976@gmail.com
0009-0006-7388-9746

V. Čebašek
University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia
0000-0002-8667-2339

V. Rupar
University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia
0000-0002-0296-8467

Abstract
The mechanical behavior of deposited clastic materials at landfills can be analyzed using orthophoto imagery acquired by unmanned aerial vehicles (drones). Tension crack geometry observed on landslide scarp and body along landfill working slopes is used to define a correction parameter for the residual internal friction angle (ψ). This parameter is applied to adjust initial friction angle values and is essential for determining the mobilized friction angle used in slope stability analyses. Slope stability calculations should be based on the mobilized friction angle, as the material consists of loose, unsaturated, mica-rich silty-sandy and weakly clayey deposits. Laboratory results are included to provide an estimate of shear strength parameters in deeper, intact zones not affected by cracking and suction effects, which influence compression and dilatancy behavior. Statistical analysis of crack shape is used to estimate the dilatancy angle (ψ), which is then applied in correcting the residual friction angle for stability assessment. Environmental influences, including wind action (Košava), precipitation, and vibrations, may affect crack development and provide insights into failure mechanisms and sliding surface geometry. These results improve understanding of mechanical degradation in clastic materials and support more reliable parameter selection for landfill slope modelling.

Keywords
Landfill slopes, Clastic materials, Shear strength, Internal friction, Dilatancy.

1 Introduction

The development of modern technology and the use of high-capacity mining equipment have enabled the continuous exploitation of significant quantities of lignite and accompanying sediments in open-pit mines. Excavated geological materials that do not represent an energy resource are deposited in internal and external dumps, where they form large-scale earth structures. These can cover areas exceeding 10 km² and reach heights of over 100 m. The stability of these structures is of key importance for the safety and efficiency of mining operations, as it directly affects production continuity. A particular design challenge is achieving a balance between the intensity of excavation and the dynamics of material disposal.

Research on surface weathering of semi-cohesive rocks remains insufficient worldwide (Jevremović 1999), and these materials form three of the six systems of the observed dump. Reliable data on their mechanical, deformation, and rheological properties, as well as their behavior in dumps, are still limited, further complicating geotechnical slope design. This paper analyzes the deformation behavior of deposited material, presents vertical zoning of the slope, and proposes a new method for estimating the internal friction angle based on orthophoto imagery. The results are part of the author's doctoral research (Božić 2026).

2 Open Pit Mine "Drmno" and Internal Dump Landslide

The "Drmno" open-pit mine is the largest and most important in the Kostolac coal basin. It is located in the eastern part of the Republic of Serbia, near the town of Kostolac. Excavation is carried out using six BBS (bucket-wheel excavator - belt conveyor - spreader) systems and one BBC (bucket-wheel excavator - belt conveyor - crusher) system. Figure 1 shows the layout of the six BBS systems, covering the terrain from the surface down to the lignite roof, with seven excavators engaged (six bucket-wheel excavators and one bucket-chain excavator). The planned mining technology aims to increase the annual excavation capacity to 12 × 10⁶ t of coal, which will significantly increase the dimensions of the dump as well.

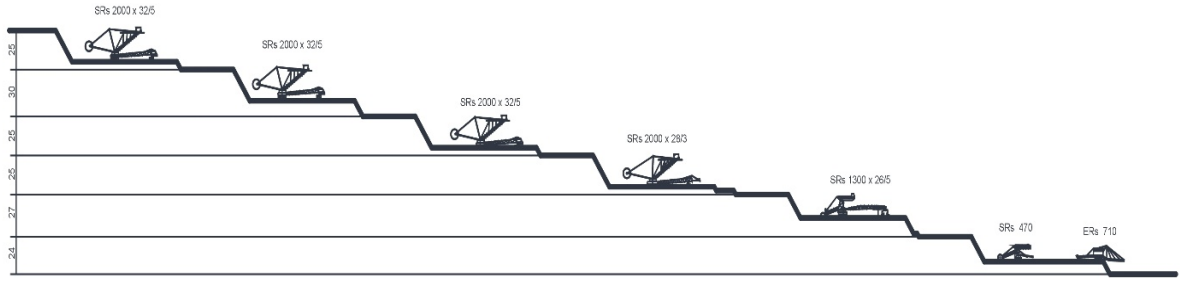


Fig. 1 Drmno Open-Pit Mine Mining Scheme.

