ABSTRACT
Moraine dams, impounding glacial lakes, are among the weak natural dams because of their slope, freeboard and composition. Glacial lake outburst floods occurring due to the failure of moraine dams are significant hazards for the valley downstream the failure, as they possess huge amount of hydraulic energy that can kill thousands and destroy infrastructures and riverine landscape. Also, the entrainment of debris to the flow from the breaching process and downstream channel may develop the flow into a much bigger disaster or even a series of hazard chain. Ice and rock avalanche or landslide, glacier calving, degradation of ice cores, earthquake and atmospheric events trigger the breaching phenomenon which generates a series of waves overtopping the dam or seepage causing the failure of the dam. Various approaches have been discussed in this review paper to produce an understanding of the failure mechanism of moraine dams: experimental works, empirical relationships, analytical solutions, and numerical modelling. No concrete experimental investigations and parametric solutions pertained to the failure mechanism of moraine dam is found in the review, but various empirical relationships are discussed and suitable approaches for numerical modelling are suggested as per the requirement of the task.

1. Introduction
Climate change leads to unorthodox changes in weather pattern which is a serious issue for cryosphere as they are more vulnerable compared to other parts of the world (IPCC, 2013). It results in rapid melting of a glacier and extreme rainfall. These conditions act as catalyst to the formation of moraine dammed lakes if provided with suitable concave landform (depression) (Clague and Evans, 2000), formed typically between glacier snout and end moraines (Costa and Schuster, 1988). Glacial lakes containing a huge volume of water behind weak moraine dams possess high probability of glacial lake outburst events (Richardson and Reynolds, 2000; Benn et al.)

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Displacement and seiche waves are induced by triggers of glacial lake outburst floods: ice avalanche (Vuichard and Zimmermann, 1987), rock avalanche, and calving from terminal face of lake terminating glacier (Richardson and Reynolds, 2000), which can overtop the dam and begin the dam breaching process (Westoby et al. 2014). These outburst floods can release huge volume of water rapidly that can produce deep and high velocity flow possessing a massive erosion and transportation capacity over extensive areas (Anacona et al. 2015). Therefore, they can develop quickly into debris flow with densities of about 1.5 t m$^{-3}$ (Emmer and Vilimek, 2013), exacerbating the disaster. The susceptibility of a given lake to outburst floods is not constant and may change significantly over time, especially due to changes in the lake (dam) setting and the setting of the lake's surroundings (Emmer et al. 2018), and some researchers also infer that there will be a substantial increase in GLOF incidence throughout the twenty-first century as glaciers and lakes respond more dynamically to anthropogenic climate warming (Harrison et al. 2018). The threat of potential disaster possessed by such a large volume of water behind a weak and unstable structure cannot be neglected.

Glacial lake outburst floods are very dangerous natural disasters that can destroy human lives and infrastructures worth billions. Although endangerment of human life, infrastructure and power supplies are the immediate impacts of these GLOFs, their conversion into flash floods, large-scale floods or debris flow possess much bigger threats (Liu et al. 2014). There is an evidence of 12,445 fatalities caused by this hazard event throughout the world (Carrivick and Tweed, 2016); 140 people in Gietro Glacier, Switzerland, 421 in European Alps (Petrakov et al. 2012), 4500 in Huaraz, Peru (Huggel et al. 2002), 6000 in India (Allen et al. 2016) and 20 in Bhutan (Pitman et al. 2013). Apart from this, they have significant social and economic consequences such as aggradation and degradation of valleys in both local and large scale (Kershaw et al. 2005), destruction of farmlands, hydropower, and bridges (Bajracharya and Mool 2009). Sometimes, in countries like Bhutan where hydropower have a significant contribution to nations GDP, these outburst floods can affect a substantial portion of the country’s economy (Carrivick and Tweed 2016).

Most of the moraine dams are made up of poorly consolidated and sorted sediments, and have a relatively low width-to-height ratio than those of landslide dams (Evans and Clague 1994), making them vulnerable to failure. Therefore, the research of mitigation techniques such as hydraulic syphon techniques for lowering the lake level (Grabs and Hanisch 1992) and hazard assessments of the areas downstream (Somos-Valenzuela et al. 2016) is entailed. Hydraulic studies related to dam safety is required for hazard assessments in moraine dam failure prone areas (Pilotti et al. 2014). However, the study of the mechanism of moraine dam failure is equally important for the full understanding of these events that will help in the careful planning of prevention works.

