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Physical Modeling of Rockfill Material for Construction of Specific Waste Disposals Using a Large-Scale Direct Shear Apparatus

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Abstract

Characterization of bimrocks remains a major challenge in rock mechanics due to the complex interaction between strong core blocks and weaker matrix material. Although several empirical approaches exist to estimate their shear strength, large-scale experimental validation is limited and no widely accepted predictive framework has emerged. In particular, the influence of block proportion, block size distribution, matrix properties, and interface conditions on shear behavior at engineering scale is still not sufficiently quantified.

This paper presents the preparation and testing of a physical model for large-scale direct shear testing of rockfill material using a shear box with dimensions of 1.0 × 1.0 × 0.6 m. The material, sourced from the Borov Dol mine pit, represents excess rockfill generated during excavation and intended for the mine's waste dump area.

The applied normal stress is generated by four vertical hydraulic presses with a total capacity of 1 MPa, while the horizontal shear load is applied using two inclined hydraulic presses positioned at an angle of approximately 11° relative to the horizontal plane. The lower frame of the apparatus is static, and the upper frame moves during shearing.

Mixtures of fresh and altered andesitic rock, as well as their combinations, were tested. Results show that higher proportions of large blocks increase the internal friction angle. The influence of fine particles, intact rock strength, and surface roughness on shear behavior was also examined. The obtained data were compared with the Hoek–Brown and Barton strength criteria to support the development of a simplified approach for rapid extrapolation of large-scale test results.

Keywords

Direct shear apparatus, Rockfill mixtures, Physical modeling, Shear strength, Time of failure.

1 Introduction

The disposal of mining waste is an important issue both globally and in Macedonia due to its technical and environmental implications. Large quantities of waste are generated during ore extraction and must be disposed ofin accordance with strict engineering principles to minimize environmental impacts and maintain dump stability. This paper presents a case study of the waste dump at the Borov Dol mine, based on the results of investigations made in the period of 2025/26.

The Borov Dol mine, located in R. Macedonia, comprises an active open pit and a waste. The dump consists of excavated waste rock of different fractions and geological compositions and serves for the disposal of non-economic material produced during mining. Mining production began in 2020, with copper, gold, and silver as the main products, and is expected to prolong the operating life of the Bučim mine until 2030. The planned volume of mine waste is estimated at 50 million m³, while the required disposal space is estimated at 75–80 million m³.

The shear strength of rocky mine waste (overburden) is a key parameter in assessing dump stability. Such material commonly consists of coarse blocks embedded in a finer-grained matrix and may be classified as block-in-matrix (BIM) material or rockfill.

Several empirical approaches have been proposed to estimate the strength of such materials.However, a unified method is still not widely accepted in rock mechanics (1). The mechanical behavior of cohesionless bimrocks depends on the interaction between blocks and matrix (1;2). Studies by Lindquist (1994) (3) and Lindquist & Goodman (1994) (4) show that increasing volumetric block proportion (VBP) leads to higher friction angle (φ) but lower cohesion (c) and UCS, while Yu-Chen et al. (2019) (5) identify volumetric fraction (Vf) as a key parameter. Coli et al. (2009) (6) reported large-scale direct shear tests, though not fully consistent with ISRM recommendations. Based on these findings and the extensive practical experience of the Faculty of Civil Engineering, large-scale direct shear tests (1.0 × 1.0 × 0.6 m) were conducted on modeled cohesionless materials for engineering characterization.

2 Overview of the methods used for determining the shear strength

The determination of the shear strength of dumped mine rock is a key issue in mine dump stability analysis. Because these materials are coarse-grained and heterogeneous, their characterization often requires non-standard approaches, including large-scale direct shear testing.

