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Numerical Modelling of Debris Flows for Simulation-Based Decision Support: An Indian Perspective

Minu Treesa Abraham[1,2] · **Neelima Satyam[3]** ·
Julia Kowalski[1]

Abstract Debris flows are catastrophic landslides owing to their very high velocities and impact. The number of such flows is likely to increase due to an increase of extreme weather events in a changing climate. At the same time, risk reduction and mitigation plans call for a quantitative assessment of the hazard. Numerical models are powerful tools in quantifying debris flows in terms of flow height and velocity with respect to both space and time, and to derive mitigation-relevant diagnostics such as impacted area. However, the current modelling practices possess critical challenges that limit their application in a forward-directed analysis to predict the debris flow's impact. This work provides an overview of the past and current practices in debris flow modelling, their potential use in simulation-based decision support and the challenges and future research scope in computational debris flow modelling, based on the recent literature.

Keywords Debris flows · Numerical models · Landslides · Risk reduction · Model-based decision support

✉ Minu Treesa Abraham
abraham@mbd.rwth-aachen.de;
minu.treesa.abraham@ngi.no

Neelima Satyam
neelima.satyam@iiti.ac.in

Julia Kowalski
kowalski@mbd.rwth-aachen.de

[1] Methods for Model-Based Development in Computational Engineering, RWTH Aachen University, Aachen, Germany

[2] Instrumentation and Monitoring Section, Norwegian Geotechnical Institute, Oslo, Norway

[3] Department of Civil Engineering, Indian Institute of Technology Indore, Indore, Madhya Pradesh, India

Introduction

Debris flows are flow-like landslides with severe aftereffects. They are natural geomorphological processes; however, their interaction with the human environment can result in loss of lives, properties and socio-economic setbacks. From 1950 to 2011, 239 debris flow events have occurred worldwide, resulting in 77,779 fatalities [1]. The global rise in population as well as a continued urbanisation in landslide-prone areas has also increased the human exposure to such hazards, thereby increasing the risk involved [2]. A call for model-based debris flow impact assessment capability naturally arises from this development; however, debris flows are extremely complex multi-physics processes, and therefore hard to predict. As per Varnes classification [3], a debris flow is defined as moving mass of loose soil particles ranging from clays to rocks with high water content, driven by gravity. Further, the definition was modified to surging flow of saturated debris with very rapid to extremely rapid speed in a steep channel, which entrains material from the flow path [4], where debris is defined as mixture of materials, with higher percentage of coarse particles. The two predominant triggering process are classified into failure or landslide triggered, and runoff triggered. Failure-triggered debris flows occur as the result of a minor failure at the crown, which moves downslope, entraining bed material. Runoff triggered debris flows occur when loose debris deposits, which are remains of past landslides or earthquakes, are mobilised due to heavy rainfall or snow melt. This work focuses on failure triggered debris flows, which are triggered by a landslide at the crown.

The mechanism of failure triggered debris flows are often complex, and can be furthermore divided into pre-failure, failure, post-failure and propagation stages. In the **pre-failure** stage, hill slope undergoes minor deformations. Such

deformations can be monitored using precise instrumentation [5], observing the changes in pore water and displacements. A localised **failure** occurs eventually, and the soil fails along a critical shear surface [6]. Large displacements happen during this stage, and the behaviour post-failure discriminates between different types of phenomena [7]. The **post-failure** stage is characterised by large plastic strains and the acceleration of failed mass. When there is no abrupt increase in acceleration, as when the ratio between driving and resisting forces are moderate, the phenomenon can be termed a slide. For the slide to turn into a flow, the change in stress state should happen within a very short time, and the slope is no longer stable. The propagation stage will be different for both slides and flows. The propagation continues till a new equilibrium state is reached. In the case of slides, the displacements are usually small, and the failed mass gets deposited close to the source. In the case of flows, the failed mass can travel very long distances from the source. It can also entrain material along the path, bulking its volume to several times the volume of the initially failed mass. The material can also get deposited along the path, depending on the topography. When the flow is channelised, it is categorised as a 'debris flow', whereas its unchanneled counterpart is termed a 'debris avalanche'. Without the confinement of a channel, debris avalanches flow at very high velocities when compared to debris flows, entraining considerable material from the bed [8].

Details of the mechanisms involved in all these stages are obtained by conducting controlled laboratory investigations such as undrained triaxial tests, constant shear drained triaxial tests [9, 10]. These tests are conducted under idealised conditions of drainage, which is typically not representative for a realistic the scenario in the field. Direct measurements of stress changes in the field were also attempted; however, these can be successfully conducted only if the instrumentation was implemented into the slope before the occurrence of debris flows, or when debris flows are artificially released. The major challenge in this approach is the lack of true reproducibility, as any subsequent debris flow will occur under different conditions. Artificial debris flow studies in laboratory set ups such as flumes are also limited by the issues related to up-scaling their results, while centrifuge tests are much helpful in reproducing stress levels similar to real events [11]. Considering the challenges and limitations of testing in the laboratory and in the field, numerical models can be considered as powerful tools which can simulate the processes. Understanding all different stages of debris flows in detail requires sophisticated numerical evaluations, and the usual practice is to evaluate the rapid onset propagation stage of debris flows separately from preliminary failure stages. This approach is clearly limited as it restricts the predictive quality of the simulated process. Considering the computational demands, however, separation of

stages is what makes the simulation computationally feasible and provides an opportunity to assess the propagation stage based on the outputs from failure stage. The propagation stage is the most crucial part of debris flows concerning impact predictions, as they travel long distances with high velocities. The runout path determines the area affected by debris flow, and the flow height and velocity determine the impact of debris flow on structures they interact with. In this work, the current practices in debris flow runout modelling are summarised, elaborating on the potential use of numerical models for simulation-based decision support. The key factors to be considered while selecting a numerical model and the challenges and future scopes in numerical modelling of debris flows are discussed in brief, particularly considering applicability to geohazard mitigation in India.

