Vol. 15, No. 44, Fall 2025, Pages 49-64

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

Research article

Modeling and Analysis of Joint Systems Using a Combined and Multi-Stage Clustering Approach: A Case Study of the Lucho Granite Mass, Zahedan

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(Received*: January 2025* , Accepted*: April 2025*)

DOI: *10.22034/ANM.2025.22633.1658*

Keywords

Staged factor analysis
Hydrothermal copper
Stream sediments
Geochemistry
Feizabad

English Extended Abstract

Summary

This study aims to develop a novel method for identifying and analyzing structural joint sets, crucial for rock mass stability and engineering projects like tunneling and mining. A hybrid, multi-stage approach was used, combining the K-means algorithm for initial clustering and Agglomerative Hierarchical Clustering (AHC) for analyzing complex relationships. The dataset includes orientation and dip measurements from 172 joint planes in the Lucho granite mass of Zahedan. The K-means algorithm improved initial clustering accuracy by reducing intra-cluster variance, while AHC formed six final clusters with high spatial coherence, enhancing inter-cluster variance and reducing intra-cluster dispersion. This method effectively eliminated noise and outliers, facilitating 3D spatial pattern analysis and revealing complex data relationships. The findings demonstrate the method's superiority over conventional approaches, providing valuable quantitative parameters for geological pattern interpretation, joint orientation analysis, and potential applications in geoscience and engineering fields.

Introduction

Structural joints significantly influence the engineering properties of rock masses and are crucial for projects like tunneling and mining. Accurate classification and analysis of these joints are essential for ensuring project safety and efficiency (1-3). Traditional methods like stereonets provide basic visualization but fall short in handling complex, multidimensional data and identifying hidden patterns due to their subjective nature and two-dimensional limitations (4, 5). Modern approaches, including data mining and machine learning, offer advanced tools for more precise joint analysis by revealing complex relationships and enhancing pattern detection (6, 7). Clustering techniques, particularly K-means and Agglomerative Hierarchical Clustering (AHC), are effective in identifying joint patterns by improving data grouping accuracy and interpreting complex geological events (8-11). This study integrates K-means and AHC to improve clustering precision in analyzing joint data from the Luicho granite mass in southwestern Zahedan. The hybrid approach reduces errors, eliminates noise, and enhances understanding of joint orientation and spatial distribution, providing reliable insights for engineering applications (12-14).

Methodology and Approaches

The study presents a methodology for geological analysis using data mining algorithms for fracture and joint analysis in rock environments. Traditional software tools in this field often rely on conventional

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computational methods such as stereographic plotting, fracture orientation analysis, slope stability assessment, and subsurface modeling, but they lack integration with advanced data mining techniques (15, 16). This study presents a novel data mining approach that leverages clustering algorithms, including K-means and hierarchical clustering (AHC), to identify and classify fractures. This method offers advantages over conventional techniques by reducing user interpretation errors and enabling quantitative analysis. The research focuses on the Zahedan granite batholith, located in the Sistan and Baluchestan province, which features a complex geological structure with varying rock types such as diorite, granodiorite, and biotite granite. Joint structures are prevalent, posing challenges for geological and mining operations (17, 18). A total of 172 geological structural joints were surveyed in the field, and their orientations were analyzed, revealing significant dispersion in 3D space. This data is critical for understanding stress patterns and improving mining operations. The K-means algorithm was applied to categorize the joint data into multiple clusters based on spatial orientation. The process was iterative, minimizing the variance within clusters while maximizing the variance between clusters. A significant challenge in K-means is determining the optimal number of clusters (K), which was addressed using statistical methods and prior evidence. To improve clustering, the study introduced a multi-step K-means process where outliers were detected and removed after each iteration, enhancing the homogeneity of the data. The final clustering was refined using hierarchical agglomerative clustering (AHC), integrating closely related clusters based on spatial correlation. The optimal angle for merging clusters was determined to be 30°, based on tectonic conditions and field observations. Key evaluation metrics, such as intra-cluster variance and inter-cluster variance, were used to assess clustering quality, and cosine similarity was employed for spatial correlation analysis. The combination of K-means and AHC provided a robust approach for analyzing fracture patterns and improving the accuracy of geological interpretations.

