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Debris Flow Modelling Using RAMMS Model in the Alpine Environment With Focus on the Model Parameters and Main Characteristics

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Debris flows are among the natural hazards that can occur in mountainous areas and endanger people's lives and cause large economic damage. Debris flow modelling is needed in multiple applications such as design of protection measures or preparation of debris flow risk maps. Many models are available that can be used for debris flow modelling. The Rapid Mass Movement Simulation (RAMMS) model with its debris flow module, (i.e. RAMMS-DF) is one of the most commonly used ones. This review provides a comprehensive overview of past debris flow modelling applications in an alpine environment with their main characteristics, including study location, debris flow magnitude, simulation resolution, and Voellmy-fluid friction model parameter ranges, (i.e. μ and ξ). A short overview of each study is provided. Based on the review conducted, it is clear that RAMMS parameter ranges are relatively wide. Furthermore, model calibration using debris-flow post-event survey field data is the essential step that should be done before applying the model. However, an overview of the parameters can help to limit the parameter ranges. Particularly when considering the similarity between relevant case studies conducted in similar environments. This is especially relevant should the model be applied for estimating debris-flow hazard for potential future events. This model has been used mostly in Europe, (i.e. Alpine region) for modelling small and extremely large debris flows.

Keywords: debris flow, RAMMS, review, magnitude, friction parameter, alpine environment

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INTRODUCTION

According to the updated Varnes classification, debris flows are defined as very to extremely rapid surging flows of saturated debris that occur in steep channels with significant entrainment of material and water (Hungr et al., 2014). Due to these characteristics debris flows can cause large economic damage and endanger human lives (Mikoš et al., 2004, 2007). Especially endangered are the so-called debris flows and torrential fans, (i.e. alluvial fans). These are relatively flat parts of mountainous regions that are often quite heavily populated (Bezak et al., 2019). Reliable debris flow prediction is often not possible due to limited geological information or details about triggering mechanisms such as extreme rainfall event (Takahashi, 2014). Therefore, the so-called back analysis of past debris flow events can be used to design

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Source (authors, year)	Location (year)	Magnitude [m^3]	Simulation resolution [m]	Dry-coulomb type friction parameter μ (Mu) [/]	Viscous-turbulent friction parameter ξ (Xi) [m/s^2]	Short description of the study
Cesca and D'Agostino (2008)	Fiames DFs, Dolomites, Italy (2006)	Six cases: 15,000; 10,600; 46,800; 11,000; 5,200; 2,100	20; 10; 10; 10; 5; 5	0.18; 0.2; 0.19; 0.37; 0.39; 0.45	500; 40; 15; 40; 100; 1,000	Comparison between RAMMS and FLO-2D. Cell size affected the shape of the inundated area markedly. The deposition area was overestimated, and deposition thickness underestimated, especially for the cell size 20 m. RAMMS had constantly excessive lateral dispersions.
Hauser (2011)	Arth DF; Goldau DF (2005), Switzerland	50.000–80.000; ~190.000	2; 2.5	0.20	10	$\xi < 50$ m/s^2 was used to limit DF velocities. ξ was positively correlated with DF velocity and μ was negatively correlated.
Hussin (2011)	Barcelonnette, France (1996; 2003)	100,000; 83,000–95,000. Both cases included entrainment where this is much larger than initial volume	5	0.06	500	Detailed sensitivity and probability analyses were conducted. The DEM accuracy greatly affected the topography of the area and the geometry of DF channel. This directly affected the DF behavior in terms of velocity and DF height. A rapid decrease of the channel slope caused a decrease in velocity and run-out distance. This led to an increase in the deposit height at the head of deposited DF. The run-out distance and the maximum DF height of the modeled DF was most sensitive to changes in ξ followed by μ.
Scheuner et al. (2011)	Mattenbach DF, Switzerland (2004); Walchensee, Germany	300–700; 900–7,100	2	0.1; 0.15	200; 125	The two case studies illustrated that RAMMS is a useful support tool for experts evaluating natural hazards. Different scenarios were analyzed.
Berger et al. (2012)	34 DF in Illgraben, Switzerland (2001–2010)	50,000–100,000	2.5	0.07	400	A large database of DF events from Illgraben was used for model calibration. In case of DF of 50,000 m^3 (return period 1 year), flow velocities were 4–6 m/s and peak discharge 75–125 m^3/s. For the 100,000 m^3, maximum velocities were 6–8 m/s and peak discharge 100–200 m^3/s
Hussin et al. (2012)	Barcelonnette, France (2003)	83,000–95,000 (larger part is entrainment)	5	0.06	500	A sensitivity analysis of the rheological and entrainment parameters was conducted. The effects of the entrainment modelling on the DF run-out, height, and velocity were estimated.
Scheidl et al. (2013)	Arundakopfbach DF Seefeldbach DF, south Tyrol, Italy (2002)	15,000; 70,000	NA	0.08; 0.18	300; 350	A short review of turbulent and Coulomb friction parameters is provided. Model was calibrated using information about deposition area.

