

Discontinuity Identification in Rock Masses Using a Region-growing-based Method: A Case Study Using the RockBench Dataset

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Abstract: *Rock mass discontinuities exert a fundamental control on the mechanical behavior and stability of rock engineering structures. With the increasing availability of high-resolution point clouds acquired by LiDAR and photogrammetry, automated identification of rock mass discontinuities has become an important topic in rock engineering and geomatics [4,5]. However, the performance of existing automatic methods is often sensitive to data quality, and systematic validation using standardized benchmark datasets remains limited. In this study, a region-growing-based method is implemented for the identification of rock mass discontinuities from three-dimensional point cloud data. Local normal vectors and curvature are estimated using principal component analysis, seed points are selected based on surface smoothness, and regions are progressively grown under constraints of normal vector consistency and spatial continuity. The method is evaluated using a publicly available benchmark dataset from the RockBench repository [1]. The results demonstrate that the proposed method can effectively delineate major discontinuity planes and extract their geometric parameters, including orientation and spatial extent. Statistical analysis reveals several dominant discontinuity sets that are consistent with previously reported geological characteristics. A parameter sensitivity analysis further illustrates the robustness and limitations of the method. This study highlights the applicability of region-growing-based discontinuity identification for rock mass characterization using high-resolution point cloud data.*

Keywords: Rock mass discontinuity, Point cloud, Region growing, LiDAR and photogrammetry, RockBench dataset.

1. Introduction

Rock mass discontinuities, such as joints, bedding planes, and faults, exert a fundamental control on the mechanical behavior and stability of rock engineering structures. These discontinuities also play a critical role in controlling deformation and dynamic responses in complex rock engineering environments, especially in high-steep and structurally controlled rock masses [10]. The spatial distribution, orientation, and persistence of these discontinuities strongly influence deformation mechanisms and failure modes in rock engineering applications, including slope instability, rockfall hazards, and excavation-induced damage. Accurate characterization of rock mass discontinuities is therefore essential for reliable geological interpretation, numerical modeling, and engineering design [4,5,6,9].

Traditional characterization of rock mass discontinuities relies primarily on field mapping and manual measurements, which are often time-consuming, subjective, and limited by accessibility and safety constraints. In recent years, advances in three-dimensional data acquisition technologies, particularly terrestrial laser scanning and photogrammetry, have enabled the collection of high-resolution point clouds that provide detailed geometric representations of rock surfaces. These developments have significantly expanded the potential for quantitative and remote characterization of rock mass discontinuities at engineering scales.

To exploit the rich geometric information contained in point cloud data, numerous automatic and semi-automatic methods have been proposed for discontinuity identification. Existing

approaches include edge detection and image-based techniques, clustering of normal vectors, model fitting methods such as RANSAC, and region-growing-based segmentation algorithms. Among these, region growing methods have attracted considerable attention due to their intuitive geometric interpretation and ability to identify planar features from dense point clouds. However, their performance is often sensitive to parameter selection, data quality, and surface roughness, and comprehensive evaluation using standardized benchmark datasets remains limited.

In this study, a region-growing-based method is implemented for the identification of rock mass discontinuities from three-dimensional point cloud data. The method is evaluated using a publicly available benchmark dataset from the RockBench repository, representing a road cut slope in Kingston, Canada. The objectives of this study are to evaluate the effectiveness of a region-growing-based approach for rock mass discontinuity identification using a standardized benchmark dataset, to analyze the sensitivity of key parameters, and to discuss its applicability and limitations for practical rock mass characterization.

2. Dataset Description and Preprocessing

2.1 RockBench Dataset

The point cloud data used in this study were obtained from the publicly available RockBench repository, which was established to provide standardized datasets and reference cases for the assessment of rock mass characterization methods based on LiDAR and photogrammetry. The RockBench initiative aims to promote reproducible research

and objective evaluation of automatic and semi-automatic approaches for rock mass discontinuity identification.

In this study, a benchmark dataset representing a road cut slope located in Kingston, Ontario, Canada, was selected, as shown in Figure 1. The site corresponds to a typical

engineered rock slope formed during highway excavation, where multiple sets of rock mass discontinuities are clearly exposed. Owing to its realistic geological conditions and engineering relevance, this dataset has been widely adopted as a reference case for evaluating point-cloud-based rock mass characterization methods.



