International Journal of Innovative Technology and Interdisciplinary Sciences
https://journals.tultech.eu/index.php/ijitis
ISSN: 2613-7305
Volume 7, Issue3
DOI: https://doi.org/10.15157/ijitis.2024.7.3.98-114
Received: 10.06.2024 ; Revised: 20.08.2024; Accepted: 11.09.2024

Research Article

Scan Line Survey for Early Detection of Landslide Potential in Hard Rock Slopes

Javid Hussain[1,2,3, 4], Xiaodong Fu[1,2,3,4], Nafees Ali[1,2,3, 4], Jian Chen[1,2,3,4]*, Sayed Muhammad Iqbal[1,2], Altaf Hussain[1,2]

[1] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] China-Pakistan Joint Research Center on Earth Sciences, Islamabad 45320, Pakistan
[4] Hubei Key Laboratory of Geo-Environmental Engineering, Wuhan 430071, China
*** jchen@whrsm.ac.cn**

Abstract
Discontinuity surveys involve collecting rock data through fieldwork and are an important characteristic of evaluating the quality of rock masses in rock engineering. The characteristics of a rock mass, such as strength, deformability, and permeability, are considerably influenced by its discontinuities. Landslides and slope collapse in hard rocks demonstrate distinct qualities in comparison with those occurring in soft geological formations. The primary purpose of the investigation is to employ a scan line survey technique to assess and estimate the frequency of landslides in the Warcha Sandstone outcrop located in Karuli Piran village, Chakwal district, Pakistan. Scan line approach and physical classification of rock types are frequently utilized to identify controlling factors. We carried out a systematic investigation of the stability of the Warcha Sandstone cliff to recognize potential failure modes. The outcomes highlight a potential risk of vertical cliff instability through toppling, with the expected failure direction identified from northeast to southwest. A comprehensive physical inspection estimate underscores the gravity of the situation, indicating that a probable landslide could lead to substantial damage and road blockage. It is recommended to promptly implement precautionary measures, such as controlled blasting to remove the high-risk toppling region or to enhance resistance to stabilize the slope.

Keywords: Scanline; Toppling; Warcha Sandstone; discontinuity analysis; Slope failure

INTRODUCTION

In rock engineering, discontinuity surveys are a crucial part of estimating the rock-mass quality based on data collected from fieldwork [1]. Rock discontinuities have a significant impact on the rock mass's strength, deformability, and permeability[2]. Therefore, numerous applications require quantitative discontinuity analysis of fractured rock masses. These include (i) classifying and characterizing rock masses for use in tunneling, mining, and slope design; (ii) characterizing and modeling discrete fracture networks for use in fluid flow in fractured rocks and geothermal energy abstraction; and (iii) assessing natural hazards and ensuring slope stability.

Geometric discontinuities data for rock mass characterization could be acquired using many approaches, including scanline and window sampling [3], [4], borehole imaging using optically and acoustical televiewer techniques [5], and logging of orientated borehole samples [6]. Over the last several decades, advanced remote mapping approaches such as digital photogrammetry, light detection and ranging (LiDAR), and unmanned aerial vehicles (UAVs) have emerged as the leading methods for capturing highly detailed 3D digital data of rock faces [7]. These approaches are now extensively used and considered state-of-the-art. Before implementation, it is crucial to assess the benefits and constraints associated with each of these approaches. Conventional field evaluations, which rely on scanline sampling, need secure access to the rock face and mapping settings that are safe against rockfall. Furthermore, the scope of mapping is limited by the geologist's availability, and the process itself is inherently time-consuming. However, visually inspecting the rock face up close has many advantages, such as being able to see (i) thinly spread discontinuities, (ii) coatings or infills at those spots, (iii) extremely thin intercalations of layers (like clay) that contribute to strength, and (iv) surface roughness and curvature [8]. In addition, it is frequently necessary to use thorough visual inspection to identify the source of a discontinuity, such as a bedding plane, an extensional joint with plumose structures, or a fault plane with slickenside striations. The scanline technique has been used since the 1970s, although it is still not widely used in commercial engineering geological or geotechnical investigations, despite its suitability for conjunction with other linear explorations (drilling) [9]. The rationale for this depends on the idea that scanline mapping and analysis are time-consuming and hence expensive compared to the usual but more subjective outcrop surveys. The standard outcrop survey approach involves the collection of data on the characteristics of discontinuities seen on chosen outcrops. This is often done by categorizing them into classes, such as spacing classes. This type of presentation can result in challenges when using quantitative geotechnical interpretations later on. Moreover, it could be cognitive and might not precisely represent some conditions.

The determination and usage of joint sets are vital for evaluating the stability of a given region [10]. The procedure of categorization and detaching joint sets or subgroups of discontinuities in data composed from joint surveys is a complex and fundamental step in rock engineering design [11]. This investigation was carried out to scrutinize the slopes and to make a forecast about the possible failure mode in the Warcha sandstone formation that is amenable for the vertical cliffs that are positioned in the Karuli hamlet of Kallar Kahar Tehsil, Chakwal district, Pakistan. These cliffs are located in the Salt Range, close to the M-2 highway.

METHODOLOGY

Geographical and Geological setting

The Warcha Sandstone is conspicuously discovered in the Salt Range of Punjab, Pakistan [12] as shown in Figure 1. This area is categorized by its uneven terrain and different geological formations, comprising widespread salt deposits that give the range its name. The Salt Range spans crosswise numerous districts, including Jhelum, Chakwal, and Khushab, and is known for its rich mineral resources and substantial paleontological spots. The zone exhibits an assorted landscape.