2.1 Internal Dump Landslide

At the "Drmno" open-pit mine, 48 million m³ of sediments are excavated and deposited annually. Disposal is carried out at the internal dump located in the southern part of the mine. The structure of the dump consists of the body (deposited soils) and the foundation with a slope of up to 5° (unexcavated, damaged coal of variable thickness and well-bearing, overconsolidated silty-clayey sediments with sand lenses).

With daily expansion toward the northern final slope, in the direction of the Danube River, the stress state changes due to simultaneous dump elevation. As stresses increase, settlements and sliding occur, which are more dangerous for the dump body than for the foundation (Gojković et al. 2008). This is a consequence of the structure and type of soil forming the dump body. The body consists of loose soft rocks (loess-like soils, clays, silts) and cohesionless materials (gravel and sand), with varying permeability, consistency and compressibility.

The most extreme terrain destabilization affects three of the six BBS systems, located at the lowest elevations of the dump, starting from the slope toe. These systems exhibit cracks up to 0.25 m wide (Figure 2a), settlements exceeding 2 m (Figure 2b), and frequent tension cracks longer than 50 m (Figure 2c), along with landslides covering an area of 0.5 km². A solution to this issue is seen in developing a method for optimizing the internal friction angle value, which would enable slope stability analysis of the designed dump height of 200 m and a disposal front 3 km long.

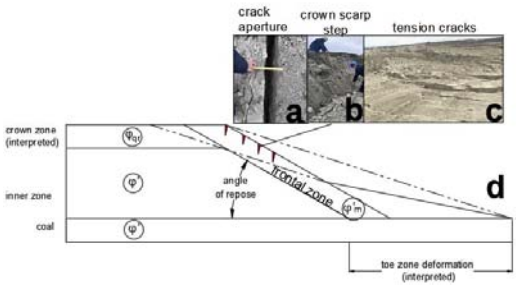


Fig. 2 Basic model of slope.

3 Research Concept of Mechanical Characteristics of Deposited Clastic Materials

The described conditions at the three lowest dump systems limit the movement of personnel and machinery, thereby restricting in situ testing of soil properties. There is also a problem with sampling loose material for laboratory testing. Until 2021, the principle of analogy of physical-mechanical and deformation properties of soil and coal was applied, based on 18,000 samples from 1,600 boreholes across the lignite deposit area (Grupa autora 2011).

However, this concept did not lead to a solution, as all experimental stabilization measures - such as installation of gravel piles, construction of coal retaining structures, drainage channels, diaphragms, and a dense network of wells around the dump perimeter, channels filled with drainage material at the base, as well as buttressing the deformed slope section with a larger mass of excavated soil - proved to be unsuccessful (Božić and Petrović 2021).

At present, there are no established guidelines for preserving the structure of deposited soil or for simulating the slip surface geometry in highly deformed dump segments. Laboratory determination of mechanical properties of clastites is additionally limited by testing conditions. In loose and unsaturated soils, direct shear testing may be affected by specimen disturbance, changes in density, and particle rearrangement during testing. Similarly, conventional triaxial compression tests under constant radial pressure may not adequately reproduce stress conditions in slopes undergoing continuous geometric and loading changes due to ongoing excavation activities (Maksimović 2014).

Literature data indicate that shear strength determination at very low effective stresses may involve significant experimental uncertainty, since measured values can be of the same order as parasitic testing effects (Maksimović 2014). Although originally reported for fine-grained soils, these limitations may also be relevant for loose dump materials in near-surface slope zones.

The initial basis for changing the research concept emerged in 2021 following preliminary UAV surveys using Wingtra and Aibotix drones (Grupa autora 2020b), which enabled the identification of deformation patterns on orthophoto images (Figure 3).

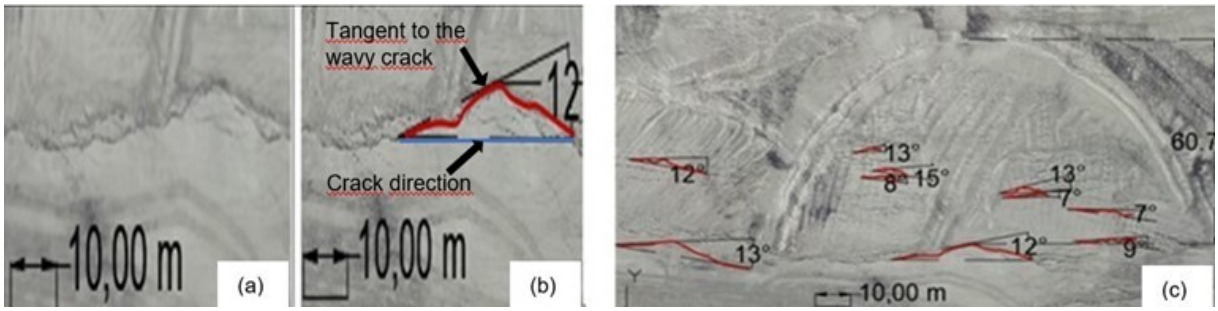


Fig. 3 Display of a crack in the landslide front before (a), after the dilatancy angle reading (b) and examples of readings of dilatancy angles of freely selected tension cracks on landslide (c).

