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Experimental research of discontinuity parameters of soft rock mass

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Abstract: In everyday engineering practice, the ground surrounding tunnel structures consists of rock masses with discontinuitie. The falling and sliding of rock wedges during tunnel construction is common and mainly depends on the geometry and roughness of the discontinuities. Discontinuous surfaces with varying characteristics largely determine the quality of the rock mass, so knowledge of their behavior is extremely important. Due to various factors, local (and sometimes global) instabilities of rock blocks occur precisely on discontinuous surfaces. For this reason, analyzing and researching the strength parameters of discontinuities is crucial for developing rheological models of rock mass behavior. This paper presents research on discontinuity parameters in soft rock masses (marly limestone), conducted under laboratory conditions at the Faculty of Civil Engineering in Podgorica. The research was conducted as part of the authors' scientific work, with emphasis on time-dependent deformations of the rock mass. The uniqueness of the testing apparatus lies in the atypical dimensions of the samples used for this type of testing. Samples measuring 30 × 15 × 15 cm were cut from marly limestone taken from the coal mine basin in Pljevlja, Montenegro. A natural discontinuity was simulated by artificially creating one at half the height of each sample, after which the two halves were placed into a purpose-built steel apparatus. The samples were tested in the laboratory, using the existing equipment with necessary modifications and newly designed equipment to enable the proper execution of the experiment. The samples were placed in three frame constructions with three different constant values of normal loads. The horizontal load was applied using hydraulic cylinder simultaneously for all three frames, during which the increase in displacement and change in shear stresses were measured. Previously developed roughness models (in Agisoft software) serve as the basis for establishing the mathematical relationship between the roughness of discontinuous surfaces and their shear characteristics, used to generate roughness profiles for correlation analysis. Given the limited number of experimental studies on time-dependent deformations of soft rocks along discontinuities worldwide, this paper aims to contribute to the scientific literature by presenting initial results based on specific experimental data.

Keywords: soft rock; time-dependent deformations; experiment; discontinuity; roughness

1. Introduction

In engineering geology and geotechnics, rock mass fracturing is a key factor affecting the behaviour of rock material, especially in tunnel zones. Rock masses are rarely homogeneous and continuous; instead, they are typically intersected by discontinuities—joints, bedding planes, shear zones, and fractures—that determine their mechanical stability and deformation behavior.

Recent studies have increasingly emphasized the role of discontinuity roughness in determining the shear strength and overall stability of rock masses (e.g., Zhang et al., 2021; Wang et al., 2022; Dong et al., 2023). However, soft rocks—especially marly limestones—remain underrepresented in experimental datasets. While hard rock discontinuities have been extensively studied, the time-dependent deformation characteristics of soft rock discontinuities have received limited attention.

A significant research gap exists in understanding how discontinuity geometry, surface roughness, and time-dependent deformation interact in soft rocks under realistic loading conditions. This gap is particularly relevant in tunnelling projects, where insufficient experimental characterization of soft rock discontinuities has contributed to stability problems. For example, inadequate shear strength estimation

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in weak sedimentary formations has led to wedge failures during excavation and premature degradation of support systems in several case studies reported in Southeastern Europe and Asia.

The present study addresses this gap by experimentally quantifying the relationship between roughness profiles and shear strength parameters for soft rock discontinuities, with particular focus on time-dependent deformation.

Discontinuities, as natural planes of weakness, have a dominant effect on stress redistribution, load transfer, water flow, and deformation within the rock mass. Their properties—orientation, spacing, length, roughness, cohesion, friction, aperture, infill, and continuity—determine whether the rock mass behaves as a solid body or as a collection of interacting blocks.

In tunnel zones, the importance of discontinuities becomes pronounced due to stress redistribution from excavation, rock block instability potential (sliding, overturning, or falling), and increased water inflow along discontinuities.

Precise identification and characterization of discontinuities is essential for accurate geotechnical modelling and tunnel design. Without knowing their properties, any rock mass stability analysis remains unreliable. Without such analysis, rock mass models would be unrealistic and would not reflect actual resistance to destabilization caused by tunnel excavation.

The stability of rock blocks in tunnel zones largely depends on the mechanical properties of discontinuities, particularly their surface roughness and shear strength. Discontinuities are natural planes of weakness along which relative movement of rock blocks can occur, making their surface and mechanical characteristics crucial for stability analysis.