The Warcha Sandstone, instigating from the Permian epoch, is a momentous portion of the stratigraphy of the Salt Range, an area known for its exhaustive geological history [13]. The formation is mainly imperturbable of well-sorted, fine- to coarse-grained sandstone, which shows a variability of sedimentary structures, including cross-bedding, ripple marks, and occasional planar bedding. These features are revealing of a dynamic depositional environment, transitioning from fluvial to shallow marine settings. The occurrence of such sedimentary structures proposes that the Warcha Sandstone was deposited in a setting inclined by both terrestrial and marine processes, prospective within a deltaic or nearshore environment where river systems met the sea.

The stratigraphic position of the Warcha Sandstone is predominantly remarkable. It discrepantly superposes older Paleozoic rocks, illustrating of an essential gap in the geological history, possibly persistent with a period of erosion or non-deposition. This unconformity marks a perceptive tectonic or sea-level development that led to the vulnerability and succeeding erosion of the fundamental formations before the deposition of the Warcha Sandstone. Overlying the Warcha Sandstone are younger Permian strata, comprising the Amb Formation, which further emphasizes the convoluted depositional history of the region. This stratigraphic implication is shown in Figure 1, where the comparison of the Warcha Sandstone with both older and younger rock units accentuates its significance as an important indicator in the geological background of the Salt Range.

In addition, due to its sedimentological signification, the Warcha Sandstone is also anticipated for its prosperous fossil substance [14]. The fossils protected throughout the formation encompass a miscellaneous assemblage of plant material and marine invertebrates. These fossils develop esteemed prescience into the paleoenvironmental situations of the Permian period. The prevalence of plant fossils demonstrates the close of terrestrial environments, such as floodplains or vegetated coastal zones, whereas the marine invertebrates demonstrate the influence of marine misdemeanors during the time of deposition. This mixture of terrestrial and marine fossils emphasizes the transient nature of the depositional environment, meditating changes in sea level, climate, and tectonic activity during the Permian. The geological context of the Warcha Sandstone is further convoluted by the tectonic forces that have shaped the region [14]. The Salt Range is a tectonically active zone, exaggerated by the concussion of the Indian Plate with the Eurasian Plate [15]. This tectonic activity has eventuated in the uplift and folding of the rock strata, embracing the Warcha Sandstone, dominant to the sophisticated structural geology. The tectonic influence are apparent in the deformation patterns during the sandstone, comprising faulting and jointing, which have been contents of exhaustive structural examination.

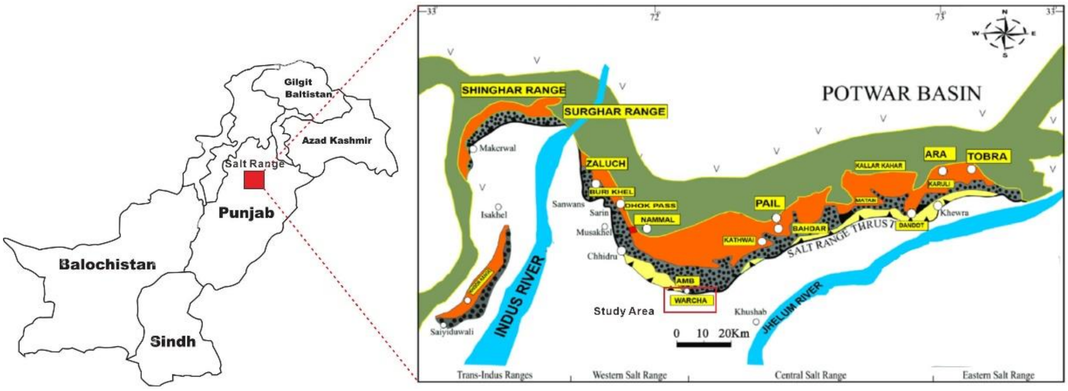

Figure 1: Study area and geological setting

The Discontinuity Analysis

Detailed geological fieldwork and a detailed Line Survey were done at Katha Sagral.Kallar Kahar Tehsil, Chakwal district, Pakistan. During the fieldwork, we have observed the following geological and engineering characteristics. The formation exposed in the study area is Warcha Sandstone and the age of the formation is described as Early Permian[16,17] . The dominant lithology of the formation is arkosic sandstone which is medium to thick bedded. The Formation was deposited in the nearshore/ fluviatile environment. Measures of dip, strike, and dip direction were noted continuously at each discontinuity.

Scanline/discontinuity analysis is an indispensable approach in structural geology that enables the meticulous measurement of the direction, distance, and durability of fractures, joints, and faults inside rock formations [18]. This technique is specifically propitious in the Warcha Sandstone of the Chakwal District. It enables us to gain enlightenment about the fracture networks, which in sequence offer vital details on the tectonic background of the region. Furthermore, it benefits us in estimating the relief of the area for different engineering purposes.

The Georient software was exploited to methodically evaluate and determine the prospective failure mechanisms throughout the Warcha Sandstone. As a specialized tool for examining geological orientation data, Georient was influential in processing the dip and strike proportions composed from the field. By inputting this data into the software, stereographic projections were produced, allowing for a comprehensive visualization of the rock's structural fabric. This accredited the identification of crucial orientations of fractures, joints, and bedding planes that could be contributing to slope instability. The main objective was to do a kinematic analysis to assess the possibility of miscellaneous types of failures, such as planar, wedge, or toppling failures, by examining the junction of potential failure planes.

Additionally, to discriminate significant orientations, Georient facilitated in the evaluation of the perseverance and spacing of discontinuities, which are prominent factors in comprehension of the stability of the rock mass. Persistence describes to the compass of a discontinuity, and affects the prospective size of unpredictable rock blocks, whereas spacing indicates the distance between parallel planes, and influences the overall stability. The software's techniques allow for an exhaustive assessment of areas within the Warcha Sandstone that are most impressionable to failure. This comprehensive analysis not only provides insights into the geomechanical behavior of the formation but also accentuated regions that may demand mitigation measures, particularly in areas wherein human activities might increase the risk of slope failures.