Figure 1: Original point cloud

The use of the RockBench dataset ensures that the analysis presented in this study is based on a standardized and openly accessible data source. All processing and analysis steps were conducted directly on the benchmark dataset, without any manual selection or prior labeling of discontinuity features.

The RockBench dataset is provided in a local scanner-based coordinate system, and the absolute geographic orientation and scale are not explicitly defined. Consequently, the analyses in this study were conducted within the original local coordinate framework. This does not affect the identification of discontinuity surfaces or the statistical characterization of their relative orientations.

2.2 Point Cloud Characteristics

The point cloud represents the exposed surface of the Kingston road cut slope and was acquired using high-resolution three-dimensional surveying techniques, as documented in the RockBench repository. The dataset contains approximately 41.3 million points, with an average point spacing of approximately 1 cm. The relatively high point density allows detailed representation of rock surface geometry and discontinuity features [1].

The slope surface captured in the point cloud exhibits complex geometric characteristics, including multiple intersecting discontinuity sets, varying surface roughness, and local variations in point density caused by acquisition geometry, occlusions, and surface orientation. In addition, sparse noise points are present around the periphery of the dataset, and some areas in the upper part of the slope show incomplete or missing point cloud coverage. These features present realistic challenges for automatic discontinuity identification and

provide a suitable test case for evaluating the robustness of region-growing-based methods.

2.3 Point Cloud Preprocessing

To prepare the dataset for discontinuity identification, several preprocessing steps were applied to improve data quality and computational efficiency. First, sparse noise points surrounding the main slope surface were removed using spatial filtering and statistical outlier removal techniques to eliminate isolated points that do not represent the actual rock surface.

After noise removal, the point cloud was downsampled using a voxel-based grid filter with a voxel size of 5 cm. As shown in Figure 2, the point cloud density in the lower right corner area becomes significantly sparse. This downsampling resolution was selected to balance computational efficiency and geometric fidelity, while preserving the essential planar characteristics of rock mass discontinuities at the engineering scale. In fact, due to the unregistered direction and size of the point cloud data itself, the actual size represented by 5 cm here should be 5 mm. Given the high quality and density of the original RockBench dataset, the applied voxel-based downsampling does not significantly affect the identification or orientation estimation of major discontinuity planes at the engineering scale considered in this study.

Unlike earlier implementations that required spatial subdivision or manual exclusion of incomplete areas, the complete preprocessed point cloud was used directly for discontinuity identification in this study. All subsequent analyses were conducted on the uniformly downsampled dataset using a single and consistent set of parameters.



Figure 2: Preprocessing and downsampling

3. Methodology: Region-Growing-Based Discontinuity Identification

3.1 Estimation of Normal Vectors and Curvature

Normal vectors and curvature were estimated for each point in the uniformly downsampled point cloud using a PCA-based approach. Accurate estimation of local surface geometry is a prerequisite for region-growing-based discontinuity identification. In this study, local normal vectors and curvature parameters were computed for each point in the preprocessed point cloud using a principal component analysis (PCA) approach [3,8].

For a given point, a local neighborhood was defined using a fixed number of nearest neighbors. The covariance matrix of the neighborhood points was constructed, and eigenvalue decomposition was performed. The eigenvector corresponding to the smallest eigenvalue was taken as the normal vector of the point, as it represents the direction of minimum variance and is approximately perpendicular to the local surface.

In addition to normal vectors, a curvature parameter was calculated to quantify local surface smoothness. The curvature was defined based on the normalized smallest eigenvalue of the covariance matrix, which provides a measure of how closely the local neighborhood approximates a planar surface. Lower curvature values indicate smoother and more planar regions, which are more likely to belong to rock mass discontinuities.

The estimated normal vectors and curvature values serve as fundamental geometric attributes for subsequent seed point selection and region growing. The overall process is shown in Figure 3.