This paper aims to provide a brief review of the failure mechanism of moraine-dammed lakes. Experimental investigations of dam failure are found to be concentrated on the formation of surge waves whereas studies about interaction of surge wave with dam materials, beginning and rate of erosion of dam material are lacking. The impacts of sediments in the augmentation of discharge in the downstream valley have not been discussed in many studies because they have considered water as the
only element in the flow. These shortcomings will be discussed in this review paper. Although various review studies related to moraine dammed lake already exists; review about modelling approaches and contemporary modelling challenges (Westoby et al. 2014), review of hazard assessment for moraine dammed glacial lakes (Emmer and Vilimek 2013) and review of physical processes involved in GLOFs (Worni et al. 2014). However, the state-of-art review about empirical relationships, experimental studies and numerical solutions of failure of moraine dam are not pellucid, therefore we attempt to clarify in this paper. Current research status on a failure process and the mechanism of moraine dams will be discussed by describing the nature of moraine dams, empirical relationships, experimental investigations and analytical solutions. To numerically simulate GLOFs, remote sensing data are integrated with Geographical Information System (GIS) and hydrodynamic modelling in recent years (Chen et al. 2010) which will also be discussed.

2. Research status on moraine dam failure process and mechanism

During the little ice age (LIA), claimed to have ended in latter half of nineteenth century, glaciers built large moraines. When the climate warmed in the twentieth century, moraine-dammed lakes were formed due to the retreat of valley and cirque glaciers from their advanced position (Clague and Evans 2000). Nevertheless, this is not the only process by which a moraine dam is formed, but they can also result by the input of sediment in lateral direction differing flux in supraglacial debris (Benn and Owen 2002). These moraine dammed lakes and their failures are common hazards in Nepal Himalayas (Vuichard and Zimmermann 1987; Kattelmann 2003), Karakoram Himalayas (Hewitt 1982), Cordillera Blanca (Lliboutry et al. 1977; Carey 2008), British Columbia (Evans and Clague 1994; McKillop and Clague 2007) and Tian Shan (Jansky et al. 2010). The studies of outburst floods have been carried out by more than 750 institutions in 45 countries from different continents (Emmer 2018). Moraine dams impounding lake possess a threat for disaster because they are of young age and lies at high altitude where the vegetation does not grow regularly because of cold temperature, thus their slopes have not stabilized yet (Westoby et al. 2014). Other reasons include- dam faces being steeper than angle of repose (downstream face slope is around 35 degrees and rather stable, while upstream face slope is much steeper, depending upon the time elapsed from the deglaciation), location being close to steep crevassed glaciers and vertical rock slopes, and finally thermal degradation or melting of an ice or snow core present in the dam (Costa and Schuster 1988). Also, the width to height ratio of moraine dam is relatively smaller compared to landslide dams in cross section, making them highly susceptible to failure than landslide dams because cross-sectional geometry of dam controls breaching rate of dams. For example, this ratio was found to be 8:1 for moraine dams in British Columbia and 20:1 for landslide dams in New Zealand (Korup and Tweed 2007). The exact mechanical properties of the soils from moraine dams cannot be determined, making it difficult to assess the slope stability by utilizing normally used methodologies (Novotny and Klimes, 2014). Stability of moraine dams depends upon several factors, namely particle size distribution, geometry, mineralogical composition,
internal structure and material properties also influencing the dam’s resistance to surface and sub-surface erosion (Novotny and Klimes 2014; Worni et al. 2014). An internal structure of the moraine dam becomes visible only after the dam is breached. Therefore, in order to assess the stability of a moraine dam properly before being breached, geotechnical/geophysical approaches must be applied (Korup and Tweed 2007). These approaches include ground penetrating radar imaging technique (Hambrey et al. 2008), seismic refraction tomography (Langston et al. 2011), self-potential (Moore et al. 2011), gravimetry soundings (Haeberli et al. 2001) and electrical resistivity imaging (Richardson and Reynolds 2000; Thompson et al. 2012).