Data Acquisition Procedure

The scanline discontinuity sampling procedure involves establishing an evaluating tape, generally extending from 10 to 30 meters in length, over a clean and as flat as feasible rock surface. This surface should be significantly larger than the size and spacing of the conspicuous discontinuities to assurance that the sample is demonstrative of the overall rock mass structure [19]. The chosen rock slopes for this procedure can conceive in several geological settings, multitudinous natural rock formations, road excavations, quarries, open pit mines, and unsubstantiated tunnels. The purpose is to incarcerate the orientation, spacing, and other characteristics of the discontinuities with high precision. To achieve this, it is necessary to ensure that the scanline is installed properly and constantly, eluding areas where the rock surface may be uneven or covered up by vegetation, debris, or weathering. This rigorous aligning validates that the assessments contemplate on the true nature of the discontinuities and are not influenced by external factors.

To obtain accurate and widespread data, it is indispensable to establish numerous scanlines at abundant directions associated with the geological structures extant [8]. By doing so, a three-dimensional sample conformation of the discontinuity network is executed, allowing a comprehensive compassion of the rock mass's structural performance. This method also helps in weakening any sampling bias that might supervene if the discontinuities are frequently disturbed with a specific direction, which is predominantly significant in assorted rock masses with multifaceted structural structures. Additionally, to measure the orientation of the discontinuities, other critical structures containing, their perseverance, aperture, roughness, and any infilling material should also be documented. These influences show an extensive role in evaluating the mechanical characteristics stability of the rock mass[18].

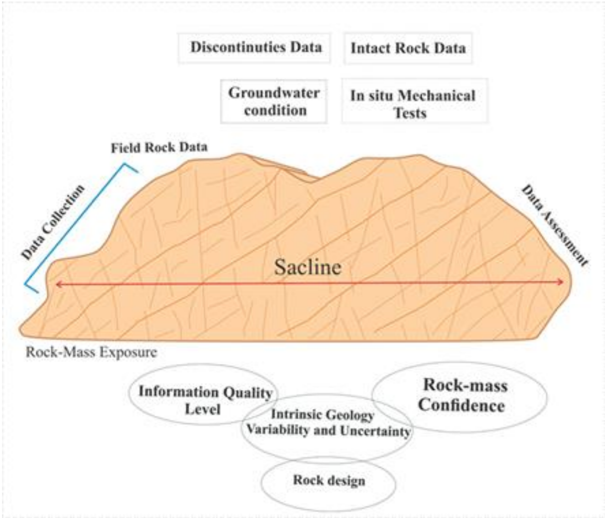

Figure 2: Discontinuity Analyses method for Scan Line Survey

Scan line mapping was conducted according to the method outlined by Piteau and Martin (1977) and recommended by Farmer (1983)[20]. In regards to the scanline sampling technique, the scanline tape is visually examined at every point where a discontinuity trace intersects with the tape. To minimize superfluous data processing, the tape is positioned on the rock face so that the first break is precisely aligned with the zero marker point on the tape. The combined investigation and mapping of the Warcha Sandstone yielded useful insights into the geological attributes of the formation under investigation as shown in Figure 3(a). The investigation started by documenting the date of the study and establishing the rock type, which was determined to be arkosic sandstone. Field-scale measurements were then conducted, including the determination of the distance of the formation using a measuring tape over a 100-meter span. The data set was gathered from multiple scanline surveys carried out in the Warcha Sandstone, Chakwal District. The characteristics surveyed comprise fractures and joints, with measurements taken to capture their dip and strike orientations. Dip and strike morals were evaluated using a Brunton compass and clinometer. The scanline was determined vertically to the leading orientation of the geological geographies, and valuations were taken at regular intervals along the line. The dip was counted as the angle of inclination from the horizontal, while the strike was inspected as the direction of the line molded by the horizontal plane.

The data computation development originates by placing the scanline along the selected segment of the outcrop, confirming it is perpendicular to the foremost geological features, such as fractures or bedding planes. With the scanline in place, the dip of each visible feature along the line is measured using a clinometer, which is positioned in contradiction of the rock surface to record the angle of inclination from the horizontal. After this, the strike direction is determined by employing a compass, ensuring that the reading is relative to the true North. Each dip and strike assessment is precisely documented in a field notebook. This process is repetitive along the complete scanline survey, capturing the orientation data for each intersectant feature, thus generating an inclusive and detailed illustration of the structural appearances of the rock mass. Joint sets were identified, encompassing orthogonal, oblique, and cross-bedded joints. Parameters such as joint length (109mm), aperture (0.9mm), and spacing (53mm) were meticulously measured. Moreover, the dip and strike of the joints were observed, exposing a dip of 71 NW and a strike of N30 E as shown in Figure 3(b).

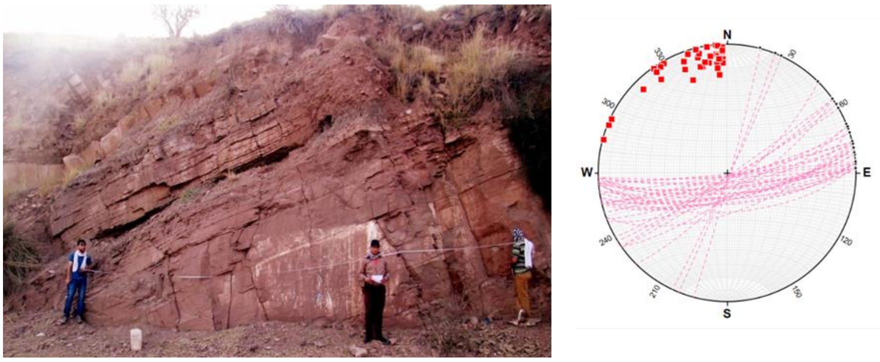

Figure 3: Sandstone rock face with fixed scanline tape, and (b) trend and plunge

Additionally, the Schmidt hammer, a non-destructive testing tool, was utilized to evaluate the strength of the Warcha Sandstone formation [21] as shown in Figure 4. By striking the surface of the rock with a rebound hammer, the rebound velocity was restrained, delivering evidence of the material's hardness and strength. This technique is predominantly valuable for field applications where acquiring core samples may not be achievable. The resulting rebound values were then associated with the uniaxial compressive strength (UCS) of the rock, providing a rapid and practical estimation of its mechanical characteristics. This method permitted effective strength classification without the necessity for destructive testing approaches, allowing precious perceptions into the formation's performance.

