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Rockfall hazard evaluation in Sargalu village: North of Iraq

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Abstract
The current study was selected due to the importance of studying rockfalls in the Sargalu village in northern Iraq, which is considered one of the tourist areas in the region. Sargalu is situated in the northeast limp of the Sordash anticline. The significance of this study lies in assessing the risks associated with these rockfalls and identifying appropriate preventive and corrective measures to achieve these objectives. The Rockfall Hazard Rating System (RHRS) was applied in this study to evaluate the risks of rockfalls in the area since there were no previous studies on this area. The RHRS relies on a set of criteria and indicators to determine the risk level in the area. Detailed geological, geotechnical, and geological engineering studies were conducted to identify the types of rockfalls present in the area.
The geological study of the area revealed the exposure of the following geological formations from oldest to youngest: Sargalu, Nawkalikan, Barsarin and ChiaGara. Tectonically, the area is located at the beginning of the High Folded Zone, which is part of the tectonic regions of Iraq. This geological setting makes it susceptible to recent tectonic deformations related to the Alpine movement.
The study on rockfall hazard estimation was classified as high-risk slopes. Kinematic analysis using the Dips software revealed that there is a possibility of planar sliding, wedge sliding, and direct toppling failures. The study concludes that the study area requires warning signs, speed restrictions on the road, daily road monitoring, and some treatments to avoid the effects of rockfalls. Additionally, detailed studies of the slopes are recommended.

Keywords: Rockfalls, Sargalu village, RHRS, Kinematic analysis

Introduction

Studying rockfalls in road-adjacent slopes is essential in the field of geological engineering. These rockfalls can occur due to human activities such as cutting and filling during road construction, as well as natural rockfalls caused by various factors, including seismic vibrations [1, 2]. Rockfalls refer to the downward movement of rock bodies or rock masses on mountain slopes under the influence of gravity, hydrodynamic pressure, and other factors, including seismic events [3, 4], The phenomenon of rockfalls has significant geological and engineering implications for human life and the surrounding environment [5, 6]. Stable rockfall locations can maintain their equilibrium and cohesion over short or long periods [7, 8]. Understanding the conditions and factors leading to these rockfalls has been the focus of various studies to define them accurately for engineers and find stability solutions for the slopes. Building roads and highways in mountainous regions presents specific challenges for geologists and geotechnical engineers. The vast extent of these projects makes it difficult to gather sufficient information to assess the stability of all the slopes along the road. Consequently, most highway slopes are designed based on somewhat basic geotechnical analyses, mainly focusing on the general stability against sliding or major collapses that could jeopardize the operation of the roads [9]. Detailed analyses of rockfall hazards are rare, except in densely populated areas of highly developed countries like Switzerland. To address this issue, highway and railway administrations have developed classification schemes that can be implemented through visual inspection and simple calculations. The purpose of these classifications is to identify slopes that are particularly hazardous and require immediate remediation or further detailed study. Regarding rockfall hazard assessment, one widely accepted system is the Rockfall Hazard Rating System (RHRS). This system was initially developed by [10] and later modified by [11]. In this study, the RHRS was chosen as the primary tool to achieve the objective of comprehensive analysis and classification of rockfall-prone slopes.

The system relies on a set of criteria and variables associated with the slope, rock characteristics, surrounding terrain, and other relevant factors to assess and classify the rockfall hazard*.*

Aims of Study
The main aims of the current study can be summarized as follows:

1. The study aims to assess the risks of rockfalls and identify their extent to determine the hazards for transportation and activities in Sargalu village, considering its status as a tourist area. This assessment will be carried out using the Rockfall Hazard Rating System (RHRS).
2. Describe the Rockfall Hazard Rating System (RHRS) used in this study to classify the rockfall hazards*.*
3. Identify the types of rockfall failures that have occurred or are likely to occur, describing them as common natural phenomena in mountainous regions that frequently recur.
4. Provide a comprehensive description of the potential risk levels in the study area and recommend appropriate and immediate measures to be taken by relevant authorities.