Runout Assessment: Past and Current Practices

The assessment of landslide runout can be conducted in two ways. Forensic back analysis, based on the data from historical events [12–14] and predictive forward analysis, is used for risk assessment [15]. The runout analysis can be broadly classified into empirical or statistical methods, based on correlations and analytical methods, based on physical processes [16]. Historically, the first attempts to estimate runout distances were based on simple geometric correlations. They were practical and easy to follow. The simplicity itself made these relations popular, and many works have documented such correlations. Often considered approaches include correlations between geometric features of debris flows, as well as the inverse correlations between volume and angle of reach [17]. These correlations were later proved valid for open pit slope failures as well, which can be used for action response plans in mines. The data used for deriving the correlations can be statistically evaluated to quantify the confidence in the relationship. Further, exceedance probabilities can be defined using the correlation equation, based on the distribution of data (Fig. 1).

Even though the empirical and statistical approaches are helpful in identifying the area that could be affected by debris flows, these approaches cannot provide any further insight into regarding the varying flow heights and velocities with respect to time. This limitation calls for the development of numerical models capable of simulating the process of runout and estimating the flow parameters [13, 18–21]. Numerical models provide outputs that can be integrated with geographical information system, to develop meaningful hazard maps. These outputs were further improved with meaningful visualisations including videos and gifs, which can be used as communication tools for spreading awareness about the hazard. Many numerical models were developed in the past decades, and a major share of them

Fig. 1 An example of probabilistic runout prediction based on the position of the release volume (Modified after [16])
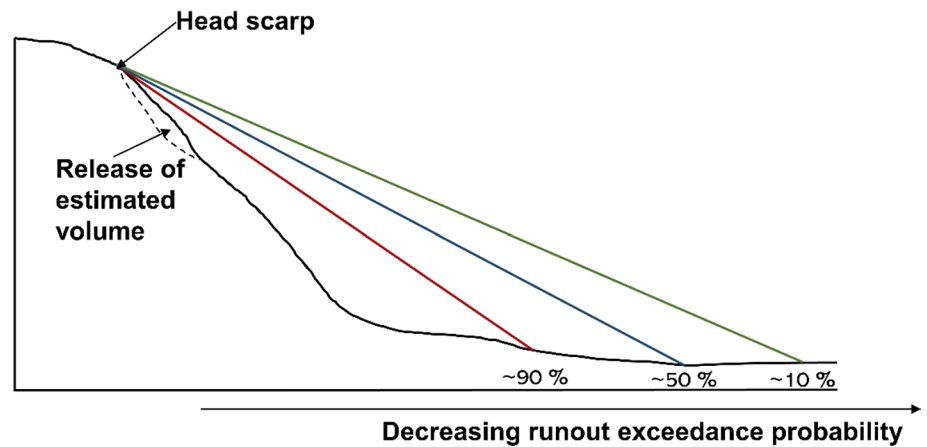
are based on continuum mechanical concept. These models have their roots in hydrodynamic theory, with some modifications to account for the rheological behaviour, entrainment and internal stresses of the debris flow material. The current modelling practices have come a long way from the initial empirical relationships; however, the methods still need improvements to simulate all the complexities associated with debris flows. In particular, capabilities for computationally feasible uncertainty management [22], has to be improved.

Numerical Modelling for Debris Flow Runout

The flow variables, such as height and velocity vary spatially, in all three directions, along the path and perpendicular to the path. Owing to the intricacies and large computational costs associated with this variation in 3 dimensions, most numerical models assume shallow water flow and ignore the variation of velocity and flow height in the vertical direction. Also, the material properties such as parameters on friction, viscosity, shear strength and pore pressure variations are varying throughout the flow, which cannot be attributed in the models efficiently. Direct measurements of these parameters are mostly not available from field measurements. The computational difficulties exist in both channelised and unchannelised flows, as the direction of propagation is sometimes not known. Channel bifurcations or merging of multiple channels can occur in the case of channelised flows, making them very challenging to model.

After the initial failure, debris flows are driven by gravitational acceleration, along with pore pressure gradient and topographic gradient. Most continuum mechanical models are based on depth-averaged shallow water equations [23] with the forces acting on the basic elements similar to the forces acting on a soil column in limit equilibrium analysis (Fig. 2), and mass conservation is trivially satisfied in discrete models. Gravity (W) predominantly drives motion,
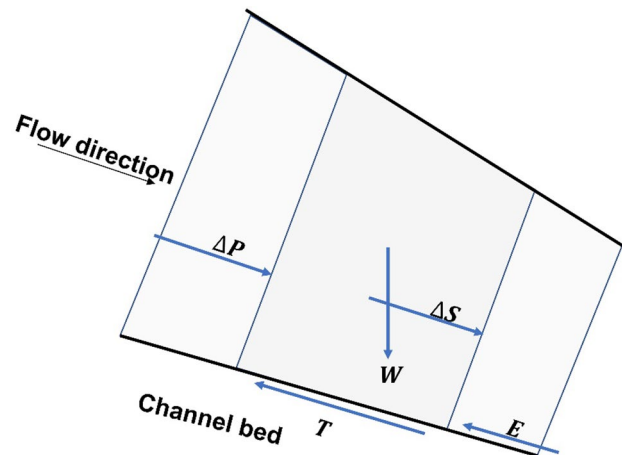
Fig. 2 Simplified depth-averaged forces acting on a column of flowing material. (Modified after [16])

with additional internal stress gradients (ΔP and ΔS) originating from the sloping free surface influencing flow dispersion. Inertia may also contribute resistance, particularly if the flow entrains new material along its path (momentum flux component, E), necessitating momentum transfer to accelerate this material. However, primary resistance to motion typically arises from basal shear stress (T), which may be influenced by pore pressure and normal stresses. Debris flows include both solid and fluid phases, where the fluid phase includes both air and water. The behaviour of flow is highly influenced by the interaction between different phases involved, fluid, solid and fluid—solid. These interactions are represented using constitutive relationships [23–27], and hence the choice of phases of flow is very critical in debris flow modelling.