Figure 4: Schmidt hammer used for Rock mechanical strength

The water stipulation in the formation was observed to be dry. When these variables were input into geological software, the subsequent categorization designated a fair rock type. The joint examination and scan line mapping provides an inclusive knowledge of the Warcha Sandstone's structural topographies and mechanical characteristics, contributing beneficial evidence for geological and engineering valuations. Table 1 shows the raw data collected, comprising dip and strike values from several scanlines. These values were used to generate the stereographic projections in Figure 7.

Table 1. Discontinuity data during scanline survey, Warcha sandstone

S.no	Dip	Strike	S.no	Dip	Strike
J1j	N85E	71NW	J21j	N86E	TINW
J2j	N78W	73NE	322)	N77W	73NE
J3j	N76W	87NE	4323}	N86E	65SNW
J4j	N85W	81NE	J24j	N72W	86NE
J5j	N76E	81NW	J25j	N58E	86NW
J6j	N77W	84NE	J26j	N4SE	80NW
J7j	N82W	80NE	427}	N86E	88NW
J8j	N70E	6SNW:	528)	N88E	83NW
J9j	N88W	87NE	529}	N5SE	88NW
J10j	N76W	88NE	J30j	NSSE	87NW
J11j	N88E	TINW	J31j	N69E	81NW
J12j	N22E	88NW	J32j	N81E	7SNW
J13)	N85W	89NW	J33j	NSSW	84NE
J14j	N60E	87NW	J34j	N76W	73NE
J15j	N1SW	88NE	J35j	N85E	7ONW
J16j	N79E	7SNW	536]	N81E	88NW
J17j	N86E	8ONW	437}	N68E	7SNW
J18j	N72E	86NW	538]	N88E	84NWw
J19j	N88E	74NW	539}	N25E	88NW
J20j	N85E	73NW	J40j	N79W	87NW

The histograms as shown in Figure 5 (a, b) demonstrate the frequency distribution of dip and strike angles from the geological data. The left histogram, displaying dip angles, discloses an engrossment of values primarily between 70 and 90 degrees, demonstrating that most dips are steep. Conversely, the right histogram, demonstration strike angles, shows a broader distribution, with prominent peaks around 75 degrees and 85 degrees. This recommends inconsistency in the strike directions, with convinced angles being more common. Together, these histograms help envisage the principal alignments of geological topographies, which is vital for understanding the structural features of the research area.

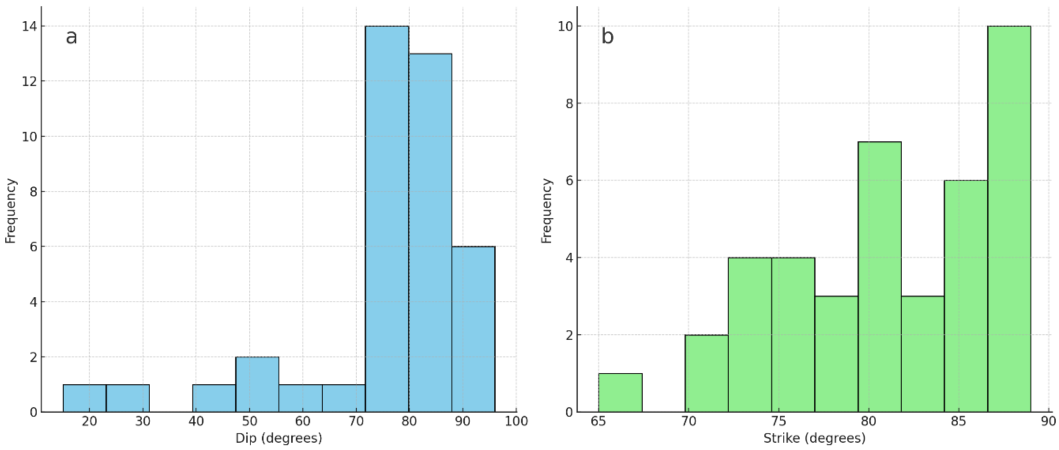

Figure 5: Histogram for (a)Dip and (b)strike

RESULTS AND DISCUSSION

The research area is mainly composed of sandstone from the Warcha Sandstone Formation, which dates back to the Permian period. In [18] research, the Warcha Sandstone was demarcated as a unit mostly containing fine- to coarse-grained sandstone with minor amounts of siltstone and shale. The sandstone shows a range of colors, from light gray to reddish-brown, and is often well-sorted and compact. It also features sedimentary structures such as cross-bedding and ripple marks, revealing of a fluvial to shallow marine depositional environment. The formation has a widespread distribution in the Salt Range and surrounding areas. The thickness of the Warcha Sandstone varies, characteristically ranging from 50 meters to 100 meters, depending on the location within the region.

Typically, there are alternating layers of nodular and massive limestone that are around 3-4 feet thick. The uppermost bed is almost 10 feet in thickness. The bedding planes are filled with worn and degraded argillaceous material. The geological development in the studied region is creating vertical cliffs that exceed a height of 20 feet along the roadside. Open vertical columnar joints are prevalent in the Sakesar Limestone, with some of these joints reaching widths of up to 2 feet in the upper horizon as shown in Figure 6.

