



Article Modified "Rockfall Hazard Rating System for Pakistan (RHRSP)": An Application for Hazard and Risk Assessment along the Karakoram Highway, Northwest Pakistan

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Abstract: Rockfall is a natural mountain hazard posing a severe threat to people, infrastructure, and vehicles along the transportation corridors. In this research, the standard Rockfall Hazard Rating System (RHRS) is slightly modified for the mountainous terrains of Pakistan through the quantification of animal activity along the highways. In the modified Rockfall Hazard and Rating System for Pakistan (RHRSP), animal activity is scored based on permanent and random animal tracks, shallow and higher altitudes, and shoulder width. The model is applied along the Karakoram Highway (KKH), which traverses a suture between Besham and Dasu (\approx 78 km), for Rockfall hazard and risk assessment mapping. An inventory of rockfalls, topples, and debris slides is compiled at 30 stations. Results show that rockfalls are mostly of the wedge and topple type failures. Fifty-seven percent of the area falls under the very-high to high hazard zone, 18% under moderate hazard, and 25% covers the low to very low hazard zone. Sixty-seven percent of the stretch is at very-high to high risk, distributed from Dubair to Dasu. The main reason for this risk is associated with narrow road width and limited shoulder width for vehicles. The RHRSP model is also applicable for other highways with the same geological and morphological settings.

Keywords: RHRSP; rockfall; Karakoram Highway; north Pakistan; CPEC; hazard; risk

1. Introduction

Rockfall is a common mountain hazard in which mass of any size falls, bounces, or rolls downward from a cliff or slope. Movement is categorized as rapid to extremely rapid and usually the preceding mass is not displaced from its origin [1–3]. The fall turns into debris fall when the falling material is detrital fragment of size <20 mm for pebbles, >20–200 mm for cobbles, and >200 mm for boulders [4]. On the other hand, toppling is a failure in natural rock slopes characterized as forward rotation of a slope of soil and rock around a fixed point under the influence of gravity or adjacent cracks and fluids [4,5]. Fractures with extreme climatic conditions of freeze and thaw serve as the main cause of rockfall [6]. Furthermore, human activity such as undercutting for roads, deforestation, and lack of vegetation in arid climatic conditions increases the process of rockfall and landslides [7]. The occurrence of rockfall and toppling becomes significant when it affects human lives and economically hits elements such as livestock, settlements, infrastructure, and transportation [8].



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Rockfall hazard and risk assessment is usually carried out qualitatively or quantitatively, depending upon the nature of the problem and data quality and quantity [1,9–16]. The quantitative method is a numerical way of evaluating hazard and risk. Quantitative Risk Assessment (QRA) has been developed to quantify the potential losses by considering fatalities, damaged buildings, and infrastructure. Quantitative approaches are usually difficult to carry out due to economic constraints, data availability issues, and most importantly acceptable and tolerable risk thresholds, which differ from country to country [17]. On the other hand, the qualitative method is most commonly applied for hazard and risk assessment because it is easy to use and apply. This approach descriptively defines hazard and risk by assigning appropriate scores or ratings based on the geologic, topographic, climatic, human, and road specific parameters [11,18,19]. For instance, if the cumulative score is lower than 300, the slope will be placed in "low-urgency treatment", whereas a score >500 requires "Immediate stabilization work" [20–22].

The first-ever method to address the rockfall hazard for transportation corridors was developed by Brawner and Wyllie [23]. Later on, two famous qualitative models were developed, including one by the Canadian National Railway Corporation [24] along with the Rockfall Hazard Rating System by the USA Federal Highway Administration [1,19,25,26]. Qualitatively, rockfall hazard has been assessed extensively in the last few decades [2,23,25,27,28]. The authors of [11] presented a comprehensive review of all the modified methods adopted in the last two decades by different countries to assess rockfall hazard and risk assessment. These are summarized as: (1) Rock Slope Rating Procedure (RSRP: New York department of transportation), (2) Italian Modification of RHRS (mRHRS), (3) Missouri Rockfall Hazard Rating System (MORFH RS), (4) Ohio Rockfall Hazard Rating Matrix (ORHRM), (5) Tennessee Rockfall Hazard Rating System (TRHRS), (6) Colorado Rockfall Hazard Rating System (CRHRS), (7) Rockfall Hazard Rating for Ontario (RHRON), (8) Rockfall Risk Rating for Settlements (R3S2), (9) Falling Rock Hazard Index (FRHI), (10) Rockfall Risk Rating System (RRRS). In the recent literature, [21] has provided a comparative assessment of three state-of-the-art technologies for rockfall hazard and risk assessment along roads. The potentials and limitations of the modified Rockfall Hazard Rating System (mRHRS), Rockfall Risk Management (ROMA), and Evolving Rockfall Hazard Assessment (ERHA) are thoroughly discussed in his research.

Modifications in RHRS models correspond to different purposes and fields of applications. Assessment of transportation corridors, settlements, excavated and natural rock slopes, and open-pit quarries have remained the major purposes of various models. Data collection requirements differ significantly in each model, starting from historical database collection, in situ measurements, trajectory modeling, and laboratory tests. In brief, data limitation problems and topographic, geologic, and climatic conditions of a particular area provide the basis for model modifications.