Based upon the formation, moraine dams can be classified as push moraine, ice-thrust moraine, dump moraine and ice-cored moraine as shown in Figure 1. Push moraines are generally low height, fewer than 9 meters, impounds only a small amount of water and are the most stable type of moraine as a certain portion of it belongs to the glacier itself. Ice-thrust moraines are formed by the accumulation of sediment and debris eroded from the base of the glacier while dump moraines are developed by dumping down the ice front of sediment and debris from within ice and on an ice surface. Thus, ice-thrust and dump moraines differ in the formation process (Costa and Schuster 1988). Ice-cored moraine, on the other hand, is most vulnerable to failure among other types of moraines discussed above because of the presence of ice cores in the dam. Degradation of these ice cores causes subsidence in moraine dam decreasing the dam freeboard which makes the moraine dam highly prone to failure. The probability of the failure is increased because even the low intensity/amplitude displacement waves induced by ice or snow avalanche onto the lake are now capable to overtop the dam and thereby, beginning the breaching phenomenon (Westoby et al. 2014). Also, the structures present in the ice cores can make conduits available for lake water into the moraine for percolation process which may also initiate the breaching process (Richardson and Reynolds 2000).

2.1. Failure mechanisms

Dynamic movement of ice, snow, rock or landslide avalanches (Jiang et al. 2004; Awal et al. 2010), glacier calving, wave overtopping, melting of ice-cored moraines (Richardson
and Reynolds 2000), atmospheric events such as intense rainfall and snowmelt, and earthquakes (Clague and Evans 2000) are the common triggers for initiating the failure mechanism of moraine dam (Westoby et al. 2014). Overtopping, incision, piping, seepage, ‘self-destruction’ of the moraine (thermal degradation of ice cores present in moraine), and flood waves originating from upper lake in the catchment are the processes by which a moraine dam fails, among which overtopping and piping are the most common processes (Costa and Schuster 1988).

Wave overtopping mechanism is illustrated in Figure 2. In the wave overtopping mechanism, the moraine dam is overtopped by a wave or series of waves developed from ice and rock avalanche or landslide falling into the glacial lake. These waves can be divided into displacement and seiche waves. Displacement waves are the pushing waves formed by the impact of avalanche and seiche waves are the standing waves formed throughout the entire lake (Westoby et al. 2014). The avalanches into the lake also augment the level of water in the lake. If the height of the produced wave is high enough to overtop the moraine dam, and the velocity of flow is larger than the critical velocity, the flow will scour the moraine dam (Liu et al. 2013). This will initiate the incision process, and if the erosion rate of the dam keeps on burgeoning, it might lead to a partial outburst of the moraine dam, and finally culminating to a complete outburst of the dam.

A piping mechanism as shown in Figure 3 is not a common trigger for a moraine dam failure as wave overtopping, but it possesses the potential to increase the rate and magnitude of the dam failure, thus the process cannot be neglected. Internal erosion in dam causes seepage to appear in the dam which will erode a hole in the exit causing an increment in the hydraulic gradient. The hole will extend along the path of the highest hydraulic gradient and forms a pipe into the lake. The water flowing from the pipe will displace the soil, initiating the breaching of the dam (Liu et al. 2013).

Typically, overtopping and piping are the common modes of failure of moraine dam; in some rare instances, however, moraine dam fails by a combined effect of overtopping and piping. For example, outburst flood due to the failure of end
The moraine dam of Guangxieco lake in 1988 was resulted by an amalgamation of the two mechanisms of failure (Liu et al. 2013).

### 2.2. Empirical relations

Empirical relations are the easiest and simplest ways for estimating various parameters necessitated for hazard assessment in the case of emergency and prevention works. However, being formulated by statistical analysis of past events, empirical relationships fail to incorporate basic laws of fluid mechanics and hydraulics. Peak discharge is an important parameter to consider while performing the assessment as it helps to visualize the intensity of the flood downstream. The list of empirical relationships of peak discharge due to the failure of a dam with various parameters of the dam before failure was already available (Westoby et al. 2014). Empirical relationships containing height of water ($H_w$) and volume of water ($V_w$) provided more accurate predictions of peak discharge of flow than those having other parameters like embankment length ($E_l$) and embankment width ($E_w$) as per the multiple regression analysis performed by Wang et al. (2018). Since the prediction of peak outflow by the models including only $H_w$ and $V_w$ are not improved significantly by the inclusion of $E_l$ and $E_w$ in the relationship, $H_w$ and $V_w$ can be considered substantial parameters to determine peak discharge than any other parameters (Wang et al. 2018). Figure 4(a–c) portrays peak discharge as a function of the potential energy of the dam, volume of water behind the dam and height of the water behind the dam.