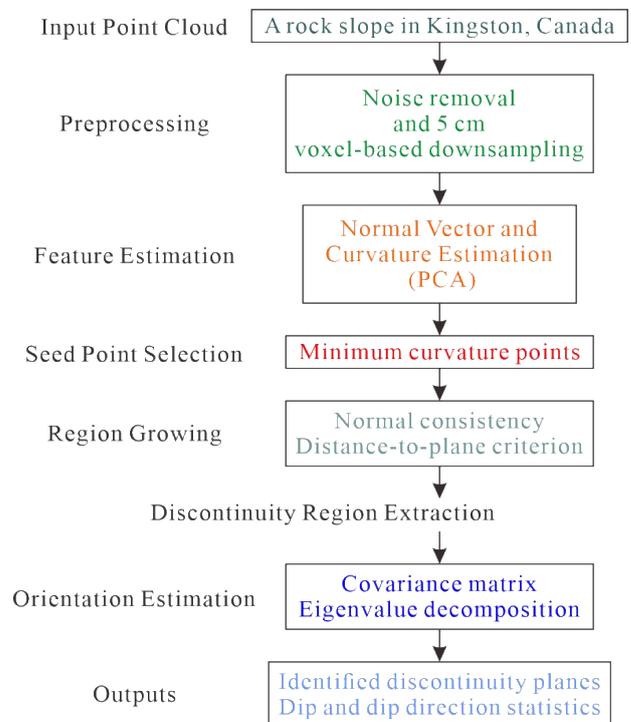


Figure 3: Workflow of the proposed region-growing-based method for discontinuity identification from the complete RockBench point cloud

3.2 Region Growing Procedure

Based on the assumption that rock mass discontinuities can be locally approximated as planar surfaces, a region-growing-based procedure was adopted to identify discontinuity planes from the point cloud. The method starts from selected seed points and progressively expands regions by aggregating neighboring points that satisfy predefined geometric criteria.

In this study, points with the minimum curvature values were selected as seed points for region growing. This strategy ensures that the growth process initiates from the smoothest and most planar areas of the rock surface, thereby reducing the likelihood of seed points being located near edges, noise, or highly irregular regions. After a seed point was selected, its neighboring points were examined, and those satisfying the growth criteria were added to the current region. The region was then iteratively expanded by considering the neighbors of newly added points until no additional points met the criteria.

Once the growth process terminated, the identified region was recorded as a candidate discontinuity plane, and the corresponding points were excluded from further seed point selection. The procedure was repeated until all eligible points in the dataset were processed.

3.3 Growth Criteria and Parameter Settings

The inclusion of neighboring points during the region growing process was controlled by a set of geometric criteria designed to ensure consistency in surface orientation and spatial continuity. First, the angular difference between the normal vector of a candidate point and the average normal vector of the current region was required to be smaller than a predefined threshold. This constraint enforces orientation similarity among points belonging to the same discontinuity plane.

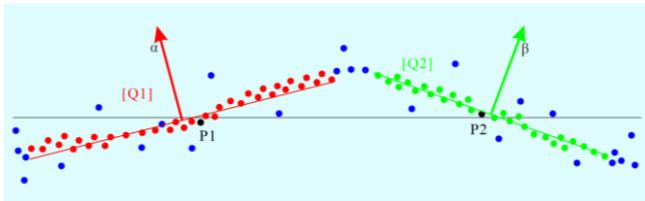


Figure 4: Regional fitting diagram

Second, a distance-to-plane criterion was applied to limit the spatial deviation of candidate points from the fitted plane of the growing region. Points with distances exceeding a specified threshold were excluded to prevent the inclusion of points from adjacent or intersecting surfaces. In addition, curvature information was used to avoid incorporating points with highly irregular local geometry. The distance-to-plane criterion was evaluated with respect to the locally estimated plane defined by the average normal vector of the growing region.

The key parameters involved in the region growing process include the number of nearest neighbors used for normal estimation, the normal vector angle threshold, the distance-to-plane threshold, and the minimum number of points required to define a valid discontinuity plane. The principle of region normal estimation is illustrated in Figure 4. These parameters were selected based on point cloud density and empirical testing, and a single and consistent set of parameters was applied to the entire slope.

Once the region-growing process identified discontinuity planes, the planes were grouped into dominant discontinuity

sets based on their spatial orientation. The grouping process involved clustering planes with similar orientations and spatial proximity, which were then classified into distinct sets based on these features. This approach enables a clear identification of the major discontinuity sets in the rock slope and their relative spatial distribution.