Modelling both phases can provide more details, and the recent literature shows a trend towards multiphase modelling. The multiphase model r.avaflow [28] is being widely used for simulations of case studies from different parts of

the world. Even when multiple mixture phases are considered, interactions between them are typically limited with the assumptions of no chemical reactions, no physical abrasions and no heat being produced [29]. Also, most models assume that the debris flow is considered to be incompressible or allow them to be just weakly compressible.

Even though multiphase models can provide more details about the flow, their value-add is clearly limited due to the number of parameters that need to be calibrated. Single-phase models, however, can be adopted when one phase dominates the flow. They marked the initial stages of numerical model development in the past and laid the foundations for advanced models of the present. Mixture models can also be used to account for the multiple phases involved, which are suitable for situations where both phases are homogenous, without any interaction between them. They are relatively simple, ignoring the relative motion between the phases, but can provide satisfactory results for the overall evaluation. The flow parameters in mixture models will be computed as the weighted average of the share of volume of each phase [30].

A more realistic representation can be provided with multiphase models, with the explanations for coarse grained front, with boulders transported by a matrix of finer particles (Fig. 3), and other interactions between phases. Such models are developed by defining separate set of equations for each phase, increasing the model complexity and computational costs [31]. To account for the relative motion, the separate equations must also be connected using additional force terms. Many multiphase models have been developed in the recent past, but the mechanical phase separation model [26] provides realistic phase separation similar to observed events. Apart from the two-phase models that study the solid and fluid interactions, three phase models are also available, which considers coarse and fine grains separately[28, 32]. Multiphase models are also relevant in case when there are internal mass-momentum exchanges between phases like ice and rock [25], and when debris flows enter another water body like river. Even though vegetation plays a critical role in debris flow dynamics and their mitigation [33–35],

incorporating heir effects into a numerical model is still challenging. Most available debris flow models, even the multiphase models, focus on the interactions between coarse grains-fine-grains and water.

Similar to phases of flow, the spatial dimensionality also decides the quality of numerical models, and the choice often depends upon the availability of computational resources and the level of details required from the simulation. Even though debris flows are three dimensional processes, the complexities associated with the computation often imply that reducing the model to two dimensions provides a better trade-off between computational feasibility and number of parameters that need to be calibrated. When risk assessment and management are prioritised, a two-dimensional models can provide satisfactory results with lesser computational efforts, and hence are widely used. To convert the real scenario into a two-dimensional problem, the variations of velocity in the vertical direction is ignored, and depth-averaged values are used, assuming shallow water conditions. The fluid pressure is also assumed to be static, and the material flux through the surfaces (free and basal) is specified using the kinematic boundary conditions, using entrainment and deposition. Quasi-one dimensional models provide another level of idealisation and are easier to compute, but are not used in practice widely, due to their limitations in providing realistic flow parameters. The cross-sectional variations are ignored in this case, keeping the shallowness assumption. Such models are helpful only in the case of narrow drainage channels, for preliminary understanding of the process and design of mitigation measures.

When the failed mass propagates downslope, it can entrain materials from the bed (Fig. 3), which can have a critical impact on the flow dynamics. Dramatic variations in initial volume can happen due to entrainment [36], and the propagation dynamics is often affected by combined effects of entrainment and rheology. Entrainment can also affect the mobility of flow, sometimes resulting in increased velocity, and sometimes a decreased velocity. The new understanding provided in a recent study [37] explains this variation in mobility due to entrainment, with the statement that inertia

Fig. 3 Process of entrainment during debris flows
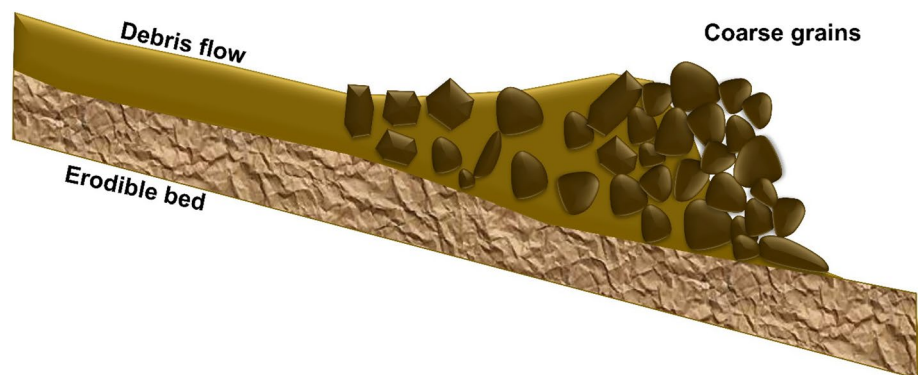
is related to the entrainment velocity. The study differentiates between erosion and entrainment and defines erosion as a mechanical process by which the bed material is mobilised by the flow, and entrainment as a mechanical process by which the eroded material is incorporated (entrained) and taken along with by the flow. Three different velocities are defined as erosion velocity, entrainment velocity and energy velocity. Landslides acquire energy and increase mobility when the entrainment velocity is less than the erosion velocity, and the energy velocity defines distinct excess energy regimes [37].