North Pakistan is a geologically complex area due to the active head-on collision of three blocks, i.e., the Indian plate, the Kohistan Island Arc (KIA), and the Eurasian plate [29]. The ongoing active deformation is a root cause for multiple mountain hazards such as earthquakes, landslides, debris flows, floods, and rockfalls along different sections of the KKH. Rockfall and toppling activity is acute along a 200 km stretch from Besham to Chilas. In 2016, the KKH remained blocked for a few days at more than 100 locations for traffic due to rainfall triggered mountain hazards [30]. Regional tectonics, geology, topography, and climate have remained the long-term agents for rockfall initiation along the highway but considering short term and frequent rockfall activity in the study area, one of the most active triggering agents has been neglected and has not been included in any rockfall hazard and risk assessment study along the KKH. It is the animal activity at higher altitudes that activate rockfalls daily, causing damage to vehicles and humans. Animal activity has been scored carefully based on animal tracks, grazing altitude, and subsequent rockfalls and placed at the appropriate position in the standard RHRS model. Transportation corridors, highways, cultural heritage, and historic sites are the major study areas for rockfall hazard and risk assessment throughout the world [2,12,14,31–37]. In northwest Pakistan, rockfall hazards and risk assessment have been carried out at a regional scale along the KKH by

Ali, et al. [31]. The objective of the present study is to modify the standard RHRS model [1] by incorporating animal activity that causes frequent rockfall incidents. We have also presented a case study to prepare rockfall hazard and risk maps along the Karakoram Highway (KKH) road, which traverses a narrow gorge of the Indus River for ~78 km between Dasu and Besham, using a modified RHRSP model. The task has been achieved by compiling a rockfall, toppling, and debris slide inventory at 30 stations and collecting topographic, geologic, rock failure, road specific, and influencing factors data.

2. Materials and Methods

2.1. Rockfall Hazard Rating System (RHRS)

The Rockfall Hazard and Rating System (RHRS) was developed by the Oregon Department of Transportation (USA), and it is a classification scheme developed for roads and highways [1]. The rating system was developed to assess dangerous slopes, which required detailed analysis. Hazard assessment and vehicle vulnerability are reflected through five main factors, further divided into several categories that are assigned weights based on least to most hazardous. The exponential scoring ranges from 3 to 81 and can be calculated using the relation $y = 3 \times [22]$. The total score for all the parameters defines the hazard and risk zones for the entire section. A summary of the model is illustrated in Table 1. Five main factors are divided into two groups, i.e., Hazard and Vulnerability. Topographic, geologic, rock failure, and influencing factors define the rockfall hazards, whereas vehicle vulnerability is assessed through road-specific factors. The topographic factor is further divided into slope angle and slope height. The role of geology is reflected through joint/fracture orientation, joint spacing, weathering, rock friction, and suspended mass. The influencing parameters are water on slope, earthquake intensity, animal activity, settlements, and rockfall history. The road specification includes road width, shoulder width, Decision sight distance (%), Average Vehicle at Risk (AVR), ditch effectiveness, and protection measures. The first step of this assessment is to compile an inventory of the rockfalls based on the stability conditions of the slope.

2.1.1. Topographic Factors

Slope angle is an important factor in determining its stability. Slope angle in the field is measured through a Laser rangefinder. Slope height is the vertical height of the slope from where fall is expected. Natural slope height plus the slope cut height defines the measured slope height (Vertical distance).

2.1.2. Geologic/Structural Factors

Lithology plays an important role in triggering rockfalls [38]. Lithological units in the study area were derived from the "Geological Road Log along the Karakoram Highway" provided by the Geological Survey of Pakistan (GSP). Joint orientation and spacing are measured at each station in the field and scored accordingly. Furthermore, conjugate fracture set orientations are also measured for stress analysis at a regional scale. The roughness of the surface, rock material characteristics, and infilling determine the rock friction. Weathering conditions and the type of suspended mass at each station are also considered in the geological factor of the rating system.

2.1.3. Influencing Factors

The stress state in a slope primarily depends upon groundwater pressure, governed by the groundwater conditions. Groundwater pressure reduces the effective stress on parts of the rock mass. In addition, water contributes to the fast erosion of rock mass through an unfavorable reaction with the filling materials in discontinuities [39]. Data related to surface draining and seepage was collected at every station in the field. According to [40], the stability of the slope is influenced by earthquakes. The study area is bounded by two major faults i.e., Main Mantle Thrust (MMT) and the Raikot fault. The earthquake intensity rating was based on the seismic hazard map and seismic zonation map by the Pakistan Meteorological Department and Peak Ground Acceleration (PGA) and seismicity map [41]. The position of settlements was determined through topographic sheet and field observations.

		Rating Criteria by Score				
Category			Points 3	Points 9	Points 27	Points 81
Slope Height (m)			7.5	16	25	>30
Ditch Effectiveness			Good catchment	Moderate catchment	Limited catchment	No catchment
Average Vehicle Risk (% of time)			25%	50%	75%	100%
Percentage of Decision Sight distance			Adequate 100%	Moderate 80%	Limited 60%	Very Limited 40%
Geologic condition	Case one	Structural Condition	Discontinuous joints, favorable orientation	Discontinuous jointsrandom, orientation	Discontinuous joints, adverse orientation	continuous joints, adverse orientation
		Rock Friction	Rough, irregular	Undulating	Planar	Clay infilling, or slickensided
	Case two	Structural Condition	Few differential erosion features	Occasional differential erosion features	Many differential erosion features	Major differential erosion features
		Difference in erosion rates	Small	Moderate	Large	Extreme
Block Size (m ³) Volume of rockfall (per event)			0–0.25 3m ³	0.25–0.5 5m ³	0.5–1 7m ³	>1 10m ³
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 slope	High precipitation or long freezing periods or continual water on slope and long freezing periods	High precipitation and long freezing periods or continual
Rockfall History			Few falls	Occasional falls	Many falls	Constant falls

Table 1. A summary sheet of Rockfall Hazard Rating System after [1].