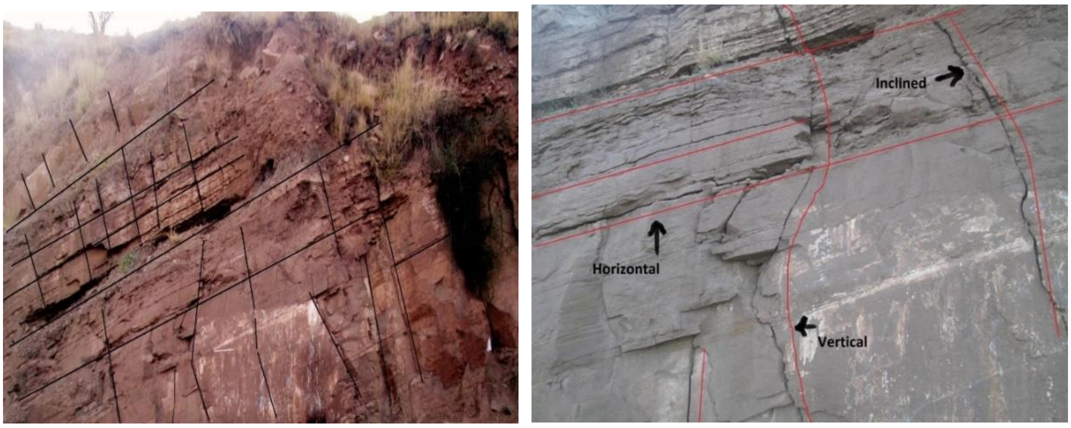

Figure 6: The Massive beds of Warcha sandstone

Discontinuity Orientation and Number of Sets

Discontinuity Sets and Orientation Analysis

In the Warcha Sandstone rock mass, the identification of discontinuity sets was achieved through comprehensive field measurements, focusing on the dip direction and dip angle of visible discontinuities. The analysis of these measurements, illustrated in Figure 7, reveals the average orientation of discontinuities, which is crucial for understanding the structural integrity of the rock mass. The stereographic forecasts in Figure 7 illustrate the spatial distribution of these discontinuities, emphasizing the foremost structural orientations that are predominant within the research area.

The outcomes designate that the discontinuities in the Warcha Sandstone are mostly oriented in a northwest-southeast direction, with dip angles fluctuating between 60° and 85°. These results propose a strong effect of regional tectonic stresses that have molded the current geological context of the Warcha Sandstone. The concentration of discontinuities in these orientations indicates that these structural features play a significant involvement in the dependability of slopes within the area. Discontinuities that are related to the slope faces are more probable to failure mechanisms, making this examination significant for estimating slope stability.

Slope Stability and Contour Mapping

To further appraise the constancy of the Warcha Sandstone slopes, a comprehensive assessment was performed based on 40 evaluations of joints and bedding planes from the study area. The field data were employed to produce contour maps, as revealed in Figure 7, which demonstrate the absorption levels of discontinuities employing Kamb contours in standard deviations. These contour maps perceptibly illustrate the density of discontinuities, authorizing the identification of areas with a higher possibility of structural inconstancy.The contour maps exhibit a considerable concentration of discontinuities in the upper northwestern portion of the study area, with contour values demonstrating areas of prospective weakness where the rock mass is more fractured. This clustering of discontinuities indicates an increased risk of slope downfall in these regions. The identification of such patterns is fundamental for understanding the geomechanically behavior of the Warcha Sandstone and for planning suitable slope stabilization measures.

Moreover, to the contour maps, the research also constructed weighted average planes to signify the data, which are accessible in the form of a rosette plot in Figure 7. This plot aggregates the assimilations of the discontinuities and provides a clear overview of the paramount structural trends. The arrangement of the majority of the discontinuities with the regional tectonic stress field further promotes the decision that these features essentially impact the stability of the rock mass.These findings prioritize the necessity to examine both the orientation and compactness of discontinuities when determining slope stability in the Warcha Sandstone. The data recommend that areas with high concentrations of discontinuities, especially those aligned with the regional stress field, are more susceptible to failure. This has substantial indications for the design and implementation of slope stabilization estimates in the region.

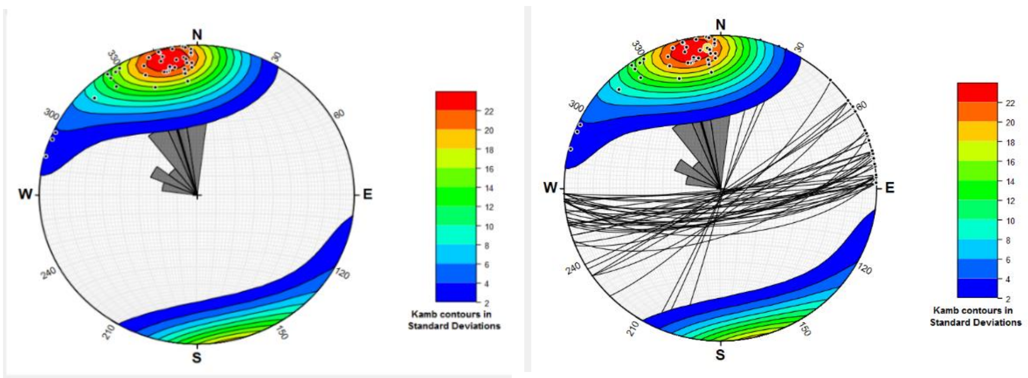

Figure 7: Contour plot of data indicating the concentration

The 3D vector plot for strike and dip visualizes the orientation of discontinuities in the Warcha Sandstone formation, providing insight into the geological structure and potential instability. The plot illustrates two vectors: the red vector characterizes a plane with a strike of 76° and a dip of 87°, while the green vector signifies a plane with a strike of 85° and a dip of 81° as shown in Figure 8. These vectors demonstrate the steep angles of the planes, which are crucial in evaluating the probability of toppling failures. By envisaging the data in three dimensions, the plot provides a clear representation of the spatial orientation of the discontinuities, assisting a better comprehension of the geological environments and enlightening effective risk assessment and mitigation strategies..