Discontinuity roughness determines the interlocking capacity of rock surfaces, while shear strength defines the resistance to sliding along these planes. The combination of these factors sets the limit of stability—if the driving forces acting on a block exceed the resistance provided by the contact surface, failure may occur in the form of sliding, toppling, or falling. Falling and sliding are most common in tunnels. Another important parameter is the time after excavation required for the rock block to fall out.

Accurate determination of roughness (e.g., via profilometry or 3D scanning) and shear strength (through laboratory and in-situ testing) enables realistic estimation of stability factors, selection of appropriate support systems, and prevention of instabilities during tunnel excavation and operation.

2. The necessity of experimental research

2.1. Importance of Experimental Investigation of Discontinuous Soft Rock Masses

Experimental investigation of discontinuous soft rock masses is crucial for developing reliable rheological models that accurately describe rock mass behavior under long-term loading. Due to the pronounced heterogeneity and complex behavior along discontinuities, theoretical models alone are often insufficient to capture all relevant mechanisms of deformation and shear. Through experimentation, it is possible to quantify time-dependent deformations, identify dominant displacement mechanisms, and determine the parameters required for mathematical modeling of rheological behaviour. Based on such results, realistic models of rock mass behavior can be formulated and applied in engineering practice, especially in the design of underground structures such as tunnels and shafts.

2.2. Complexity of Experimental Investigation of Soft Rock Masses and Its Importance

Experimental investigation of soft rock masses is challenging due to their sensitivity to changes in stress conditions, moisture, and time. Specific challenges arise in securing representative samples, preserving their structure and discontinuity geometry during preparation and testing. Furthermore, because of time-dependent deformations, experiments are often lengthy and require precise control of testing conditions.

Nevertheless, such investigations are of great importance as they enable a deeper understanding of rock mass behavior, particularly in zones dominated by plastic and viscous behavior. The results serve as a basis for developing numerical and analytical models, thereby improving the safety and efficiency of engineering solutions.

2.3. Validation and Comparison of Numerical and Experimental Results

The numerically estimated shear strengths derived from roughness profiles will be validated against direct shear test results for the same samples. The comparison allows assessment of the model's predictive capability while considering variations in surface roughness, humidity, and temperature. Differences are expected due to simplifications in the numerical model, but trends and relative variations among samples can be reliably captured. This approach provides a practical framework for integrating surface characterization with rheological modeling, ensuring that environmental factors such as moisture and temperature are incorporated into the analysis.

3. Experimental research on real samples

3.1. Sample's formating and equipment preparation

A block of approximately 3.5 tons was extracted from the open-pit mine at a depth of approximately 25 m, measured from the ground surface (Fig. 1). Immediately upon excavation, the material was loaded on transport equipment and transported from Pljevlja to Podgorica (approx. 180km). During unloading, precautions were taken to prevent any damage to the rock mass, ensuring that the block's natural orientation was maintained so that its geometry remained unchanged for processing.

Material used for testing has been sampled from the open pit "Potrlica" of the coal mine Pljevlja.

(**a**) (**b**)

Fig. 1. (a) Position of a bench from which the rock mass block was extracted; (b) loading of the rock mass block.

(**a**) (**b**)

Fig. 2. (a, b) Samples processed to target dimensions 30x15x15 cm.

A specialised plant for processing of stone was used to process material and form cuboid (prism) shaped samples with dimensions 30x15x15 cm (Fig. 2). During sample preparation, due to the highly demanding processing (with samples often splitting during cutting) of the irregularly shaped natural soft rock mass into the desired sample dimensions, the processing success rate was approximately 50%.

Simultaneously, a semi-quantitative analysis of samples was conducted the results of which confirmed the samples are marly limestone, dominantly composed (93.0%) of calcium carbonate ($CaCO_3$), while the remaining 7% includes the following components: quartz 4.80% (SiO_2), siderite 1.10% ($FeCO_2$), muscovite 1.10% ($KAl_3Si_3O_{10}OH_2$).

