

Chapter 10

Debris Flow Hazard in India: Current Status, Research Trends, and Emerging Challenges



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Abstract Debris flows are very common and frequently occurring geological processes in mountainous regions worldwide. Debris flows are less focused areas of research in India, although they are responsible for blocking the transportation corridors resulting disrupting the traffic, and blocking the rivers by forming potential landslide dams. Many times, debris flow acts as a destructive disaster costing the loss of many lives and a lot of properties every year. Debris flow hazard-vulnerability-risk assessment for its effective management is the need of this hour in the Indian context. This chapter attempts to present a detailed description of the composition, classification, causes, and characteristics of debris flow. The major triggering factors responsible for occurrences of debris flows in India and the status of debris flow research in India has also been discussed. In the last section, the challenges for debris flow research in India have been listed, and also the possible future prospects have been explored. Debris flows as a type of mass movement process needs special attention. The mitigation measures should be executed after a detailed study on the initiation mechanism, flow characteristics, depositional behavior, and overall hazard assessment.

Keywords Debris flow · Triggering factors · Hazards · Modelling · Challenges

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10.1 Introduction

Debris flows are very common and frequently occurring geological processes in mountainous regions worldwide (Hürlimann et al. 2008). The exact definition of debris flow given by Hungr et al. (2001) can be stated as “a very rapid to the extremely rapid flow of saturated non-plastic debris in a steep channel”. In the mountainous region, debris flow represents a serious hazard due to its high mobility as well as impact energy (Kaitna et al. 2007; Iverson et al. 1997). Debris volume and composition govern the mobility and impact energy of the debris flow (Jakob 2005; Iverson 1997). Debris flow comprises three distinct zones: the source zone, the transportation zone, and the deposition zone (Dash et al. 2021). The area from where the debris flow initiates or the mobilization starts is the source zone. The debris flow moves through the transportation zone and gets deposited in the deposition zone as shown in Fig. 10.1.

10.1.1 Composition

Debris flow comprises finer particles (silt and clay) and coarser particles (sand, gravels, and boulders) and moves down the slope along with water due to gravity



Fig. 10.1 Source zone, transportation zone and deposition zone of a typical debris flow **a** pre-event **b** post-event image of Pettimudi debris flow at Idukki district, Kerala State, India (Source Google Earth)

(Hutter et al. 1994). Debris can be defined as loose unsorted materials of low plasticity such as that produced by the mass wasting process (colluvium), weathering (residual soil), glacier transport (till or ice contact deposit), explosive volcanism (granular pyroclastic deposits), or unsorted anthropogenic waste such as mine spoil (Hungry et al. 2001). Debris may also contain a significant amount of organic materials, including logs, tree stumps, and organic mulch. The major component of debris flow is water which initiates and maintains the flow process.

10.1.2 Causes of Debris Flow

The morphological characteristics of the slope and the valley, the material characteristics including its grain size distribution and strength parameters play important roles in defining the flow and deposition characteristics. With the preparatory factors, debris flow needs a triggering factor to initiate. The process may start as a debris flow from the beginning, or it may start in the later stage following a landslide or flash flood. Major causes of debris flow include rainfall, cloud burst, snowmelt, glacial lake outburst, and floods. As has also been reported, forest fires and volcanic activities can initiate debris flow to some extent.

10.1.3 Classification of Debris Flow

Stini (1910) seems to be the first to focus on the specific types of landslides that are debris flows in the Austrian monograph “Die Muren”. He used terms such as debris-charged floods (Muren), debris-fronted, and surging debris flow (Murgange). The sediment-carrying floods in the mountain torrents were recognized and got attention. Earlier studies on debris flows were mentioned by Stini (1910) and Sharpe (1938). Sharpe coined important terms such as debris flow, debris avalanche, and earth flow. Sharpe (1938) described debris flow as similar to that of Stini (1910) and described it as saturated unsorted debris in a channel. Varnes (1958, 1978) retained and further expanded the framework and published it in the US Transportation Research Board report. Varnes (1978) presented a classification of landslides based on types of materials and types of movement. Types of materials involved in landslides can be classified as rock and soil. Further soils can be classified as debris and earth. Types of movement have been divided as falls, topple, slides, spreads, and flows. A flow is a spatially continuous movement in which the shear surface is short-lived, closely spaced, and usually not preserved (Cruden and Varnes 1996). Hutchinson (1968) recognized debris flows in England and classified them into channelized and hill slope debris flow. Ancey (2001) categorized debris flow under three major families based on the bulk mechanical behaviour: muddy debris flow, granular debris flow, and lahar-like debris flow. Based on the total volume of materials destabilized from the source zone, peak discharge, and area inundated, Jacob (2005)