Study Area
The study area is located administratively within the Sulaymaniyah Governorate, Kurdistan Region, in northeastern Iraq, southwest of Sulaymaniyah city center. It is situated in the Javaty Valley, approximately 60 kilometers away from the center of the governorate. The study area is bounded by the following coordinates: (N 35° 52' 35.3", E 45° 09' 59.28")

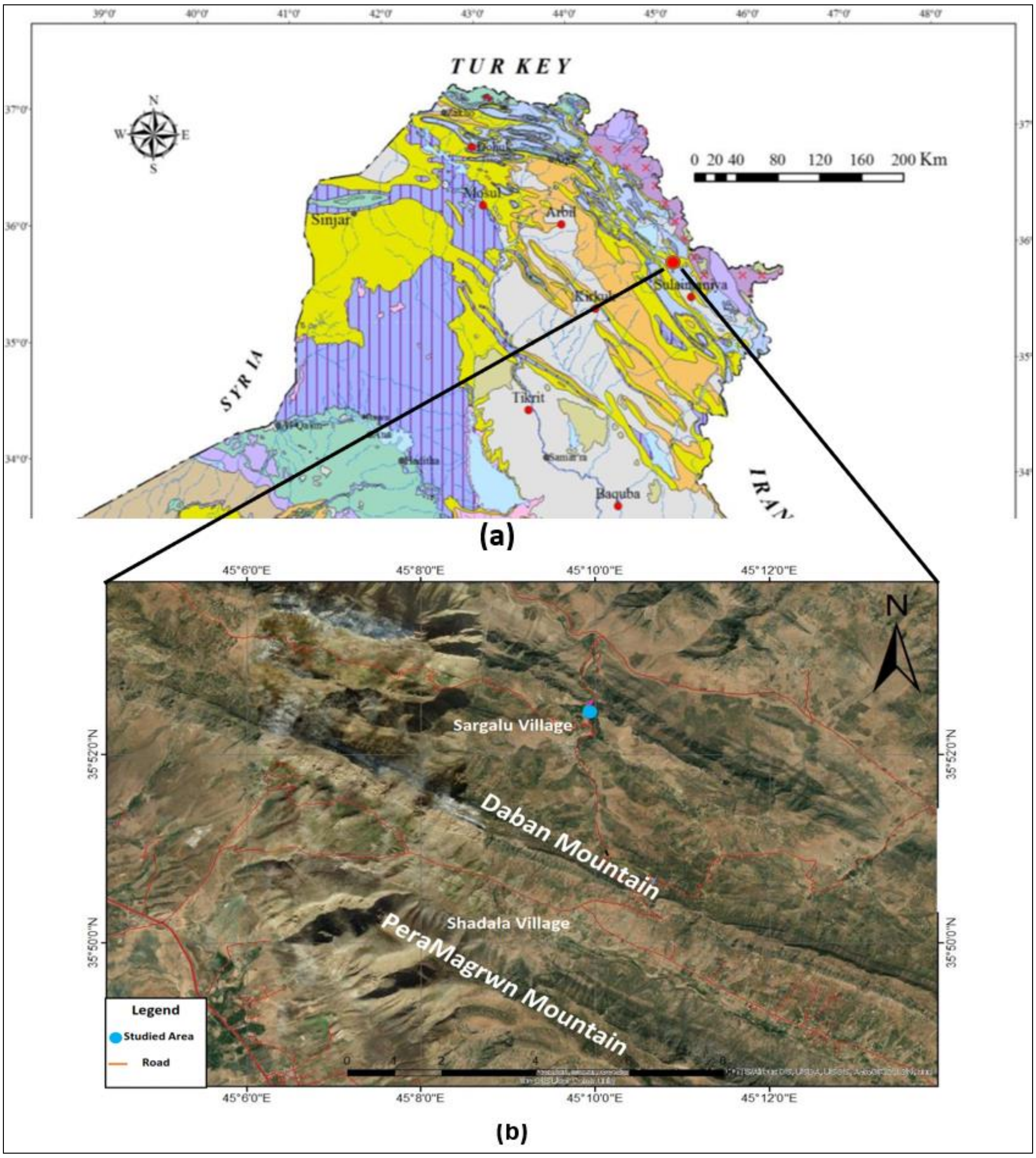

Fig 1: Map of the study area: (a) The upper part of the map of Iraq. (b) Visual image of the study area.