3.4 Extraction of Discontinuity Parameters

For each identified discontinuity region, geometric parameters were extracted to characterize its spatial properties. Given that the region growing procedure aggregates points belonging to the same discontinuity surface, the orientation of each discontinuity was estimated directly from the spatial distribution of the points within the region.

Specifically, a covariance matrix was constructed using all points belonging to each discontinuity region. Eigenvalue decomposition was then performed, and the eigenvector corresponding to the smallest eigenvalue was taken as the normal vector of the discontinuity plane. This approach provides a stable estimation of plane orientation based on the overall geometry of the aggregated point cloud, without requiring explicit least-squares plane fitting.

The dip and dip direction of each discontinuity were subsequently derived from the estimated normal vector. In addition to orientation parameters, the spatial extent of each discontinuity was characterized based on the distribution of points within the region. These parameters form the basis for subsequent statistical analysis of discontinuity sets.

4. Results

4.1 Discontinuity Identification Results

Using the proposed region-growing-based approach, discontinuity planes were successfully identified from the preprocessed point cloud of the Kingston road cut slope. The region-growing-based algorithm was applied to the entire preprocessed point cloud of the slope using a single and consistent set of parameters.

The region growing procedure effectively segmented the slope surface into multiple planar regions corresponding to exposed rock mass discontinuities. Visually, the identified regions show good spatial continuity and clear separation between adjacent discontinuity planes. Most of the major discontinuities observed on the slope surface were captured by the algorithm, including large persistent planes as well as smaller discontinuity patches.

Figure 5 illustrates the identification results for the entire slope, where individual discontinuity planes are displayed using different colors. The results indicate that the region growing method is capable of delineating discontinuities with varying sizes and orientations, while minimizing over-segmentation in relatively smooth planar areas.

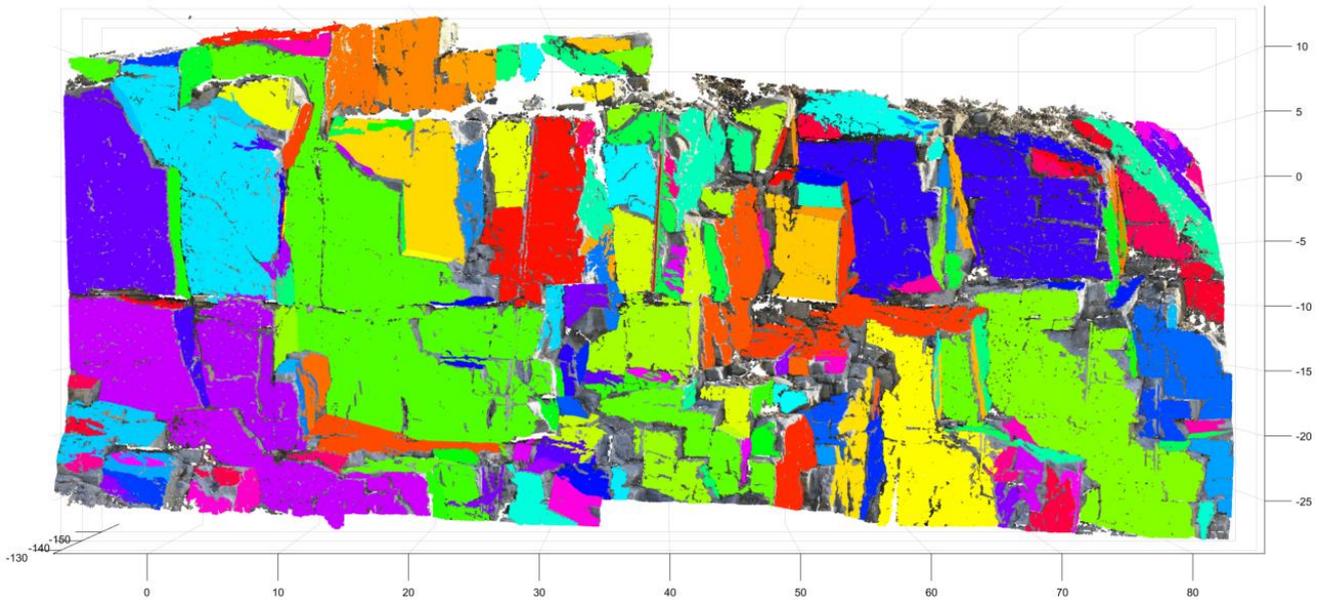


Figure 5: Discontinuity identification results

4.2 Statistical Analysis of Discontinuity Orientations

To quantitatively evaluate the identified discontinuities, the orientations of all extracted discontinuity regions were analyzed in terms of dip and dip direction. For each identified discontinuity region, the orientation was estimated directly from the aggregated point cloud without performing an explicit least-squares plane fitting.

