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## **A new rockfall propagation model: Examining rockfall risk in Manikaran, NW Himalaya, India.**

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**SUMMARY:** In August 2015, a significant rockfall catastrophe took place in Manikaran town. This event led to the destruction of a six-story Gurudwara building, resulting in the tragic loss of around 10 lives and causing injuries to 15 individuals who were asleep in the Gurudwara's Sarai accommodations. To enhance our understanding of this incident and to anticipate potential future rockfall hazards in Manikaran, a novel model for rockfall propagation is created. The novelty of this model is to integrate the effect of pre-fragmented rock mass as a source area on the remobilization of deposited blocks, which was evidenced to be of major influence in the site of Manikaran, using a rigid body approach within the Siconos software framework. This endeavor aims to provide valuable insights into the 2015 Manikaran rockfall disaster and offer predictive capabilities for assessing future rockfall risks in the area.

**Keywords:** Rockfall modelling, SICONOS, Manikaran, NW Himalaya, Rockfall hazard assessment

### **Introduction**

Rockfall is defined as when several rock blocks are detached from the surface of the slopes and fall downwards due to gravity (Cruden and Varnes, 1996). Classical 2D lumped-mass models such as CRSP (Pfeiffer and Bowen 1989), RocFall etc. continue to be widely utilized. These models represent the moving block as a material point interacting with a 2D terrain profile. In the past two decades, more complex 3D lumped mass models have been observed. Among these are, STONE (Guzzetti et al. 2002), HY-STONE (Agliardi and Crosta 2003), Rockyfor3D (EcorisQ 2022). More recently, practical case studies have utilized the application of models that explicitly incorporate both block shape and Non-Smooth Contact Dynamics to model rockfall in 3D such as RAMMS: ROCKFALL (Christen et al. 2012; Leine et al. 2014), SICONOS (Bourrier and Acary 2021). Bourrier and Acary (2022) have developed an open source GUI platform called *Platrock* to model rockfall incorporating both block shape and Non-Smooth Contact Dynamics. The *Platrock* tool can be used by both the scientific institutes and the private companies to do rockfall assessment studies. In August 2015, a significant rockfall incident occurred in Manikaran town situated in the Kullu district of Himachal Pradesh, within the NW Himalaya region of India. This event resulted in the destruction of a six-story Gurudwara building, tragically claiming the lives of approximately 10 individuals, and causing injuries to 15 people who were asleep in the Gurudwara's Sarai accommodations. In order to complement the factual August 2015 rockfall incident in Manikaran, a novel rockfall propagation model is conceived. This research aims to develop a comprehensive understanding of rockfall hazard in the Manikaran region. The study is designed to contribute to rockfall risk assessment, specifically focusing on to integrate remobilization of static boulders and propagation of pre-fragmented rock mass in the Manikaran rockfall site using detailed field measurements.

### **Methodology**

#### ***Data acquisition***



*a. Digital Elevation Model (DEM) Generation:* Through comprehensive field investigations and a drone survey conducted in April 2023, a high-resolution (2m) DEM of the rockfall zone situated upslope of Manikaran is generated.

*b. Boulder Characterization:* During field investigations, exhaustive data regarding the dimensions, shapes, and precise locations of over 100 boulders is systematically collected. The accessible boulders within the upslope region of Manikaran are scanned using a LiDAR scan utilizing an iPhone 13 Pro, resulting in the generation of point clouds to precisely quantify their shapes.

### ***Static Boulder Integration***

The identified set of over 100 boulders are aligned in accordance with the field observations through the utilization of the Cloud Compare software. These oriented boulders are incorporated into the Siconos platform as a .csv file, assuming the role of static boulders on the surface of the terrain during rockfall propagation.

### ***Discrete Fracture Network (DFN) Generation***

Recognizing that the rockfall source area within the Manikaran region does not conform to a singular point source, the creation of a Discrete Fracture Network (DFN) for this area becomes imperative. Python and Unblocksgen (Rasmussen, 2020) tool is employed for the establishment of this DFN, facilitating the generation of a blocky rock mass. This blocky rock mass is used as the foundational source area for subsequent rockfall modeling procedures.

### ***Rockfall propagation modelling***

The propagation model was developed using the Siconos software (Acary et al. 2019). Siconos is a freely available scientific software mainly designed for the modeling and simulation of nonsmooth dynamical systems. Within this software, the propagation model enables the simulation of a three-dimensional movement of blocks represented as a convex-faceted rigid body, interacting with a terrain that is represented as a triangulated surface. The detailed mechanism of propagation of rock blocks and their interaction with terrain is given in Bourrier and Acary (2022).

A Python script dedicated to rockfall modeling, taking into account rock-rock interaction and pre-fragmentation of rock mass is developed and rigorously tested within the geographical context of Manikaran.

The process of rockfall propagation modeling within the Manikaran region involves two primary phases:

*a. Calibration of Frictional Parameters:* The calibration of the new rockfall model is achieved by utilization of blocks deposited during the August 2015 event as defining the maximum runout zone. This calibrated model is iteratively refined, fine-tuning translational and rolling friction values until the blocks deposition within the model aligns with the observed August 2015 rockfall event.