While the earlier models considered the bed to be rigid, allowing no entrainment, the recent literature shows a shift towards considering entrainment for real world cases. Different entrainment models are available in literature, starting from constant rate relationships [38, 39], empirical relations related to flow parameters and topographical parameters, to mechanics-based, mathematically consistent models [26]. Entrainment will have impacts on both mass and momentum conservation equations, and recent models allow flexibility in choosing appropriate entrainment models depending upon the requirements.

Relationships defining the material behaviour are another key aspect in debris flow modelling. The term rheology is commonly employed within the context of debris flow modelling to denote the constitutive relationships governing the relationship between stresses and either strain rates or strain, occurring during material deformation. In case of soils, the simplest rheological model expresses the effective stress tensor as a function of both history of stresses and the strain tensor. Hypoplasticity and elastoplasticity are used in models to represent the behaviour of soil subject to deformations [40]. In case of fluids, the stresses induced by deformation can be categorised into two, the equilibrium stress and shear stress. The total stress tensor is the sum of these two. While the equilibrium stress defines the thermodynamic, isotropic or volumetric stress in static conditions, the second part stands for the viscous, shear or deviatoric stress conditions or the tangential stresses generated due to flow. The rheological model for fluids relates the shear stress tensor to the strain rate, which can take a wide range of relationships starting from the linear one (Newtonian) to more complex relations [27, 41, 42]. Bingham model, Coulomb model, Herschel model and Voellmy model [28, 39, 43] are widely followed in literature, some with evidence from experimental studies. The equilibrium stress or simply pressure is determined using static equation using thermodynamic variables. These relationship uses viscosity, yield stress and frictional parameters to formulate the relationship between stress tensor and strain rate tensor. These parameters are called the rheological parameters or simply the model parameters. For incompressible flows, Poisson's equation is used to calculate the gradient of pressure, and when fluid is considered weakly compressible, pressure is expressed as a function of density alone. Another approach is considering fluid pressure to be varying with the thickness with a positive correlation. The rheological relationships are critical in formulating the governing equations and thereby modelling the flow.

Once the governing equations are correctly formed by considering phases of flow, spatial dimensionality, entrainment and constitutive relationships, the major step is the choice of the numerical solution methods. When the governing equations are defined by a set of hyperbolic-parabolic partial differential equations, it is necessary that numerical techniques should be used for finding solutions. Analytical and exact solutions are also possible in case of idealised cases. An overview of different solution methods is provided in Fig. 4. Most exact solutions are available through Separation of Variables (SoV) [27], Similarity Solution (SS) [23], Method of Characteristics (MoC) [37] and some unconventional approaches like Lie Symmetry (LieS) [44, 45]. Considering numerical methods, both time and space should be discretised for obtaining the solutions. All numerical models work on a combination of space and time discretisation, to calculate the variations based on both space and time. Time can be discretised implicitly or explicitly, where the implicit approach evaluates a function at a future time, and explicit approach performs the evaluation at a future time using the information from the current time.

Along with time discretisation, space should also be discretised to estimate the flow parameters. The basic classification of space discretisation starts with the mesh-based and mesh-free approaches [46]. It can be further divided into different structures as shown in Fig. 5. Mesh-based or grid-based approaches are conventionally based on the concepts of elements, cells or volumes. The computational domain is divided into finer mesh, throughout which the variables are estimated. The grids can be formed in two ways, Eulerian or Lagrangian (Fig. 5). In a Eulerian system, the grid is fixed [39] while the properties pass through the mesh, while in a Lagrangian system, the grid is flexible and is attached to the material [47]. The mesh is free to move along with the material, but in both the approaches, the neighbouring nodes remain constant throughout the entire simulation. The mesh-based models can be solved using different numerical techniques such as Finite Difference Method (FDM) [12], Finite Element Method (FEM) [48], Finite Volume Method (FVM) [49], Discontinuous Galerkin (DG) [50] and the Spectral Multidomain Penalty Method (SMPM) [51]. These classifications are based on how the information is passed through the nodes and how the computations are done within the grid.

