International Society for Rock Mechanics and Rock Engineering
Macedonian Association for Geotechnics

ISRM Regional Symposium
Eurock 2026
Risk Management in Rock Engineering
Skopje, 15-19 September

DOI: https://doi.org/10.68732/90dbbce851adc984

ISBN: 978-9989-2053-7-8

Physical – mechanical properties of the rocks from Kuklica natural heritage site

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Abstract

The Kuklica site near Kratovo, R.N. Macedonia, represents a geologically unique area characterized by a dense concentration of naturally formed erosional columns and rock pillars locally referred to as “Stone dolls”. The site provides an excellent natural laboratory for studying the mechanical behaviour and weathering susceptibility of volcaniclastic and pyroclastic rocks exposed to long-term atmospheric and surface processes. This study presents part of the results from preliminary field and laboratory investigations aimed at characterizing the physical-mechanical properties of the Kuklica formations. Non-invasive needle penetration and Schmidt’s hammer tests were performed to assess the surface hardness and relative resistance to mechanical force of exposed rock masses. Representative samples were collected for laboratory testing which consisted of point load tests, uniaxial compressive tests, slake durability, specific and unit weight, and water absorption. The results indicate significant heterogeneity of the investigated volcanoclastic materials, with the tuff columns exhibiting low to moderate strength typical for soft volcanic rocks, while the andesitic cap rock shows considerably higher strength with slightly lower resistance but still within very highly durable material class. Lower strength values recorded on north-facing sides of the columns suggest the influence of microclimatic conditions and differential weathering processes on erosion susceptibility. This aspect should be further investigated through detailed mineralogical analyses and correlated with the structural assembly of the site. This research contributes to the ongoing DEMONITOR project, within which LiDAR surveys, photogrammetric analyses, and geophysical investigations will be integrated to develop a comprehensive model for monitoring and predicting erosion processes affecting natural heritage sites composed of weak volcanic rocks.

Keywords

Kuklica, Erosion, Laboratory tests, Seismic profiling, Natural heritage.

1 Introduction

Volcaniclastic and pyroclastic rocks form some of the most visually striking and geologically unique natural heritage sites and rock-hewn cultural landscapes globally. Prominent examples include the fairy chimneys of Cappadocia in Turkey, Ohya tuff in Japan, the cliff-side settlements of Orvieto and Civita di Bagnoregio in Italy, Devils Town in Serbia and many others worldwide. The knowledge of physical-mechanical properties of the rocks at these sites is of essential importance when understanding their changes over geological times, but also their behaviour under current and future climate conditions. These aspects have been investigated by many, such as Aydan and Ulusay, 2003; Adachi et al., 1981; Moon, 1993a and 1993b; Tommasi and Ribacchi, 1998; Marjanović et al., 2024.

In Macedonian context, the volcanoclastic and pyroclastic rocks are relatively well represented in some parts of the country, particularly to the east, in Kratovo– Kočani belt (Serafimovski, 1993). The Tertiary magmatism development in Macedonia has been investigated by Boev et al., 1995; Boev and Yanev, 2001. A prominent volcaniclastic association, locally 600-700 m thick, outlines the main NW-SE striking effusions, primarily of andesitic and dacitic type. In these rock formations, chiefly tuffitic, brecciated and tectonized, the erosion and weathering processes are interplaying over a frail and soft material, allowing for interesting landscape features to slowly form. The so called “Kuklica” site, also known as the “Stone dolls” or “Joyful Wedding” is one of such geomorphological landmarks (Fig. 1). The name comes from a melancholy legend related to eternal petrification of the wedding guests. The site is legally protected as a natural monument by the government, and it represents one of the main tourist attractions in the eastern region.



Fig. 1 Wide view of the “stone dolls” natural heritage site during the field investigations. In centre of photo are the “groom and bride”, around them are the “wedding guests”.

The genesis of the site is related to denudation as explained by Milevski, 2010; Milevski and Temovski, 2018. It features an interlayered texture with alternating more resistant rock (arguably andesite) and erodible tuffs beneath. In effect, caps or other more robust parts of the columnar shapes are made of the compact and resistant rock layers. Despite studies from geomorphological aspect, including UAV-based Milevski et al., (2025), the physical mechanical properties of the Kuklica formations had not been investigated at all. Therefore, the primary aim of the study presented in the paper is to initially characterize the basic physical-mechanical and weathering properties of the rocks from the site.