Stratigraphy of the Study Area
Stratigraphy of the study area is one of the essential aspects that must be studied due to its significance in engineering studies. It involves the geological formations exposed on the surface and the recent deposits covering the region. Through studying these formations, the existing relationships between the rock types and their distribution can be understood along with the geological phenomena in the area. The impact of these formations on the variations in rock type and nature, which in turn influence the stability of

slopes, can be determined. These formations, from the oldest to the most recent, are as follows:

Sargalu Formation (Middle Jurassic)
This formation consists of black continental limestone (bituminous limestones) and Dolomitic limestones, interbedded with brown papery shales, along with distinctive brownish chert zones in the upper part. The thickness of the formation in the study area ranges from 40 to 130 meters (Al-Shwaily *et al*., 2011).

Naokelekan Formation (Middle Jurassic)
This formation consists of thin layers of argillaceous material and is covered by alternating thin layers of bituminous limestone, shaley limestone, and shale. The thickness of the Naokelekan Formation in the study area is approximately 20 meters (Al-Shwaily *et al*., 2011).

Barsarin Formation (Middle Jurassic)
This formation mainly consists of stromatolitic dolostone, along with stromatolitic dolomitic limestone. The thickness of this formation in the study area is approximately 20 meters.

Chia-Gara Formation (Late Jurassic)
The formation consists of thin layers of limestone and marly limestone, characterized by its intermingling yellow color, along with calcareous shales that have a dark brown color and are rich in organic matter with an oily smell. The limestone is well-bedded and contains organic materials and ammonites. The thickness of the formation in the study area ranges from 100 to 200 meters (Al-Qyim and Saadalla, 1992).

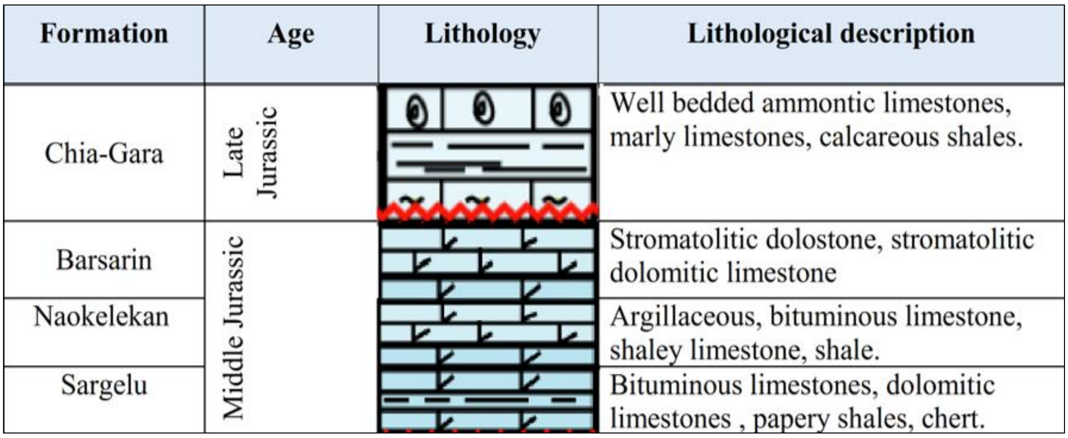

Fig 2: The stratigraphic column of formations presents in the study area.