Apart from these single variable regression equations, there are many others multivariate equations for determining the peak discharge of the flow. Pierce, et al. (Pierce et al. 2010) prepared a composite database of case studies of dam failure by combining data from Wahl (1998) and Pierce (2008). Thornton et al. (2011) performed a multivariate regression analysis of that composite database by using parameters such as $H_w$, $V_w$, $E_l$ and $E_w$. Based upon that analysis, it was concluded that with the increase in number of variables in the empirical relations, the adjusted coefficient of determination ($R^2$) increases whereas the mean prediction error and uncertainty
Figure 4. Peak discharge due to the failure of a dam as a function of different parameters adapted from (Westoby et al. 2014); (a.) Peak discharge as a function of the potential energy of dam (Costa and Schuster 1988) (b.) Peak discharge as a function of the volume of water behind the dam (Blue dashed line and Red dashed line (Walder and O'Connor 1997), Magenta dash-dot line (Singh and Snorras 1984), Black solid line(Evans 1986) and (c.) Peak discharge as a function of the height of the water behind a dam (Blue solid line and Magenta dash-dot line (Pierce et al. 2010), Black solid line (Reclamation 1982), Red dashed line (Kirkpatrick 1977) and Green solid line (Service 1981).
bandwidth decreases. Gupta and Singh (2012) discussed the conclusions from Thornton et al. (2011) and proposed correlations applicable for different scenarios from a group of equations. To tackle the problem of scarcity of geometric variables, effect of all the variables were unified. $H_w$ was used as single independent variable if the location was close to dam breach whereas both $H_w$ and $V_w$ were considered for distant locations from dam breach. A robust artificial neural network was developed to predict peak discharge from original dataset which underestimated the extreme values, thus synthetic dataset was generated using copula method to improve the efficiency of the model (Hooshyaripor et al. 2014). Another dimensionally homogeneous model was proposed and was found superior in terms of root-mean-square error and efficiency coefficient (Azimi et al. 2015).

However, all these relationships were based on a limited amount of historical cases of failure events. The number of case studies needs to be added for further validation. But, they represent the state of the art of the empirical relationships for dam failure, hence are important to be discussed (Thornton et al., 2011). A physically based numerical method was followed to obtain equations of peak outflow by regression analysis to address the shortcoming of limited number of case studies (De Lorenzo and Macchione 2014). This study also considered the parameters like $z_0$ (exponent of the level reservoir-volume curve) and $Z_0^*$ (dimensionless value of initial water depth) for piping failures (De Lorenzo and Macchione 2014). Another shortcoming of these studies was that the predicted values lacked credibility if they were beyond the given range. Froehlich (Froehlich 2016) developed a semi-theoretical relation to predict peak discharge which is limited by the potential maximum discharge due to the instant formation of the breach. Therefore, this relation is applicable even if the values of $H_w$ and $V_w$ were not taken from the given range, and can be preferred over empirical relationships that provide better fit to the compiled data.

### 2.3. Experimental investigations

Even though extensive literature review related to moraine dams can be found, there is a dearth of experimental investigations pertained to moraine dams. An experimental study was conducted based on soil science perspective from soil sample collected from moraine dams which was useful to determine slope stability and its conductivity but lacked hydraulics perspective (Novotny and Klimes 2014). For an outburst flood due to dam failure, time to inundation, time to peak velocity and duration of peak flow for different bed roughness and suspended sediment concentration were calculated by experimental investigations (Carrivick 2010). Experiments were performed on failure of general dam breaks by studying initial stage of dam break waves generation (Bukreev and Gusev 2005), partial dam break waves (Bukreev et al. 2008) and discharge and energy loss coefficients during the breaching of a trapezoidal dams (Bukreev et al. 2008). Classical water-level gauge techniques and digital imaging technique can be employed to investigate the propagation of dam-break waves in a channel with triangular bottom sill (Soares-Frazão 2007).

Some of these experimental investigations focus their concentration on impulsive waves generated by landslides. Fritz et al. (2003) initiated an experimental study of
landslide-generated impulse waves using Particle Image Velocimetry in pneumatic landslide generator. A similar approach was used to study the flow separation regions (Fritz et al. 2003), near field characteristics (Fritz et al. 2004) and the scale effects of landslide generated waves (Heller et al. 2008). Important characteristics of impulse wave at generation zone and far field of an underwater landslide (Ataie-Ashtiani and Najafi-Jilani 2008), sub aerial landslide (Ataie-Ashtiani and Nik-Khah 2008) and submarine landslides (Najafi-Jilani and Ataie-Ashtiani 2008) are also researched. Panizzo et al. (2002) showed that wavelet transform analysis can also be implemented to study these waves.

