Rockfall Hazard in Himalayan region: Assessment and Review of Trajectory Analysis Parameters for Mitigation Strategies

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Abstract. Rockfall events are among the most common natural disasters in the Himalayan region. These high velocity and high energy events cause complete traffic interruptions, significant damages to the hilly infrastructure, and sometimes injuries and fatalities. Mitigation measures against this type of landslides require thorough rockfall trajectory analysis of the susceptible regions. However, reliability of the simulation programs modelling the rockfall trajectories depends on the correct input of rock slope characteristics, falling block characteristics, and rebound characteristics, especially coefficients of restitution.

The present study reviews the reported studies on rockfall analysis of the Himalayan region and summarises the values of the input parameters related to slope, block, and rebound characteristics, and the corresponding output parameters, especially bounce height, runout distance, and kinetic energy of the falling block. An attempt has also been made to comparatively assess these parameters for the Himalayan region with the reported values for the European Alps. The influence of these output parameters, especially the block energy and bounce height, are then discussed with respect to the suitability of different rockfall mitigation measures.

Keywords: Rockfall hazard, Trajectory Analysis, Coefficient of Restitution, Bounce Height, Kinetic Energy

1 Introduction

According to Varnes [1], the rockfall is a detached block or fragment of block that travels downward along a vertical or sub-vertical cliff by bouncing and flying along falling path or by rolling on talus or debris slopes. It is a kind of fastest type of landslide in which several or individual rock blocks are detached from the slope surface and fall downward due to the action of gravity [2]. Due to its high velocity and impact energy, Rockfall events are catastrophic and are frequently encountered in the hilly region. These disastrous events cause roadblocks, damage infrastructure, and even results in casualties.

Rockfall may happen on natural and excavated slopes and the block size may vary from small to large boulders of few meters. Rapp[3] and Whalley[4] have classified the rockfall events based on the size or volume. The size or volume of rock fragments are useful distinguishing criteria for denoting different types of fall processes and the amount of material transported. The degree of rockfall is influenced by the nature of bedrock as well as chemical and physical weathering [5]. The most crucial factors to determine whether a rock could fall are slope morphometry and the properties of the falling rock [6]. The other major reasons of slope instability are the freeze and thaw cycle [7, 8] and high intensity rainfall [9]. Detachment of rock is also caused by events like earthquakes, weathering, and root penetration. Anthropogenic activities are another cause that lead to the instability of slopes due to the unplanned excavation for buildings and roadways [10, 11]. Thus, in general, the occurrence and severity of rockfall in any location are controlled by the interaction of topological, geological, climatological, temporal, and anthropogenic factors.

The falling rock block may follows various mode of motion, like freefall, bouncing, rolling or sliding, depending on the slope gradient, as shown in Fig. 1. In free-fall motion, the movement follows the translation of the center of rock or rotation of the block about its center [12,13]. If the average gradient of slope decreases, the falling rock blocks strike with the slope surface and bounce. When the slope material consists of soil or talus than straightforward rolling or sliding of the rock mass is primarily noticed. So, the trajectories of falling rock blocks are crucial in analyzing the rockfall phenomenon and to install possible countermeasures.