2 Methodology

2.1 Field works

In the first phase, a preliminary field work was performed on the locality (Fig. 2) to define positions for engineering-geological mapping, for collecting samples and for performing non-invasive field tests which consisted of needle penetration and Schmidt hammer tests. Other activities consisted of UAV photogrammetry and terrestrial LiDAR scanning, as well as seismic refraction and electrical profiling. Results from engineering-geological mapping, UAV surveys and geophysical investigations, except for the essential *p*-wave velocity classification of the soil profile, will be presented elsewhere since

they are out of the scope of this paper. It is noted that during the works all efforts were made to not damage the protected landforms, and other than the needle penetration and Schmidt hammer tests, all collected samples for the laboratory tests were taken from the toe zone of the dolls, i.e., from already fallen blocks or were cored from the fallen blocks. Schmidt hammer tests were performed only on cap layer with strong andesitic rock and testing point 5 on a volcanoclastic column (Fig. 3).

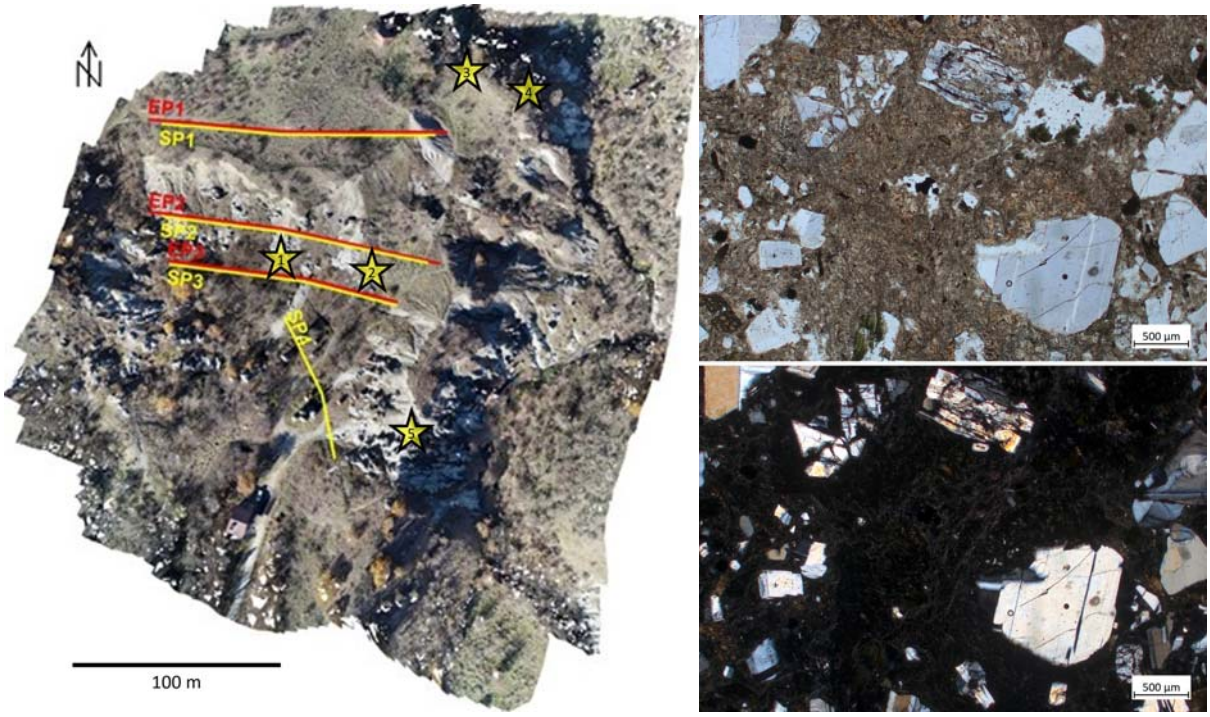


Fig. 2 Site ortho-plan with indicated electric and seismic profiling (EP and SP, respectively) and sampling points (stars) to the left; thin section of a tuff sample with parallel Nicols (upper right) and crossed Nicols (lower right).

Needle penetration (Ulusay et. al, 2014) and Schmidt hammer (SHRV) tests were performed on specific micro-localities within the Kuklica complex, taking into account to have tests on more or less exposed parts of the rock columns to sunlight (north and south aspect). The main intention for this derives from the visual observation, where different conditions of the surfaces were obvious. Collection of samples for laboratory tests is performed with the same approach. In addition, Schmidt hammer and needle penetration testing were used as proxies to estimate the uniaxial compressive strength (UCS) of the material using well-known correlations.



Fig. 3 Field works at Kuklica site, from left to right: volcanoclastic column with andesitic cap; needle penetration testing; needle penetrometer reading; Schmidt hammer reading; andesitic cap sample for overcoring (from fallen block).