proposed a tenfold classification according to debris flow size. Based on the material type, water content, presence of excess pore pressure or liquefaction at the source of the landslide, presence of a defined recurrent path (channel) and deposition area (fan), velocity, and peak discharge of the event, Hungr et al. (2001) categorized flow-type landslides into ten types namely non-liquefied sand flow, sand flow slide, clay flow slide, peat flow, earth flow, debris flow, mud flow, debris flood, debris avalanche, and rock avalanche. Based on the topographical and geological characteristics, debris flows can be categorized as hill slope and channelized debris flows. The debris flows moving down the valley slopes as tracks or sheets along their own paths are hillslope debris flows (Cruden and Varnes 1996), whereas channelized debris flows follow a pre-defined channel in mountain valleys (Nettleton et al. 2005). Hillslope debris flows are unconfined in nature and originate due to shallow failures at steep slopes (Hürli-mann et al. 2015). Open slope/unchannelized debris flow results due to slope failure, and channelized debris flow follows a pre-existing path due to the mobilization of materials along with or at the base of the channel.

10.1.4 Characteristics of Debris Flow

Debris flows are capable of moving to a greater distance, even over a gentle slope, and can damage infrastructures that come along their path (Cannon and Savage 1988). Mobilization of debris flow starts from static, nearly rigid masses of sediment saturated with water and flows on the channel (Iverson 1997). The debris flow initiates when the poorly sorted soil, rock or debris, and loose and unconsolidated materials get saturated with water and mobilize from hill slopes or channels (Costa 1984). The conditions or factors required for the initiation of debris flow (Calligaris and Zini 2012; Arratano and Marchi 2008) are: (i) availability of materials at the source zone (Davies 1986); (ii) steep slope; (iii) sparse vegetation; and (iv) water. The recurrence interval of debris flow depends upon the availability of loose, unconsolidated materials at the source zone, which is a function of weathering (Costa 1984). Destructive powers of debris flows are because of factors such as the capability of transporting and depositing a huge amount of debris materials, high to extremely high velocity, and steep fronts (Arattano and Marchi 2008). The amount of materials present along the channel and the channel dimension is needed to estimate the debris flow volume (Sarkar et al. 2015). The distance travelled and the area occupied by the debris material in the post-mobilization stage is called debris flow run-out. Debris flows run-out distance and areas are not only dependent on the topography and volume of the material but also affected by the debris flow composition and rheology (De Haas et al. 2015).

10.2 Debris Flows in India

According to the report of the National Disaster Management Authority, Ministry of Home Affairs, Government of India (NDMA 2019), about 0.42 million km² areas of the landmass (12.6%) are prone to landslides which spread over 65,000 mountainous villages in India. Among the various mass movement processes, debris flows are frequently occurring geological processes in India. Debris flows in India are mainly initiated by rainfall and cloud bursts, and recently debris flows in glacial regions have also been reported. Seismicity-induced debris flow events are not common in India. Areas affected by various mass movement processes in India mainly include three regions: the Indian Himalayan region, Western Ghats, and Eastern Ghats. Landslide-prone Indian Himalayas include three Northwest Himalayan States (Uttarakhand, Himachal Pradesh, and Jammu & Kashmir) and nine Northeast Himalayan States (Sikkim, Arunachal Pradesh, Assam, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, and West Bengal). Debris flows are observed in all landslide-prone regions of India. India has witnessed a number of devastating debris flow events in the past, which include debris flow events in Chamoli District of Uttarakhand (2021), Kerala (2018), Kotropi (Himachal Pradesh) debris flow (2017), Kedarnath (Uttarakhand) disaster-related debris flows (2013), debris flow in Leh Ladakh valley (2010), etc. The major triggering factor for the initiation of debris flow in India is rainfall and cloudbursts. Cloudbursts are observed in high-altitude areas and on the top of the mountain due to the formation of the low-pressure area (Ghosh and Prakash 2010). Extremely high precipitation leads to cloudbursts and flash floods, followed by debris flows (Joshi and Kumar 2006). Most parts of the Himalayas experience cloudburst during the monsoon period. Indian Himalayas and the Western Ghats are the two most crucial locations for various mass movement events such as landslides, debris flows, rockfalls, debris slides, etc. Compared to these two, the Eastern Ghats region is less prone to landslides and debris flows, but few incidences have been reported in the past rainy season. Increasing debris flow events in Indian Himalayas and the Western Ghats are reported in Indian Monsoon, particularly between June and September. It has been observed that in the Indian Himalayan region, the road has been cut across the debris flow channels and when these debris flow channels get activated during monsoon, debris materials disrupt the road network. The debris flow materials reach the river bed level and get deposited on the river course with the possibilities of river damming in two ways: (i) by following the regular pre-defined channel or path along natural drainage feeding the river, and (ii) by clearing the debris deposited at road level and pushing down to the valley side, which subsequently reaches to the river travelling along the natural drainage. The first case arises in the case of channelized debris flow, and the latter is the case of unchannelized or hill slope debris flow. Along the mountainous National Highway corridor, culverts have been provided to make a route for channelized debris flows, and minor tributaries are generally the carriers of debris materials along with channels to the major rivers. Although there are several factors that are responsible for the initiation of debris flows, some of the major causes for debris flow in India can be listed:

- Blocking of the natural channel due to the construction of buildings and other infrastructure
- Lack of maintenance of natural and man-made drainage systems
- Uneven rainfall pattern and cloud burst
- Road cuttings for widening
- Uncontrolled development in hazardous locations
- Sediments present near the channel is added to the main channel.