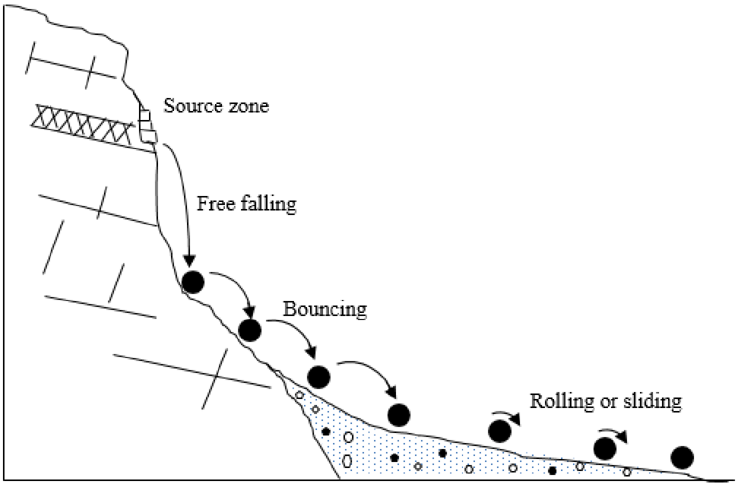


Fig. 1 Diagram showing a typical rockfall process

The Himalayan mountain belt has many unstable slopes and is seismically active due to its vulnerable geological, climatic, and geotechnical conditions [14,15]. As a result, rockfalls and other types of landslides are a common threat in this region. The slope stability assessment and rockfall studies along the Himalayan belt in India have been carried out by many researchers using different methods[16–23]. But the studies on the design of suitable mitigation measures are limited. Such mitigation measure: Rockfall protection embankment (RPE). In this paper, it is attempted to summarize the parameters of trajectory analysis and various parameters associated with rock fall such as maximum kinetic energy, velocity, bounce height, block size, etc. of different rock slopes along the Himalayan belt. From the summary of cases on trajectory analysis, adequate rockfall mitigation measure in terms of rockfall protection embankment is proposed for each of the discussed cases. The present paper also exemplifies one such mitigation measure: Rockfall Protection Embankment (RPE). The design of rockfall protection embankments (RPE) is based on the empirical approach recommended by the Highway Research Board of the Indian Road Congress [24]. These RPEs are unreinforced or geosynthetic reinforced earth structures constructed to arrest or deviate falling rocks having kinetic energy up to mega joules[25]. All these data will be helpful for researchers to not only understand the rockfall phenomenon but also in designing and implementing adequate rockfall mitigation systems along the Himalayan belt in India.

2 Methodology

First, a thorough review is done of studies conducted on 8 rock slopes of central and eastern Himalayas in India, where rock fall happened in the recent past. The values of the input parameters related to slope, block, and rebound characteristics, and the corresponding output parameters of the trajectory analysis, especially, bounce height, runout distance, and kinetic energy of the falling blocks are summarized. Additionally, an attempt has also been made to comparatively assess these parameters for the Himalayan region with the reported values for the European Alps. This summary is given in table 1. In the next phase of the study, RPEs are designed based on the required reported parameters on each rock slope, like maximum kinetic energy, transitional velocity, falling rock block size and bounce height. Other than these parameters the penetration depth at the impact position of RPEs is a reliable predictor of the embankment response and is an important parameter for the design of RPE. The values of penetration depths at the impact position on the face of the embankment are computed from the design chart proposed by the Highway Research Board of Indian Road Congress[24]. The efficiency of the embankment is then checked by the energy level criteria proposed by Lambart et al.[25]. Finally, the design RPEs are verified with minimum dimension criteria as per the recommendation of IS 14458 (Part 1): 1998[26]. The entire methodology is depicted in Fig 2.