3.2. Crack's formation

An artificial crack (Fig. 3) was created in the laboratory by splitting specimens into two halves. In order for the planes of discontinuity to have a regular shape, linear groove (Fig. 3(b)) was cut along the sample, after which a splitting force was applied at half its height (approximately 7.5 cm). At the cut grooves (Fig. 3c), using a cylinder to apply loading at a controlled rate, the samples were divided into two, approximately equal halves, followed by forming of discontinuity planes of different roughness. Upon defining discontinuity planes, all samples were wrapped in foil. Previously, after the geometry had been formed, all the samples were paraffin-coated to preserve their natural moisture content.

(**a**)

(**b**)

Fig. 3. (a) Cutting a groove at the sample center; (b) forming of discontinuity.

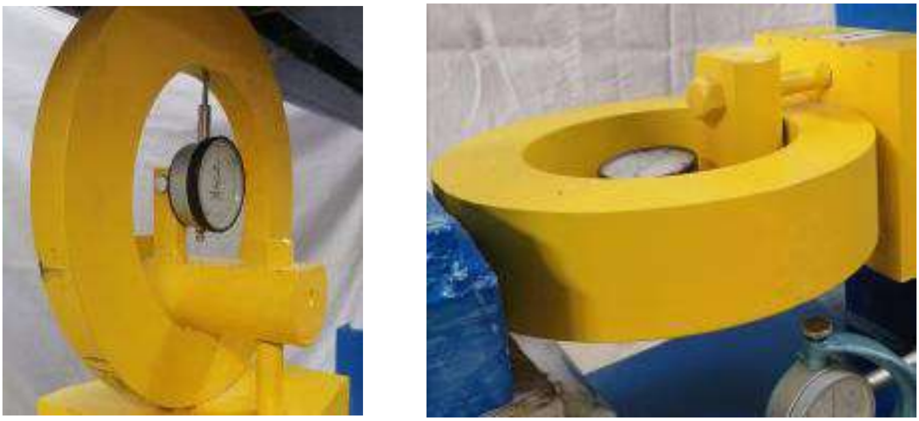
3.3. Defining research equipment

When the samples have been prepared, the next step was to design new and modify the existing equipment to be used for uniaxial and triaxial creep testing of the intact rock samples. The trial series included testing three samples with different roughness levels. For this purpose, existing frames were specifically prepared at the laboratory of the Faculty of Civil Engineering. The frame operates on the principle of lever arm and deadweight.

The new equipment elements were designed by the authors with the aim of conducting an experiment that replicates natural rock mass conditions as closely as possible.

First, steel molds were formed, which serve to position the formed halves of the samples. Considering that the height of the half-sample is approximately 7.5 cm, the internal height of the mold was set to 5 cm to allow for undisturbed shear behavior along the discontinuity planes. Thickness of walls and bottom of the steel mold is 1cm. The samples are fixed using a factory produced mortar for casting and grouting, which takes several hours to set after have been poured to fill the voids between the sample and the mold, making the sample immovable in the mold. When securing both halves, efforts were made to fit them tightly to better simulate naturally closely spaced cracks.

In order to overcome friction that occurs in the apparatus, the experiment provided for adjustment of movable parts to fit over the cylinder-shaped steel elements. In addition to the samples, frames, benches and rollers, key components of the equipment are elements for measurement of change in stress and strain. For this purpose, steel rings (dynamometers) were developed with a base plate on which gauges for measurement of normal and shear displacements were mounted. The steel rings are of the same diameter but different thickness due to a different order of magnitude (forces) occurring in the normal and shear direction respectively, which are the subject of measurement by dynamometers (Fig. 4).



(a) **(b)**

Fig. 4. Rings with gauges for normal stress: (a) Rings no: 1, 2, 3, d = 2 cm; (b) Rings no: I, II, III, d = 6 cm.

3.4. Sample testing

After equipment was finalized, samples were ready for testing. During testing, numerical analysis of defining roughness model has been performed (detailed in part 3.5).

Experimental test was performed using frames such as shown in Fig. 5. First, trial test with 3 samples was performed. After that, in five series with three samples in each one was performed as a part of main experiment. The experiment included testing of samples of different roughness.

For all three foregoing discontinuity planes, the testing was performed under three different constant levels of normal stress. Normal stresses of 0.1 MPa, 0.2 MPa and 0.4 MPa were applied.