10.3 Triggering Factors for Debris Flow in India

10.3.1 Debris Flow Due to Rainfall

Rainfall is the major triggering factor for debris flow initiation in India. Due to rainfall, either the slopes get saturated or mobilization starts during the rainfall. Due to the water penetration, pore pressure increases by decreasing the resisting parameters, which may make the saturated slope mobilizing. If the triggering phenomenon is rainfall, the debris flow characteristics might depend on rainfall intensity, overland flow, water content, and degree of saturation of the debris material. The major hydrological factors responsible for the mobilization of debris flow are the availability of adequate water for saturation (fully or partially) and sufficient pore water pressure for the initiation of slope failure (Iverson et al. 1997). Positive pore pressures accompanied by soil saturation result in the initiation and mobilization of debris flow. Positive pore pressure development may occur in two ways: from the direct infiltration of the water on the landslide body or may be from the groundwater inflow (Iverson et al. 1997).

10.3.2 Debris Flow Due to Earthquake

Earthquakes are major devastating natural hazards that claim hundreds of lives and huge property loss in the Indian Himalayas. Some of the major earthquakes in the past include the Assam earthquake (1897), Uttarkashi earthquake (1991), Chamoli earthquake (1999), Sikkim earthquake (2011), etc. These earthquakes triggered many landslides. Most of the Indian Himalayan regions come under zone IV, and V of India's seismic hazard zonation map and are high to very highly susceptible to earthquakes. About 421 landslides were triggered by the 2011 Sikkim earthquake (Ghosh et al. 2012), whereas Martha et al. (2015a) mapped a total number of 1,196 newly triggered landslides using very high-resolution satellite data. The collision of the Indian plate with the Eurasian plate and Intraplate movements within the Indian plate are the two main causes of the earthquake in the Indian Himalayas (Singh and Som 2016). The triggering of landslides due to earthquakes depends upon the distance of the landslide zone/area from the epicenter and the fault rupture, magnitude of the

earthquake, and the maximum shaking intensity (Keefer 1984). Landslides due to earthquakes are of two types such as co-seismic and post-seismic landslides (Parkash 2013). A co-seismic landslide takes place during the earthquake event. Post-seismic landslides generally occur after the earthquake due to the fissures, cracks, and deformations that originally developed due to the earthquake itself. Barnard et al. (2001) conducted mapping of 338 landslides, including 56 earthquake-induced landslides in Garhwal Himalayas after the 1999 Chamoli earthquake. Barnard et al. (2001) found that no debris flow occurred due to the earthquake but reported 33 debris flows mainly due to human activity. Earthquakes are not only responsible for the triggering of fresh landslides but also the reactivation of already existing landslides. In comparison to rainfall-induced debris flows, seismic/earthquake-induced debris flows are less common in Indian Himalayas. When the triggering phenomenon is an earthquake, factors such as the peak ground acceleration (PGA) and the tendency of the soil to liquefy are important.

10.3.3 Debris Flow Due to Landslides

It has been observed in Indian Himalayas that the initiation of debris flow takes place in two ways. In the first case, the materials available along the natural drainage or debris flow channel get saturated by rainfall or cloud bursts and propagate. In the second case, a landslide occurs at the top of the debris flow channel, which acts as a debris flow source zone, and the flow process gets initiated. Iverson et al. (1997) mentioned that mobilization of debris flow from landslide involves three processes: (i) widespread Coulomb failure within a sloping soil, rock, or sediment mass, (ii) partial or complete liquefaction of the mass by high pore-fluid pressure, and (iii) conversion of landslide translational energy to internal vibrational energy.

10.3.4 Debris Flow in the Glacial Region

A massive debris flow occurred on 16 July 2017 near the terminal moraine of the Meru glacier in the Bhagirathi basin of the Garhwal Himalayas (India). A huge amount of loose and unconsolidated debris materials mobilized and blocked the river Bhagirathi by forming a temporary lake (Singh et al. 2018). The major cause of this debris flow was high-intensity rainfall and moraine-dammed Lake Outburst. Due to rapid climate change in the Himalayan region, glaciers are retreating, which leads to debris flow occurrences in glaciated regions (Kumar et al. 2019). Due to the deposition of debris materials in the river valley, there is a shifting of approximately 150 m (Kumar et al. 2019) of the river Bhagirathi from west to east (Singh et al. 2018).

10.4 A Few Recent Debris Flow Events in India

India has witnessed many devastating debris flow events in the recent past. These include the debris flow event in Leh Ladakh (2010), the Kedarnath tragedy (2013), the Kerala flash flood and debris flow (2018), the Kotropi debris flow (2017), etc. Apart from these, numerous debris flows occur in the Indian Himalayan region, which has not been mentioned or studied. In monsoon seasons, these debris flows are the major devastating processes in the Indian Himalayan region and Western Ghats as well.