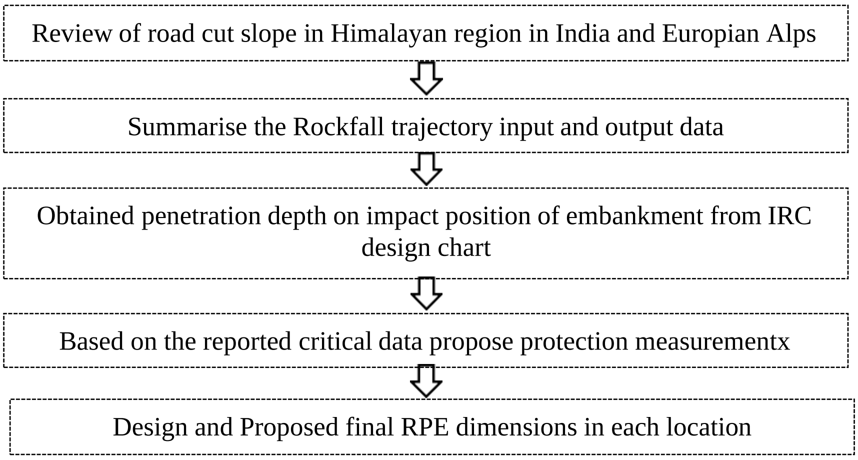


Fig. 2 Methodology of the study

3 Rockfall trajectory input and output data

3.1 Area of investigation

An extensive review is conducted to obtain the geological parameters and input and output data of trajectories of 8 rock slopes (see Fig. 3) central and eastern Himalayan regions of India. Among all the rock slopes, two are in Solang[27] and Kullu[28] districts of Himachal Pradesh. Which are popular tourist destinations in the country. The vulnerable slopes are located in the road which connects the Rotung Tunnel South Portal (RTSP) to Manali which is an important roadway as it is the only highway to reach Lahul Spiti and Leh during the winter seasons. Two rock slopes are in Nainital[29] and Saknidhar[19] districts of Uttrakhand along the NH 58 highway between Devprayag and Rishikesh. The roadway in this region allows movements of pilgrims to the significant Hindu pilgrimage circuit known as “Char Dham”. One rock slope is Theng rock slope[30] in North Sikkim Highway (NSH) which serves as a crucial link between Chunthang town to Tung and other parts of the state. Three rock slopes are along NH 44A[24, 25, 26] which connects Lengpui airport to Aizawl in the state of Mizoram.

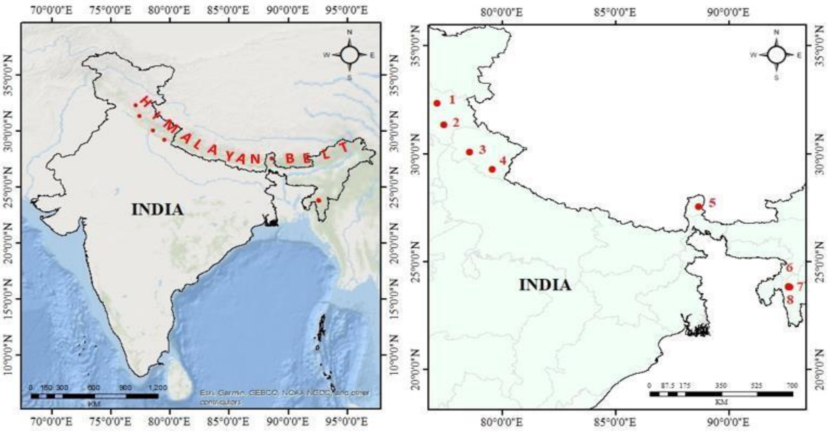


Fig. 3 Study area map of 8 locations in India along the Himalayan region

3.2 Rockfall data

Table 1 shows the summary of the input and output parameters of the reported rockfall trajectories analysis along the above mentioned study area. These values are primarily the results of mathematical models and simulations caused by various researchers. The critical parameters for rockfall simulation are slope geometry, slope roughness and coefficient of restitution (COR) as shown in Table 1. Slope geometry is required to model the slope under investigation and to represent the slope that influence the motion of the falling rock block. The rock block movement may change depending on the roughness of the slope gradient which can change the angle of impact. Frictional angle is another important parameter for the analysis. The low values of friction angle may cause the rock block to travel downward and create the worst-case situation. COR is the most important parameter in the simulation of rockfall trajectories that determines the response of the falling rock block after impact. Based on the value of COR of the material,

Table 1. Slope and trajectory input and out parameters of reported rock slope along Himalayan and Alps region