The horizontal load was applied to the sample via a hydraulic press horizontally positioned and connected to a large hydraulic cylinder positioned vertically in an additional frame with deadweight. The preferred hydraulic oil pressure was controlled by the weight of the deadweight on the frame’s lever arm, which transferred a multiplied load onto the cylinder pivot. By means of the oil supply system from the large cylinder (principle of communicating vessels) and all smaller vessels on the shear apparatus (positioned horizontally), the shear force was applied to the lower half of the sample (lower fixed mould), as illustrated in Fig. 5.

Value of displacement of the lower mold, meaning differential displacement of the lower and upper half of the sample along discontinuity was recorded by the mechanical device for displacement measurement (Fig. 5).

As previously mentioned, the lower mold and the ring to which vertical loading is applied are placed on rollers to eliminate friction during the experiment duration. During the testing, it is required to maintain vertical loading constant, as it tends to change as the result of the vertical movement over the rough surfaces and changes in shear stress and strain.

(a) **(b)**

Fig. 5. (a) Equipment's elements for testing; (b) frame for testing with equipment.

The main characteristic of such an experiment is the creep phenomenon during discontinuity shearing. Time-dependent deformations were obtained under constant stress. The creep period of the samples varied from several days to several months, depending on the level of normal stress, sample roughness, temperature, and other factors. Bearing this in mind, we worked on numerical modeling and analysis of sample roughness while the laboratory tests were in progress.

4. Determination of sample's roughness by numerical methods

4.1. Creating of roughness model

For a long time, the very simple use of traditional methods with satisfactory accuracy had a justified primacy in relation to demanding and time-consuming mathematical calculations. Nowadays, with the development of modern computer aids, it is possible to develop models that are based on the mentioned mathematical formulations, but which solve the problem of the roughness of discontinuities in a much shorter time. In order to numerically describe the roughness of discontinuous surfaces, it is necessary to obtain a roughness model. Agisoft software was used for these purposes. The model creation process is based on importing photographs that capture the actual surface condition of the samples from multiple angles. The number of photographs depends on the need to capture the entire surface from several angles, based on which the software generates the model. The quality of the model depends on the quality of the photos. After creating the model, it is possible to export the non-continuous surface into a dwg file. This approach allows for deriving a mathematical formulation of the curvature for each generated profile, and, based on established theories of discontinuity roughness, determining the mathematical relationship between roughness and shear strength.

4.2. Production of photos for model

To create a quality model of the discontinuity plane with roughness, it is necessary to prepare high-quality photographs. For all 20 specimens analyzed in the experimental research, several photographs of each roughness plane were taken. A professional photographer took photos from different positions (Fig. 6), ensuring that the photographed surfaces overlapped.

(**a**) (**b**)

Fig. 6. (a) Making photos of discontinuity plane; (b) photo of sample plane.

4.3. Making roughness model

Photos of discontinuity surface for all samples were made in high quality resolution (300 dpi). This is a primary requirement for creating a high-quality model of the discontinuity plane with roughness. All photos have been used for importing in software and making sample's model.

Agisoft software package is used to create roughness models of the samples. The program works on the principle of importing photos on the basis of which the model is created. In order for the model to be used as an output data, it is necessary to ensure the matching of the size of the samples in the model and in the export file (cad file). In this regard, each sample was marked with red points along half its length and width before photography; these were later used in the model as reference points for adjusting the scale in the CAD file. The quality of the model also depends on the density of the points that form it. Through an iterative process, the number of points that produced a high-quality model without requiring excessive processing time was determined. The model shown in Fig. 7 is ready to be exported to a CAD file. After scaling to real dimensions, it could be analyzed in the next stage. In cad file, we could see surface with lines that define roughness surface (Fig. 8).

As mentioned above, the plan is to use five 2D profiles obtained from the 3D surface to develop numerical equations based on the shear strength of each small triangular segment along each line of discontinuity. Following mentioned, it's planning to use five 2D profiles obtained by 3D surface, that could be used for develop numerical equations based on shear strength of each small triangle entire each line of discontinuity.

After that, correlating the roughness and shear strength of each of the five profiles could provide insight into the surface behavior.

Fig. 7. Roughnes model made by photos.

