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Dynamic Monitoring of Mudstone Swelling During Water Absorption Via Point Cloud Features

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Abstract: This study focuses on Jurassic red-bed mudstone, a prevalent geomaterial in Sichuan Basin infrastructure projects, particularly the Chengdu-Wanzhou high-speed railway. Known for its water sensitivity, this mudstone undergoes swelling deformation and fissure development upon moisture exposure, posing risks to track stability, slope integrity, and foundation resilience. Traditional monitoring methods, reliant on single-point diatometers, are limited by their inability to capture 3D deformation dynamics and are hindered by contact-induced boundary constraints, low data efficiency, and lack of full-field analysis capabilities. To address these challenges, an innovative 3D dynamic monitoring system integrating an improved capillary rise test with oblique photogrammetry is introduced. This system comprises a custom capillary water absorption apparatus, a hemispherical multi-camera array for full-field coverage, and a Raspberry Pi-based data acquisition unit. High-frequency imaging throughout capillary water absorption enables multi-view 3D reconstruction, generating time-series point cloud models for spatiotemporal deformation analysis. Key findings reveal a three-stage capillary water absorption process, with axial height growth transitioning from rapid (0–148 min) to metastable (148–306 min) and stable (306–501 min) phases, accompanied by decreasing water absorption rates. Fissure networks evolve from sporadic microcracks to a reticular pattern, exhibiting axial and radial heterogeneity influenced by boundary conditions. Swelling-induced displacement fields show spatial anisotropy, with radial expansion on lateral surfaces and axial uplift on top surfaces, reaching maximum displacements of 5.39 mm and 2.86 mm, respectively. Non-uniform swelling induces a 1.64° surface rotation, indicating substantial shear and torsional strains. Volumetric swelling reaches 7.15%, correlated with fissure density, while surface roughness evolves heterogeneously, reflecting differential stress zones. This research provides a comprehensive framework for understanding water-rock interactions in red-bed mudstone, supporting risk assessment and mitigation strategies for swelling-induced geological hazards.

Keywords: ***Red-bed mudstone, Point cloud, Dynamic monitoring, Swelling deformation.***

Introduction

This study investigates the swelling behavior of Jurassic red-bed mudstone, a highly water-sensitive geomaterial prevalent in Southwestern China's Sichuan Basin. Its presence poses significant challenges for major infrastructure projects like the Chengdu-Wanzhou high-speed railway, where moisture-induced swelling and fissuring lead to critical issues such as track unevenness and slope failure. Therefore, characterizing the spatiotemporal evolution of this deformation is crucial not only for fundamental understanding but also for developing effective mitigation strategies to ensure the long-term stability and safety of transportation corridors in the region.

Traditional methods for monitoring mudstone swelling, such as dial gauges or LVDTs, rely on single-point contact measurements under constant pressure. While simple, this approach has critical limitations. It only captures vertical displacement, failing to characterize the full three-dimensional (3D) deformation field and thus being susceptible to errors from non-uniform water uptake. Furthermore, physical contact can constrain the specimen's natural swelling, while the point-wise data acquisition lacks efficiency and comprehensiveness for analyzing complex strain states. Consequently, these techniques are ill-suited for high-precision, dynamic analysis of swelling mechanisms in realistic scenarios.

Methodology

This study presents an innovative system and methodology for 3D dynamic monitoring of material swelling deformation during capillary water absorption. By integrating an improved capillary rise test with oblique photogrammetry, we developed a comprehensive setup capable of high-frequency, omnidirectional monitoring of a mudstone specimen's surface morphology under simulated groundwater conditions. The core of this system consists of three integrated components: (1) a custom-designed capillary water absorption apparatus, (2) a photographic system featuring an array of cameras arranged in a hemispherical configuration to ensure full-field coverage, and (3) a data acquisition unit built upon a low-cost, miniaturized single-board computer (Raspberry Pi 5). This integrated platform captures multi-view 2D image sequences throughout the entire capillary process. These images are subsequently processed using multi-view 3D reconstruction algorithms to generate time-series 3D point cloud models, enabling a detailed spatiotemporal analysis of the swelling behavior.