Methodology
The research methods included several stages, which are as follows:

Field Work Stage
In this stage, several reconnaissance surveys were conducted in the study area to understand its geology, relying on topographic maps. A complete geological survey was carried out for the prevailing landslides in the study area. The assessment of these landslides' risks was performed using a global system called the Rockfall Hazard Rating System (RHRS) (Pierson, *et al*., 1990) Table (1). The area studied for specific elements and categories related to the RHRS to calculate the amount and nature of rockfall and the risks associated with these landslides in the study area. The calculations include the following elements:

1. Describing the slope by measuring the Slope Height, the slope face, and the direction of inclination.
2. Evaluating the effectiveness of ditches (Ditch Effectiveness).
3. Assessing the average risk to vehicles (Average Vehicle Risk).
4. Determining the percent of Decision Sight Distance for visibility.
5. Measuring the roadway width, including paved shoulders.
6. Taking measurements of the geometrical dimensions of unstable or collapsed blocks within the slope.
7. Assessing the Geologic Character, which can be divided into two conditions.
   The first case: When structural geological conditions dominate the landslides, the evaluation includes the assessment of the structural geological conditions and the nature of discontinuity surfaces**.**
   The second case: When geological conditions resulting from weathering and exposure dominate the landslides, the evaluation includes assessing variations in rock type and the degree of differential weathering.
8. Evaluating the size of the collapsed rock blocks (Block Size).
9. Identifying previous failure events (Previous Failures)**.**
10. Assessing the climate and the presence of water on the slope (Climate and Presence of Water on Slope).

Table 1: Basic properties in the rockfall hazard rating system (RHRS) and their intensity rating according to (Pierson, *et al*, 1990).

Factor	Rank			
	3 Points	**9 Points**	**27 Points**	**81 Points**
Slope Height (m)	7.5-15	15-23	23-31	> 31
Ditch Effectiveness	Good catchment	Moderate catchment	Limited catchment	No catchment
Average Vehicle Risk (AVR)	25%	50%	75%	100%

Percent of Vision Sight Distance			100%	75%	50%	25%
Paved Roadway Width (m)			> 13	13 - 11	11 - 8.5	< 8.5
Rock Diameter or Quantity of Rockfall Event (m)			< 0.3 or < 0.9	0.3-0.6 or 0.9-2.7	0.6-1.5 or 2.7-9.1	> 1.5 or > 9.1
Geologic characteristics	Case 1	Structural Condition	Discontinuous fractures, favorable orientation	Discontinuous fractures, random orientation	Discontinuous fractures, adverse orientation	Continuous fractures, adverse orientation
		Rock Friction	Rough Irregular	Undulating, smooth	Planar	Clay, gouge infilling, or slickensided
	Case 2	Structural Condition	Few differential erosion features	Occasional erosion features	Many erosion features	Major erosion feature
		Difference in Erosion	Small difference	Moderate difference	Large difference	Extreme difference
Climate and Presence of Water on Slope			Low to moderate precipitation; no freezing periods; no water on slope	Moderate precipitation or short freezing periods, or intermittent water on slopes	High precipitation or long freezing periods or continual water on slope	High precipitation and long freezing periods, or continual water on slope and long freezing periods
Rockfall History			Few falls (< 2/yr)	Occational falls (<2 to12/yr)	Many falls (>1/month but <1/week)	Constant falls (> 1/week)

Office work stage

This stage included several tasks to complete the study:

1. Analyzing the potential types of landslides using the Dips software.
2. Discussing, interpreting, and analyzing the results specific to the study area, and providing recommendations. As per table (2)
3. Describing the roles played by discontinuities during landslide occurrences at the studies area, and determining the stability of the slopes.

Table 2: Risk Assessment Levels Classification according to (Qiao, 2014).

Risk Level	Total points	Nature of Risks in Slopes
Level 4	199 >	Low-risk slopes / Slopes do not require detailed studies.
Level 3	399-200	Moderate-risk slopes / Slopes require warning signs and routine monitoring along the road weekly.
Level 2	599-400	High-risk slopes / Slopes require warning signs, speed limit designation on the road, daily patrols, some treatments to avoid the effects of collapses, and recommendations for detailed slope studies.
Level 1	600 ≤	Very high-risk slopes / Vehicle traffic on the road is stopped, detailed studies of the slopes are conducted, measuring the nature of occurring and potential collapses, and direct intervention to address potential collapses.