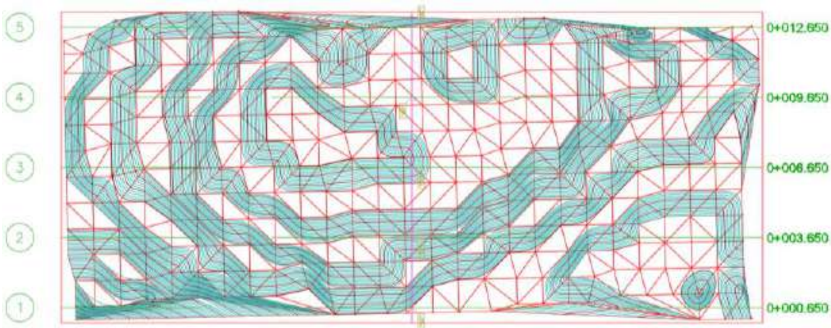


Fig. 8. Roughness surface of sample export from Agisoft.

5. Numerical Relationship Between Roughness and Shear Strength

The discontinuity surface profile is typically obtained as a series of X–Z coordinates exported from AutoCAD or similar software tools. These coordinates represent the actual uneven surface of the joint.

To quantify the roughness, several numerical descriptors are used. A common one is the root mean square (RMS) slope, Z_2:

$$Z_2 = \sqrt{(1/L \int_0^L (dz/dx)^2\, dx)} \approx \sqrt{(1/n \sum (\Delta z_i/\Delta x_i)^2)} \quad (1)$$

Where:

- Δz_i = vertical difference between consecutive points,
- Δx_i = horizontal difference,
- L = total profile length,
- n = number of segments.

The Joint Roughness Coefficient (JRC) can be estimated empirically based on Z_2. One commonly cited relation is:

$$JRC = a \times (Z_2)^b \quad (2)$$

Barton and Choubey (1977) proposed an empirical model to estimate shear strength along rough joints:

$$\tau = \sigma_n \times \tan[JRC \times \log_{10}(JCS / \sigma_n) + \varphi_b] \quad (3)$$

Where:

- τ = shear strength,
- σ_n = normal stress,
- JCS = joint compressive strength,
- φb = basic friction angle.

Combining all the above steps, the final functional relationship is:

$$\tau = \sigma_n \times \tan[(a \times Z_2^b) \times \log_{10}(JCS / \sigma_n) + \varphi_b] \quad (4)$$

This allows the estimation of shear strength directly from surface geometry (Z_2), which is crucial for rock block stability analysis and classification of rock masses.

The application of Barton's empirical shear strength equation to numerically derived roughness profiles assumes that surface geometry fully captures the mechanical interlocking effects. However, scale effects, progressive surface degradation, and lithological variability may influence results, and laboratory-prepared discontinuities might not fully reproduce the complexity of natural joints.

Experimental constraints prevented repeated tests at multiple normal stress levels on the same sample, leading to separate specimens for each stress level. Sample moisture, varying from completely dry to fully saturated, significantly affects shear strength, and fluctuating laboratory temperature (14–35 °C) and relative humidity (40–100 %) during the long testing period may have influenced creep measurements. Variations in surface roughness further contribute to data variability.

Despite these limitations, the derived JRC values provide a useful quantitative measure of surface roughness for each specimen. These values can be applied to evaluate shear strength trends, compare samples, and support further modeling, while acknowledging the influence of moisture content, surface degradation, and environmental variability on the results

6. Conclusions

This paper presented the research of discontinuity parameters on examples of soft rock mass (marly limestone) carried out in experimental laboratory conditions at the Faculty of Civil Engineering in Podgorica.

The samples were tested in the laboratory, using the existing equipment with necessary modifications and newly designed equipment to provide for proper conducting of the experiment.

Previously developed roughness models (in Agisoft software) form the basis for establishing the mathematical relationship between the roughness of discontinuous surfaces and their shear characteristics, enabling the creation of roughness profiles for correlation analysis.

Finally, a closer determination of the discontinuity characteristics will enable a better understanding of the entire rock mass. Therefore, experimental research is invaluable for obtaining concrete, applicable data on which models of rock mass behavior can be based.

The formation of rheological models along discontinuities involves the assessment of time-dependent deformations (e.g., creep) under constant normal and shear stresses. These models are usually based on combinations of idealized rheological elements such as Hookean (elastic), Newtonian (viscous), and composite systems like Kelvin–Voigt or Burgers models.

