Indian Geotech J
https://doi.org/10.1007/s40098-025-01250-2

ORIGINAL PAPER

Precise Replication of Complex Rock Fracture Surfaces Combining 3D Printing, Mold-and-Cast, and Statistical Analysis

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Received: 5 September 2024 / Accepted: 14 April 2025

Abstract It is crucial in geomechanics to understand how fracture surface roughness influences shear failure mechanism, fluid flow, and solute transport through rocks. In this regard, performing identical experiments on fractures poses difficulties due to their inherent heterogeneity and anisotropy. It is challenging to replicate natural rock samples with controlled roughness. This study investigates how artificial rock samples can be generated with controlled roughness (joint roughness coefficient (JRC)), using a combination of three-dimensional (3D) printing and mold-and-cast methods for a specific rough surface as an example. A sample with a certain JRC value using fractal theory was used to create synthetic rough fractures. The fractures were then replicated using 3D printing and concrete molds. Profilometry and photogrammetry were both used to evaluate the accuracy and precision of roughness replication. Both methods resulted in the successful replication of rough fractures. However, photogrammetry demonstrated superior accuracy (absolute mean difference of roughness ($\bar{\delta} = 1.1$), compared with profilometry ($\bar{\delta} = 2.8$)). Due to the limitations of the JRC parameter, various statistical parameters were used to evaluate the accuracy of the simulation of 3D roughness surfaces with laboratory samples. Amplitude-based, spatial-based, and hybrid methods, along with empirical cumulative distribution function plots, were utilized in the statistical analysis, revealing high similarities between the original and replicated samples. This study shows that 3D printing may be implemented to produce artificial rock samples with identical roughness for studying shear failure, fluid flow, and solute transport in rough fractures in the laboratory. Additionally, to assess the joint surface roughness, photogrammetry is more accurate than profilometry, due to the reduction of human error and higher precision.

Keywords Synthetic rock fracture · 3D printing · Rough surface replication · Photogrammetry · Joint roughness coefficient · Statistical analysis

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Introduction

In the design step of rock engineering projects such as slopes, dams' seepage, tunnels, and geothermal energy resources, characterization of rock mass behavior is necessary. A rock mass consists of intact rock and discontinuity features such as fractures and bedding planes. The rock fracture properties play an essential role in governing the characteristics of the rock mass behavior [1–4]. Since the rock fracture surface is not smooth and planar, mapping and characterization of its surface in both laboratory and numerical experiments are important. The morphology of natural rock fractures is highly variable and heterogeneous. Due to this variability, achieving two exactly identical samples is nearly impossible. Replicating the similarities in asperities and the height of the up and down surfaces of fractures becomes more important when their shear behavior under different stress boundary conditions is examined. On the other hand, to accurately investigate fluid flow and solute transport, it is essential to employ asperities and surface roughness distributions that accurately replicate the characteristics of original fracture surfaces. Asperities and the complexity of surfaces influence surface tortuosity, which affects the linear or nonlinear