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Source (authors, year)	Location (year)	Magnitude [m^3]	Simulation resolution [m]	Dry-coulomb type friction parameter μ (Mu) [/]	Viscous-turbulent friction parameter ξ (Xi) [m/s^2]	Short description of the study
Schneider et al. (2014)	Carhuaz GLOF, Peru (2010)	450,000	8	0.16 (granular debris flow); 0.01 (flood); 0.08 (viscous debris flow); 0.04 (hyperconcentrated flow)	500; 500; 500; 500	Cascade processes after GLOF were modelled using RAMMS and another model. Additionally, three scenarios were investigated where volume ranged from 100,000 to 3,000,000 (4,800,000 DF) m^3.
Frank et al. (2015)	Illgraben DF (2008); Spreitgraben DF (2010). Switzerland	~58,000; ~110,000	1 and 2	0.1–0.4 (after calibration: 0.05); 0.2/0.3 using entrainment after calibration	200–2,000 (after calibration: 1,200); 200 using entrainment after calibration	An entrainment model was incorporated into RAMMS–DF model for the Spreitgraben DF. **ξ** > 500 m/s^2 resulted in fast travelling times and no erosion. Erosion behavior could not be precisely represented using only one **μ** value for the entire DF path (**μ** = 0.20). With regard to erosion depth, **μ** = 0.30 is the best fit. Including entrainment substantially improved the prediction of spatial DF runout patterns as well as DF propagation.
Schraml et al. (2015)	Reiselehnrinne Creek (Pitztal) DF (2009); Festeticgraben Creek (Gesäuse) DF (2006), Austria	~20,000–25,000; ~10,000	2	0.11; 0.07 (0.23 in forest stand)	200; 300	A comparison of RAMMS and DAN3D models was conducted for two case studies. Best-fit parameters were determined in the calibration process. Sensitivity analysis was conducted in: i) The Reiselehnrinne Creek – best fit for runout distance (15,000–50,000 m^3, **μ** = 0.03–0.16, **ξ** = 100–700 m/s^2), and ii) the Festeticgraben – best fit for deposition area (10,000–20,000 m^3, **μ** = 0.01–0.24 (and 0.03–0.32 outside the DF channel), **ξ** = 100–1,400 m/s^2). Significant sensitivity was found to the variation in **μ** and DF volume, and lower sensitivity to variation in **ξ**.
Fischer et al. (2016)	Richleren DF (1987); Minstigerbach DF (1987); Glyssibach DF (2005); Varuna DF (1987). Switzerland	~4,000; ~30,000; ~70,000; ~185,000	2	0.27; 0.09; 0.1; 0.15	175; 150; 200; 150	Comparison of Flow-R model to RAMMS was performed for local studies for 4 DF using confusion matrix. The calibration of the RAMMS model was performed using all available information, (e.g. velocities, maximum discharge rates, affected areas).
De Finis et al. (2017a)	Gadria DF, Alps, Italy (2013)	~10,000	NA	No entrainment: 0.11 (after calibration: 0.02–0.3). With entrainment: 0.12 (after calibration)	No entrainment: 600 (after calibration: 130–800 tested values). With entrainment: 500 (after calibration)	Sensitivity analysis without entrainment showed that max. DF height is not overly sensitive to **ξ**, whereas it strongly depended on **μ** (inverse law for **μ** = 0.08–0.14). The DF velocity increased with **ξ** increasing and **μ** decreasing. The sensitivity of DF velocity to **μ** was much higher for high values of **ξ**. The application of entrainment in the simulation led to a decrease in the best-fit value of **ξ**, which corresponds to an increase in DF velocity.