It might be argued that the characteristics of impulse waves generated during landslide may resemble the impulsive surge waves caused by ice avalanche in the lake impounded by moraine dams. But, the difference in density of the sliding blocks, the geomorphic structure of moraine dams, slope movements like landslides, and rockslides in lateral moraines and various other factors result in surge wave of different characteristics (Klimeš et al. 2016). The issue of difference in density of sliding blocks were well addressed in study of water pressure loads acting on downstream dam (Chen et al. 2014) and study of surge waves induced by glacier avalanches and its effects on dam failure mechanisms (Chen et al. 2017), but these studies did not address the discussion on failure process of moraine dam, sediment entrainment in the flow and peak discharge of the flow.

Experiments of avalanche-related hazards can provide insight to the characteristics of impulse waves caused by ice or rock avalanche and landslide. However, these studies mainly focus on the hazard effects of avalanche itself and do not pay much attention to their impacts on reservoir or glacial lakes behind natural dams. These research concentrate their attention on granular effects of an avalanche, velocity distribution and avalanche boundary evolution (Pudasaini et al. 2005), shape and characteristics of flowing avalanche in channelized flow (Wieland et al. 1999) and energy dissipated by shear stress as the flow meets with the obstructions (Denlinger and Iverson 2001). But, they lack the study of the propagation characteristics of surge wave induced by an avalanche and its impact on the failure mechanism of natural dams.

To study the characteristics of outburst flood and debris flow, an experimental investigation was done based on failure of triangular shaped and trapezoidal-shaped moraine dam due to wave overtopping (Shrestha and Nakagawa 2016) and both overtopping and seepage (Shrestha et al. 2013). It was an innovative experimental research to include seepage failure mode in moraine dams (Shrestha et al. 2013), but both experiments failed to integrate wave generation and propagation mechanism and focused only on the evolution of discharge over the time. No concrete experimental study on failure mechanism or propagation of dam break waves of moraine dam was found during the literature review.

2.4. Analytical and parametric solutions

Similar to experimental investigations, analytical and parametric solutions for moraine dam failure seem to be lacking. However, many analytical and parametric
solutions for general dam failure are available. A research used numerical simulation to calculate the height of the wave (Somos-Valenzuela et al. 2016) and compared it with the analytical solution provided by Heller and Hager (Heller and Hager 2010). Among these the analytical solution proposed by Capart (Capart 2013) provides a simple and detailed solution with minimum input parameters. The peak discharge, time to peak discharge and the transition distance after which the peak flood will start to attenuate are given as follows:

\[
Q_p = \left(\frac{2}{3\pi}\right)^{3/2} \frac{g^{1/2} k^{3/2} \mu^3 S_D^3 A_L^{3/2}}{b_B^{1/2}}
\]

\[
T_p = \left(\frac{3\sqrt{6\pi}}{2}\right) \frac{A_L^{1/2}}{g^{1/2} k^{1/2} \mu S_D b_B^{1/2}}
\]

\[
\chi_T = 9 \left(\frac{S_v}{f}\right)^{1/3} \frac{A_L}{b_v^{1/3} b_B^{2/3}}
\]

where \( g \) is acceleration due to gravity, \( k \) is dimensionless transport coefficient, \( \mu \) is reduction factor, \( S_D \) is the inclination of the downstream face, \( A_L \) is the surface area of a lake, \( b_B \) is the breach width, \( S_v \) is the valley slope, \( f \) is friction coefficient and \( b_v \) is the valley width.

2.5. Numerical solutions

2.5.1. Complete physically based numerical models

Finite volume method is the most widely used approach to solve a general dam break problem using either Cartesian grids or unstructured triangular grids. Adaptive meshing, however, is considered to provide more accurate solutions for given time and computation cost. Even though shallow water equation is commonly solved to obtain the results, errors are induced in early stages of dam break problems (Minussi and Maciel 2012). A brief summary of different approaches taken to solve dam break problems numerically is shown in Table 1.