Evaluation of Failures Hazards at Study Area

The study area is considered one of the roads that was constructed by cutting and filling operations, which disturbed the natural balance of the slopes, resulting in landslides occurring in various parts of the slopes overlooking the road.

In this study, the Rockfall Hazard Rating System (RHRS) was used to assess the risks of rockfalls along the road in the study area. One of the main reasons for choosing this system is its significance and the ease of applying it in the study area. In this part of the study, the Rockfall Hazard Rating (RHRS) System was applied to the slopes overlooking the study area by evaluating the categories of properties of the RHRS on the landslides and rockfalls along the slopes and assigning appropriate values (points) to each slope or group of slopes. The length of the road is 88 meters. is located on the northeast wing of the Sardash anticline within Sargalu village, This study area is characterized by its narrow paved road and the absence of a ditch, as depicted in Feg.3. The line of sight visibility is relatively low fig.3. One of the main hazards in the area is the congestion of vehicles and tourists during the tourist seasons, as illustrated in feg.4. Additionally, the geological conditions play a prominent role in the study area due to the large rock blocks exposed to potential collapse. The values of the Rockfall Hazard Rating System (RHRS) coefficients in the study area are summarized in Table 1.

Fig 2: Shows an overall view of the slopes, the width of the paved road, and the absence of a ditch for rockfall

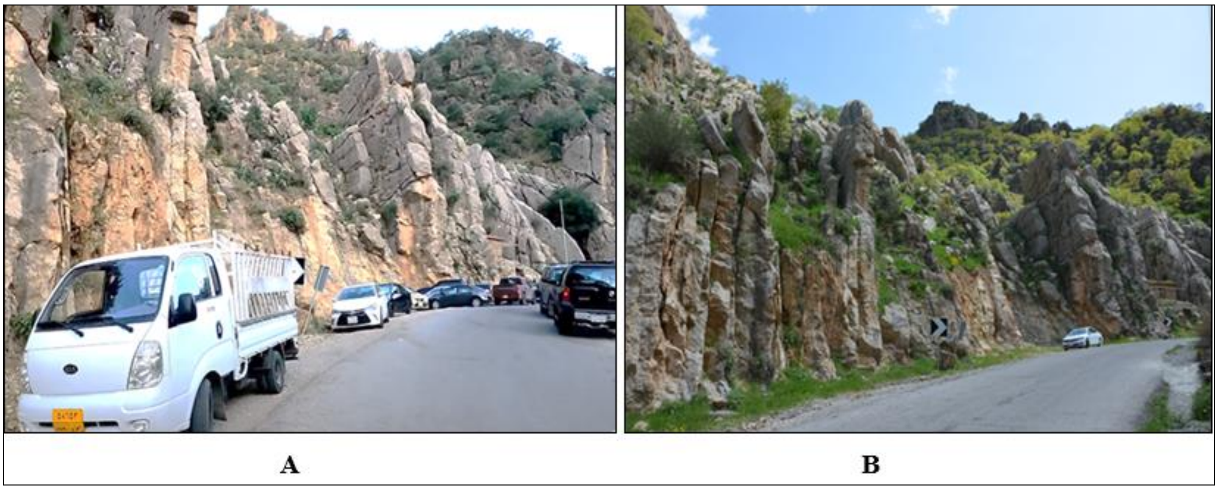

Fig 3: Depicts a general view in the study area during two different seasons: (a) Tourist season, (b) Other seasons.

Fig 4: The risk of rock masses exposed to collapse on the road.