2.1.4. Rock Failure

The history of rockfall should be carefully acquired for an accurate rating. Archives of Frontier Works Organization (FWO) and interviews of local people provided the historic rockfall information. In the case of a single block, the size of the block is considered, whereas, in the case of many blocks with different sizes, measurement of volume is carried out. In the current research, we have measured the volume of fallen blocks at each station. Talus development at the toe is observed and rated in the field. A landcover map of the area was prepared through Landsat imagery.

2.1.5. Road Specifications

A digital road map of the study area was obtained from the Survey of Pakistan (SOP). Road-related data such as road width, shoulder width, ditch effectiveness, and protection measures were directly observed and measured during fieldwork. The Average Vehicle at Risk (AVR) defines the spatial occurrence of a vehicle in the hazard zone, and it is obtained through the following relation:

$$AVR = \frac{(ADT \cdot SL)}{PSP} \cdot 100$$
(1)

Decision Sight Distance (DSD) is the distance a driver requires to decide an unwanted event to stop or respond. A laser rangefinder was used to measure the sight distance in meters. The percent of DSD is obtained by:

$$PDSD = \frac{ASD}{DSD} \cdot 100\%$$
(2)

where PDSD = % sight distance, ASD = Actual Sight Distance, and DSD = Decision Sight Distance.

2.2. Modified Rockfall Hazard Rating System for Pakistan (RHRSP)

2.2.1. An Overview of Rockfall Activity through Animals

Rockfall is the most studied and frequent mountain hazard worldwide, caused by various sources [35,42]. The most common triggering agents are earthquakes, rainfall, weathering, erosion, and freezes-thaws, but animal activity at higher elevations is classified as a less common triggering agent. Although the triggering of rockfalls through animals has not been placed in the first category, its impact is observed worldwide. Its historic evidence extends back to an art book named "Modern painters", where the author mentions the throwing of stones from a goat that caused an injury [43]. Although this simile does not belong to the geohazard category, it proves that animals causing rockfalls were not even neglectable in historic times. In the last few decades, various researchers have included animals as the source of rockfall triggering. One thousand three hundred miles of California highways were affected by continuous rockfall events over the course of a year. For a thorough assessment of this issue, rockfall data were collected from 92 stations, and it was concluded that animal activity was responsible for initiating 0.3% of the total rockfall events [44]. Similarly, Dorren [45] presented a review of rockfall mechanics. Among the other rockfall causes, he included animal activity as a minor cause but an effective triggering agent. Partsinevelos et al. [46] applied an integrated seismic and image data processing technique for rockfall monitoring and early warning. He had mentioned the goats' herd as a major source of seismic noise and rockfall triggering. Similarly, quantifying weather conditions for rockfall hazards, Macciotta, et al. [47] considered the animal movement on a slope as the cause of the loosening of material, hence increasing the potential of rockfall hazard.

A study undertaken for rockfall hazard assessment along the cut slope of the Indian state highway in Maharashtra concluded that rockfalls are initiated through biological activities, including animals. This research rated animal activity and animal dens as the major cause of rockfalls [48]. The triggering of rockfalls at higher altitudes and at steep slopes is categorized as secondary rockfall triggering caused by animals and anthropogenic activities followed by earthquakes, rainfall, and erosion triggering [49]. A dataset of fatal global landslides compiled from 2004 to 2016 also concluded that animal activity is one of the triggering agents of landslides [50].

Apart from the published literature, which mentioned rockfall events through animal activities, a bulk of evidence comes through news reports, social media, and electronic media, where personnel such as mountaineers, bikers, hikers, climbers, and visitors mention their tragic interactions with rockfalls. Mountaineers have continuously reported these events specifically along goat tracks at higher altitudes, which have caused injuries and fatalities.

2.2.2. Quantification of Animal Activity

To quantify the animal activity along the study area at shallow or higher altitudes, a strong emphasis was given to animal movements, locating their random and permanent tracks, grazing altitude and steepness of the slope, and the shoulder width of the road

(Figures 1 and 2). From Besham to Dasu, much of the slope is steeper, therefore the stones reaching the road is primarily controlled by grazing height plus the shoulder width. In some cases, grazing animals at higher altitudes push stones that are captured by shrubs during downslope movement. Conversely, a large stone pushed from a higher altitude might gain momentum and becomes dangerous for humans and vehicles. A higher rating has been given to the situation when animals are grazing very close to the road and at shallow altitudes with no or extremely low shoulder width. In this situation, even a small stone directly approaches the road very quickly (Figure 1). A minimum score is assigned in the case where grazing will take place at shallow or higher altitudes, but the chances of falling stones reaching the road is minimal. This is mainly due to the gentle slope and plentiful shoulder width. (Figure 2). In mountainous regions, as with the KKH, shoulder width plays an important role in accommodating falling stones. In the study area, shoulder widths do not have standard limits and are therefore classed as a major factor in the quantification of rockfall by animal activity.



Figure 1. Quantification of rockfall activity caused by animal movement at lower and higher altitudes. (a) Sheep grazing at the gentle slope and lower altitude can push stones, which might cause moderate damage. (b,c) Stone falling caused by goats grazing at the steep slope and at the random track can directly damage the vehicles.



Figure 2. (a) Animals always follow a permanent track to reach the grazing altitude. Cows push larger stones compared to goats. (b) Goats grazing at a random track push stones that might not reach the road due to wider shoulder width.