Location	ID	Authors	Rockfall site	Latitude	Longitude	Slope Materials	Normal COR (Rn)	Tangential COR (Rt)	Slope (deg.)	Density (kg/m^3)	Friction Angle (deg.)	Slope Roughness	Rock blocks no	Height of seeder (m)	Max Block Mass (kg)	Bounce Height (m)	Max. KE (kJ)	Max. translational velocity (m/s)	Max. Run out distance (m)	Max. block size (m)
Himalayan Region, India	**1**	Verma et al. [27]	Solang valley, Himachal Pradesh	N32°20'2"	E77°8'42"	Bedrock Weathered rock Concrete Asphalt	0.53±0.04 0.47±0.10 0.48±0.10 0.40±0.04	0.85±0.04 0.55±0.10 0.53±0.10 0.90±0.03	65-90	2700	28	2	8000	12.5 9.2	50 100 300 500	4.26 4.26 5.21 5.11	5.83 11.52 34.92 58.23	15 14.91 14.97 14.98	19	1.2
	2	Singh et al. [28]	Kullu , Himachal Pradesh	N31°21'30"	E77°25'30"	Rock Talus with vegetation Debris Asphalt	0.45±0.04 0.32 0.3 0.4	0.85±0.04 0.8 0.75 0.9	30-45	-	38 ± 2 35 30 30	-	50	20.83	1225	10	300	21	30	1.6
	3	Sardana et al. [29]	Nainital, Uttarakhand	N29°16'0"	E79°33'0"	Bedrock Weathered rock Asphalt	0.35±0.04 0.47±0.10 0.40±0.04	0.85±0.04 0.55±0.10 0.90±0.03	75-85	-	30	2	200	10.6	100	3.4	13.1	-	16	1.6
	4	Vishal et al. [19]	NH-58, saknidhar, Uttarakhand	N30°5'9.5"	E78°32'52"	Bedrock covered by blocks (sandstone) Weathered rock Hard paving Soil Asphalt roadway	0.35 0.47 0.4 0.39 0.4	0.85 0.55 0.9 0.57 0.9	40-70	-	30	0	100	10.02	10	1.2	379.9	7.882	9.21	1.22
	5	Mithresh and Krishna [30]	Theng rock slope, Sikkim	N27°33'27.53"	E88°39'12.45"	Bedrock Bedrock with little vegetation Boulder field with bushes Boulder field with forest	0.5 0.39±0.03 0.5±0.18 0.5±0.18	0.95 0.89±0.06 0.65±0.18 0.5±0.18	45-75	-	30	-	50	230	500	1.6	800	45	-	1.55
	6	Verma et al.[31]	Near lengpui airport, Mizoram	N23°49'09"	E92°37'32"	Bed Rock Soil Asphalt	0.45±0.04 0.3±0.1 0.4±0.04	0.85±0.04 0.8±0.1 0.9±0.04	70-80	2700	-	2	500	12.8	2000	1.17	196	13.2	18	1.52
	7	Verma et al.[32]	Near Lengpui airport, Mizoram	N23°48'27"	E92°39'40"	Bed Rock Shale [illegible]	0.45±0.04 0.47±0.04 0.4±0.04	0.85±0.04 0.85±0.04 0.9±0.04	80-90	2700	36	2	300	29.3	20000	6.9	5047	22.2	18	2.5

Location	ID	Authors	Rockfall site	Latitude	Longitude	Slope Materials	Normal COR (Rn)	Tangential COR (Rt)	Slope (deg.)	Density (k (kg/m^3)	Friction Angle (deg.)	Slope Roughness	Rock blocks no	Height of seeder (m)	Max Block Mass (kg)	Bounce Height (m)	Max. KE (kJ)	Max. translational velocity (m/s)	Max. Run out distance (m)	Max. block size (m)
Himalayan Region, India	**8**	Sardana et al. [33]	Near Lengpui airport, Mizoram	N23°50'19"	E92°37'27"	-	0.46-0.50	-	75-90	-	-	5	243	30	1000	9	240	23	-	1.7
Europian Alps	**9**	Giani et al. [34]	Apennines Parma, Italy	N43°15'02"	E12°34'51"	Debris surface	0.48	0.79	-	-	36	-	40	-	-	3.05	-	19	-	-
			Lepontine Alps (Northern Italy)	N46°24'47"	E8°41'14"	Granite quarry	0.25	0.47	-	-	25-30	-	43	-	-	-	-	19	-	-
	10	Perret et al. [35]	Near Steg, Liechtenstein	N47°07'0"	E9°34'0"	Cubical limestone block of about 3 m^3 detached from a low, forested rock cliff,	-	-	-	-	-	-	50	256	-	1.5	1146	20.1	-	-
	11	Topal et al. [36]	Afyon in Turkey	N38°45'23"	E30°31'59"	Trachitic andesite	0.47±0.05	0.79±0.05	-	-	40	2	1000	-	8000	28	9012	-	40-225	

the velocity of bouncing rock block are changes. So, COR represents an overall value that includes all the properties of impact, deformation, and sliding at impact [37]. Based on the output parameters of trajectory analysis, eg. maximum run-out distance, bounce height, total kinetic energy and mode of slope failure various mitigation strategies can be suggested.