Table 3: Summary of the evaluation of the categories of properties for the RHRS system in the study area

Factor			Points
Slope Height (m)			9
Ditch Effectiveness			81
Average Vehicle Risk (AVR)			3
Percent of Vision Sight Distance			81
Paved Roadway Width (m)			81
Geologic characteristics	Case (1)	Structural Condition	81
		Rock Friction	27
	Case (2)	Structural Condition	3
		Erosion Difference	3
Rock Diameter or Quantity of Rockfall Event (m)			27
Climate and Presence of Water on Slope			3
Rockfall History			3
Total points			402

Thus, the slopes in the study area were classified as level two risk according to Table (2) in the risk assessment levels classification, which indicates a moderate level of risk. In such cases, warning signs, speed limits, daily road patrols, and some treatments to avoid the effects of landslides are required. Additionally, it is recommended to conduct detailed studies for the slopes along the road.

Rockfall assessment in the study area

The results of the Rockfall Hazard Rating System (RHRS) showed that the area is a high risk of rockfalls. The slope face in the study area has a length of 88 meters, facing 305 degrees, and has a slope angle ranging from 70 to 90 degrees. The exposed formation in the slope face is the Qamchuqa Formation, consisting of large dolomite rocks with layer thickness ranging from 1 to 1.5 meters, as shown in Feg.5. This is due to the significant spacing between joints, as illustrated in Feg.6. The rock layers are intersected along with three sets of discontinuities with dip and dip direction of 80/308 in the first set, 30/126 in the second set, and 20/260 in the third set. Kinematic analysis indicated that the slopes are prone to various types of rockfall events, as depicted in the stereographic representation in Fig.7.

1. **Planner sliding:** The occurrence of the pole of discontinuity Set#1 in the collapse area indicates the possibility of this type of collapse.
2. **Wedge sliding:** There is a possibility of wedge sliding in this region due to the intersection of the discontinuity levels Set#2 within the area of collapse.
3. **Flexural topping:** Flexural topping is likely to occur because there is intersections of discontinuity levels Set#2 within the area of influence for this type of toppling.
4. **Direct toppling:** This type of toppling is possible because the first Set#1 of discontinuity levels occurs within the area of influence for direct toppling.

Fig 5: Shows the large dolomite masses in province.

Fig 6: Presents an overall view of parts of the slopes and interspaces in the study area.