In mesh-free methods, particles are considered instead of a grid, and the framework is always Lagrangian. The advantage over a grid-based approach is the flexibility with which
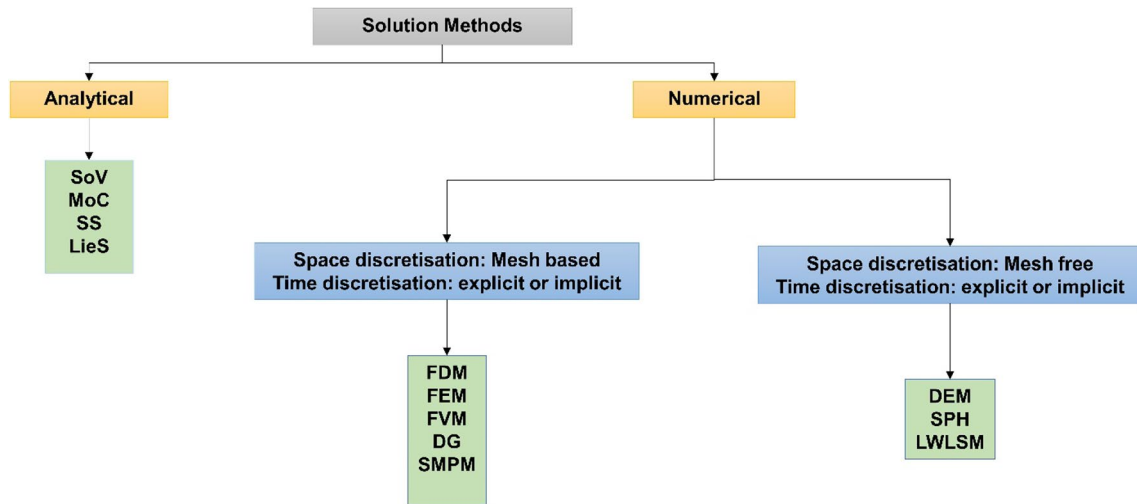
Fig. 4 Some solution methods applied to solve ordinary and partial differential equations governing debris flows. Both space and time discretisation should be used to employ a numerical solution (Modified after [29])
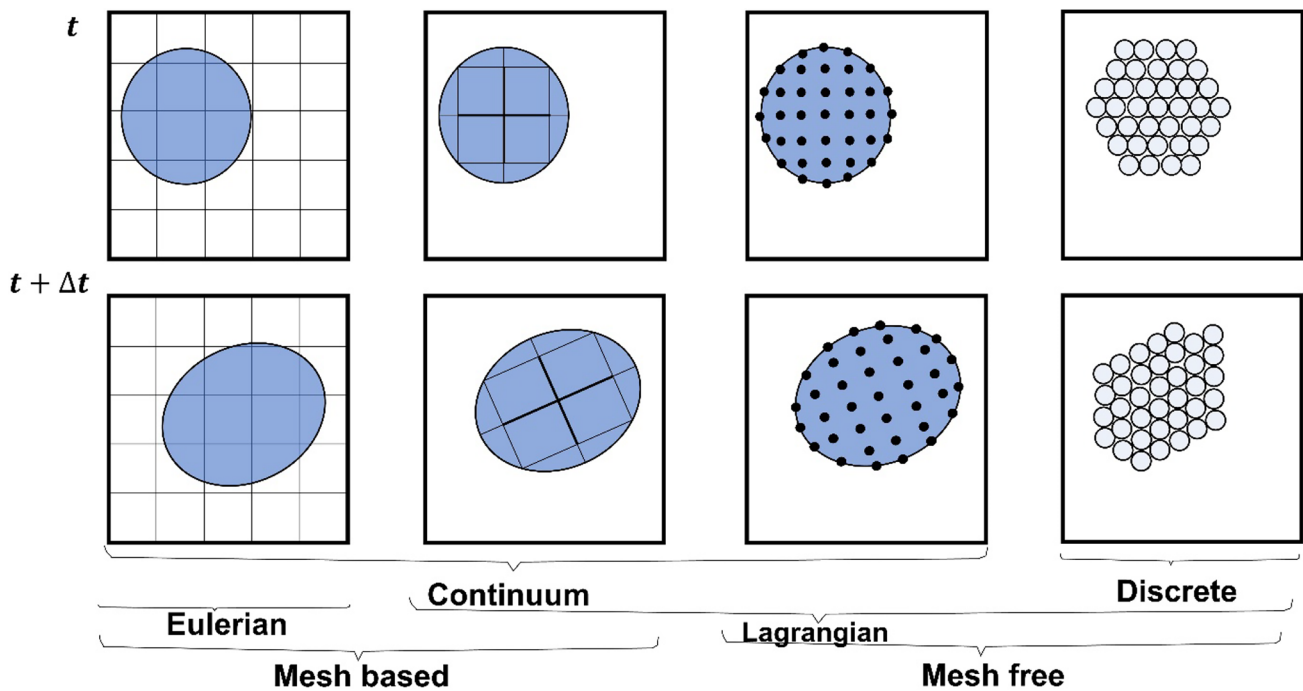
Fig. 5 Basic structures for space discretization (Modified after [29])

the particles can move, by changing the neighbouring points. Mesh free methods are highly suitable for large deformation problems like debris flows and both continuum and discrete approaches can be used. Discrete Element Method (DEM), Smooth Particle Hydrodynamics (SPH) and Local Weighted Least-Squares Method (LWLSM) are some numerical techniques used for solving variables in a mesh-free space.

With the availability of numerical models with the decisions on phases, dimensions, constitutive relations, entrainment and solution methods, the next critical step is the inputs required for a numerical model. High-quality topography data, precise release zone and the calculation domain usually prescribed using impact area are the critical inputs required for most of the model [52, 53]. While the topographical input such as a digital elevation model or point cloud data and release area are required to model the simulation, the impact area determines the spatial bounds or can be used for model calibration [54]. The resolution

of topographical data forms the basis of resolution of simulated results in mesh-based approaches, and fine resolution data can be obtained by conducting aerial surveys before and after the occurrence of event. The pre-event surveys can provide the topography before the occurrence of event, and the post event surveys can provide insights on release zone, impact area and the post event topography. Apart from these inputs, a number of parametric inputs are required to define constitutive relationships and the material behaviour [12]. While some of these parameters can be obtained from laboratory or field investigations, such as the bulk density of the material, the complex rheological parameters are difficult to be obtained without calibration. The choice and quality of each input have critical role in the reliability of the simulated results. Geotechnical field investigations are crucial before the numerical modelling, to understand the material properties. The engineering properties of soil or rock control the flow dynamics in several ways. Geotechnical and geophysical investigations are also crucial in understanding the erosion and depositions happened in the field after a debris flow event [55]. This information is critical in back analysis process, especially when model parameters need to be calibrated.