4 Methodology of the Study

Orthophoto images of an inaccessible structure of extreme dimensions enabled a more detailed study of the behavior of different types of deposited materials, as well as the classification of slope deformations. Based on these images, zones with varying risks of deformation and sliding were identified (Božić and Petrović 2021). Through the frequency of tension cracks on the plateau and the slope of the system, criteria were obtained for estimating the depth and shape of the slip surface (Božić and Petrović 2021; Božić 2026), which represent key elements for vertical engineering-geological zoning of the slope.

The main idea is to facilitate the assessment of the distribution of physical, mechanical and deformation properties of deposited micaceous silty-sandy, weakly clayey sediments, with increasing dump height. The conducted zoning made it possible to complement existing classifications of slope deformations, such as the classification by A. M. Demin (Gojković et al. 2008).

For the purposes of this study, describing the phases of slope deformation over one month aims to present the concept of a method for determining shear strength parameters in the frontal, inaccessible zone, as well as to establish criteria for adopting different values of mechanical and physical properties within the same deposited material.

In addition to orthophoto analysis, this research also used data from core logging of four exploratory boreholes with a total length of 120 m (Božić and Petrović 2021; Božić 2026; Grupa autora 2020b), results of laboratory testing of 57 soil samples (Božić and Petrović 2021; Božić 2026; Grupa autora 2020a), and interpretation of 38 standard penetration tests (Božić and Petrović 2021; Božić 2026; Grupa autora 2020a).

4.1 Stages of Deformation of Working Slopes

Based on the research (Božić 2026), four stages of deformation development were defined. The first stage is the formation of the slope with the designed geometry. In the second stage, gravitational tension cracks develop due to initial lateral movements, dividing the slope into vertical blocks with a maximum measured surface scarp height of 2.2 m, corresponding to an estimated slip surface depth of 5 m based on crack density analysis. During this phase, apparent cohesion induced by capillary effects temporarily maintains the stability of these steep, individual blocks, preventing immediate collapse.

The third stage is characterized by cascade settlement of the material. As shear deformations progress, the collapse of the loose soil structure causes a volume reduction (negative dilatancy), forcing the blocks to drop and form a step-like morphology. In the fourth stage, water infiltration destroys the matric suction. Combined with mining vibrations and hydrostatic pressure in the cracks, a drastic reduction in shear resistance occurs, activating the landslide (Božić 2026).

Within one month, simultaneous mass movements can lead to large-scale landslides. Analysis of the orthophoto image confirmed these mechanisms, identifying two subsequent block-type, detrusive landslides: a larger isometric one (0.4 km²) and a smaller frontal one (0.04 km²) (Božić 2026).

4.2 Vertical Zoning of Working Slopes

After analyzing all the research results (Božić 2026), the working slope was divided into the following zones: crown, frontal and inner. A schematic representation of the zoned working bench slope is shown in Figure 2d. The foundation of the dump consists of coal, which, from the perspective of the mechanics of loose rocks, is not the focus of this study. The idea of slope zoning is to explain the vertical distribution of internal friction angle values, using a simplified model as presented in Table 2.

5 Determination of the dilatancy angle and its application

5.1 Determination of the dilatancy angle

The dilatancy angle ψ represents a measure of the volumetric change of soil during shearing and can be defined by the following formula:

$$\tan\psi = \frac{d\varepsilon_v}{d\varepsilon_s} \quad (1)$$

Where ε_v Increment of volumetric strain (-)
ε_s Increment of shear strain (-)

Dilatancy may manifest as either contraction or expansion, depending on the compactness and structure of the soil. In this research, it is used to correct the quasi-residual friction angle φ_{qr} in order to determine the mobilized internal friction angle in the frontal zone φ'_m.