Given the high quality and high density of the RockBench point cloud, the identified discontinuity regions generally form single-layer, near-planar point sets. Therefore, the orientation of each discontinuity was determined by

constructing a covariance matrix using all points belonging to the region. Eigenvalue decomposition was then performed, and the eigenvector corresponding to the smallest eigenvalue was taken as the normal vector of the discontinuity plane. This approach provides a stable and consistent estimate of plane orientation based on the overall spatial distribution of the points within each region.

It should be noted that the reported dip and dip direction values are expressed with respect to the local coordinate system of the point cloud rather than a global geographic reference frame.

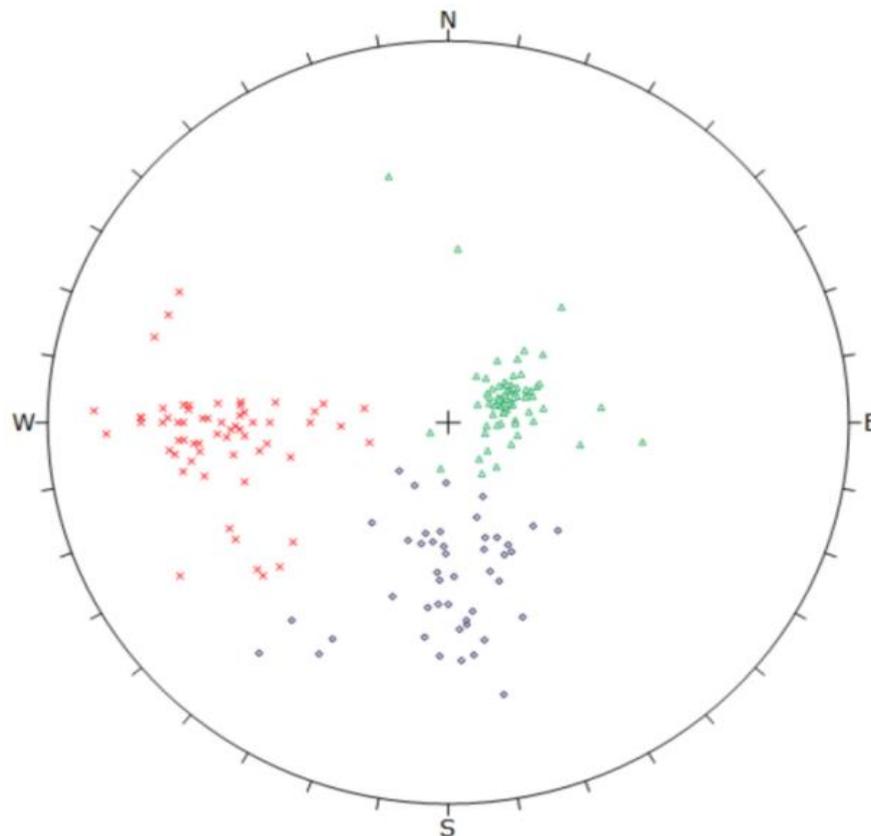


Figure 6: Discontinuities dominant grouping

The dip and dip direction of each discontinuity were subsequently derived from the estimated normal vector. Figure 6 presents the grouping of the identified discontinuity planes based on their spatial orientation. Several dominant discontinuity sets can be observed, each represented by distinct colors, reflecting consistent orientation patterns. These groupings align with the expected geological features of the study area, confirming the method's capability in identifying major discontinuities across the slope surface [2,8,13,14].

4.3 Parameter Sensitivity Analysis

A parameter sensitivity analysis was conducted to assess the influence of key region growing parameters on the discontinuity identification results. In particular, the normal vector angle threshold and the distance-to-plane threshold were varied within reasonable ranges while keeping other parameters constant.