4 Mitigation measure

Where rockfall is one of the predominant hazards the implementation of an adequate rockfall mitigation system is a crucial component of the sustainable design of the hilly infrastructure. Rockfall protection embankment (RPE) is one of the most suitable preventive measures that are usually constructed adjacent to transportation facilities in hilly areas.

4.1 RPE design steps

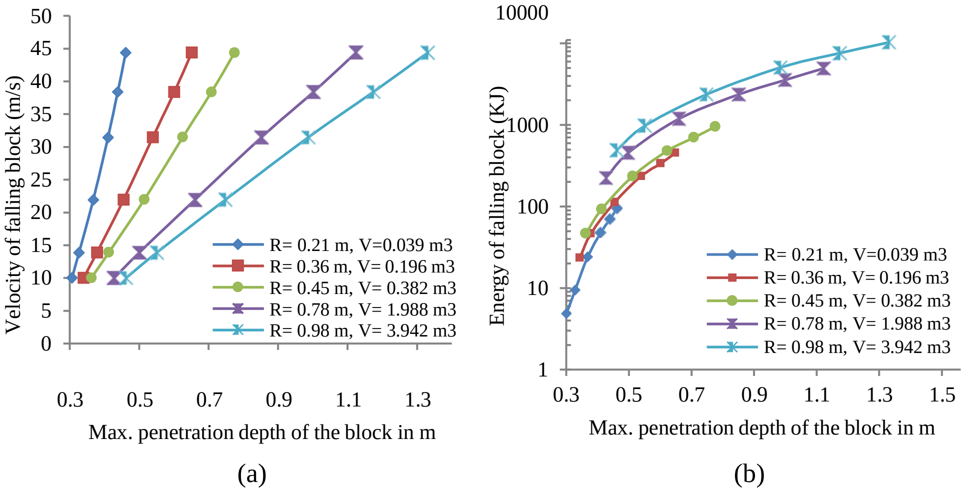
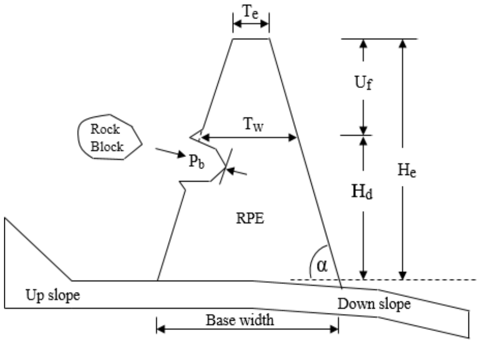


Fig.4. Maximum penetration of block in relation to (a) velocity at impact and (b) impact energy [24]

In the present study a trial is undertaken to design trapezoidal shaped RPEs to protect the transportation facilities and minimize vehicular disruption and threats to road users in the reported 8 rockfall location in the Himalayan region (see Table 1). The design of RPEs as per the recommendation of the highway research of Indian Road Congress (IRC) are followed, where penetration depth with respect to impact energy plays a vital role in design calculations. Based on the highest impacted energy of the rock block the approximate thickness of the embankment at the position where it is most likely to be impacted can be determined from the design chart of maximum penetration of block vs. velocity and energy of impact (see Fig. 4) proposed by IRC. The criterion is simple as it requires only the block kinetic energy and embankment cross-section dimension which stated 25 % threshold for downhill penetration I considered as relevant beyond which structure may no longer be stable. The schematic representation of the relevant parameters for RPE is shown in Fig. 5. The steps followed for the design of RPE are given in the flow chart, Fig. 6.



P_b = Penetration of the mass in RPE
T_e = Top width of the RPE
T_w = Min. thickness of the RPE
U_f = Upper free section of the RPE
H_e = Min. height of the RPE
H_d = Design height
α = Inclination angle of the uphill

Fig. 5. Definition of the measure of the detected parameters

For the considered rockfall site , a trapezoidal RPE of inclination angle of 70° is assumed for the design of protection measure of each rock slope. The safety coefficient depending on the reliability of the simulation and the safety coefficient for precision of the slope γ_R and γ_P are taken as 1.07 as per the conditions. The minimum top widths are also checked as per the guideline of retaining slopes in hilly areas given in, IS 14458 (Part 1) 1998. The final section of the designed RPE for each reported rock slope is given in Table 2.