2.5.2. Coupled approach

GIS-based numerical simulations of moraine dam failure provide a better and detailed insight into the breaching process and outburst flood propagation downstream, which contributes significantly to the hazard assessment. From avalanche modelling to lake wave generation, and then to breaching process and flood propagation, moraine dam failure is a cascade phenomenon (Somos-Valenzuela et al. 2016). To model such a complex phenomenon, most of the researchers have divided the whole process into various stages. Then, the results obtained from one stage either by numerical calculations or software has been integrated into the next stage and thereby, obtaining a final output. Recently, r.avaflow, an advanced open-source computational framework that has the potential to model the whole cascade phenomena has been able to
| Approach                                      | Equations solved                   | Scheme                               | Grids/meshes                  | Features                                      | Source                        |
|----------------------------------------------|------------------------------------|--------------------------------------|-------------------------------|-----------------------------------------------|-------------------------------|
| Finite volume approach                       | Shallow water equation             | Roe’s scheme                         | Unstructured triangular       | –                                             | Anastasiou and Chan (1997)    |
| Second-order total variation diminishing     | Shallow water equation             | HLLC Approximation Riemann solver    | –                            | Sediment transport and bed evolution          | Yue et al. (2008)             |
| Second-order upwind cell-center finite volume method | Shallow water equation             | Harten-Lax-van Leer Approximation Riemann solver | Unstructured triangular       | –                                             | Aliparast (2009)              |
| Constrained interpolation profile and moving particle semi implicit | Advection equation Conservation of mass | Constrained Interpolation profile and Moving particle semi implicit | Cartesian grid for CIP scheme and No grid for MPS scheme | –                                             | Hu and Sueyoshi (2010)        |
| Finite volume approach                       | Reynolds-averaged Navier stokes equation Shallow water equation | Volume of fluid                     | Cartesian staggered grid      | –                                             | Ozmen-Cagatay and Kocaman (2010) |
| Finite volume approach                       | Shallow water equation             | Flux vector splitting                 | Cartesian grid                | –                                             | Baghlani (2011)               |
| Finite volume approach                       | Conservation of mass               | Volume of fluid method                | 5 mm regular grid             | –                                             | Minussi and Maciel (2012)     |
| Finite volume approach                       | Conservation of mass               | Volume of fluid method                | Adaptive meshing, high-resolution mesh at air–liquid interface, coarse mesh everywhere else | –                                             | Fondelli et al. (2015)        |
| Finite volume approach                       | Shallow water equation             | Von Neumann method                   | Staggered grid                | –                                             | Budiasih and Wiryanto (2016)  |
reproduce the documented and reconstructed patterns of hazard events (Mergili et al. 2018). r.avaflow can route rapid mass flows, avalanches, or process chains from a defined release area down an arbitrary topography to a deposition area (Mergili et al. 2017), and can also estimate the spatial-temporal evolution of flow heights and velocities as well as travel times and volumes of these complex mass flow events (Mergili et al. 2018). Some of the software utilized to model the various stages of outburst floods are enlisted in Table 2.

These softwares have their own features, and individual software possesses an advantage over others in different aspects. Additionally, computation cost and computation time of the software, the nature of the failure of the dam and the requirement of the task influences the selection of the suitable software. Thus, it is difficult to select one the best software for modelling GLOFs in all kinds of scenarios. Nevertheless, based upon the observation from Table 2, a few conclusions can be drawn out. RAMMS is suitable for avalanche modelling. It can compute material entrained by mass flows, but when the result of RAMMS was compared with the output obtained from FLO-2D for predicting motion of potential outburst flood (Mergili et al. 2011), it was reported to predict higher flow depths, smaller area of flood and stoppage of flow, which was in sharp divergence with the result of FLO-2D (Zhang and Liu 2015). FLO-2D solves mass and momentum conservation equations of sediment and water, but it cannot include material entrainment (Worni et al. 2014). If preference of the user is to utilize a single platform for modelling, and not to complicate the modelling process with many softwares, then BASEMENT might be a viable option (Lala et al. 2017). Furthermore, BASEMENT was found to be delivering accurate results on dam breaking phenomenon which were in accordance with the site observations (Worni et al. 2012). It can also perform dynamic analysis of the GLOF process chain downstream of the avalanche (Worni et al. 2014; Lala et al. 2017).