In addition to direct testing, empirical approaches were considered for comparative interpretation. Barton and Kjaersli (1981) (7) proposed a modification of the Barton failure criterion for overburden rock and rockfill contacts, in which the governing parameters depend on the type of contact considered. The method also incorporates field tilt tests for estimation of roughness-related parameters. Depending on the material structure, different sets of parameters are considered. For joint-controlled behavior, the relevant parameters follow the Barton and Choubey (8) failure criterion and include JCS (or σp), JRC, and the friction angles φr or φb for weathered and fresh rock, respectively. For granular-type behavior, the governing parameters are the intact rock strength S, grain roughness R, and the basic friction angle φb. In cases combining block interaction and joint effects, the key parameters include the intact rock strength S, JRC, and the residual friction angle φr.

A comparative assessment was also made using the Hoek–Brown (9) failure criterion. In this approach, the material constants are expressed as functions of the Geological Strength Index (GSI), the intact rock parameter m_i, and the disturbance factor D. For the highly disturbed dumped material considered in this study, low GSI values were assumed, while the compressive strength input was based on available test results.

3 Description of the apparatus and method of testing

All tests were performed in the accredited Geotechnics Laboratory of the Faculty of Civil Engineering in Skopje using a large-scale direct shear apparatus for coarse-grained rockfill-type materials (Figure 1). The apparatus, originally constructed by the “Jaroslav Černi” Institute, was modified from 1.5 × 1.5 × 0.6 m to 1.0 × 1.0 × 0.6 m to allow normal stresses up to 1.2 MPa. It consists of upper and lower frames, each 0.30 m high, separated by a predefined horizontal shear plane. Normal load is applied by

four vertical hydraulic jacks (total capacity 1000 kN), and shear load by two jacks inclined at 11° to the horizontal. The lower frame is fixed, while the upper frame moves on rollers to reduce resistance.

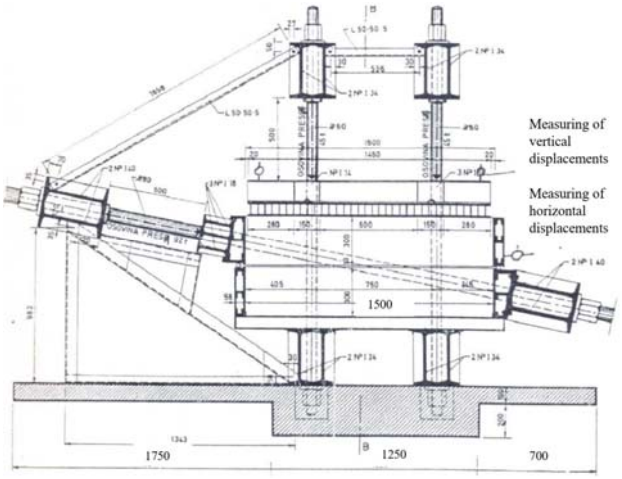


Fig.1 Large scale direct shear box with size 1,0x1,0x0,6 m applied during the testing.

4 Testing

The waste dump material is deposited in situ without controlled compaction. In the initial phase of the investigation, the unit weight, point load strength index (I_{s50}), and uniaxial compressive strength of intact rock fragments were determined. The measured compressive strength of the blocks ranged from 86 to 119 MPa, while the unit weight varied between 17.3 and 18.1 kN/m³.

In the second phase, the investigation program included 16 grain-size analyses (8 before and 8 after shearing) and 8 large-scale direct shear tests. The tested material was predominantly coarse-grained, with coarse fractions accounting for 89–95%, sand-sized particles about 5%, and silt fractions less than 1%.

The water content ranged from 5 to 6%. During the large shear test, the material generally consisted of block fragments 40–80 mm in size embedded in a fine-grained matrix, giving it the characteristics of a block-in-matrix soil (10). Some of the tested samples are given in Figure 2.



Fig. 2 Materials from the Borov Dol Waste Dump used for testing.