Once the solutions strategies are also set up in a reliable and reproducible manner, the model can be used for simulation studies, and the most vital aspect at this step is the calibration of model parameters [13, 56]. The model parameters are used to define the constitutive relationships, and there are other parametric inputs which defines the entrainment and boundary conditions [14]. The input parameter values can be used from the previous knowledge obtained from field or laboratory measurements, but this would make the simpler constitutive relationships complex, demanding additional parameters and computational costs. Material sampling and testing are also required in this approach, which are time consuming efforts. Even when the parameters are estimated from laboratory experiments, the small-scale tests usually do not represent the vast area covered in field, and the parameters are highly varying across the space. Owing to these difficulties, the model parameters are often found using back analysis, by calibrating the numerical model [56]. This is carried out using information from the field, available for historical debris flows. The information can include the impact area, flow height and velocities at different locations.

An example of the process of simulation using the information of impact area is shown in Fig. 6. Here, the simulations are repeated by varying the model parameters, till the simulated area matches the observed area best according to a predefined metric. While most studies do this process of calibration using sensitivity analysis and trial and error [12, 57, 58], attempts are made recently to use sampling techniques for selecting the parametric inputs and using probabilistic approaches for calibration [20, 59]. The advancements in this direction can aid in optimising the model parameters and creating a large database for historical landslides, which can eventually support in forward analysis of debris flows.

Simulation-Based Decision Support

Modelling the runout and predicting flow patterns, velocities, heights and distances can aid in risk reduction, as

Fig. 6 Process of calibration using impact area: **a** Trial simulation 1 with shorter runout distance, **b** trial simulation 2 with exceeded runout distance and **c** trial simulation that perfectly matches with the observed impact area
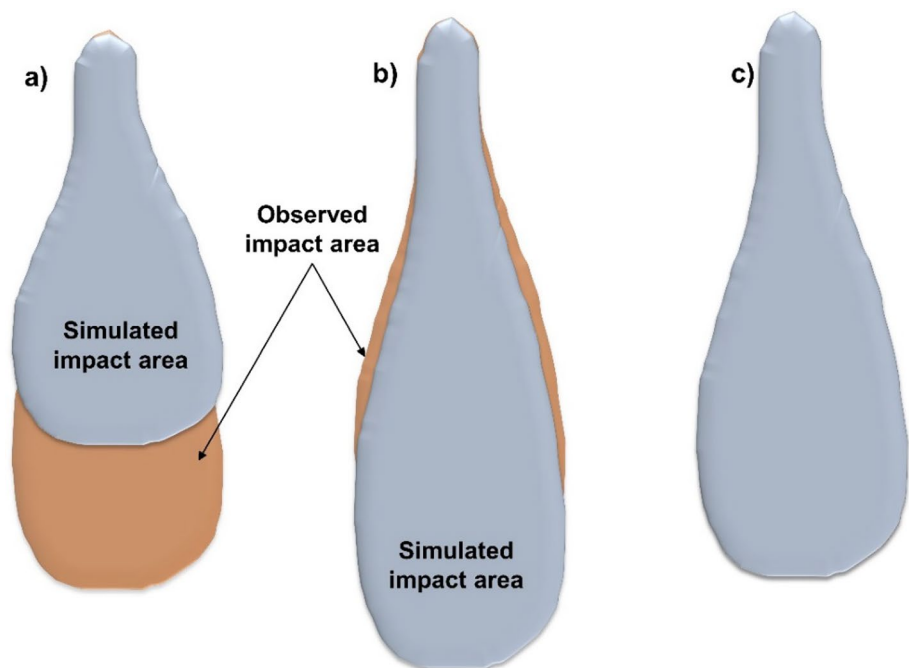
they provide options for defining area affected by the hazard and useful information for adopting proper mitigation approaches [60]. The useful information from back analysis can further aid in future forward analysis, through which the hazard maps can be developed before the occurrence of debris flows. The simulation can provide insights on the change in topography induced due to debris flow and identify the elements that are exposed to risk (Fig. 7).

The failed mass, along with the entrained mass from the erodible bed gets deposited in the downslope flatter areas or flows further to rivers or streams resulting in landslide dams or floods. The large travel distances of debris flows result in exposing elements located in flatter areas far away from the release zone also to the risk. An example is shown in Fig. 8, from Puthumala, Kerala, India [55], where more than 60 houses (red outline in Fig. 8a) were completely destroyed in a debris flow event. The release zone was located almost a kilometre away from the village, but the flowing mass resulted in complete devastation of the area. Hence it is vital to have a simulation-based decision support system for quantifying the risk associated with the hazard. The simulations can be easily used to spread awareness about the impending hazard and the associated risk.

While simulations can quantify the hazard in terms of intensities such as flow height and velocities, vulnerability is another key aspect that needs to be quantified for risk assessment. Vulnerability can be defined as characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard, which can be further classified into physical, functional or systemic [61]. While functional vulnerability refers to the capacity of systems, institutions or communities to perform essential functions in the face of a hazard, systemic vulnerability means considering the interconnectedness and interdependencies within a system. Physical vulnerability, on the other hand, pertains to the susceptibility of physical elements such as buildings, infrastructure and natural resources to damage or destruction caused by a hazard. Physical vulnerability is more important in the context of understanding the effects of a hazard from a civil engineering perspective. The degree of loss or damage to a given element within the area affected