Results and Conclusions

This study utilizes the K-means clustering algorithm to analyze joint data, initially grouping the joints into 12 clusters based on geological features, regional tectonic conditions, and field observations. The algorithm was applied iteratively in five stages, with joint assignments adjusted according to proximity to updated cluster centers. Outliers were excluded using a predefined threshold, improving internal cohesion and reducing the dispersion within clusters. This iterative process aimed for convergence within 500 iterations, ensuring the stability of the algorithm. The final clustering results revealed a reduction in outliers, improved separation between joint categories, and minimized variance both within and between clusters. Detailed characteristics of the final clusters, including central coordinates, member counts, and intra-cluster variance, provided valuable insights into the spatial distribution of joints in the region. In the next stage of analysis, the Agglomerative Hierarchical Clustering (AHC) method was applied to refine the joint clusters, utilizing a cosine similarity criterion. The AHC algorithm progressively merged clusters with the highest spatial correlation, forming a hierarchical pattern. Dendrogram analysis, with a cut-off value of 0.8660 (equivalent to a 30-degree cosine angle), grouped joints with similar spatial orientations into nine clusters, which were further refined into six optimized groups. The resulting clusters exhibited enhanced spatial consistency and geometric coherence, with a high between-cluster variance (83.64%), confirming the accuracy of the clustering process. The final clusters displayed distinct spatial and geometric features, offering a clearer understanding of joint distribution. The integration of the K-means and AHC algorithms effectively improved the identification and analysis of joint patterns. This approach enhanced the spatial coherence and directional alignment of the clusters, providing a more comprehensive understanding of the joint distribution in the region. The final joint clusters (J1 to J6) exhibited variations in their spatial and geometric distributions, influenced by regional geological and tectonic factors. Clusters J1 and J2 demonstrated low intra-cluster variance and high geometric coherence, while J5 showed greater variability. The distribution of joint poles and orientations highlighted the impact of regional stresses and geological formations, which are essential for structural geology and engineering applications. Furthermore, stereographic projections of joint orientations provided insights into the relationship between joints and regional stresses, aiding the assessment of geotechnical risks in engineering designs. The joint orientations and characteristics in the Luccio granite mass play a significant role in both the extraction process and the stability of quarry walls.

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These joints, shaped by regional tectonic forces, influence extraction methods and wall stability. Horizontal release joints (J1) facilitate the extraction of large stone blocks with minimal energy and lower breakage risks, though they can compromise wall stability if surrounding rocks lack cohesion. Moderate dip joints (J2), associated with reverse joints, complicate block extraction and increase the risk of wall instability. High-dip joints (J3 to J6), acting as shear planes, reduce extraction costs but pose risks to wall stability due to tectonic changes that may cause rock slippage. Effective management of these joint structures is essential to mitigate instability risks, requiring reinforcement and precise cutting techniques to ensure safe and efficient extraction.

This study combines K-means and AHC algorithms to provide a comprehensive approach for joint analysis in rock masses, demonstrated through a case study of the Luccio granite mass in Zahedan. The method successfully identified six distinct joint clusters with clear spatial and geometric characteristics. By applying K-means clustering and refining with AHC using cosine similarity, the clusters were optimized, resulting in minimal intra-cluster variance and high spatial correlation. This approach enhanced the accuracy and reliability of joint identification, especially by removing outliers. The spatial distribution analysis revealed diverse tectonic influences, with high-dip joints (J3, J4, J5, J6) posing risks to wall stability, while low-dip joints (J1, J2) required careful management. This methodology provides a more accurate understanding of joint distribution and serves as a foundation for advanced studies, numerical modeling, and geomechanical analysis. It is applicable in mining project planning, tunnel design, slope stability, and modeling rock mass behavior. Future developments, especially for larger datasets and underground structure simulations, will further improve the understanding of joint distribution patterns and geological structures in rock masses.

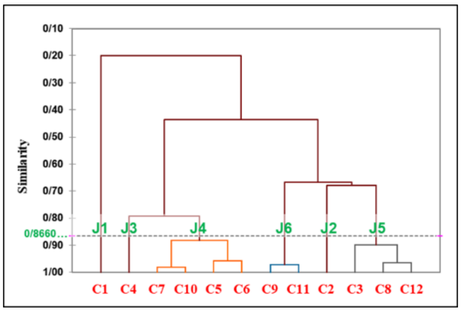

Fig. 1. **Dendrogram of final Joint systems clustering using Agglomerative Hierarchical Clustering based on cosine similarity**

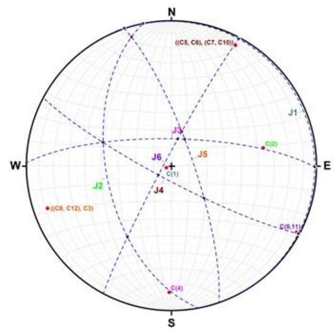

Fig. 2. Stereographic projection of the orientation and intersection of joint sets in the Lucho granite Mass

Table 1. Geometrical and statistical features of the final joint clusters based on dendrogram analysis with a cut-off level of 0.8660.

Final Joint Set	Initial Joint Grouping	Number of Joints	Within-cluster variance	X- Pole Vector	Y- Pole Vector	Z- Pole Vector	Pole Position (Azimuth and Dip
J1	C(1)	6	0.028	-0.033	-0.013	0.988	Az248.9<87.9
J2	C(2)	15	0.028	0.777	0.151	0.590	Az79<36.7
J3	C(4)	15	0.046	-0.017	-0.948	0.242	Az181<14.3
J4	C(5,6-7,10)	69	0.065	0.449	0.837	0.131	Az28.2<7.9
J5	C(8,12-3)	28	0.091	-0.887	-0.305	0.197	Az251<11.9
J6	C(9,11)	18	0.049	0.865	-0.463	0.055	Az118.2<3.2
J1	C(1)	6	0.028	-0.033	-0.013	0.988	Az248.9<87.9

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