After specimen preparation, vertical loading was applied to generate normal stresses on the shear plane in the range of 200–1000 kPa. The load was introduced in three stages, each maintained until vertical displacement stabilized, with the maximum normal stress held constant for 24 h. After consolidation, shear loading was applied incrementally, with each step maintained until horizontal displacement ceased. Horizontal and vertical displacements were recorded continuously throughout the tests to monitor shear response and volumetric change.

As expected, and consistent with previous findings reported in the literature, the friction angle increases with increasing coarse fraction content. For specimens composed predominantly of fresh andesite, the friction angle ranges from 40.3° to 42.2°. In tuff-dominated specimens, it ranges from

29.3° in the more weathered material to 36.2°. For andesite–tuff mixtures, the friction angle varies between 30.2° and 37.1°, depending on the proportion of andesite in the mixture.

The results from the large shear test for specimen no. 3 are presented in figure 3.

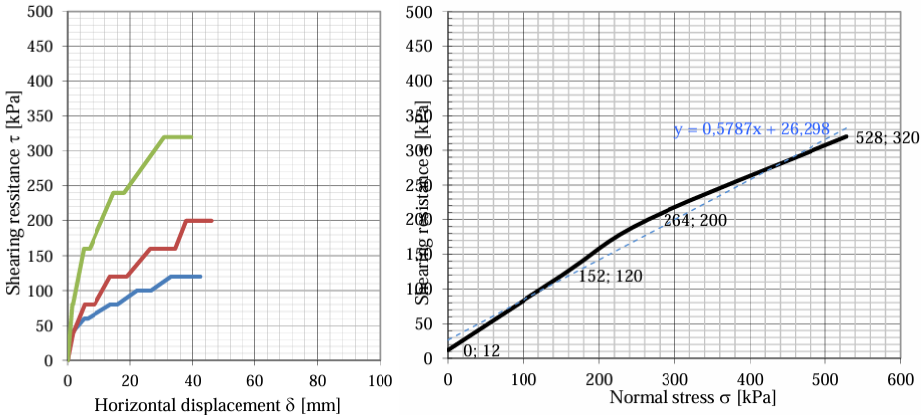


Fig.3 Results from the large-scale direct shear test for specimen no. 3 (10).

5 Comparative analysis of different failure criteria

To evaluate the applicability of the commonly used failure criteria, simulations were conducted using a comparative approach based on the Barton and Hoek–Brown methods. For the Barton method, the input parameter φr was varied within the range of 30° to 35° (30°, 32°, and 35°). The diagrams illustrating the adopted input parameters for both approaches are presented in Table 1, while the result for φr=32° is given in Figure 4.

Table 1. Input parameters for comparative analysis

Input Parameters Barton	**Input Parameters Barton Hoek-Brown**
JRC = 12	σci = 80MPa
JCS = 80	GSI =15
fr = 30, 32, 35	mi=25
	D=0
	Ei=32000
	Unit Weight= 0.022 MN/m3
	Slope Height =50m
	Mohr-Coulomb Fit
	c =0.303746MPa
	f= 49.8717
	Erm =1166.37MPa

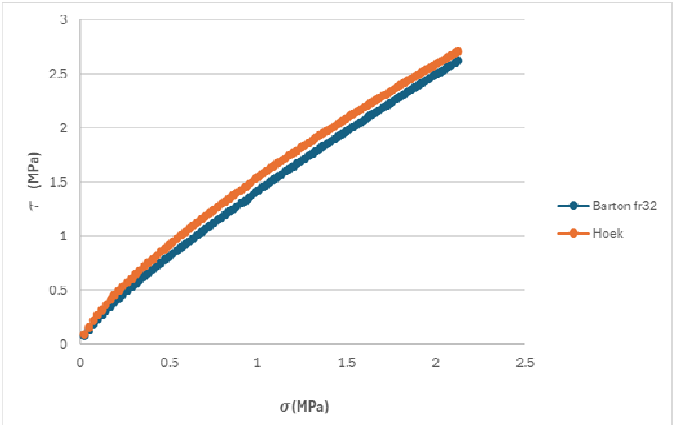


Fig. 4 Comparison of the results from the Barton and Hoek and Brown empirical methods.