In engineering practice, rheological models enable prediction of displacement along weak planes over time, which is essential for the design of tunnel structures, underground structures, slope stability assessment, and barrier performance in mining or hydropower systems.

Experimentally, long-duration shear tests under constant normal stress provide data for calibrating rheological models and determining parameters such as viscosity coefficient, relaxation time, and limiting strain. Also, data processing follows, which should introduce a time component into the rheological model of discontinuity sliding.

Bearing the above in mind, future research will define a rheological model for specific experimental testing, using the obtained data to more precisely determine the behavior of discontinuous soft rocks in practical engineering applications, including tunnel construction.

The correlations established between roughness profiles and shear strength parameters provide a practical tool for preliminary stability assessment in tunnelling designs involving soft rock masses. By integrating these correlations into rheological models, engineers can better predict time-dependent displacement along discontinuities and design more effective long-term support systems.

For tunnel design, this means improved estimation of stability factors under both short-term excavation loads and long-term operational stresses. In stability assessment, the method offers a means to evaluate potential wedge or block failures in cases where direct shear testing is impractical. In long-term support strategies, the time-dependent component of the model can inform the scheduling of maintenance and reconstractions.

References

Bujišić, M., Tomanović Z., 2024. "Experimental research of time-dependent deformation of soft rock along discontinuities", Laboratory of Faculty of Civil Engineering, University of Montenegro

Dong, L., Wang, D., Sun, X., Jiang, Y., Luan, H., Zhang, G., Zhou, G., Liang, B., 2023,. Experimental Study on the Mechanical Properties and Acoustic Emission Characteristics of Deep Soft Rocks under Low-Frequency Dynamic Disturbance. *Applied Sciences*, *13*(11), 6399. https://doi.org/10.3390/app13116399

Kozubal, J., Tomanović, Z., Zivaljević, S., 2016. The soft rock socketed monopile with creep effects – a reliability approach based on wavelet neural networks, *Arch. Min. Sci*., Vol. 61 (2016), No 3, p. 571–585,

Loiotine, L., Wolff, C., Wyser, E., Andriani, G. F., Derron, M.-H., Jaboyedoff, M., Parise, M., 2021. QDC-2D: A Semi-Automatic Tool for 2D Analysis of Discontinuities for Rock Mass Characterization. *Remote Sensing*, *13*(24), 5086. https://doi.org/10.3390/rs13245086

Pells, K. S., Skretting, K., Dershowitz, T., Herda, H. H., 2024. Rock Mass Structure Characterization Considering Finite and Folded Discontinuities: A Parametric Study. *Rock Mechanics and Rock Engineering*, DOI: 10.1007/s00603-024-03787-9.

Palmström, A., 2001. Measurement and characterization of rock mass jointing, Chapter 2 of the book: *In-Situ Characterization of Rocks*

Tomanović, Z., 2012. The stress and time dependent behaviour of soft rocks. *GRAĐEVINAR*, 64 (12), pp. 993-1007. https://doi.org/10.14256/JCE.815.2012.

Tomanovic, Z., 2006. Rheological model of soft rock creep based on the tests on marl. *Mech Time-Depend Mater* 10, 135–154. https://doi.org/10.1007/s11043-006-9005-2.

Wang, F., Wu, B., Wang, S., Meng, F., Xiu, Z., Wang, C., 2022. Shear Response of Rough Rock Discontinuities Subjected to Impact Loading: Experimental Study and Theoretical Modelling. *Lithosphere*, *GeoScienceWorld* Special Issue 11: Article 1192067. DOI: 10.2113/2022/1192067.

Zhang, Q., Luo, Z., Jang, B. A., Wang, Q., Zhong, Z., 2021. A Study of Instantaneous Shear Mechanical Properties on the Discontinuity of Rock Mass Based on 3D Morphological Properties. *Geofluids*, Volume 2021, Article 5549223. DOI: 10.1155/2021/5549223.

Zhang, G., Wu, S., Guo, P. et al., 2023. Mechanical Deformation, Acoustic Emission Characteristics, and Microcrack Development in Porous Sandstone During the Brittle–Ductile Transition. *Rock Mechanics and Rock Engineering*, 56: 9099–9120 (December 2023). https://doi.org/10.1007/s00603-023-03533-7.

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