Fig. 7 Change in topography due to debris flows
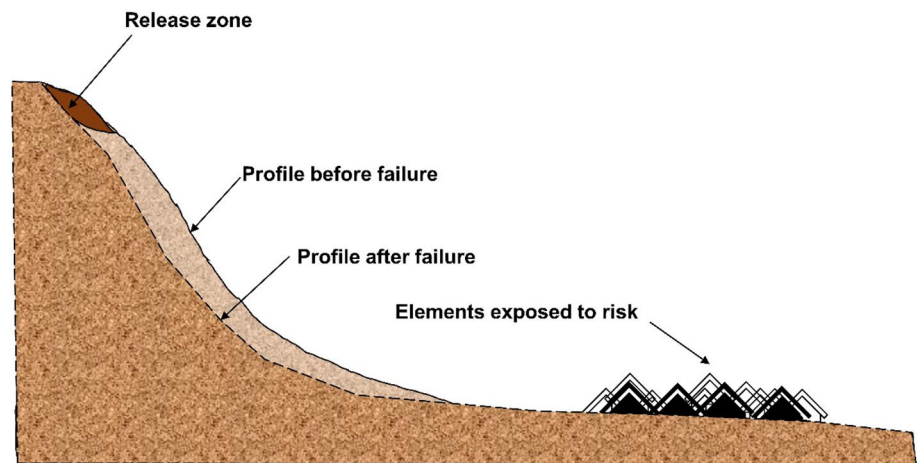
Fig. 8 Google Earth images of Puthumala debris flow, 2019, **a** before the occurrence of debris flow and **b** after the occurrence of debris flow

by the hazard can be quantified on a scale of zero to one, varying from no damage to complete damage. The quality of infrastructure, exposure of infrastructure to hazard and their maintenance are critical aspects in deciding the physical vulnerability. One approach to quantify vulnerability based on debris flow simulations is the use of the so-called debris flow intensity index, which is the product of the flow height and the square of the flow velocity [62]. Based on its value, four damage classes are discriminated, see list in Table 1.

The simulation results can be directly used to produce maps based on these damage classes, to quantify the estimated damage. Another method in this regard is the use of vulnerability curves, which are defined as functions of flow parameters such as flow height and velocity. These curves are specific to the localities and should be obtained from back analysis [63]. Figure 9a shows a vulnerability curve based on flow height, derived using a case study from Selvetta.

Databases of debris flow events with field observations are highly critical inputs for back analysis, both for model calibration and for development of vulnerability curves. The advancements in the model development are also results of continuous field observations, and the research is moving towards simulating debris flows in close to real scenarios [29]. The progresses so far are providing satisfactory bulk behaviour, which can be used effectively for developing hazard maps and risk assessments, while the micro-level modelling requires further refined models.

Challenges and Future Research Scope in Indian Scenario

Debris flow modelling is still considered to be an expert domain [16], which are specialty services [64] with limited guidelines [65]. The literature on model development is often complex with the underlying physics and mathematical equations, and the decisions involved in each stage of modelling can result into entirely different outputs. Even when the same decisions are followed, the quality of input data and the uncertainties associated with data are often not accounted. With satisfactory bulk performance of numerical models, more attention should be paid to the process of calibration, uncertainty quantification and standardising workflows for debris flow modelling. While the numerical modelling research is gaining pace in this direction, much more focus is required in countries like India in this domain. India accounts for a major share of fatal landslides in the world [66], and debris flows, and the cascading events have resulted in severe casualties in the recent past. In India, the maximum number of debris flows is triggered by heavy

Table 1 Damage classes and definitions for impacts to residential buildings [62]

Damage class	Damage description
Some sedimentation	(I) Sediment-laden water ingresses building's main floor or basement; requires renovation; up to 25% insured loss
Some structural damage	(II) Some supporting elements damaged and could be repaired with major effort; 25–75% insured loss
Major structural damage	(III) Damage to crucial building-supporting piles, pillars and walls will likely require complete building reconstruction; 75% insured loss
Complete destruction	(IV) Structure is completely destroyed and/or physically transported from original location; 100% insured loss
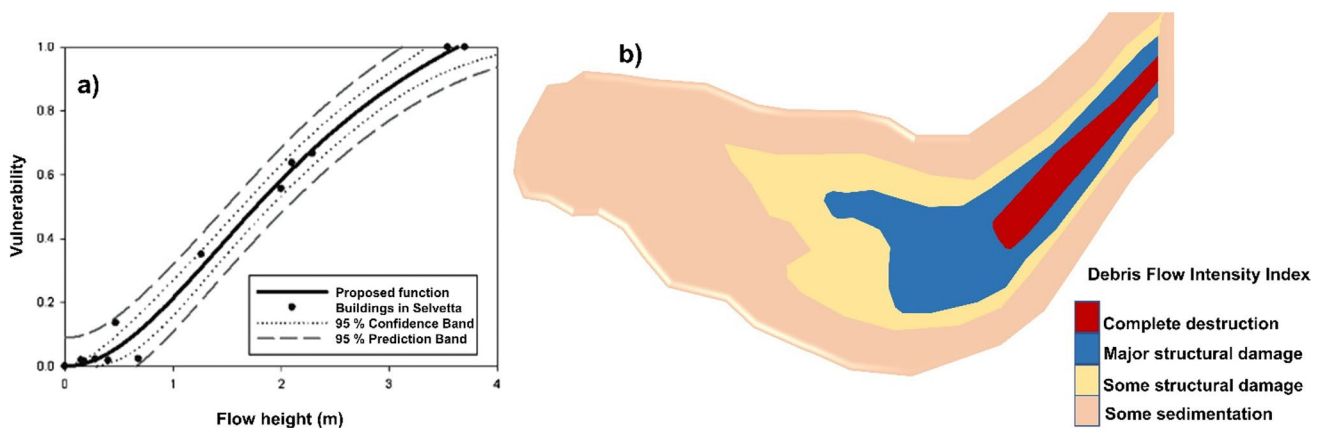
Fig. 9 Estimating vulnerability from debris flow simulations; **a** Vulnerability curves [63] and **b** debris flow intensity index [62]