Analysis of the results indicates that, for the adopted input parameters, a very good agreement between the curves is achieved. The difference is approximately 15% for φr = 30°, about 8% for φr = 32°, and reduces to approximately 3% for φr = 35° between the two methods.

In the next step, the empirical methods were compared against the results obtained from laboratory testing. Gray andesite was selected as a representative material, as it demonstrated the highest physico-mechanical properties among the tested samples.For the Barton criterion, φr = 30° was adopted, while the Hoek–Brown input parameters were taken as defined in Table 1.The corresponding curves are presented in Figure 5.

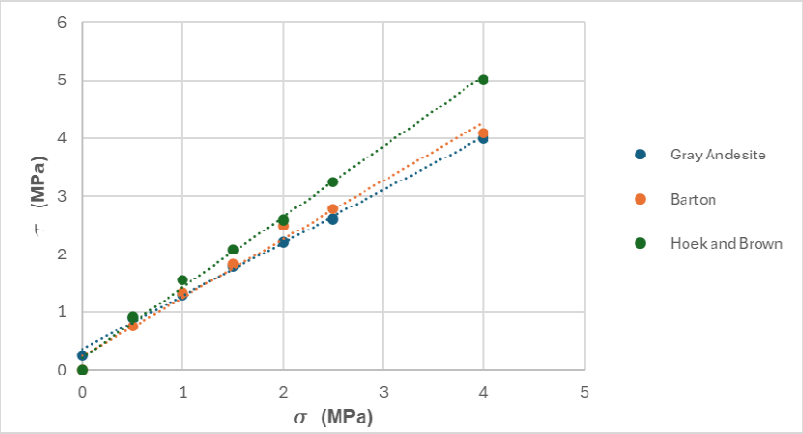


Fig.5 Comparison of the results from the Barton, Hoek and Brown empirical methodswith the laboratory results.

From the presented curves, it can be observed that the results obtained using the Barton method show excellent agreement with the laboratory results from large-scale direct shear tests. The Hoek–Brown results are approximately 20% higher.Considering that the Barton method is specifically developed for fill material, while the Hoek–Brown criterion is intended for intact rock, the observed differences are expected and reasonable. In a subsequent phase, the input parameters for the Hoek–Brown criterion may be further calibrated in order to achieve a better agreement with the other two curves. The use of empirical methods is of significant importance and can be applied in future stages for the interpolation of results at stress levels that cannot be achieved in laboratory testing due to equipment limitations.

6 Conclusion

The stability assessment of mining waste dumps remains a critical issue due to its technical and environmental implications, as demonstrated through the case study of the Borov Dol mine. The performed investigations highlight that the shear strength of rocky mine waste is strongly influenced by material composition, particularly the proportion and condition of andesite and tuff fragments within a block-in-matrix structure.

Large-scale direct shear testing proved to be an effective method for characterizing such heterogeneous materials. The tested specimens exhibited high coarse-grained content, with friction angles ranging from approximately 29° to 42°, depending on lithology and degree of weathering. Fresh andesite materials showed the highest shear strength, while tuff-dominated materials exhibited lower values, with mixed compositions yielding intermediate behavior.

Comparison with empirical approaches indicates that the Barton method provides very good agreement with laboratory results, confirming its suitability for this type of material. In contrast, the Hoek–Brown criterion tends to overestimate shear strength by approximately 20%, which is consistent with its formulation for intact rock rather than block-in-matrix materials. Further calibration of Hoek–Brown input parameters may improve its applicability.

The study confirms the importance of combining laboratory testing with empirical methods, particularly for extrapolating shear strength behavior to stress levels beyond laboratory capabilities. For future work, the same methodology should be extended to a broader dataset of samples to improve the reliability and general applicability of the results.

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