Digital Characterization of Localized Deformation Bands in Homogeneous Rock under True Triaxial Stress: Postprint

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Abstract

In deep complex stress fields, the heterogeneous behavior of microcrack evolution and localized deformation concentration within rock masses constitutes a key mechanism inducing catastrophic events such as rockbursts and slip failures. In image analysis, the ease of structure identification largely depends on its scale, boundary sharpness, and grayscale contrast. In contrast, compaction bands, due to their diminutive scale, blurred edges, and weak grayscale contrast, pose a significant challenge for image identification and extraction. Particularly under true triaxial stress states, where stress path disturbances are enhanced, conventional segmentation methods become even more inadequate for extracting such structures. To address this issue, this study employs Bleurswiller homogeneous sandstone as the research subject, conducting high-resolution industrial CT scanning under four typical true triaxial stress conditions (σ_1=σ_2=60MPa, σ_2=60MPa/σ_3=40MPa, σ_2=80MPa/σ_3=40MPa, σ_2=80MPa/σ_3=60MPa), and establishes a standard image preprocessing pipeline (median filtering, edge cropping, grayscale normalization, etc.) to ensure stable and comparable image quality. For image analysis, a local porosity analysis method and K-means clustering are first employed for preliminary segmentation to locate potential deformation bands and their approximate outlines. Building upon this, the coefficient of variation (COV) metric is introduced to construct a "local porosity-COV" joint feature model, which, combined with spatial heterogeneity features extracted via sliding windows, further enhances the identification accuracy of fine compaction structures. Finally, morphological operations (erosion-dilation-connected component analysis) are applied for spatial optimization of the clustering results, significantly improving the boundary clarity and overall continuity of the extracted structures, thereby constructing a well-visualized deformation band atlas. Experimental results demonstrate that this method can stably extract narrow, low-contrast compaction band regions under multiple stress states, achieving an average Silhouette coefficient (a metric evaluating cluster compactness and

inter-class separation) of 0.79, with three-dimensional reconstruction results consistent with macroscopic experimental observations. This research provides a generalizable new pathway for the digital characterization of localized rock structures under high stress, offering valuable reference for intelligent image analysis and engineering rock mass evaluation.

Full Text

Preamble

Digital Representation of Localized Deformation Bands in Homogeneous Rock under True Triaxial Stress

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Abstract

In deep underground complex stress fields, the heterogeneous evolution of microcracks and localized deformation concentration within rock masses constitute key mechanisms triggering catastrophic events such as rockbursts and slip failures. In image analysis, the identifiability of structures largely depends on their scale, boundary sharpness, and grayscale contrast. In comparison, compaction bands, characterized by their diminutive scale, blurred edges, and weak grayscale contrast, pose a significant challenge for image recognition and extraction. Particularly under true triaxial stress states where stress path disturbances are intensified, traditional segmentation methods prove even more inadequate for extracting such structures.

To address this issue, this study employs Bleurswiller homogeneous sandstone as the research subject and conducts high-resolution industrial CT scanning under four typical true triaxial stress conditions (σ_1=σ_2=60MPa; σ_2=60MPa/σ_3=40MPa; σ_2=80MPa/σ_3=40MPa; σ_2=80MPa/σ_3=60MPa). A standardized image preprocessing pipeline—including median filtering, edge cropping, and grayscale normalization—is established to ensure stable and comparable image quality. For image analysis, local porosity analysis and K-means clustering are first employed to perform preliminary segmentation, delineating the locations and approximate contours of potential deformation bands. Building upon this, the coefficient of variation (COV) metric is introduced to construct a "local porosity-COV" joint feature model, which, combined with spatial heterogeneity features extracted via sliding windows, further enhances the identification accuracy of fine compaction structures. Finally, morphological operations (erosion-dilation-connected component analysis) are applied to spatially optimize the clustering results, significantly enhancing the boundary sharpness and overall coherence of the extracted structures, thereby constructing well-visualized deformation band maps.

Experimental results demonstrate that this method can stably extract narrow, low-contrast compaction band regions across multiple stress states, achieving an average silhouette coefficient (a metric measuring cluster compactness and inter-class separation) of 0.79. The three-dimensional reconstruction results are consistent with macroscopic experimental observations. This research provides a generalizable new pathway for the digital representation of localized rock structures under high stress, offering valuable insights for intelligent image parsing and engineering rock mass evaluation.

Keywords: Deformation band identification; CT image analysis; Coefficient of variation (COV); K-means clustering; Local porosity

Note: Figure translations are in progress. See original paper for figures.