The hammering and needle penetrations were spread systematically throughout the site during the field survey along the base contour of the north and main ridge, to the accessible heights of about 1.5-2 m (Fig. 2). A portable SH70 Maruto penetrometer was used with standardized nomogram for

converting applied force vs. penetration depth into compressive strength (Ulusay & Erguler 2013). The penetrations were performed in the pillar bodies, targeting fine particle matrix, i.e., avoiding andesitic fragments larger than 2 mm. A total of 20 tests were performed successfully, whereas locations with no penetration after exceeding the maximum piston force of 100 N are noted. Similarly, hammering was performed on the exposed and shadowed side, totalling 13 tests, which were correlated to the UCS with additional information on unit weight (Miller, 1965).

2.2 Laboratory tests

The laboratory tests were performed in the Geotechnical laboratory of the Faculty of Civil Engineering in Skopje and consisted of the following:

- Point load tests (PLT) – 50 tests (batch of 10 subsamples for every of the 5 main samples);
- Uniaxial compressive strength tests (UCS)–2tests;
- Slake durability tests (SD) – 5 tests with 5-fold wetting-drying cycles;
- Water absorption (WA) – 5 tests;
- Specific and unit weight (SW/UW) – 5 tests.

Since the investigations are of preliminary nature, a relatively small number of samples were tested. All laboratory tests were performed according to ISRM Suggested methods (ISRM, 2007).

2.3 Seismic profiling

Although geophysical properties of the subsoil and the rock mass are going to be subject to in-depth analysis elsewhere, it was essential to include basic seismic profiling in this overview, so that link between the weathering and erosion can be comprehended. For this purpose, it will suffice to mention that the seismic profiling was performed along three profiles extending 110-125 m in length, and accordingly, reaching 30-35 m in depth (Fig. 2). Registered *p*-wave velocities and their gradients from these three profiles were then averaged to determine the depth of the weathering zone and thickness of the substrate susceptible to erosion. It is understood that weathering is an important agent for the decrease in strength and therefore, seismic velocities, of these volcano-clastic rocks.

3 Results and Discussion

In general, the obtained results show wide spread of values, depending on the analysed parameter. As an illustration, Fig. 4 presents two results from the point load tests.

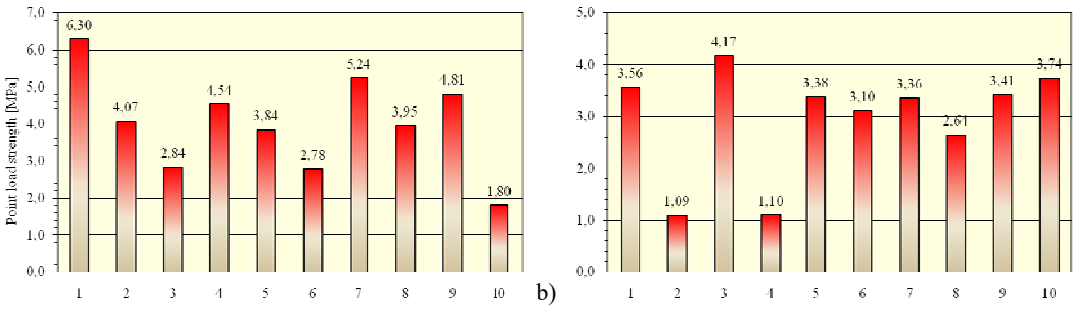


Fig. 4 Results from point load test on samples from a) cap rock, b) volcanoclastic column material.

All results are within the expected range for tuffaceous rocks. The strength values of the volcanoclastic tuff columns all fall in the class of soft rocks, according to ISRM (2007) classification, while the capping layer of andesite exhibits values over 50 MPa. Some outliers are also observed. With respect to the strength values obtained from needle penetration tests, it is found that the north-facing side of the columns appears to be weaker by 30 to 50% (on the basis of three tested columns). It is possible that the north face is more exposed to freezing-thawing processes, but there are no detailed meteorological data to confirm this. The unit and specific weight of the tuff columns show averages 22.6 kN/m^3 and 26.0kN/m^3, respectively. From Fig. 5, it is observed that all tested samples after the second cycle (Id_2) can be classified as high durability and very high durability. Interestingly, with continuation until 5 cycles, the cap andesitic rock exhibits highest drop, with one of the samples falling in category of medium high durability, which seems to be common issue (Gökçeoğlu et. al, 2000). Due to the sudden drop of sample plt4 it can be considered as an outlier. The slaking is in

general agreement in relation to water absorption, with sample plt1 exhibiting the lowest value. Explanation is possible by comparison of the UCS value of this sample, which is much higher than that of the other samples. It is probably the result of local variations of mineralogical composition, which should be further investigated.