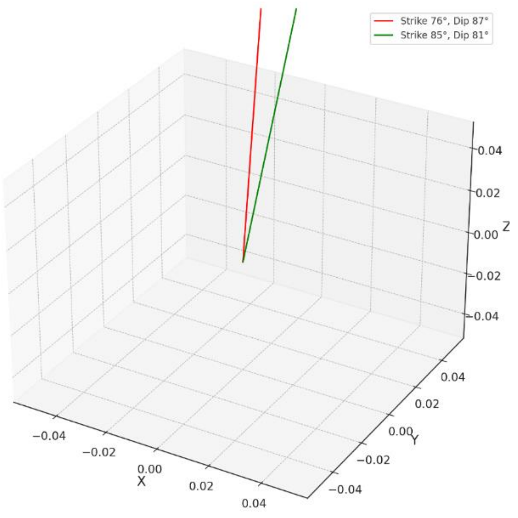

Figure 8: 3D Vector Plot for Strike and Dip

Spacing and Frequency

The cluster analysis determined three sets, and the distribution of the normal set and the mean of each set were measured. The scanline convergence distances for a distinct accumulation of discontinuities are extorted from the entire dataset that contains all scanlines. An analysis is carried out for each discontinuity in the Warcha sandstone, and the normal set spacing values are determined. To perform the computation, a suitable variable must be utilized to pick the discontinuity set. The spacing analysis outcomes are illustrated in Figure 9.

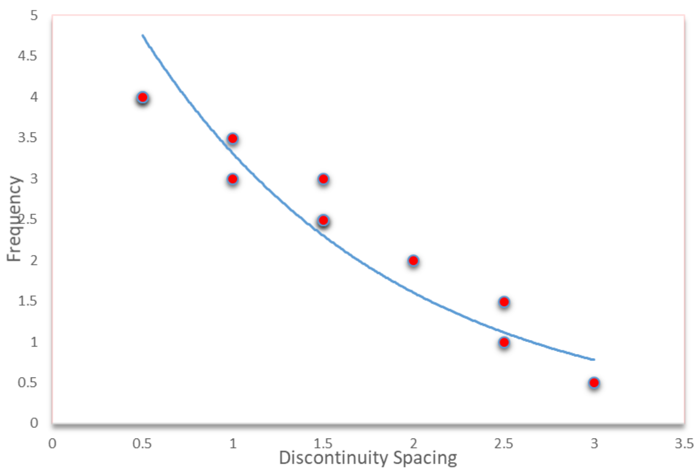

Figure 9: Graph shows the relationship between the spacing of joints and frequency

Risk Assessment

The improved risk matrix for landslide potential, based on scanline mapping, provides a clear visual representation of the risk levels by categorizing the probability of occurrence against the severity of impact as shown in Figure 10. The matrix uses a color gradient ranging from green (low risk) to red (high risk), with yellow representing medium risk, facilitating an intuitive understanding of risk distribution. The highest risk is identified in the top-right cell, characterized by a low probability of occurrence but a high impact (risk value of 2), emphasizing that even infrequent but potentially severe events require significant attention. This matrix, derived from the detailed scanline mapping of the Warcha Sandstone formation, highlights those areas with significant potential consequences, even if unlikely, that must be prioritized for effective risk management and mitigation strategies. The visual representation accentuates the emphasis on continuing controlling and the accomplishment of preservative estimates to mitigate the high-risk zones identified through the scanline survey.

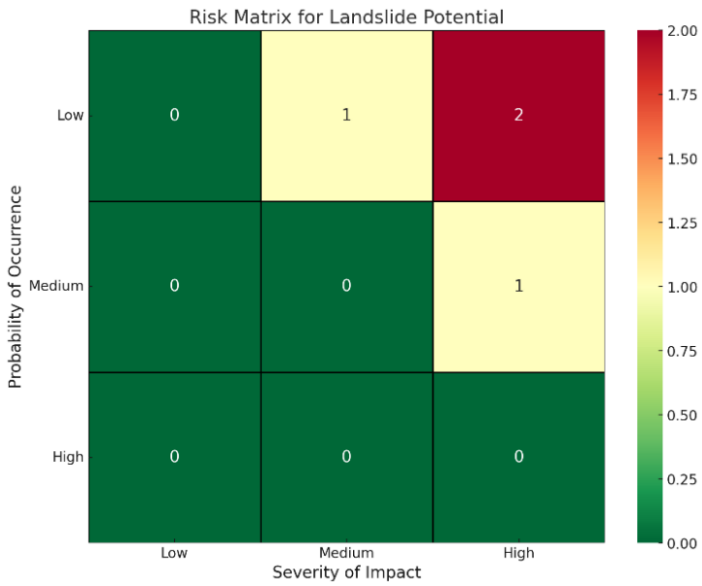

Figure 10: Risk Matrix for Landslide Potential

The stereonet investigation implemented on the Warcha Sandstone formation reveals essential understandings of the structural integrity of the exposed rock, accentuating a considerable vulnerability to toppling failure. The stereonet diagram illustrates the connotation between the slope face, discontinuity planes, friction circle, and the critical zone where potential landslides may appear. The slope face, instantiated by a thick black line, is the exposed surface of the sandstone formation, and its orientation plays a critical role in determining how gravity impacts the rock mass. Discontinuity planes, revealed as thinner black lines, are natural fractures within the rock. When these planes align critically with the slope face, they can develop potential failure surfaces, increasing the risk of rockslides or toppling.

