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Rock Mass Discontinuity Detection at Tunnel Faces under Artificial Lighting: Practical Implications for Photogrammetric Mapping

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1. Introduction and Problem Definition

Rock mass discontinuities play a dominant role in controlling tunnel stability, excavation damage, and potential failure mechanisms. Accurate identification of discontinuity orientation is therefore essential for kinematic analysis and support design (Peng et al., 2024). While conventional compass-based mapping remains reliable, it is often restricted at active tunnel faces due to safety, accessibility, and time constraints.

Image-based photogrammetry has emerged as a practical non-contact alternative, allowing rapid three-dimensional documentation of tunnel faces (Figure 1). However, in underground environments, photogrammetric performance depends almost entirely on artificial lighting. Unlike surface conditions where sunlight provides relatively uniform illumination, tunnel faces are characterised by strong lighting gradients, shadows, and spectrum-dependent surface responses (Mukhlisin et al., 2023).

In practice, artificial lighting in tunnels is usually arranged for visibility rather than for geometric accuracy. Lighting intensity, colour temperature, and direction are selected empirically, with little consideration of their influence on image texture, tie-point stability, and reconstructed geometry. As a result, photogrammetric models produced under different lighting setups often show inconsistent quality and orientation accuracy, even when camera parameters remain unchanged (Mushtaha et al., 2022).

The lack of a practical understanding of how artificial lighting affects photogrammetric discontinuity detection represents a key limitation in applying image-based methods in tunnelling. Without clear guidance, engineering geologists face difficulty in achieving repeatable and reliable structural orientation data under low-light conditions.

This study addresses this gap by examining how artificial lighting characteristics influence the accuracy of photogrammetric rock mass discontinuity detection at tunnel faces, with emphasis on practical implications rather than methodological complexity. The observations in this study were conducted at multiple tunnel face locations along the alignment of the Raw Water Transfer Project, which has an approximate total tunnel length of 35 km. Data collection was carried out during excavation when new tunnel faces were exposed. All observations were obtained within the same tunnel project and are generally associated with similar granitic rock formations along the alignment.

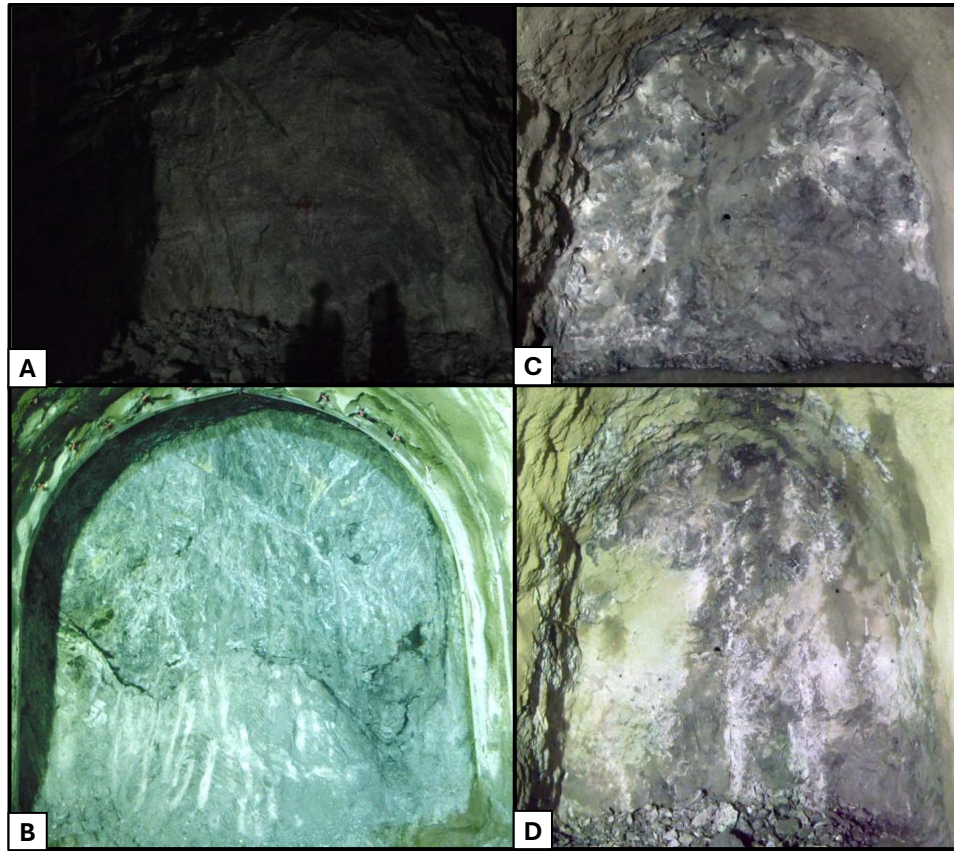


Figure 1 Tunnel face images captured under different artificial lighting conditions demonstrating their influence on image-based photogrammetric analysis. **(A)** Poor image quality caused by low lighting intensity, resulting in insufficient illumination and reduced visibility of discontinuities, which negatively affects photogrammetric reconstruction. **(B)** Influence of artificial lighting color temperature, producing a strong color cast on the tunnel face that may mislead geological interpretation, particularly in assessing rock weathering and surface conditions. **(C–D)** Well-illuminated tunnel face images with appropriate lighting conditions, providing clear visibility of structural features and surface textures suitable for reliable photogrammetric analysis.

2. Discussion

The results of this study demonstrate that artificial lighting is a controlling factor in photogrammetric reconstruction quality and should be treated as a primary acquisition parameter rather than an auxiliary condition. Variations in illuminance, colour temperature, and lighting direction significantly affect image texture consistency and shadow formation, which in turn influence tie-point distribution and orientation accuracy.

Moderate illumination levels produced more stable reconstructions than both low and excessively high lighting intensities. Insufficient light reduced feature contrast, while excessive intensity introduced glare and local overexposure, degrading image matching. Similarly, neutral colour temperature provided greater radiometric stability compared to warmer or cooler spectra, suggesting that spectral balance plays an important role in maintaining consistent surface appearance across image sets.

Lighting direction was found to be particularly critical at tunnel faces. Oblique and single-angle lighting enhanced local relief but generated persistent shadow zones that obscured parts of the discontinuity network. Dynamic lighting reduced shadow extent but introduced inconsistencies between images, reducing reconstruction robustness. In contrast, direct frontal lighting produced the most uniform illumination, minimising shadow-induced geometric distortion and yielding the most consistent discontinuity orientation results.

These observations highlight that photogrammetric errors observed in underground environments are often not caused by camera limitations or processing algorithms, but by suboptimal lighting geometry. Even advanced software workflows cannot compensate for radiometric inconsistency introduced at the image acquisition stage.

From an engineering perspective, the findings suggest that lighting configuration should be standardised alongside camera geometry when photogrammetry is applied for tunnel-face mapping. Treating lighting as a controllable design parameter enables more reliable orientation data, improving confidence in subsequent kinematic assessments.

More broadly, this study reinforces the need to integrate lighting considerations into digital rock mass documentation workflows. As tunnel construction increasingly adopts image-based monitoring and digital twins, the role of artificial lighting becomes central to ensuring data quality rather than merely providing visibility.

3. Conclusions

Artificial lighting has a direct and measurable impact on the reliability of photogrammetric rock mass discontinuity detection at tunnel faces. By focusing on lighting characteristics rather than detailed algorithmic optimisation, this study provides practical insight into why photogrammetric performance varies widely under underground conditions.

Recognising and controlling lighting effects is essential for achieving repeatable and engineering-relevant photogrammetric results in tunnels and other low-light environments.

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