Table 1. Summary table of field and laboratory tests for physical-mechanical properties of the rock masses from Kuklica site.

Test point	**Rock type**	**UCS* from averaged SHRV (MPa)**	***UCS*** from averaged SH70 (MPa)**		**UCS from PLT*** (MPa)**	**UCS from cored samples (MPa)**	**γ- unit weight (kN/m^3)**	**Specific weight (kN/m^3)**
1	andesite cap	128.80			24.73	58.72	26.04	26.16
2	andesite cap	103.30	south side 30.9		88.35	50.11	22.82	26.88
3	tuff column (1) with cap		south side 10.6	north side 5.8	65.00		23.11	26.55
4	tuff column (2) with bridge cap		south side 7.9	north side 4.5	18.12		22.45	26.51
5	tuff column (3) capless	56.9	south side 10.6	north side 7.7	20.35		22.29	24.87

*according to Miller 1965 $\log_{10}(UCS) = (0.00088 * \gamma * SHRV) + 1.01$
** correlation based on Ulusay et al. 2014
***$UCS = I_{plt}*22$

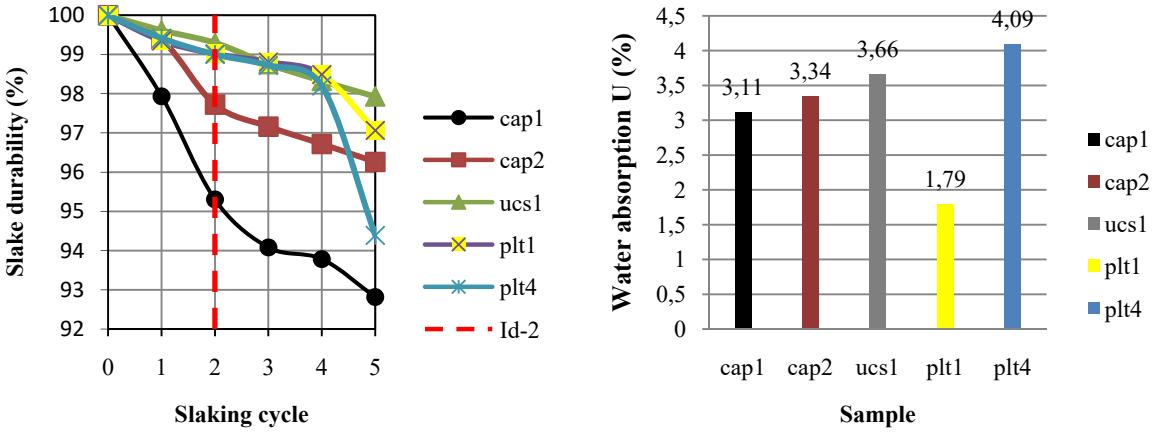


Fig. 5 Results from slake durability tests with five slaking cycles (to the left) and water absorption tests (to the right).

Given the mineralogical composition and volcaniclastic genesis of the formation (with secondary and broken crystals submerged in the vitreous matrix), it is confirmed, as expected, that the rock matrix is primary vitreous, exceeding 60% of material (Fig. 2), which makes it metastable and susceptible to devitrification, primarily to clayey branch of minerals, which could be responsible for some cases of increased slaking like in sample plt4. The depth of this change is likely corresponding to the registered seismic properties, wherein a clear change of *p*-wave gradient suggests topsoil strata of about 4.15 m deep (from 2.5 to 5.8 m, locally) with an average velocity of about 440 m/s. This is the zone where weathering is the highest and erosion can continue with similar rates. Future monitoring projects are yet to confirm the erosion rate, but a few mm/year is to be expected, unlike in the cases of some other similar, but more frail formations, where cm/year might apply (Marjanović, 2024). Judging from relatively high matrix and block compressive strengths, and by mere visual overview of old footage (Fig. 6) and their comparison with the recent ones, it is safe to assume that the weathering process is relatively slow, but so is the erosional process (with rainfall as predominant agent), as there are minor rounding and smoothening effects with no significant visual changes within relatively long time span.