Table 2. Designed dimension of RPE on reported rockfall site.

Location	**ID**	**Authors**	**Rockfall Site**	**Input Parameter**				**Designed Trapezoidal RPE dimensions**			
				Bounce Height (m)	**Max. KE (kJ)**	**Max. translational velocity (m/s)**	**Max. block size (m)**	**Min top width of RPE Te (m)**	**Min height of RPE He (m)**	**Base width of RPE (m)**	**C/S area of RPE (m^2)**
Himalayan Region, India		Verma et al.[27]	Solang, Himachal Pradesh	5.11	58.2	14.98	1.2	0.8	7	5.9	23.43
		Singh et al. [28]	Kullu, Himachal Pradesh	10	300	21	1.6	0.8	13.2	10.41	73.98
		Sardana et al. [29]	Nainital, Uttarakhand	3.4	13.1		1.6	0.8	5.4	4.73	14.93
		Vishal et al. [19]	NH-58, saknidhar, Uttarakhand	1.2	380	7.882	1.22	0.8	3	2.98	5.68
		Mithresh and Krishna [30]	Theng rock slope, Sikkim	1.6	800	45	1.55	0.8	3.4	3.27	6.93
		Verma et al. [31]	Near lengpui airport, Mizoram	1.17	196	13.2	1.52	0.8	3	2.98	5.68
	7	Verma et al. [32]	Near lengpui airport, Mizoram	6.9	5047	22.2	2.5	0.8	10.22	8.22	46.03
	8	Sardana et al. [33]	Near lengpui airport, Mizoram	9	240	23	1.7	0.8	12	9.54	62.01