Following the acquisition of time-series point clouds, a rigorous pre-processing pipeline was implemented to ensure data quality. This involved precise camera calibration, denoising, and adaptive resampling. Subsequently, all models were aligned within a unified coordinate system using a two-stage registration process (coarse and fine alignment) guided by fiducial markers. With each model accurately registered, its spatiotemporal coordinates relative to the initial state were established. Leveraging this high-fidelity dataset, we employed advanced 3D analysis techniques including geometric feature extraction for crack identification, regional segmentation for swelling zone delineation, and ICP-based distance calculations for displacement field quantification. This multi-faceted approach successfully captured key deformation parameters of the red-bed mudstone, providing unprecedented insights into the dynamic evolution of fracture networks, displacement fields, non-uniform tilting, volumetric expansion, and surface roughness changes during capillary water absorption. Consequently, this methodology enabled the detailed characterization of the following critical aspects of mudstone deformation.

Results and discussion

The comprehensive analysis of the swelling process reveals a highly complex and spatiotemporally heterogeneous deformation field in the Jurassic red-bed mudstone. The temporal evolution of water absorption is characterized by three distinct phases: an initial rapid uptake (0–148 min), followed by a metastable growth period (148–306 min), and concluding with a stable phase (306–501 min). This multi-stage swelling behavior directly correlates with the dynamic development of the surface fissure network, which progresses from a sporadic state to a well-defined, interconnected reticular pattern before stabilizing. Crucially, this progression occurs under significant spatial constraints; crack density exhibits a pronounced non-uniform distribution both axially ("sparse at base–dense at mid-upper") and radially (high-density periphery to low-density center), highlighting that boundary conditions are a primary driver for strain localization.

Further quantitative analysis underscores the limitations of one- or two-dimensional monitoring approaches. The displacement field is marked by clear spatial anisotropy: the lateral surface undergoes predominantly radial expansion, while the top surface experiences significant axial uplift, with maximum values reaching 5.39 mm and 2.86 mm, respectively. The axial displacement itself follows a characteristic "S"-shaped curve, reflecting the material's transition through slow, accelerated, and final saturation stages. Most notably, the specimen's top surface underwent a measurable spatial rotation of 1.64°, providing direct evidence of substantial internal shear and torsional strains. This phenomenon confirms that the swelling stress field is not purely volumetric but induces complex 3D deformation, including non-uniform tilting, which would be entirely undetectable with conventional point-based sensors.

This intricate 3D response is further manifested in the bulk volume change and micro-morphological alterations. The total volumetric expansion rate was precisely quantified at 7.15% (from 116.94 cm^3 to 125.30 cm^3), showing a strong positive correlation with localized fissure density. This indicates that macro-cracking serves as a critical mechanism for relieving internal swelling pressures. Similarly, surface roughness analysis unveiled unique spatial patterns, a U-shape on the lateral face and a concentric gradient on the top surface, that are directly linked to zones of differential stress at boundaries (e.g., constrained base, free edges). In essence, our findings demonstrate that capillary-driven swelling in mudstone is a multifaceted process where bulk expansion, localized fracturing, and shear deformation are intrinsically coupled. Therefore, a full 3D characterization, as presented here, is indispensable for capturing these mechanisms and developing accurate predictive models for related geotechnical hazards.

Conclusions

This study has established a novel method for the 3D dynamic monitoring of mudstone swelling under capillary action, addressing the limitations of traditional 2D techniques. The integrated system enabled the capture of time-series 3D point clouds, which revealed unprecedented details of the swelling process. Key findings include a three-stage temporal evolution of swelling and fissuring, a spatially anisotropic displacement field characterized by radial expansion and axial uplift, and direct evidence of complex 3D deformation like surface rotation driven by internal shear. This research not only advances the fundamental understanding of water-rock interactions but also provides crucial data for improving the safety and stability of infrastructure built upon such challenging geomaterials.