10.4.1 *Kotropi Debris Flow (2017)*

The Kotropi debris flow (Fig. 10.2) event occurred on 13 August 2017 in the Kotropi village of Mandi District in the State of Himachal Pradesh along National Highway 154. More than 46 people died because of this debris flow, and ten went missing (Pradhan et al. 2019). This debris flow was so devastating that two State transport buses of Himachal Pradesh were swept away down 800 m from the road, and about 300 m length of the National Highway was completely buried by debris materials (Sharma et al. 2019). The runout length of this debris flow was 1155 m with a width of 190 m and an area of 133,674 m² (Saini and Gangwar 2018). Kotropi debris flow was reactivated for the third time with a return period of 20 years in the years 1977, 1997, and 2017 (Pradhan et al. 2019). The main triggering factor for this debris flow was high-intensity rainfall.

10.4.2 *Debris Flow Events During Kedarnath Disaster (2013)*

The Kedarnath disaster occurred during 16–17 June 2013, when a 600 km long Central segment of Himalayas received extreme rainfall. Due to heavy rainfall, a large number of mass movements took place across the state of Uttarakhand, and the Kedarnath village was destroyed by two large debris flows that took place on 16/17 June 2013 (Allen et al. 2016). Detailed information on the causes and consequences of the 2013 Kedarnath disaster can be found in published literature (Sati and Gahalaut 2013; Das et al. 2015; Martha et al. 2015b; Allen et al. 2016; Chatteraj and Ray 2015; Ray et al. 2016; Rautela 2018). The debris flows completely destroyed the north-western part of the Kedarnath village (Das et al. 2015). Five districts of the Uttarakhand State, namely Rudraprayag, Chamoli, Uttarkashi, Pithoragarh, and Bagheswar, were severely affected (Khanduri 2018) and received very heavy precipitation during this event (Ray et al. 2016). Martha et al. (2015b) identified a total number of 6,013 landslides across the entire Bhagirathi and Alaknanda catchment, out of which a total of 3,472 were triggered due to the June 2013 event. The Kedarnath disaster of 2013 was the worst ever disaster in the history of Uttarakhand State.

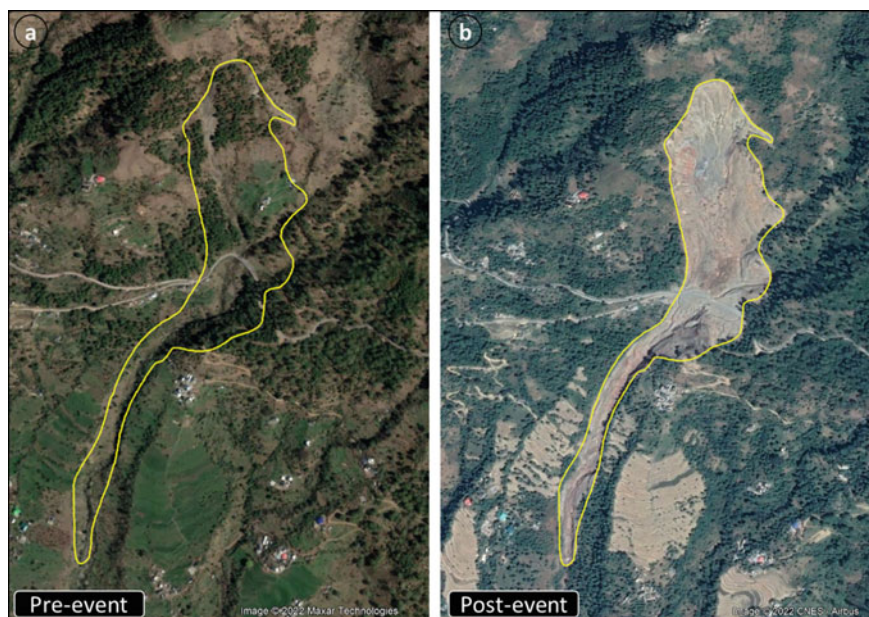


Fig. 10.2 Kotropi debris flow in Himachal Pradesh, Indian Himalayas (Source Google Earth)

10.4.3 Debris Flow Events in Kerala (2018)

Due to extremely high rainfall from 1 June to 26 August 2018 in two spells, the State of Kerala witnessed devastating mass movements and flooding (Kanungo et al. 2020). According to the report of the State Government, about 5.4 million people were affected, and 433 persons lost their lives. Due to this event, about 1200 villages in all 14 districts were affected, and 942 buildings were damaged (Hao et al. 2020). Hao et al. (2020) prepared a complete landslide inventory after the 2018 monsoon event in Kerala. A total of 4,728 landslides were identified, out of which debris flows (2,816 in number) were the most common phenomena initiated during this event. The Idukki was the worst affected district of Kerala, having 47.02% of total landslides in Kerala, and debris flows in Idukki District were 679 in number.