The red circle on the stereonet characterizes the friction circle, which delineates the range of orientations that would avoid sliding based on the rock's interior friction angle. Discontinuity planes that interconnect this circle designate zones where sliding could occur if the rock is not stabilized. The shaded area on the stereonet indicated as the crucial zone, highlights the orientations of discontinuity planes predominantly susceptible to failure. When these planes lie within the critical zone, the possibility of a landslide or toppling event is distinguished, predominantly under encouragement circumstances such as heavy rainfall or seismic activity. This examination categorizes the northeast-to-southwest orientation for possible landslide measures, suggesting that any toppling failure would probably follow this directional trend. The occurrence of high-risk blocks within the sandstone formation, as accentuated in the diagram, poses a significant threat to the adjacent roadways. These blocks have the potential to dislodge and obstruct the road, creating a substantial hazard to both infrastructure and public safety.

Given these findings, it is imperious to carry out proactive procedures to alleviate the recognized geological hazards. Structural assistance of the rock face, such as using bolts, nets, or retaining walls, could stabilize the discontinuity planes and prevent rockfalls. Slope stabilization procedures, including grading or applying shotcrete, could further improve the formation's stability. In some cases, rerouting the road to avoid the most hazardous areas may be essential, predominantly if stabilization efforts are insufficient or too costly. By addressing these vulnerabilities, stakeholders can reduce the risk of damage, confirm the safety of the transportation corridor, and preserve its functionality. This comprehensive approach highlights the importance of early detection, continuous monitoring, and effective engineering solutions in managing geological hazards.

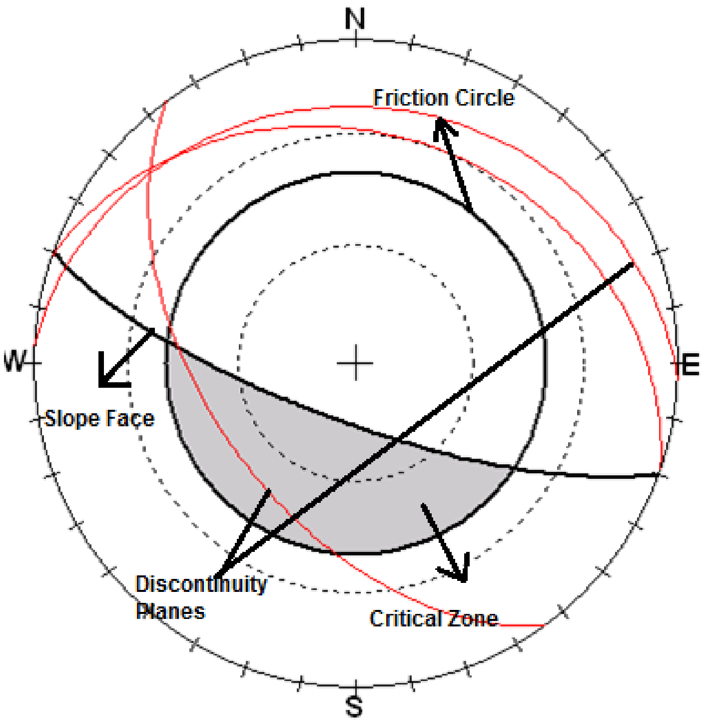

Figure 11: Predicted model of landslide potential

Contributions to Geotechnical Engineering Practice

This research introduces substantial developments in the early detection of landslide potential in hard rock slopes through the application of the Scan Line Survey approach, especially within the Warcha Sandstone formation. Contrasting previous investigations, which basically utilized Scan Line Surveys for general structural mapping, our research improves this technique to develop the accuracy of detection of critical discontinuities that contribute to slope instability. A significant innovation of our research is the integration of Scan Line Survey data with stereonet analysis, contributing to a more comprehensive understanding of the spatial associations between discontinuities and slope orientation. This technique outperforms traditional methods that often depend on stereonet plots alone. Furthermore, our investigation is innovative in its application of these techniques to hard rock environments, where the unique appearances of discontinuities stance diverse challenges compared to softer rock or soil slopes. Our predictive models, established from the survey results, offer practical insights for infrastructure protection, predominantly in signifying specific slope stabilization proceedings and roadway rerouting. This research not only develops the methodological framework for landslide detection but also contributes a robust, comprehensive hazard mitigation strategy, making it a distinguished contribution to the field of geotechnical engineering.

CONCLUSIONS

A vigorous geological and structural geology framework is dominant in assisting the examination and advancement of all rock engineering projects. In the current research, innovative scanline survey methods were utilized to evaluate the future landslide potential in hard rock formations. Through meticulous fieldwork, various discontinuities were recognized within the research region. These geological indiscretions, which comprise fractures and faults, have been originating to substantially subsidize the instability and failure of slopes. The extensive stereographic analysis carried out as part of this research has discovered that the dominant failure mechanism in the investigated vertical cliff is toppling. This type of failure, categorized by the forward rotation and overturning of rock masses, poses a serious risk to the stability of the slope. Given the intensity of the determined hazard, it is domineering to contrivance instant and effective precautionary measures. Among the recommended interventions, controlling toppling-prone regions through precise blasting procedures stands out as a critical strategy. Such measures are designed to mitigate the high-risk areas and prevent potential landslides, thereby ensuring the safety of both the infrastructure and the surrounding environment.

AUTHOR CONTRIBUTIONS

JH: Conceptualization, Data curation, Formal Analysis, Methodology, Investigation, Software, writing–original draft, Writing–review and editing. CJ: Investigation, Project administration, Resources, Supervision, Validation, Writing–review, and editing. FXA: Data Curation, Formal Analysis, Supervision, Validation, Writing–review and editing. NA: Conceptualization, Data curation, Methodology, Investigation, Software, Validation, Project Administration, Visualization. SMI: Conceptualization, Data curation, Methodology, Investigation, Validation, Project Administration, Visualization. AH: Conceptualization, Data curation, Methodology, Investigation, Software, Validation, Visualization.