| Source | Avalanche modelling | Lake wave generation | Breaching process | Flood propagation |
|--------|---------------------|----------------------|-------------------|------------------|
| (Lala et al. 2017) | RAMMS | BASEMENT | BASEMENT | BASEMENT |
| (Somos-Valenzuela et al. 2016) | RAMMS | FLOW 3D | BASEMENT | FLO 2D |
| (Mergili et al. 2018; Mergili et al. 2017; Mergili et al. 2018) | r.avaflow | r.avaflow | r.avaflow | r.avaflow |
| (Schneider et al. 2014) | RAMMS | IBER | – | RAMMS |
| (Bajracharya et al. 2007) | – | – | NWS-BREACH | NWS-FLDWA, |
| (Shrestha et al. 2010) | – | – | NWS-BREACH | BOSS-DAMBRK |
| (Christen et al. 2010) | RAMMS | – | – | – |
| (Anacona et al. 2015; Alho et al. 2007; Wang et al. 2012) | – | – | – | HEC-RAS |
| Alho and Aaltonen (2008) | – | – | – | HEC-RAS, |
| (Carrivick 2006) | – | – | – | SOBEK, from Delft |
| (Carrivick et al. 2009, 2010) | – | – | – | Delft3D |
| Jain et al. (2012) | – | – | – | MIKE 11 |
| Pitman et al. (2013) | – | – | – | TITAN 2D |
| Petrakov et al. (2012) | – | – | – | FLO 2D |
| and Pilotti et al. (2014) | – | – | – | – |
Since, a wide range of modelling software is available which are capable of modelling in 1 D, 2 D, and 3 D, suitable software can be selected as per the requirement of the task.

3. Conclusion and discussion

As discussed previously, experimental investigations of dam failure have stressed the formation of surge waves, however, very little focus is given to the attenuation of surge waves. Attenuation of these surge waves is critical for the full understanding of the failure mechanism of a moraine dam. Also, the concentration of studies on other aspects of the failure mechanism such as the interaction between surge wave and the materials, the initiation and erosion rate of dam materials are required.

Most of the research has been carried out by considering dam-break flow with water as the only material present in the flow, without accounting the impacts of sediment which plays a major role for the enlargement of discharge in valley downstream. However, recent studies have been able to incorporate the effects of solid particles in the flow so as to make the study more realistic (Mergili et al. 2018), and this trend is supposed to be continued in future studies as well.

Moraine dam failure, itself, is a cascade phenomenon; initiated from the ice and rock avalanches or other triggering events causing displacement wave generation that results in breaching of the dam and finally the propagation of outburst floods. Furthermore, the moraine dam failures have the potential of yielding a series of hazard chains: glacial lake outburst flood, debris flow, the formation of debris flow dams, and then finally a flood. But, most of the research concentrated on the cascade process of moraine dam failure (Somos-Valenzuela et al. 2016), while, very little attention was paid to the series of hazard chain that might result due to the failure of moraine dam. Research works on the series of hazard events initiated by the failure of moraine dam appears to provide significant contribution for further advancement in this field.

A brief overview of the state of art pertained to the failure of moraine dammed lakes is provided in this review paper. Different aspects and investigation methods of the mechanism of moraine dam failure are discussed. Conclusions are drawn as follows:

- Moraine dams, formed during LIA, impounding large volume of water are found to be a huge threat because of its structure and composition of materials. Wave overtopping or piping are the two common mechanisms of failure for moraine dams.
- Empirical relationships of peak discharge with various parameters like volume and height of water before the failure of the dam, potential energy of water stored in a lake, embankment length and embankment width are discussed. The volume and height of water were found to be relatively significant factors in empirical equations for predicting the peak discharge of flow after dam failure. These empirical relationships had few shortcomings and methods to overcome these shortcomings are also suggested.
- Very few experimental investigations are done on the failure mechanism of moraine dams. Experimental studies were found to focus their concentration on impulse waves generated by landslides and granular effects of avalanche. Much
attention is required to investigate the failure mechanism of moraine dams for predicting their failure risk.

- Various approaches have been adopted for the physically based modelling of glacial lake outburst flood. Several softwares are compared to simulate the moraine dam failure process. The advantage and disadvantage for each software are concluded: FLO-2D can solve expressions for conservation of mass and momentum of sediment and water numerically, but material entrainment cannot be included; RAMMS can compute material entrained by mass flows and is suitable for avalanche modelling. If preference of the user is to utilize a single platform for modelling, and not to complicate the modelling process with many softwares, then BASEMENT might be a viable option.

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