3. Application of Modified Rockfall Hazard Rating System

3.1. Study Area

The study area is located in the Kohistan district and is a 78 km stretch of the KKH in the Indus Valley. (Figure 3). The study area is bounded within the longitudes 72°51′49.44″ E, 73° 13′19.55″ E and latitudes 34°54′42.48″ N, 35°16′22.46″ N. Altitude in the area ranges from 568 m ASL at Besham to 4888 m snowy peaks on both sides of the Indus River. The world's ninth highest mountain peak, Nanga Parbat, with an elevation of 8125 m, is located in this region. Nanga Parbat Haramosh Syntax, located over a peninsula of the basement of the Indian plate, divides the Kohistan and Ladakh Island Arc terranes. The valleys in Kohistan have steep slopes and thin dispersed alpine-type vegetation, with snow cover mostly in the winter season [51]. The Indus River is the main drainage artery of the area.



Figure 3. (**A**) Regional tectonic framework of the northwest Himalaya. The study area is shown with a red box. (**B**) Location map and point inventory of 30 rockfall stations in the study area. Active faults, Kamila-Jal structural features, and seismicity are the dominant factors controlling the distribution of rockfalls from the Besham to Dasu section.

The study area boundaries fall in the upper and Lower Kohistan districts and is categorized as being in the medium-rainfall region where average annual rainfall is in the range of 600–1000 mm. Monsoon in this region usually arrives in early June, but its cycle can vary due to climate change patterns.

The stretch from Besham to Dasu is vulnerable to catastrophic flash floods every year during monsoon, and its frequency increases with the rapid weather change. Due to the lack of early warning systems, infrastructure, community training for advanced mitigation options, and financial constraints, the adaptive capacity of Pakistan to natural disasters, including flood hazards, Glacial Lake Outburst Flood (GLOF), and landslides is very limited [52]. According to the 2019 Provincial Disaster Management Authority (PDMA) of Khyber Pakhtunkhwa province, 32%, 22%, and 60% of the Upper, Lower and Pattan Kohistan areas, respectively, are at risk of flash floods. Intensive short-duration rainfall coupled with a steep slope and rugged topography initiates these flash floods as well as other mountain hazards, including rockfalls and debris slides.

3.2. Geological Settings

North Pakistan is a geologically complex area due to the active head-on collision of three blocks, i.e., the Indian plate, the KIA, and the Eurasian plate [29]. The Indian-Asia collision is the major tectonic event that has resulted in crustal shortening, the formation of major active faults, and subduction in the region [53]. The study area lies within the northwest Himalayas, where the crustal thickness increases from the south to the north due to collision [29,51]. The Kohistan and Ladakh Island Arcs in north Pakistan are sandwiched between the Indian plate and the Asian plate. The Indian plate is subducted under the Karakoram block of the Eurasian plate. This has caused crustal shortening and crustal thickening. Active ongoing deformation is manifested by the active seismicity across the northwest Himalayas, Karakoram, and Hindukush [54]. The study area is part of the KIA, traversed by the KKH with general geological units from south to north.

The major lithological units from Besham to Dasu are Besham Group, Jijal complex, Kamila amphibolites, Mansehra granite, and Chilas complex (Figure 4). Jijal complex is the southernmost stratigraphic unit, composed of ultramafic rocks with garnet granulites and Alpine type metamorphic rocks located over the Main Mantle Thrust [51]. Towards the north, the Chilas complex intrudes into the Garnet free Kamila amphibolites. It is composed of ultramafic dunite, peridotite, anorthosite, and gabbronorite [29]. To the south of suture, the Indian plate's basement comprises the Besham group, comprised of quartzite, cataclastic gneisses, and biotitic gneisses metamorphosed ~65 Million years ago during the orogeny of the Himalayas [55].

3.3. Slope Variation in Study Area

The main factors of rockfall and debris slide are the highly fractured hard rocks of steep slopes. Due to the slope factor, failures along the fractures are common in the Indus gorge and especially in the study area. Rockfalls and debris slides are accelerated by ground-shaking due to earthquakes and facilitated by heavy rains in the region. This steep slope promotes rockfall activity and is mostly concentrated along the highway from Dubair to Dasu (Figure 5a). The slope percentage of the two upper classes, i.e., 30° to 45° is 50.45% and 45° to 70° is 22.18%, which collectively makes 75% of the slope in the area, is greater than 30° (Figure 5b). Compressive stresses (thrusting) due to convergence are dominant, followed by strike slip and extensional stresses (Figure 5c).

3.4. Rockfall Inventoy

The main purpose of a landslide inventory is to assess the distribution, type, and pattern of landslides from watershed to regional scale and is counted as the first step towards susceptibility, hazard, and risk assessment [56,57]. Rockfall hazard is slightly different compared to typical large and shallow landslides and avalanches in terms of the affected area and economic losses along the transportation corridors. Through detailed

fieldwork, the current study prepared an inventory of rockfalls, toppling, and debris slides from Besham to Dasu along the Karakoram highway. The road section primarily runs along the giant Indus River and, on the other side, is bounded by sub-vertical to vertical slopes prone to rockfall and toppling. A slope map of the study area was prepared using the 12.5×12.5 m ALOS PALSAR Digital Elevation Model (DEM) (https://asf.alaska. edu/ 29 May 2019). Based on slope map and high-resolution GOOGLE Earth imagery, 30 locations were selected to collect the data. Local people were also interviewed for any historic rockfall activity and their observations regarding daily rockfall incidents.