10.4.4 Leh Ladakh Debris Flow Event (2010)

Debris flow at Leh valley occurred on 6 August 2010, had a disastrous effect on the valley area. The main triggering factor for this debris flow was a cloud burst (Juyal 2010; Ghosh and Prakash 2010). Due to this disastrous debris flow, 234 lives were lost, more than 800 went missing, and more than 1,000 houses were completely or partially destroyed (Gupta et al. 2012). 24 villages of the Leh region were severely

affected, and heavy destruction to the National highways, hospitals, airports, bus terminals, radio stations, mobile towers, and private properties were observed (Ghosh and Prakash 2010).

10.5 Debris Flow Studies in India

In the Indian subcontinent, debris flows generally occur due to rainfall. Cloud burst-induced debris flows occur almost every year in the Indian Himalayan region. In comparison to landslide hazard/susceptibility studies or slope stability assessment studies, very few studies have been conducted specifically on debris flow. Sati (2007) studied the economic and environmental assessment of two debris flow zones in the Garhwal Himalayas. Sujatha and Sridhar (2017) prepared a debris flow susceptibility map of the Palar sub-watershed in the Western Ghats of Tamil Nadu State using an analytical network process (ANP). Chatteraj et al. (2018) carried out 3-dimensional debris flow modelling of the 2014 debris flow event that occurred in Malin Village of Maharashtra State, a part of Western Ghat. The study used a continuum model-based simulation using RAMMS (Rapid mass movement software) for quantification of the debris flow intensity parameters such as the flow height, debris flow velocity, pressure along the path and momentum. Chatteraj et al. (2019) conducted a simulation of four debris flow sites in parts of the Garhwal Himalayas. Kumar et al. (2019) studied the mechanism and evolution of debris flow that occurred in the Gangotri glacier region using pre-and post-event observation, hydro-meteorological data and remote sensing analysis. Negi et al. (2020) carried out debris flow susceptibility assessment of the Ladakh–Nubra region using a GIS-based multi-criteria evaluation method by combining hydrological, topographical and environmental parameters for rainfall-induced debris flow. Chatteraj and Ray (2015) performed debris flow modelling of the 2013 Kedarnath area of Uttarakhand. Sujatha (2020) presented an approach for debris flow susceptibility assessment along the 8 km long Kodaikanal–Palani road corridor (Tamil Nadu State) using an analytical network process (ANP). Runout modelling and calibration of frictional parameters, including geotechnical investigation of Kurichermala debris flow in the Wynad district of Kerala (Western Ghats), was presented by Abraham et al. (2021). Jain et al. (2021) carried out inventory mapping, rainfall data analysis, and debris flow modelling of 6 large debris flows in the Idukki, Malappuram, and Wayanad districts of Kerala (Western Ghat) that occurred during 2018–2020. The debris flow modelling of the 2014 event at Malin (Maharashtra) was performed by Sajwan and Sengupta (2021) using the particle flow code (PFC2D) model. Bera et al. (2021) presented a debris flow susceptibility map of the Kalimpong region in Indian Himalayas by integrating the debris flow initiation and runout areas. Dash et al. (2021) conducted runout modelling, and hazard assessment of active debris flow in the Indian Himalayas (Tangni debris flow) using a continuum theory base model. Dash et al. (2022) generated the debris flow susceptibility zonation map of an approximate 1,200 sq. km area in the Chamoli district of Garhwal Himalaya, India, using statistical models.

Apart from these, several studies on the reporting of debris flow events, mechanism, causes and consequences, and detailed investigation of debris flows have been published by several authors, such as the 2013 Kedarnath disaster and debris flow events (Allen et al. 2016; Ray et al. 2016; Martha et al. 2015b), 2018 Kerala disaster and debris flows (Saini and Gangwar 2018; Vishnu et al. 2018), Kotropi debris flow (Sharma et al. 2019; Martha et al. 2019; Pradhan et al. 2019).

10.6 Scopes and Challenges for Debris Flow Modelling in India

10.6.1 Challenges

Debris flow modelling can be performed using two approaches. In the first approach, back analysis of a well-documented debris flow event is carried out to obtain the flow intensity parameters in which the calibrated values of input parameters can be used to predict the flow intensity parameters of the future potential debris flow. In the second approach, the data that is collected from the field is used and processed suitably for early warning. Both of these approaches are used for the future prediction of debris flow. But for the first approach, well-documented historical data on past debris flow is required, while in the second approach, data from field-based monitoring systems are necessary. The two major challenges for debris flow modelling in India are the lack of historical data on past debris flow events and the absence of field-based monitoring system.