The procedure for determining the dilatancy angle ψ is shown in Figure 3. Figure 3a presents a section of an orthophoto image with a crack, while Figure 3b illustrates the measuring procedure of the angle ψ between the tangent to a wavy crack and its general direction of propagation. Figure 3c shows a set of different measured values of the dilatancy angle ψ, indicating spatial heterogeneity of deformations within the landslide.

Note: Conventionally, the dilatancy angle ψ is defined as the ratio of volumetric strain to shear strain under laboratory conditions. In this study, ψ is estimated from the shape of cracks observed on orthophoto images. This field-based approach provides a practical approximation for soil dilatancy, accounting for local contraction (compression) induced by suction loss, shear deformation, and vibration effects.

The data were randomly sampled from both the front and the body of the landslide to avoid subjectivity in data selection. The analyzed working slope had a total length of 61 m.

Statistical analyses of the data were carried out based on the orthophoto image and the values of angle ψ are presented in Table 1. Further analysis was performed based on obtained values with confidence level of 85% (Božić 2026).

Table 1. Values of dilatancy angles ψ (°) at the front and body of the landslide.

Position	**Dilatancy angle ψ (°)**						
Landslide front	13	12	9				
Landslide body	12	8	15	13	13	7	7

5.2 Frontal zone friction angle

The methodology is based on the analysis of crack geometry in the frontal zone of the slope affected by landslides, aiming to estimate soil shear strength parameters. The quasi-residual internal friction angle φ_{qr} is corrected by the dilatancy angle ψ, thereby obtaining the mobilized internal friction angle φ'_m.

$$\varphi'_m = \varphi_{qr} - \psi \quad (2)$$

Where φ'_m Mobilized internal friction angle in the frontal zone of loose soils (°)
φ_{qr} Quasi-residual internal friction angle from the crown zone of loose soils (°)
ψ Dilatancy angle representing volumetric deformation within the shear band in the frontal zone (°)

In the frontal zone of the slope, loose soil under shear stress, with suction contributing to local compression, undergoes particle rearrangement and local compaction**,** generating the dilatancy angle ψ within narrow localized zones of concentrated deformation. This angle reflects local changes in density and particle arrangement**,** and is used for a more accurate estimation of the mobilized internal friction angle φ'_m.

It should be noted that the dilatancy angle ψ arises solely from local compaction under shear, with suction contributing to additional compression**,** and does not represent a property of the entire material.

Although not directly applied in this study, Maksimović's hyperbolic failure envelope theory could provide a useful extension by modeling the dependence of the mobilized internal friction angle φ'_m on

local compaction, suction effects, and the dilation angle ψ**,** allowing a more accurate assessment of slope stability.

6 Comparison of internal friction angle obtained by different methods

Table 2 presents internal friction angles for the crown, frontal, and inner zones of the working slope, derived from SPT testing (crown), direct shear tests (inner), and orthophoto analysis (frontal) (Božić 2026). The values illustrate the reduction of friction angle in the frontal zone, affected by settlements and landslides, relative to the inner slope mass. For the crown and inner zones, the effective friction angle (φ′) is reported, while for the frontal zone the quasi-residual friction angle (φ_{qr}), mobilized friction angle (φ'_m), and dilation angle (ψ) are given, along with statistical parameters (minimum, maximum, mean, SD) at 85% confidence.

Table 2. Internal friction angles for all slope zones.

Slope zone	index	unit	method	number	Min	Max	mean	Reliability 85%	SD
crown	$\varphi' \approx \varphi_{qr}$	degree	SPT	7	28.60	29.80	29.10	29.00	0.50
frontal	ψ	degree	dilatancy	10	7.00	15.00	10.90	11.00	2.90
frontal	φ'_m	degree	New method*	/	/	/	/	18.00	/
inner	φ'	degree	SPT	31	28.98	33.35	31.00	29.80	1.03
inner	φ'	degree	direct shear	27	32.30	33.70	33.00	32.00	0.60

* - modified friction angle according to new methodology $\varphi_{qr85} - \psi_{85}$

The parameters represent computational values for the working slope model (Figure 2).

7 Conclusion

The proposed method for optimizing the internal friction angle in deposited silty materials represents an initial scientific contribution in the field of slope stability analysis. It indicates the possibility of improving the assessment of sliding length and type of deformation, as well as its application in determining the optimal spacing of working faces and defining operational technology. Furthermore, the proposed method can be used as a supplement to the results of residual strength testing using the ring shear method on processed samples of loose clastites, thereby improving the quality of shear strength parameter determination.

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