The results indicate that the identification outcomes are moderately sensitive to the selected parameter values. Increasing the normal vector angle threshold led to larger regions and occasional merging of adjacent discontinuity planes with similar orientations. Conversely, overly strict angle thresholds resulted in fragmented regions and increased over-segmentation. A similar trend was observed for the distance-to-plane threshold, where excessively large values caused the inclusion of non-planar points, while small values restricted region growth and reduced plane continuity.

Despite these variations, the main discontinuity sets and overall orientation patterns remained stable across the tested parameter ranges. This demonstrates that the proposed approach exhibits reasonable robustness with respect to parameter selection and is suitable for practical rock mass discontinuity identification using point cloud data.

5. Discussion

5.1 Performance of the Region Growing Method

The results demonstrate that the region-growing-based approach is effective for identifying rock mass discontinuities from high-resolution point cloud data. By initiating region growth from points with minimum curvature, the algorithm preferentially selects seed points located on smooth and near-planar surfaces, which reduces the likelihood of initiating growth at edges, noise, or highly irregular regions. This strategy contributes to the formation of spatially coherent discontinuity regions and limits over-segmentation of planar surfaces.

The use of normal vectors and curvature derived from local neighborhood analysis provides a physically meaningful basis for region expansion. In particular, the orientation-based growth criteria ensure that points aggregated into the same region exhibit consistent surface orientation, which is essential for reliable discontinuity identification. The resulting discontinuity regions show good continuity and clearly defined boundaries, even in areas where multiple discontinuity sets intersect.

For the high-quality, dense, and predominantly single-layer point cloud used in this study, estimating discontinuity orientations directly from the covariance structure of the aggregated regions proved to be stable and robust. This approach avoids the variability sometimes observed in explicit least-squares plane fitting and is consistent with recent studies emphasizing distribution-free and geometry-driven estimation of three-dimensional discontinuity parameters [15].

5.2 Comparison with Previous Studies

Previous studies on point-cloud-based discontinuity identification have employed a variety of approaches, including Hough transform-based methods, RANSAC-based plane detection, clustering of normal vectors, and hybrid techniques combining segmentation and model fitting. While these methods have demonstrated effectiveness in different contexts, many rely on explicit plane fitting or iterative random sampling, which can be sensitive to noise, point density variations, or parameter selection.

In contrast, the region-growing-based method adopted in this study emphasizes local geometric consistency and spatial continuity. By growing regions from low-curvature seed points and aggregating points with similar orientations, the method naturally delineates discontinuity planes without requiring repeated model fitting or random sampling. For benchmark-quality datasets such as RockBench, this results in stable identification of dominant discontinuity sets and consistent orientation statistics. In addition to region-growing-based approaches, clustering-based methods have also been proposed for discontinuity identification from point clouds, such as multi-point clustering algorithms that group points based on geometric similarity [10,12]. While these methods can effectively identify discontinuity sets in complex scenarios, they often require careful parameter tuning and may be sensitive to point density variations.

The use of an open benchmark dataset further facilitates comparison with previous studies. Although a direct quantitative comparison is beyond the scope of this work, the identified discontinuity patterns and orientation distributions are generally consistent with results reported for the same dataset using alternative methods. This suggests that the proposed workflow provides a reliable and reproducible approach for discontinuity identification from high-resolution point clouds.

6. Conclusions

This study investigated the identification of rock mass discontinuities from high-resolution point cloud data using a region-growing-based approach. A benchmark dataset from the RockBench repository representing a road cut slope in Kingston, Canada, was employed to ensure reproducibility and comparability. After preprocessing, including noise removal and voxel-based downsampling, discontinuity identification was performed by combining curvature-based seed point selection with orientation-consistent region growing. For the high-quality, single-layer point cloud considered in this study, discontinuity orientations were estimated directly from the covariance structure of the

aggregated regions, providing stable and consistent results.

The results demonstrate that the proposed workflow is capable of effectively delineating discontinuity planes and capturing dominant orientation patterns of the rock mass. The method shows reasonable robustness to parameter variations and produces statistically meaningful discontinuity sets without relying on explicit least-squares plane fitting. These findings suggest that region-growing-based discontinuity identification, combined with PCA-based orientation estimation, provides a reliable and practical solution for rock mass characterization using high-resolution point clouds. Future work will focus on improving parameter adaptivity, enhancing computational efficiency for large-scale datasets, and extending the approach to more complex geological conditions.

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