10.6.1.1 Non-availability of Complete Quantitative Historical Data on the Debris Flow Events

Historical data on debris flow events are required for the calibration as well as validation of the numerical or physical models. This needs precise quantitative field data along with the debris flow inventory of those areas to establish the relationship. But lack of data on past events restricts the researchers to go for an alternative approach that can be performed without any past data or limited data. Debris flow susceptibility mapping can be carried out by locating debris flows and integrating them with thematic data layers, which are able to describe the spatial distribution of debris flows. But for debris flow hazard and risk assessment, flow intensity parameters need to be included, and the frequency-magnitude relation plays an important role. Direct measurement of debris flow is quite difficult, and very few researchers have captured it (Berti et al. 1999; Turnbull et al. 2015). Such quantitative data on debris flow are used to calibrate, validate, and predict theoretical and laboratory scale results (McCoy et al. 2010).

10.6.1.2 Absence of Permanent Debris Flow Monitoring System

Direct observation of debris flow is difficult due to (i) remote and inaccessible terrain, (ii) sporadic nature of occurrence (McCoy et al. 2010), and (iii) variation of hydro-metrological events such as rainfall. Direct observation of debris flow initiation, propagation, and flow behavior is difficult because of its sudden occurrence & transient character (Sosio et al. 2007), and it takes very less time (Chen and Lee 2007). So, the data collected from field-based monitoring systems are used for calibration and validation and for understanding the debris flow process. But the case is more complex when there is no field-based monitoring system and direct observation of the event. Landslide, early warning system has been installed in very few places on the Indian subcontinent for real-time monitoring of vulnerable slopes, such as at Tangni landslide of Uttarakhand (Chaturvedi et al. 2014), Pakhi landslide of Uttarakhand (Kanungo 2019), Kotropi landslide of Himachal Pradesh (Thakur et al. 2021), Idukki district of Kerala (Ramesh 2009; Ramesh and Vasudevan 2012). But presently, no in-situ debris flow monitoring system is available in India.

10.6.2 Scopes

Debris flow modelling for related hazard and risk assessment, as well as for management and mitigation, is a multi-disciplinary approach. There are a number of aspects of debris flow on which research has been done and also is going on, such as debris flow hazard/susceptibility assessment, rheological modelling, runout modelling, initiation mechanism, depositional mechanism etc. The present paper deals with the scope of the modelling approach of debris flow runout for delineation of inundation areas keeping in view the lack of historical data and permanent monitoring system and by using an indirect method of debris flow modelling with limited data.

10.6.2.1 Development of a Suitable Framework for Debris Flow Modelling with Limited Data and Considering the Present Status of the Debris Flow

Debris flow modelling can be carried out empirically or numerically. Empirical approaches are not suitable in the case of a lack of data. Numerical simulation-based approaches need some field data for validation purposes. So for the Indian scenario, it is essential to formulate a suitable framework, which can be performed with limited data collected from the field in a post-event stage. Indirect methods can be adopted to reconstruct past events. Opinions from local people, as well as the expert working on the same area and familiar with the debris flow, should be considered as key evidence for this. Extensive fieldwork, satellite data, remote sensing-based assessment, and qualitative hazard analysis on the basis of past observation play important roles in such an approach. When there is a complete absence of historical data, laboratory

scale investigation and numerical validation can be a predictive alternative; but the validation of any output with field evidence is considered more accurate.

10.6.2.2 Site-Specific Debris Flow Modelling Through Simulation and Hazard/Risk Assessment with Potential Release Areas

The approaches for runout estimation can be categorized into three major groups such as empirical, analytical, and numerical approaches (Dai et al. 2002). Empirical approaches can be well utilized for the estimation of debris flow runout in a study area with precise and complete historical data on debris flow events. This approach is simple and easy to use. Analytical methods (Sassa 1989; Hutchinson 1986) for estimating debris flow runout are based on lumped mass models, where the entire mass of the debris is considered as a single point (Dai et al. 2002).

Numerical models can be categorized into two broad categories: continuum-based model and discrete element or discontinuum model. A numerical model based on continuum mechanics needs a suitable rheological model. The relevant rheological parameters must be found in the field by back analysis or laboratory analysis (Dai et al. 2002; Chen and Lee 2004). The numerical modelling of a debris flow from the Indian Himalayas has been shown in Fig. 10.3. For the assessment of debris flow hazard, two aspects have to be set out: (i) debris flow occurrence and (ii) characteristics of the debris flow (Rickenmann 2005). The probability of debris flow occurrences can be determined from debris flow hazard/susceptibility studies, which will describe the spatial distribution of debris flow in an area. Frequency-magnitude relation is used to determine the probability of debris flow occurrences. This is based on the historical data of past events. In the second stage, the characteristics of a debris flow can be quantified by modelling, which describes the (i) initiation process, (ii) propagation in the channel, including entrainment, and (iii) depositional process.

Hürlimann et al. (2008) evaluated different techniques and approaches that are used to calculate debris flow parameters for hazard assessment by performing the back analysis of well-documented debris flow events. Their specific major findings stated that (i) the empirical model is suitable for a particular study area or condition, where it has been developed or on which it is based; (ii) for hazard mapping, calibration of rheological parameters for past events is the preliminary work; and (iii) numerical modelling is capable of giving the exact values, while analytical methods may be useful for preliminary flow behavior. Pirulli (2010) carried out the forward analysis of a potential debris flow event of 10,000 m³ of volume by using the rheological outputs obtained from the back analysis of a 2005 debris flow event that took place in the same basin. Forward analysis of the events with the calibrated values for hazard assessment is a useful tool (Pirulli 2010). To adapt the calibration-based approach, the events that are being considered should have similar lithological or material, morphological, and rheological behavior.