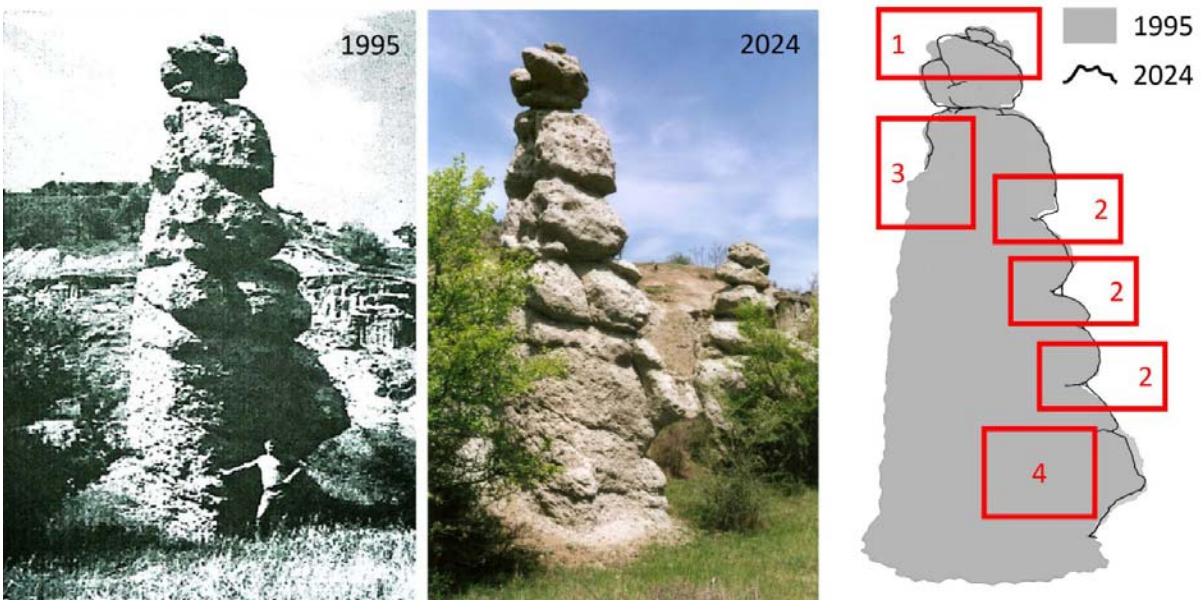


Fig. 6 Visual comparison of a landform from pre-1995 (to the left) and 2024 (in the middle), with the overlap (in the right): 1 – smoothening of the entire silhouette but especially from top-down; 2 – deepening of the incisions; 3 –detachment or volume decrease of protruding parts; 4 –relief differentiation in lower parts.

4 Conclusion

This study presents a preliminary assessment of the physical–mechanical and weathering properties of the rocks forming the Kuklica Natural monument site. The results indicate significant heterogeneity of the investigated volcanoclastic materials, with the tuff columns exhibiting low to moderate strength typical for soft volcanic rocks, while the andesitic cap rock shows considerably higher strength with slightly lower resistance but still within a very highly durable material class. In fact, all samples showed very high durability after two cycles, with slight degradation in some samples to high durability after five-cycle testing. Lower strength values recorded on north-facing sides of the columns suggest the influence of microclimatic conditions and differential weathering processes on erosion susceptibility. This aspect should be further investigated trough mineralogical studies and an understanding of the structural assembly obtained from the UAV surveys. Although preliminary, the study provides an important initial database for understanding the engineering-geological behaviour of the Kuklica formations, with an estimated reach depth of the weathering process and an initial assumption of the erosion dynamics. Future investigations within the DEMONITOR Project should integrate laboratory testing with LiDAR, UAV photogrammetry, and geophysical surveys to improve monitoring and prediction of long-term erosion processes at the site and suggest further monitoring dynamics given the anticipated erosion rate but also potential climate change conditions in the long run. Additional attention is also needed for simplifying the procedure in the long-run and using slake durability, wetting-drying and freezing thawing tests for indicating weathering and erosional dynamics (Ulusay and Aydan, 2018). Specific structures such as arch bridges and columns with different heights, in combination with variations in grain size of the tuff matrix, open prospects for investigation of the columns as bimrocks and for stability analyses.

5 Acknowledgement

This research was supported by the Science Fund of the Republic of Serbia, Grant TF Cl389-YF, Project No. 7515, Project acronym DEMONITOR, and also supported by the Ministry of Education, Science, and Technological Development of the Republic of Serbia, Contract No. 451-03-34/2026-03/200126 for the Faculty of Mining and Geology, University of Belgrade, and is within the framework of UNESCO Chair in Geological Hazard and Risk Mitigation, at The University of Belgrade #2026RS3592. Disclaimer: *The designations employed and the presentation of material throughout this publication do not imply the expression of any opinion whatsoever on the part of UNESCO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The ideas and opinions expressed in this publication are those of the authors; they are not necessarily those of UNESCO and do not commit the Organization.*

The study is also supported by the Ministry of Environment & Physical Planning of R.N. Macedonia, with field being performed under issued permit for scientific research in the environment.

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