Figure 4. Geological Road log showing the locations of rockfalls, debris slides, and topples along the highway (Modified from Geological Survey of Pakistan Road Log).



Figure 5. (a) Variation of slope in the study area. (b) More than 70% of the slope in the study area is greater than 30°. (c) Compressional stresses are dominant in the study area followed by strike-slip and normal faulting.

4. Results and Discussion

4.1. Assessment of Potential Rockfall Sites

4.1.1. Rockfall at Besham

Rockfall activity is not severe near the Besham area. Data collected from six stations along the KKH shows that elevation varies slightly from 675 m to 738 m (Table 2). The

slope is mostly gentler, around 20° to 30°, with one station where the slope gets steeper to 50°. Rock slope height changes from 5 m to 30 m between the stations. Slope height was measured from the highest point where boulders are expected to fall. (Figure 6e) The rocks are moderate to highly weathered and are highly fractured and jointed with a continuous and planar joint pattern. (Figure 6b,h) The distance between the discontinuities is from 1 cm to 70 cm. Ditch effectiveness falls in the limited to moderate category, posing a continuous threat for heavy traffic passing through this route. The maximum length and width of fallen blocks are measured as 15 m and 9 m, respectively (Table 2). Slopes are covered with vegetation at a few locations, but animal activity is almost nonexistent between these six stations at higher altitudes. Water on the slope falls into the moderately well-drained category. Shoulder width provides an emergency shelter during driving or maintenance activities and is an area for drivers to maneuver to avoid crashes. Here, inner and outer shoulder width varies from1–3 m between the stations, which is very short, bearing in mind the strong rockfall activity coupled with the steep slopes. (Figure 6g).



Figure 6. An overview of the measurement of field parameters for the RHRSP model. (**a**) A bus was damaged by a rockfall in the Kohistan district. (**b**) A planar joint surface. (**c**) Continuous water on the slope is a source of constant disruption of the road. (**d**) block size or volume per event is measured in the field. (**e**) Vertical height of the slope is measured rather than slope length. (**f**) Hanging block will directly hit the vehicle or human from a steep slope with an ineffective ditch. (**g**) Overhanging slopes and sharp horizontal curves restrict the Decision Sight Distance (DSD). (**h**) Multiple fracture sets are measured in the field. Soils are more susceptible to erosion. Wedge type is a common mode of failure.

	3 Points	9 Points	27 Points		81 Points
	Slope Angle (°)	0–15	15–30	30–45	>45
	Slope height (m)	15 to 50	50 to 100	100 to 200	>200
HAZARD Topographic factors	Joints/Fractures orientation	No adversely oriented joints	Randomly oriented joints	Adverse orientation/Less than 10 feet length	Adverse orientation/greater than 10 feet length
Geologic/Structural Factors	Joints spacing (m)	0.2 or less	0.2–0.5	0.5–1	Greater than 1
	Weathering	Fresh	Slight	Moderate	High
	Rock friction	Rough	Undulating	Planar	Clay infilling
	Suspended mass	Fine material	Fine/cobbles	Cobbles to boulders	Boulders
	Water on slope	Dry slope	Moist	Continual water on slope	Flowing water on slope
	Earthquake Intensity	5 and lower	5–6	6–7	7 and larger
Influencing factors	Animal activity	Grazing at shallow/higher altitudes with a gentle slope. Falling stones may or may not approach the road.	Grazing at permanent or random animal tracks at shallow/higher altitude with enough shoulder width to avoid stones from coming to the road	Grazing at permanent/random tracks at shallow/higher altitudes with very low shoulder width. Falling stones approach the road	Grazing at permanent/random tracks at shallow altitude with no shoulder width. Grazing very close to the road. Falling stones reach directly to the road
Rock Failure	Settlements/Population	None	At or below the highway	At lower altitude from highway and less populated	At Higher altitude and densely populated
	Rockfall History	Few Falls	Occasional Falls	Many Falls	Daily Falls
	Talus development	No fallen rock at toe	Few rock fragments or slides at toe	Scattered pile of fallen rock	Developed talus of rock/debris slide at either side of the road
	Size of fallen rocks (m ³)	<0.5	0.5–1	11.5	1.5 and more
	Landcover	Vegetation cover	Scarce vegetation	Interlayering of hard and soft rock slope	No cover/Bare Hard Rock

 Table 2. Modified Rockfall Hazard Rating System for Pakistan (RHRSP) (After [1]).

	3 Points	3 Points 9 Points 27 Points		81 Points	
	Road width (m)	13	10	7.5	3.5
	Shoulder width (m)	4	2–4	Less than 2	No width
VULNERABILITY	Percent of Decision Sight distance	Adequate, 100%	Moderate, 80%	Limited, 60%	Very Limited, 40%
Road Specifications	Average vehicle at risk (% time)	25% of time	50% of time	75% of time	100% of time
	Ditch Effectiveness	Good catchment	Moderate catchment	Limited catchment	No catchment
	Protection measures	Completely protective	Few Protective measures	No Protection	Blasting and cutting slope

4.1.2. Rockfall at Dubair

Dubair and its surrounding areas fall in the vicinity of the Main Mantle Thrust (MMT), providing a driving force for potential slope failures [58]. The severity of rockfall activity around the MMT is also mentioned by Ali, et al. [59]. Field data for five stations near Dubair show that elevation varies from 652 m to 882 m. Slope varies between 23° and 43°, and the cut slope is approximately 5 m to 41 m in height (Table 2). The road is 7 m wide, but the shoulder road is 1–3 m on either side of the road, with no protection measures for the instabilities, and therefore ditch effectiveness is assigned a none value. (Figure 6f,g). Weathering degree is low to moderate. Animal activity is common at higher altitudes, causing routine stone falling. In addition, several wedge failures, debris slides, and hanging rock blocks can be observed along the rock slope. The failed rocks are 20 m in diameter at a few places. The rocks are highly fractured and jointed with a joint spacing of 0.5 m to >1 m. It is also observed that the rock exposures have 2–3 prominent discontinuity sets. One joint set is responsible for wedge-type failure, whereas the other joint set initiates toppling failure (Figure 6h).