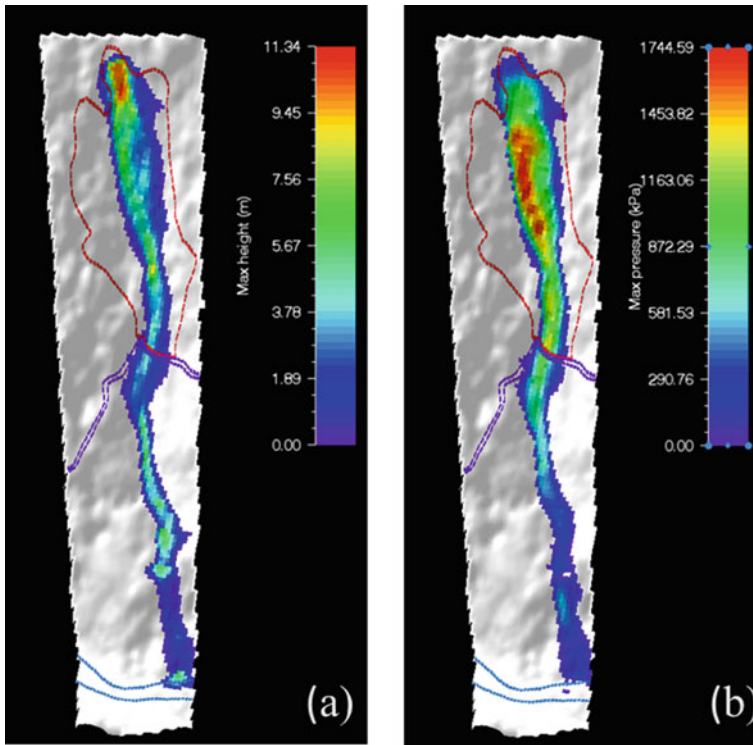


Fig. 10.3 Example of numerical modelling of debris flow runout **a** simulated height **b** simulated pressure

10.6.2.3 Experimental Study on Debris Flow

The entire process of a debris flow can be defined mainly in three stages: failure, propagation, and deposition. The core objectives of debris flow studies focus on understanding the mechanism of each of these stages (Hutter et al. 1994). Debris flows can be studied both in the field as well as in the laboratory. Although the data from the real field are more accurate and precise, it is practically difficult to obtain the data during the debris flow to get quantitative information on the flow intensity parameters such as velocity, flow, deposition height, momentum, and impact energy. Still, there are cases of some direct observations of debris flows in the real field. Due to these difficulties of directly observing natural debris flows and the uncertainties involved in the interpretation of field deposits, the analysis of debris flow has been augmented by experimental studies. So, the common alternatives to this direct observation of debris flow events are reproducing it under controlled conditions at a reduced scale in the laboratory and analyzing it on the basis of accepted theory (Davies 1990).

Experimental studies on debris flows are conducted using a physical scale model established in the laboratory scale. Physical scale modelling of debris flow refers

to the replication of debris flow in the laboratory on a scale-down model, which represents the real field situation and essentially includes all the conditions that exist in the field. There are several ways by which experimental study in the field and in the laboratory can be performed apart from direct observation during the debris flow event (Iverson 2015). One such type includes the installation of sensors in the natural hillslope and watering it artificially to create the rainfall scenario until failure occurs (Ochiai et al. 2004, 2007). Some experimental studies are based on the discharge of debris (mixtures of water and sediment) onto the well-instrumented natural slope or debris flow channel under a controlled environment (Bugnion et al. 2012). Bugnion et al. (2012) conducted a real-scale field experiment to investigate the hillslope debris flow impact pressures by constructing a 41 m long, 8 m wide channel in Canton Aargau, Switzerland. The same study can be conducted in the laboratory for the failure mechanism of landslides and for the investigation of the initiation, propagation and deposition mechanism of debris flow.

A debris flow flume model is designed and fabricated in the laboratory of CSIR-Central Building Research Institute, Roorkee, for experimental study on debris flow (Fig. 10.4).