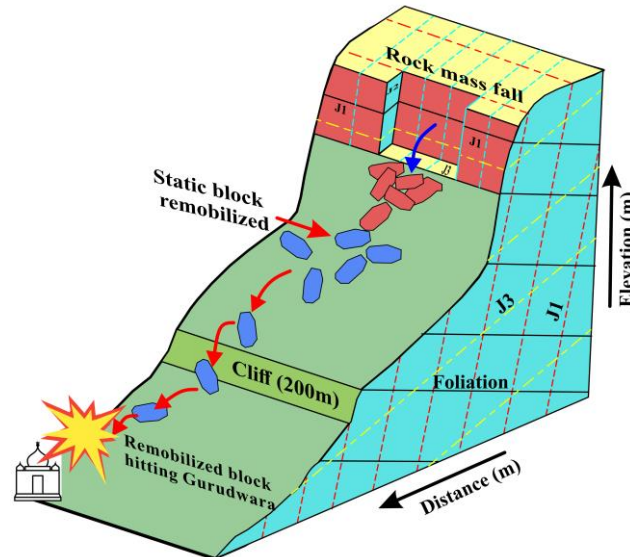
*b. Rockfall Hazard Prediction:* The prediction of rockfall hazards within Manikaran is executed by reactivating static blocks positioned on the upslope surface. Subsequently, the calibrated friction values is applied to forecast the rockfall hazard in Manikaran, taking into account the reactivation of static blocks on the upslope surface. Furthermore, kinematic parameters including kinetic energy, velocity, and jump height are computed for individual boulder trajectories. This comprehensive analysis aims to assess the collective impact of the source rock mass and the presence of static boulders on Manikaran, encompassing its residents, tourists, and critical infrastructure.

## **Results**



### ***Mechanism of Manikaran rockfall event***

A schematic diagram of the mechanism of Manikaran rockfall event during 2015 is shown in Fig. 1. During field investigation of the rockfall site and interaction with local people, we found that the rockfall event was not a single block that affected the Gurudwara building, instead, the main rockfall source blocks triggered the chain of rockfall events by remobilizing the static blocks present on the surface of the runout path of the moving blocks.



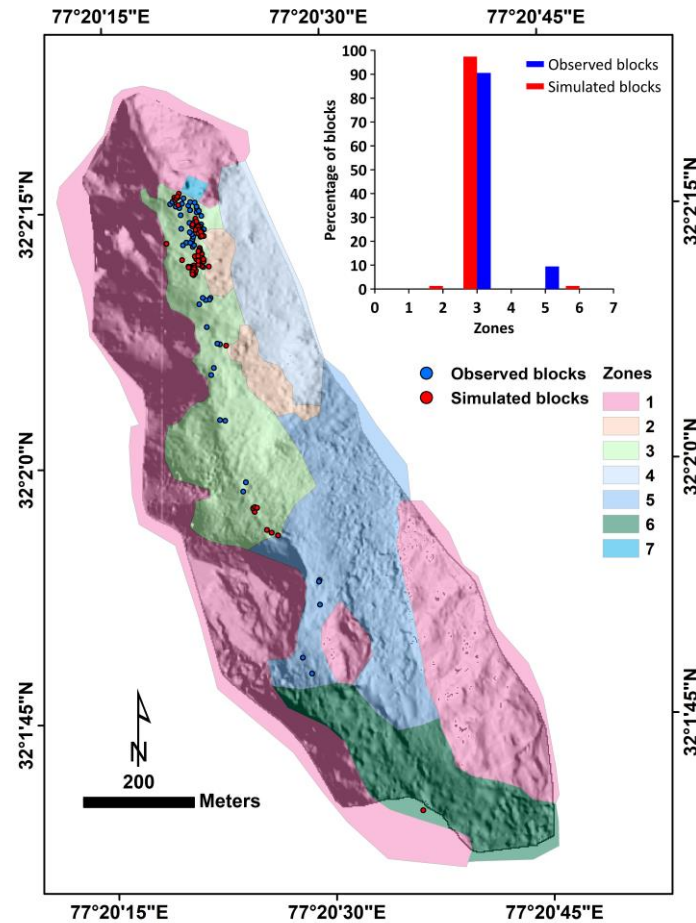
**Figure 1.** Schematic of Manikaran rockfall event in 2015 showing static block remobilization

### ***Rockfall propagation modelling***

The 3D point cloud of rockfall propagation zone was generated and cleaning of trees on the surface was done using Cloud Compare software. The cleaned 3D point cloud of rockfall zone was used for generating high resolution (2m) DEM of the area. The DFN for the source area of rockfall was generated and used as rigid blocks to interact with the static blocks lying on the terrain. The calibration of the frictional parameters (translation and rolling) for the Manikaran rockfall site is done (Fig. 2). The calibrated model will be used for the prediction of rockfall hazard in Manikaran and surrounding areas.

### **Conclusions**

The unstable rock mass and static boulders on the steep upslope of Manikaran poses a grave danger to local people, lakhs of religious people visiting ancient Ram Mandir and Gurudwara Sahib in Manikaran. Therefore, through this study, a novel rockfall propagation model considering the role of pre-fragmented rock mass as a source area on static boulders lying on the terrain is developed. The novel rockfall model enables the quantification of kinematic parameters of boulders throughout their trajectory, encompassing free flight, interactions with the ground, and the newly developed aspect of "interaction with lying boulders". This novel development is perfectly suited for the Manikaran case as per field investigations. We anticipate that the kinematic traits of boulders calculated using this innovative model will offer valuable insights for determining necessary remedial actions at any location uphill from Manikaran. For the first time, this study addresses the influence of pre-fragmented rock mass and surface static boulders in rockfall propagation models. The results of this research will contribute to the broader understanding of rockfall propagation and its implications for mitigating risk in similar geographical contexts.



**Figure 2.** Calibration of frictional parameters by comparing observed deposited blocks of 2015 rockfall event and simulated blocks.

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