rainfall or cloudburst. While failure triggered debris flows are more common in the Western Ghats and Eastern Ghats, the Himalayas witness more runoff triggered debris flows. Even though India has witnessed many devastating debris flows in the recent past, including the Chamoli disaster in 2021, major events from Kerala since 2018, the Kotropi debris flow in 2017 and debris flows during Kedaranath disaster in 2013, very few studies have been conducted in this regard, when compared to the studies being conducted in slope stability analysis and landslide susceptibility studies [67]. While the local scale studies are more focused on process-based slope stability modelling, regional scale studies focus more on landslide susceptibility maps [68–70]. Among the few studies available in literature on debris flow modelling, a major share uses Rapid Mass Movements (RAMMS) [39] debris flow module for the simulation of debris flows [54]. The studied cases include debris flow events from Himalayas and Western Ghats, and most studies report the results of back analysis. RAMMS is a single-phase mesh-based numerical model using continuum concepts, and the interactions between different phases are not considered. It considers constant rate entrainment and the constitutive relationship used for modelling the fluid phase is Voellmy-Salm rheology. Apart from using the available commercial packages or open-source tools, limited attempts were made in developing numerical models [12] or advancements in concepts of available numerical models.

One major limitation in the current debris flow modelling practices in India is the calibration process. Apart from choosing arbitrary values for rheological parameters, or references to literature, very few studies report a proper calibration procedure for debris flow modelling. One reason for this is the non-availability of quantitative data for conducting calibration. Apart from the data available from satellite sources, instrumentation in debris flow channels and availability of pre and post digital elevation models from the same source are still a question in Indian scenario. A good example of a well-documented case study would be the multi-hazard event happened in Chamoli [71], where the flow boundaries, reconstructed peak discharges, travel times and frontal velocities were used to optimise the model parameters. Even with the availability of rich data when compared to other events, the flow tail was not evaluated, and the complex processes were modelled with simplifying assumptions. With the non-availability of flow height, velocity values and fine resolution topographical data, the simulations often rely on coarse resolution digital elevation maps (10–12.5 m resolution, from satellite sources), which results in losing many details of simulations. Conducting aerial surveys are not widely adopted, due to the non-availability of pre-event topographical details of fine resolution, and high alterations happened in the post event terrain due to rescue operations.

Permanent monitoring of debris flow sites is difficult in Western and Eastern Ghats where new channels are formed due to failure triggered debris flows. Monitoring includes real time measurements of pore pressure changes, displacements and velocity using in-situ or remotely based observation systems. Even though there are monitoring systems in India [72], which can be used for forecasting shallow landslides, there are no dedicated debris flow monitoring systems. One reason for this is in case of failure triggered debris flows, the release zones are remotely located and are inaccessible, which makes it highly difficult to instal a permanent system with good connectivity. Without proper warning system, the information about occurrence of a new channel is only available only after the disaster in the current circumstances. Even though cracks in ground and formation of springs are often observed prior to the occurrence of debris flows, sufficient time for instrumentation is not available in most cases. In the case of Himalayan terrain, the channels are predefined and can be instrumented with sufficient availability of research funding. Focusing on the instrumentation of existing debris flow channels is the need of the hour to understand the process in detail. This can be helpful in quantifying the vulnerability associated with infrastructures such as roads, exposed to recurring debris flow hazards.

Even when susceptibility maps can be prepared with data-driven approaches, process-based numerical models are unavoidable from a risk context, and there should be more focus on developing a database of historical debris flows with calibrated model parameters. Such a database will aid in forward analysis and quantitative risk assessment. Increasing number of casualties associated with debris flows in India demands for urgent scientific intervention in this domain, with a focus on developing a framework for enhancing the capabilities of numerical models to get reliable results with limited data inputs. This is a critical research question that needs to be addressed for countries like India. While calibration of entrainment parameters is still challenging, there exists no studies evaluating correlations between complex rheological parameters and different types of Indian soils. Experimental studies are needed in this direction, which can build a strong database for forward analysis of debris flows. Well instrumented large scale model tests using different grain size distributions and degrees of saturation can help in understanding the rheological properties better. A large database of varying debris material should be used to understand the relationship between measurable properties like grain size, water content and shear parameters with the conceptual rheological parameters. This can be done using inverse analysis of well instrumented and documented model tests. A centralised data collection system and open data hubs are also highly needed at this stage, and efforts should be made by the landslide practitioners and researchers to

conduct collaborative case studies on historical debris flows to develop a strong database.

Summary

To summarise, this work provides an overview of the current numerical modelling practices related to debris flows, without a deep description of the underlying physics. The steps involved in the modelling process, the decisions taken and the consequences are discussed briefly based on recent literature, along with the potential use of numerical models for quantitative risk assessment. This is highly relevant in Indian context, as the country is lagging behind in focused debris flow research despite being one of the highly critical debris flow prone countries in the world. The consideration of debris flow modelling as expert domain has limited the number of researchers working in this domain, but with the availability of open-source codes and advancements in proper documentations, the young geotechnical researchers in India should be motivated to conduct research in this highly demanding field. Formulation of workflows, limiting uncertainties and enhancing the existing methods for limited data availability are critical aspects from a research perspective. With strong scientific intervention, debris flow research can provide promising outcomes in developing countries like India, with robust and reliable hazard maps and quantitative risk assessments, which can be critical in decision making for risk reduction.

Declarations

Conflict of interest The authors declare no conflict of interest.

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