4.1.3. Rockfall at Jijal

The Jijal area is comprised of low to high grade metamorphic and ultramafic rocks. The entire complex exhibits acute shearing and deformation owing to its contact with the MMT in its North and Pattan fault (Figure 1) in the south. The steep topography associated with the enormous rockfalls of this section results from deep river incision of ultramafic rocks [60]. Field measurements indicate a steep slope of 40-55° and a cut slope height of 25–63 m, varying between different stations along the highway (Table 2). The Jijal section is often interrupted by disrupted slides and sudden rockfalls due to torrential rainfall and animal activity at altitude. Two active debris flow gullies in Jijal town are approaching the KKH. As per interviews with local people, the recurrence interval is one year, especially during monsoon season, and the main debris supplying source is the mining activity at the hilltop. The presence of talus/debris deposits is also observed at a few locations, with the diameter of the fallen slide being 35 m. The road width is compromising, but the inner shoulder width is usually occupied by debris at many locations. The rocks are highly weathered, jointed, and fractured due to the closeness to faults and active seismicity. The orientation of the joints is oblique to bedding, with some being parallel as well. The distance between the discontinuities is 1.5 m to 3 m, filled with clayey soils. The orientation of joint data indicates the dominance of wedge-, planer-, and topple-type slope failures. (Figure 6e–h).

4.1.4. Rockfall from Jijal to Dasu

The 55 Km long section from Jijal to Dasu mainly comprises mafic to ultramafic complexes. This section witnessed the devastating 1974 Pattan earthquake, along with the major Main Mantle Thrust (MMT), Kamila Jal shear zone, and strike-slip Kamila faults (Figure 1) [61]. The incision of River Indus has caused more than 6000 m deep gorges in the Pattan and Dasu areas, where the major hazard-triggering factors are intense rainfall, complex geology, drainage, and thrust faults [62]. Rockfalls, toppling, and debris slides are the most common mountain hazards along this section. Rockfall activity often causes damage to vehicles on the route (Figure 6a). Rockfall data was collected from 17 stations from Pattan to Dasu. The most common unstable pattern along this section is wedge sliding and toppling, observed at all of the surveyed outcrops. (Figure 6h). Material from the upslope moves downslope in the form of falling, rolling, and bouncing; therefore, the development of talus slope is not common. Instead, small debris slides are a routine geohazard in this region, caused mainly by short, intense rainfall. Field records show that failed mass can reach 150 m in diameter, occasionally blocking the KKH. Slope ranges from 45° to 75° throughout the section, and cut slope height is 20 m to 220 m (Figure 6e,f). Road width is roughly constant at 7 m, but shoulder width is not more than 1 m without protection measures (Table 2). The Rocks are jointed and fractured with abundant suspended rock

blocks. Block toppling and block sliding are common modes of failure from Jijal to Dasu. Three to four discontinuity sets were identified, depicting an acute degree of scattering due to intense shearing. The aperture of discontinuities is characterized as tight to moderate and spacing as close to wide. The filling of discontinuities varies from soft to hard material, indicating water circulation on the slope. This slope water has resulted in the moderate- to high-degree of weathering observed in the field.

4.2. Geostructural Interpretation

To assess the type of active deformation, the brittle fracture data of 30 stations were taken along the KKH from Besham to Dasu (Figure 1). In each case, a clear set of brittle conjugate fractures were chosen for the stress analysis to find out the type of stress, classified as vertical (normal), horizontal (thrust), or lateral (strike-slip). The aim is to sort out the dominance of brittle fracture types to understand the deformation under the regional tectonic and structural framework.

The data collected from the different stations can be broadly divided into two groups. One of them represents the footwall of the Main Mantle Thrust (MMT) and is located on the Indian plate, whereas the second group represents the hanging wall of the MMT and the Kohsitan–Ladakh arc (Figure 1). The first group consisted of stations 1 to 7, located on the leading edge of the Indian plate (Figures 1 and 7, stations 1–7). These stations are hosted within the core zone of Indus syntaxis, which is bounded on the eastern side by a right-lateral oblique-slip fault and on the western side by a left-lateral oblique-slip fault. The syntaxis is bounded by the Main Mantle Thrust (MMT) on the northern side. The principal stress σ^2 is steeper than σ^1 and σ^3 at stations 2 to 7, which indicates the dominance of the lateral (strike-slip) stresses due to syntaxial bend.

The second group consisted of stations 8 to 30, distributed over the Kohistan–Ladakh arc between Jijal and Dasu (Figures 1 and 7, stations 8–30). This group is further subdivided into four minor groups. These minor groups consisted of stations 8 to 13, 14 to 18, 19 to 21, and 22 to 30 due to their close proximity. Station 8 is located close to the MMT in the southern exposure of the Jijal complex, and fracture data shows northeast–southwest directed thrusting. Meanwhile, stations 9 and 10 are located in the central part of the Jijal complex, and fracture data shows northeast–southwest directed thrusting. In this group, the major fractures show a thrusting component that matched well with the regional northeast–southwest compression in this region. However, the two extensional set of fractures located in the central part could be associated with local folding that causes extension in the hinge zone.