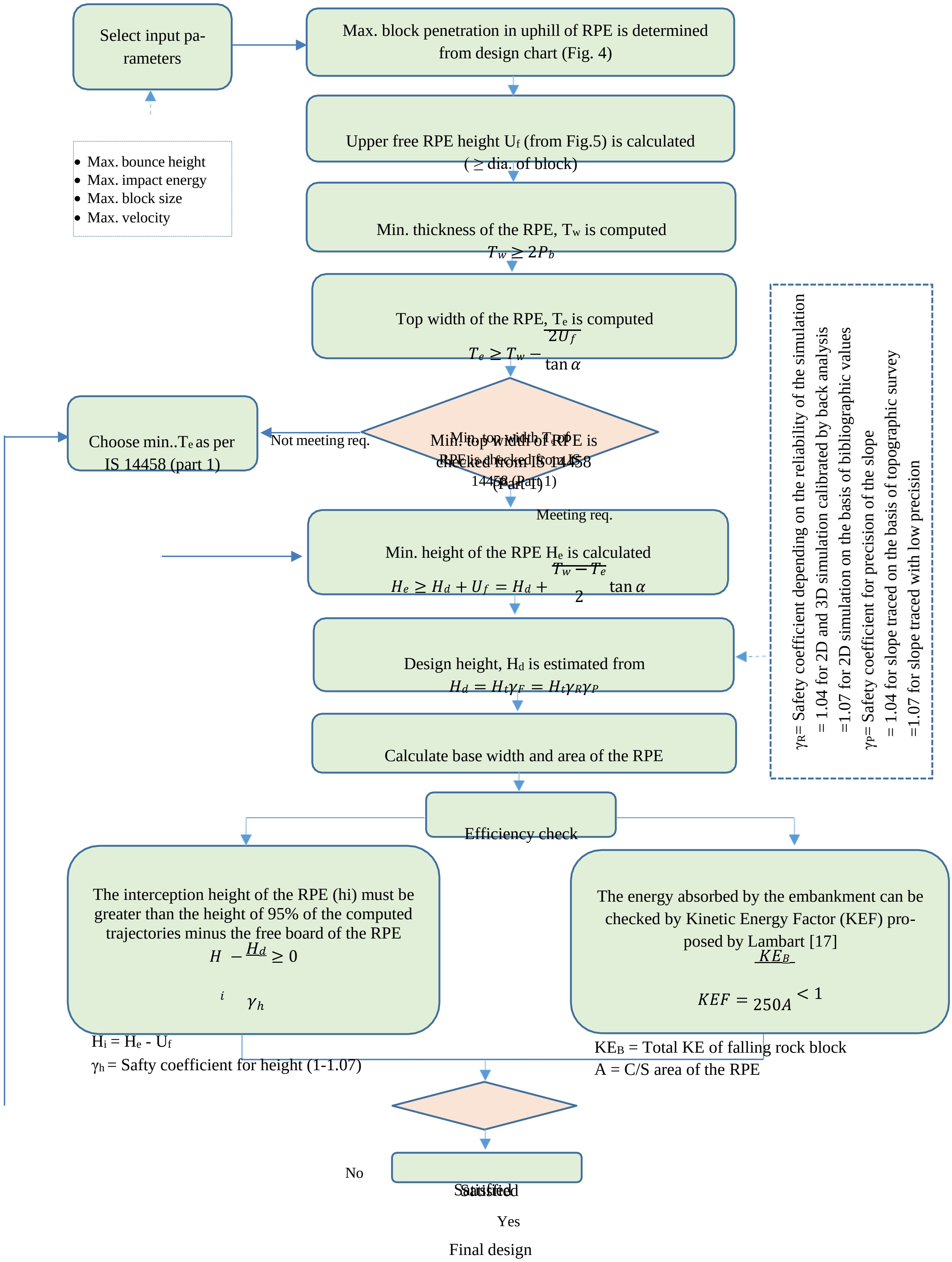

Select input parameters
- Max. bounce height
- Max. impact energy
- Max. block size
- Max. velocity
Max. block penetration in uphill of RPE is determined from design chart (Fig. 4)
Upper free RPE height U_f (from Fig.5) is calculated ($\geq$ dia. of block)
Min. thickness of the RPE, T_w is computed $T_w \geq 2P_b$
Top width of the RPE, T_e is computed $T_e \geq T_w - \frac{2U_f}{\tan\alpha}$
Min. top width of RPE is checked from IS 14458 (Part 1)
Not meeting req.
Choose min. T_e as per IS 14458 (part 1)
Meeting req.
Min. height of the RPE H_e is calculated $H_e \geq H_d + U_f = H_d + \frac{T_w - T_e}{2}\tan\alpha$
Design height, H_d is estimated from $H_d = H_t\gamma_F = H_t\gamma_R\gamma_P$
γ_R= Safety coefficient depending on the reliability of the simulation
= 1.04 for 2D and 3D simulation calibrated by back analysis
=1.07 for 2D simulation on the basis of bibliographic values
γ_P= Safety coefficient for precision of the slope
= 1.04 for slope traced on the basis of topographic survey
=1.07 for slope traced with low precision
Calculate base width and area of the RPE
Efficiency check
The interception height of the RPE (hi) must be greater than the height of 95% of the computed trajectories minus the free board of the RPE $H_i - \frac{H_d}{\gamma_h} \geq 0$
$H_i = H_e - U_f$
γ_h = Safty coefficient for height (1-1.07)
The energy absorbed by the embankment can be checked by Kinetic Energy Factor (KEF) proposed by Lambart [17] $KEF = \frac{KE_B}{250A} < 1$
KE_B = Total KE of falling rock block
A = C/S area of the RPE
Satisfied
No
Yes
Final design

Fig. 6. Flowchart of RPE design as per Highway research board, IRC[24]

5 Summary

An assessment of the governing parameters of trajectory analysis for the design of rockfall protection embankment is developed from the review of the reported rock slope. All the important parameters of trajectory analysis including input and output parame-ters of 8 rock slopes along the Himalayan belt in India and 3 rock slopes of the EuropeanAlps are summarized. These reviews will be helpful for the researchers to predict the rock slope behavior and design possible countermeasures against rockfall in the Hima-layan region of India. Based on the important output parameters of trajectory analysis obtained from the reported rock slope from the literature, a protection embankment is designed for each rock slope using the design criteria recommended by Highway Research Board, Indian Road Congress[24]. The efficiency of the design is validated using energy level criteria proposed by Lambert et al.[25] The design steps provided in this paper will be helpful for the engineers involved in projects related to hilly infrastructure.

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