ACKNOWLEDGMENTS

We extend our appreciation to all those who helped directly and indirectly. Javid Hussain is the awardee of the ANSO scholarship from 2023 -2026 and, Nafees Ali is the awardee of the ANSO scholarship of 2021-2024

DATA AVAILABILITY STATEMENT

Data will be made available upon request from the corresponding author.

REFERENCES

1. Peng, X.; Lin, P.; Huang, B.; He, Y.; Wang, M. A New Method to Automatically Identify and Characterize Rock Mass Discontinuities Using a Smartphone: Experiences from a Slope and a Tunnel. *Tunn. Undergr. Sp. Technol.* 2024, *152*, 105922.

2. Corkum, A.G.; Lorig, L.J.; Varun, V. Rock Mass Permeability Evolution during Triaxial Shearing Based on Three-Dimensional Distinct Element Model (3DEC) Simulation. *Comput. Geotech.* 2024, *168*, 106150.

3. Ranjkesh Adarmanabadi, H.; Rasti, A.; Mojtabai, N.; Tabaei, M.; Razavi, M. Effects of Discontinuities on the Rock Block Geometry of Dimension Stone Quarries: A Case Study. *Geomech. Geoengin.* 2024, *19*, 110–122.

4. Gu, Z.; Xiong, X.; Yang, C.; Cao, M. A Method for Analyzing Discontinuities Characterization Using the Integration of Underground Drift Point Cloud with 3DEC Software. *Ain Shams Eng. J.* 2024, *15*, 102744.

5. Williams, J.H.; Johnson, C.D. Acoustic and Optical Borehole-Wall Imaging for Fractured-Rock Aquifer Studies. *J. Appl. Geophys.* 2004, *55*, 151–159.

6. Brudy, M.; Kjørholt, H. Stress Orientation on the Norwegian Continental Shelf Derived from Borehole Failures Observed in High-Resolution Borehole Imaging Logs. *Tectonophysics* 2001, *337*, 65–84.

7. Pu, R. Mapping Tree Species Using Advanced Remote Sensing Technologies: A State-of-the-Art Review and Perspective. *J. Remote Sens.* 2021.

8. Assali, P.; Grussenmeyer, P.; Villemin, T.; Pollet, N.; Viguier, F. Surveying and Modeling of Rock Discontinuities by Terrestrial Laser Scanning and Photogrammetry: Semi-Automatic Approaches for Linear Outcrop Inspection. *J. Struct. Geol.* 2014, *66*, 102–114.

9. Atherton, P.R. A Scan-Line Hidden Surface Removal Procedure for Constructive Solid Geometry. In Proceedings of the Proceedings of the 10th annual conference on Computer graphics and interactive techniques; 1983; pp. 73–82.

10. Jaiswal, A.; Verma, A.K.; Singh, T.N. Evaluation of Slope Stability through Rock Mass Classification and Kinematic Analysis of Some Major Slopes along NH-1A from Ramban to Banihal, North Western Himalayas. *J. Rock Mech. Geotech. Eng.* 2024, *16*, 167–182.

11. Havaej, M. Characterisation of High Rock Slopes Using an Integrated Numerical Modelling-Remote Sensing Approach. 2015.

12. Grant, R.E. Structural Adaptation in Two Permian Brachiopod Genera, Salt Range, West Pakistan. *J. Paleontol.* 1968, 1–32.

13. Hussain, J.; Zhang, J.; Fitria, F.; Shoaib, M.; Hussain, H.; Asghar, A.; Hussain, S. Aggregate Suitability Assessment of Wargal Limestone for Pavement Construction in Pakistan. *Open J. Civ. Eng.* 2022, *12*, 56–74, doi:10.4236/ojce.2022.121005.

14. Ahmad, S.; Khan, S. Improved Diagnosis of the Carbonate Reservoirs: A Case Study from the Potwar Basin, Northwest Pakistan. *Carbonates and Evaporites* 2024, *39*, 44.

15. Ghazi, S.; Ali, S.H.; Sahraeyan, M.; Hanif, T. An Overview of Tectonosedimentary Framework of the Salt Range, Northwestern Himalayan Fold and Thrust Belt, Pakistan. *Arab. J. Geosci.* 2015, *8*, 1635–1651, doi:10.1007/s12517-014-1284-3.

16. Wardlaw, B.R.; Pogue, K.R. The Permian of Pakistan. *Permian North. Pangea Vol. 2 Sediment. Basins Econ. Resour.* 1995, 215–224.

17. Khan, S.; Ahmad, S.; Hanif, M.; Jan, I.U.; Azhar Farooq Swati, M.; Khan, S.; Saboor, A. Lithofacies, Paleoenvironments and Sequence Stratigraphic Modelling of the Wargal Limestone: Implication for Reservoir Characterization in the Salt Range, Northwest, Pakistan. *J. Himal. Earth Sci.* 2014, *47*, 41–60.

18. Chowdhury, R.; Bhattacharya, G.; Flentje, P. *Geotechnical Slope Analysis*; Crc Press, 2009; ISBN 0203864204.

19. Guta, H.E. Use of Unmanned Aerial Vehicles Compared to Terrestrial Laser Scanning for Characterizing Discontinuities on Rock Exposures 2017.

20. Ghouth-Ali, A.R.A. *Procedures for the Investigation of Dimension Stone Resources: The Suitability of Jibal Aja and Jabal Salma Plutons, near Hail, Saudi Arabia*; University of Glasgow (United Kingdom), 1997; ISBN 0438741528.

21. Shafique, U.; Bakar, M.Z.A. Evaluation of Relationships between Drilling Rate Index and Physical and Strength Properties of Selected Rock Units of Pakistan. *Nucl.* 2015, *52*, 79–84.