Stations 14 to 18 are located in the southern part of the Kamila amphibolite. At station 14, the fracture data shows the change in the compression direction from the northeast–southwest to the northwest–southeast direction. Meanwhile, at stations 15 and 17, the fracture data shows the strike-slip component dominance, with the northeast–southwest-directed regional compression. However, the fracture data at station 16 shows the compressional dominance from the east-northeast–west-southwest direction. At station 18, the angle of principal stresses $\sigma 1$, $\sigma 2$, and $\sigma 3$ are 31, 35, and 39 degrees, respectively. Therefore, the stereographic projection shows a composite impact of the thrusting, extension, and strike-slip components. This variation in the stress regime from thrusting to strike-slip in this group may be due to the impact of the bending of the MMT towards the east due to a major antiformal structure named Nanga Parbat Haramosh massif.

Stations 19 to 21 are located in the central part of the Kamila amphibolite unit. The fracture data at station 19 shows the strike-slip dominance, while at station 20, the effect is composite (compression, extension, and strike-slip). At station 21, the σ 1 is steeper than σ 2 and σ 3, which shows extensional dominance.

Similarly, in the last minor group, which is located in the northern exposure of the Kamila amphibolite, the fracture data at stations 22, 24, and 28 shows north-northeast–south-southwest and northwest–southeast directed thrusting dominance, while the data at



stations 25, 26, 29, and 30 show strike-slip dominance, and the data at stations 23 and 27 shows extensional dominance (Figures 1 and 7).

Figure 7. Stereographic projection of conjugate fracture data of 30 stations from Besham to Dasu along the KKH. Strike-slip stresses are dominant from stations **2–7**. Stations **8–30** are further divided into minor groups, depicting a dominant compression followed by strike-slip and extensional stresses.

Our stress analysis based on stereographic projections shows that compressive stresses (thrusting) due to convergence are dominant, followed by strike-slip and extensional stresses. The strike-slip impact is due to the eastward syntaxial bend, termed as Nanga Parbat syntaxis, whereas the Indus syntaxis influenced stations 1 to 7, which also show dominant strike-slip stresses. Similarly, the extensional stress dominance is connected with the crustal stacking and collapse in the region, although they are determined to be low in proportion.

4.3. Rockfall Hazard Assessment

Rockfall hazard along the KKH from Besham to Dasu is shown in Figure 8. From the figure, it is evident that rockfall hazard is acute in 57% and moderate in 18%, whereas it is low to very low in only 25% of the area along the entire road section at various places. High and very high hazard zones are not a continuous path along the highway; rather, they are concentrated around various places such as Jijal, Pattan, Leo, Mandraza, and the surrounding area of Dasu. The Besham to Dubair section falls into the low to moderate hazard zone, and is associated with comparatively gentler slopes and a lower population. Rockfall hazard is high surrounding the Jijal area. From Jijal to Pattan, rockfall hazard is high to very high due to active high-frequency debris flow gullies, shallow landslides, and steep slope coupled with narrow highway and intense human and animal activity at higher altitudes due to settlements. The danger of rockfall hazard from Pattan to Dasu also fluctuates between moderate to high and very-high owing to 35° to 79° slope variation and the dominance of suspended mass, favoring toppling failure. Rockfalls and debris slides routinely occur after every rainfall in the area, with the KKH being blocked for a few hours or days. Generally, the rainfall activity is more intense from March to October. Therefore, rockfall and debris slides are expected to occur more frequently from March to October, during the rainy spells of the year, with the exception of ground shaking due to earthquakes.



Figure 8. Rockfall Hazard map along the Karakoram highway from Besham to Dasu.

4.4. Rockfall Risk Assessment

According to [63], the risk is defined in terms of the exposure of the elements at risk, their vulnerability, and most importantly, the hazard. In RHRS, which is the most well-known rock hazard evaluation method, the risk parameters are associated with traffic conditions, mainly AVR, PDSD, and ditch effectiveness, etc. Furthermore, the risk is directly linked to the exposure of vehicles on the road, which is rated through assigning scores to various parameters [27]. Risk assessment of an area assigns it a level of risk, which provides a way for planners to minimize, control, and monitor the probability of future geohazards [64]. The final rockfall risk assessment map along the highway is shown in Figure 9. The hazard and risk zones are more or less similar in pattern along the entire highway stretch. The zone falling in the very high- to high-risk category starts from the Jijal complex to Kuwde, Pattan, Leo, Kiru, and Mandraza. Starting from Besham and passing through Khenai and Dubair are the zones of moderate to low risk. About 50% of the highway stretch is occupied by very high- to high-risk zones. It is also seen that 26% of the highway is under the low hazard zone and about 35% is under the low-risk zone. (Figure 8 and 9). Based on our results, it is clear that a major part of the highway falls under the unacceptable risk category that requires urgent remedial work. According to [22], the road must be prioritized based on the risk scores, but [27] mentioned that this prioritization should vary from place to place because, in our study area, the entire section does not fall under the same risk category. The Frontier Works Organization (FWO) has managed the KKH for decades and is responsible for removing any blockage due to natural hazards and for building and repairing roads. Different risk levels demand appropriate risk control measures. For risk level I, continuous monitoring is suggested daily and demands effective engineering measures for slope stability. Daily inspection, warning boards, and speed limit boards are required for risk levels II and III. Although risk levels IV and V fall within a relatively safer zone, an inspection of the slope once a month is recommended. Despite all safety measures, it is strongly recommended that the local community should be provided with information through social media campaigns, newspapers, and personal visits to enable them to tackle the natural hazards.