The experimental setup is 6.5 m in length, out of which 1.5 m from the top of the channel section has been utilized as a storage tank to contain the debris flow materials (Fig. 10.4). This storage tank is considered as the source zone of a typical debris flow. The width and height of the flume model are 0.5 m and 1 m, respectively. Lengthwise the whole channel section consists of 3 segments of 1.5 m, 1.5 m, and 2 m in length from top to bottom. These channel sections are interconnected and can



Fig. 10.4 Debris flow experimental facility developed at CSIR-CBRI, Roorkee



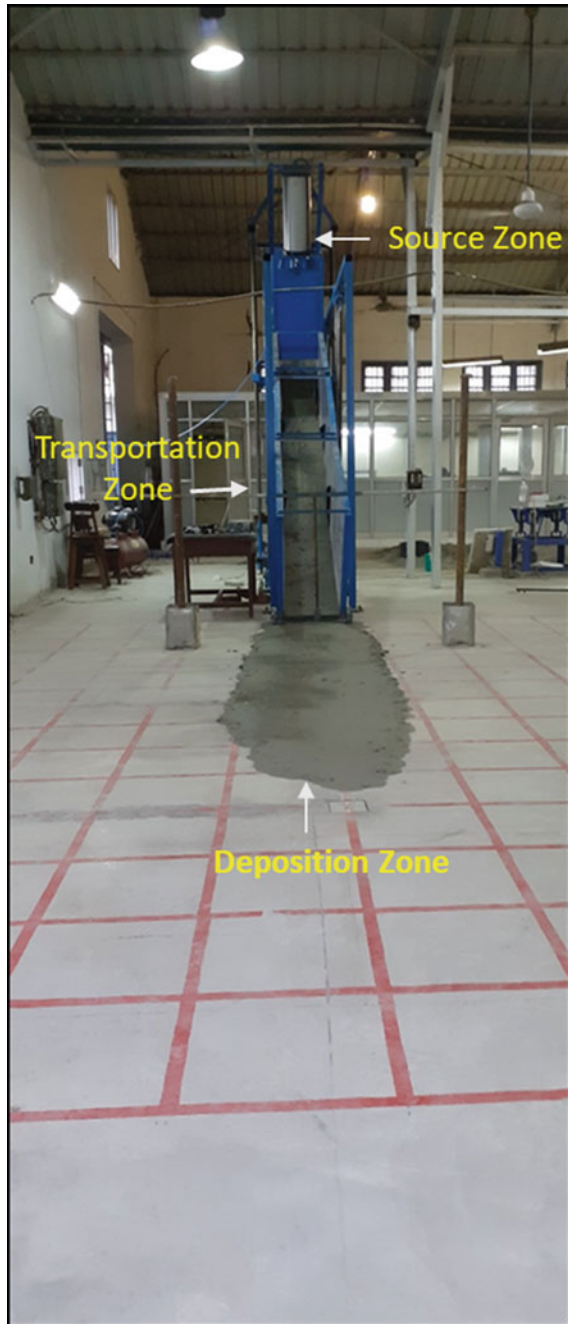
Fig. 10.5 Sensors installed on the flow path and the deposition zone **a** laser sensor for measuring flow height **b** pore water pressure sensor **c** the rough surface of the flow path

be tilted to desired angles. The sidewalls of the channel are made up of transparent plexiglass. The base of the channel is made up of an aluminum plate and is rough. The channel section acts as a flow path or transportation zone for the debris flow. The deposition zone for the debris flow material is made horizontal (i.e., flat) with a concrete floor. The storage tank is closed with a provision of an openable gate. Sensors are installed to capture quantitative data on flow intensity parameters. The sensors installed and the base of the flow channel has been shown in Figs. 10.5 and 10.6 shows the runout and deposition of an experimental debris flow conducted at CSIR-CBRI, Roorkee.

10.7 Conclusions

Debris flows are the most destructive geological processes in mountainous terrains. Indian Himalayan region and the Western Ghats, are frequently affected by debris flow processes, which destroy engineering projects and infrastructures as well as huge socio-economic and environmental degradation parallel with loss of lives. For planning and execution of debris flow mitigation measures, debris flow modelling studies should be conducted in order to assess the hazard and risk related to future debris flows in the area under study. The major triggering factor for the initiation and propagation of debris flows in the Indian Himalayan region and in other regions is rainfall. India has witnessed numerous disastrous earthquakes in the past, which have initiated or developed numerous numbers of landslides. But it has not yet been reported in the case of debris flow. In developed countries like Italy, Switzerland, and China, debris flow studies are carried out using past debris flow records and validated with the past documented field parameters. In India, due to the absence of well documented historical data on debris flow events, approaches based on the field observations of recent debris flow events with little past information should be developed. Numerical simulation approaches can be suitable for debris flow modeling and subsequent debris flow hazard and risk assessment in India. One of the major concerns regarding landslide hazard/susceptibility mapping in India is that such a map needs to describe different mass movement processes such as debris flow, rock

Fig. 10.6 Experimental reconstruction of debris flow and depositional morphology depicting the zones of debris flow



fall etc. In debris flow hazard/susceptibility assessment studies, debris flow runout analysis should be incorporated using a suitable approach depending on the data availability and expert knowledge. In case of the absence of historical data, it is difficult to establish the frequency-magnitude relation of debris flow which is used to find out the probability of occurrences of the event with a predicted interval. In such cases, indirect methods can be adopted.

Acknowledgements The authors are grateful to Director, CSIR-Central Building Research Institute, Roorkee, Uttarakhand (India) for granting permission to publish this paper.

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