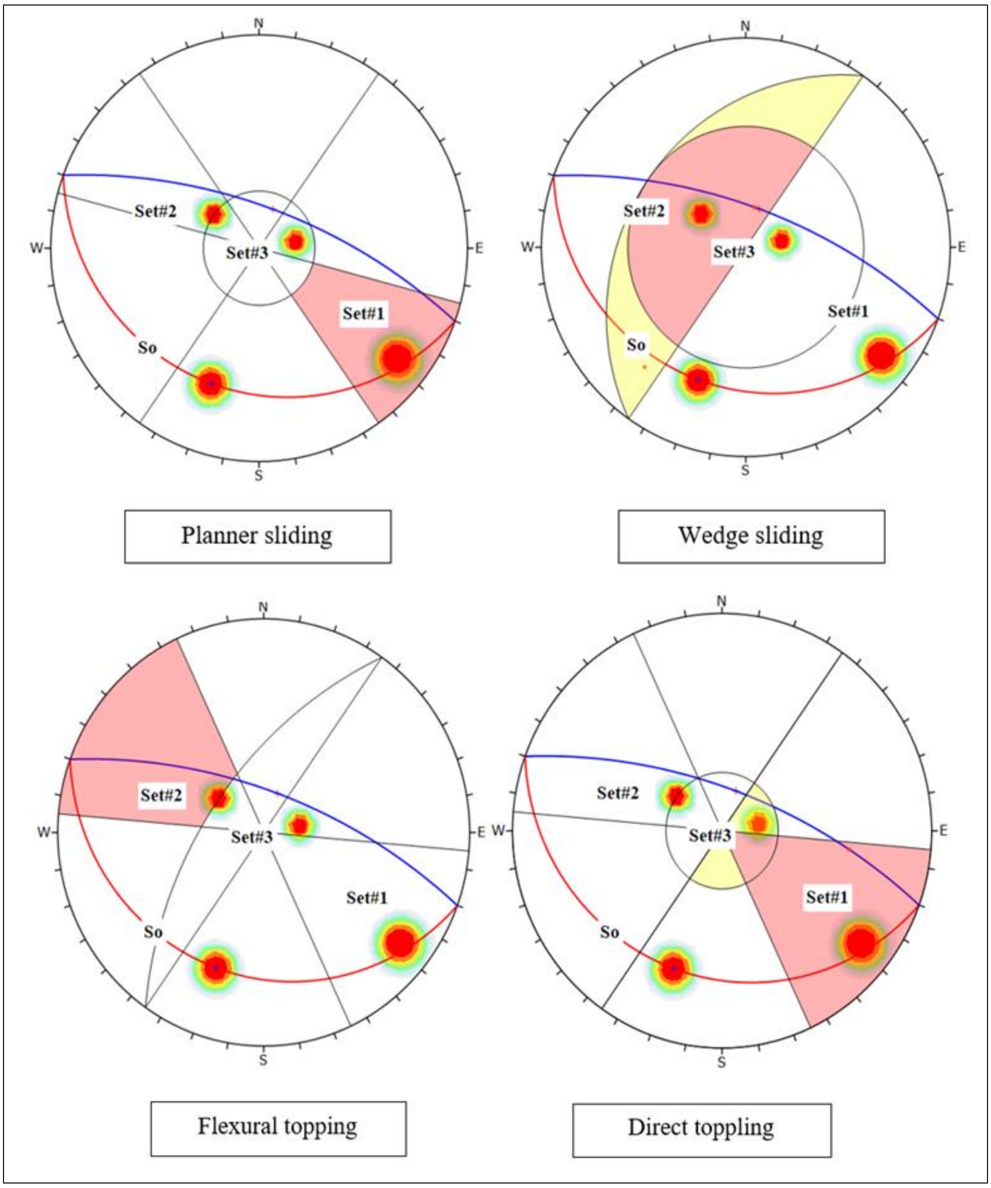

Fig 7: three-dimensional projection diagram of the study area

Conclusions

The researcher reached the following conclusions:

1. The study area is characterized by a high frequency of actual and potential collapses due to the road cutting almost perpendicularly to the axis of the fold. It is considered a region with medium to very high risks."
2. According to the landslide risk assessment system, the study area falls under level two, which is classified as high risk. Therefore, slopes in these areas require warning signs, speed limits on the road, and daily monitoring. It is also recommended to conduct a detailed study of these slopes to identify additional measures needed to effectively mitigate the risks."
3. Weathering and erosion factors play a significant role in the occurrence of collapses in the area, leading to the weakening of rock resistance and the removal of supportive parts of rock masses. These factors include the effects of storms, heavy rainfall, strong winds, as well as temperature fluctuations and continuous exposure to weathering over time. These weathering processes lead to rock degradation and erosion, reducing their strength and causing voids and collapses, changing the shape of slopes, and increasing the risk of sliding and rockfalls. Therefore, these factors should be considered when evaluating the stability of mountainous areas and rock slopes to minimize the risks of collapses."
4. Water, especially during rainy seasons, plays a major role in reducing the internal friction angle on surfaces prone to sliding. When water wets the surfaces, it reduces the friction between the surface and other bodies, increasing the surfaces' slipperiness and the likelihood of sliding. This effect is particularly noticeable on sloping and rocky surfaces where water accumulates, weakening friction and stability, thereby enhancing the probability of sliding and collapses. Hence, proper water drainage management and control of water accumulation are vital to maintain surface stability and reduce the risks of sliding and resulting accidents."
5. Regarding the desk study using the Dips software, potential collapses in the study area include planar sliding, wedge sliding, and flexural topping and direct toppling.
6. The main cause of collapses in the study area is related to the folding processes, in addition to structural and

rock-related factors. The study indicates the possibility of further collapses occurring in the future."

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