4.5. A Comparative Assessment with Similar Studies

Rockfall hazard and risk assessment have remained an important topic for researchers over the last three decades. Assessing hazard and risk for rockfalls involves several methodologies, which mainly depend on the purpose and scale of the investigation. The common target areas are highways, transportation corridors, river terraces, cultural and historical sites, open-pit coal mining sites, valleys, and rock cliffs. With the change in the purpose of the investigation, the methodological framework differs significantly. Transportation corridors and highways are the most common target of rockfall hazard and risk assessment studies, which are usually performed through modified RHRS models [2,14,27,31,34,38,48,65,66]. Similarly, historical and cultural heritage sites have been investigated for hazard and risk mapping through numerical analysis, experimental work, and modified risk rating systems [21,35,37,67,68]. The physically-based computer model is applied for assessing rockfall hazard and risk in Yosemite valley, USA [33]. Most hazardous areas of rockfall in the openpit coal mines were determined through a novel Evolving Rockfall Hazard Assessment (ERHA) model by Ferrari, Giacomini, Thoeni, and Lambert [12]. Modern-day GIS and LiDAR technology has been utilized for a rockfall hazard and risk assessment study in Malaysia [69]. The current model also computes the hazard and risk along the KKH, but with a slight modification. This modification is the quantification of animal activity at slopes that trigger rockfall.

Modification of the RHRS models has remained a continuous process after the first model developed by Brawner and Wyllie [23] and the most adopted RHRS model [1]. The RHRS model by Pierson, Davis, and Van Vickle [1] assesses rockfall hazard along Oregon's roads. This model laid the foundations for modern RHRS models. The parameters used in the RHRS model refer to both hazard and risk definitions explained by Fell, et al. [70].

Later, Wyllie [71] suggested to divide the model into hazard rating and risk rating. The first attempt to modify the RHRS model was carried out by the New York department of transportation by developing the Rock Slope Rating procedure (RSRP). With minor modifications, Budetta [27] developed the mRHRS model. To address rockfall hazard in the USA and other parts of the world, various rockfall models have been developed, namely MORFH RS (Missouri), ORHRM (Ohio), TRHRS (Tennesse), CRHRS (Colarado), RHRON (Ontario), R³S² (Austria), and FRHI, RRRS (Greece) [11]. All the modified RHRS models are easy to use. Modifications are based on the requirement of each transportation board. The modification of models is actually the consideration and explanation of all the parameters in detail from the basic RHRS model. The need of modification of a model further extends to the geological, topographic, and climatic conditions of the particular area for which the model has been developed. The current RHRSP model presents a novel attempt to quantify the animal activity on slopes, which is a major source of rockfall triggering in the mountainous terrains of Pakistan. RHRSP is equally applicable to other parts of the world with the same geological and morphological conditions.



Figure 9. Rockfall Risk map along the Karakoram highway from Besham to Dasu.

5. Conclusions

The major findings of this research are as follows:

- 1. The standard RHRS system has been modified to quantify animal activity that is responsible for causing rockfall triggering in the mountainous terrain of Pakistan. The modified model will be known as the Rockfall Hazard Rating System for Pakistan (RHRSP).
- 2. The quantifying parameters of animal activity are grazing altitude, shoulder width of road, random and permanent animal tracks, and slope steepness. A minimum score will be assigned to a condition when the slope is gentle and there is a minimum chance of falling stones reaching the ground. Conversely, the highest scores will be

assigned when falling stone from steep slopes directly reach a road with no shoulder width.

- 3. From the kinematic analysis of rockfalls at 30 stations, it is observed that rockfall failures are mostly of the wedge and topple types associated with steep hard rock cliffs. Fifty-seven percent of the highway falls under very-high and high hazard zones, specifically between Jijal and Pattan villages, and 18% of the moderate hazard zone is distributed throughout the entire stretch. The low–very-low hazard zone is mainly present between Besham and Dubair, covering 25% of the entire stretch. This low–very-low hazard area is most likely due to the gentle slope, lower population, and limited animal activity at altitude.
- 4. Sixty-seven percent of the entire stretch is under moderate to high and very-high risk between Dubair and Dasu due to narrow road width, limited shoulder width, deep gorges, and insufficient protection measures.
- 5. Interpretation of conjugate fracture set data through stereographic projection shows that stations 2–7, located within the core zone of Indus syntaxis, indicate the dominance of lateral (strike-slip) stresses due to a syntaxial bend. The rest of the stations are divided into four minor groups i.e., 8–13, 14–18, 19–21, and 22–30. Stations 8, 11, 12, and 13 show northeast–southwest directed thrusting, which matches the region's regional northeast–southwest compression. Stations 9 and 10 show extensional dominance associated with local folding. From stations 14–21, strike-slip and compressional stresses are accompanied by the composite impact of thrusting, extension, and strike-slip components. Stations 22, 24, and 28 show north-northeast–southwest and northwest–southeast directed thrusting dominance. Stations 25, 26, 29, and 30 depict strike slip components, whereas stations 23 and 27 show the dominant extensional component.
- 6. This stress variation observed along the entire stretch suggests that this region has complex tectonic architecture, which caused severe deformation in the rocks in the form of fracturing and shearing, ultimately supporting the failure in the form of rockfall toppling and rockslides.

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