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TABLE 1 | (*Continued*) A review of debris flow (DF) and Glacial Lake Outburst Flood (GLOF) modelling using RAMMS software and its debris flow module. Studies are sorted by the publication year of the source, and then in alphabetical order. NA indicates that the information was not provided in the cited reference. Multiple parameters are shown when combinations of these parameters were used.

Source (authors, year)	Location (year)	Magnitude [m^3]	Simulation resolution [m]	Dry-coulomb type friction parameter μ (Mu) [/]	Viscous-turbulent friction parameter ξ (Xi) [m/s^2]	Short description of the study
De Finis et al. (2017b)	Sernio fan (anomalous basin-fan system), Alps, Italy	NA	NA	0.05–0.2 (average: 0.12)	300–650 (average: 520)	No back calculation was possible. The sensitivity analysis showed that a decrease of the frictional parameters led to an increase in the runout, but not to a widening of the flow path. If the entrainment was not considered, DF was confined within the channel and avulsion was never observed. The runout changed if the entrainment was considered: In this case, for any combination of the friction parameters, DF always exited from the channel.
Frank et al. (2017)	Meretschibach DFs (2014); Bondasca DFs (2012), Switzerland	8,000–10,000; ~90,000	0.5; 2	0.6; 0.3	200; 400	RAMMS runout model was used to calibrate friction parameters **μ** and **ξ** by firstly inactivating RAMMS entrainment module to find plausible values for general DF properties. Then the RAMMS entrainment module is activated to further refine coefficient **μ**. This one parameter controls erosion along the DF path and thus deposited DF volume as well as DF runout distance. **ξ** Was calibrated using the approximate DF discharge (block release volume or hydrograph) and was the dominant control over DF velocities when DF was moving rapidly.
Kang et al. (2017)	Seoul DF; Chuncheon DF, Republic of Korea (2011)	NA	NA	0.1; 0.2	950; 800	Comparison between RAMMS and FLO-2D was performed. Relatively small watershed areas were investigated. Calibration was performed using information about past events.
RAMMS (2017)	Randa, Switzerland (2010)	5,000; 10,000	2	0.05–0.4 (after calibration: 0.225). First guess: tan(**α**)–slope angle in the deposition area	100–200 for granular flows and 200–1,000 for mud flows (after calibration: 130). First guess: 200	The choice of the friction parameters requires careful calibration of the model. This is done by using reference information such as: field data, photographs of runout zones, estimations or measurements of flow velocities, flow heights, and estimations of the material composition. This should be done by a person with expertise in DF characterization. It is common that different DF events in the same torrent show significant differences in composition. This fact makes the calibration of the friction parameters much more difficult and requires a calibration for different events.

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Source (authors, year)	**Location (year)**	**Magnitude [m³]**	**Simulation resolution [m]**	**Dry-coulomb type friction parameter μ (Mu) [/]**	**Viscous-turbulent friction parameter ξ (Xi) [m/s²]**	**Short description of the study**
Chung et al. (2018)	Xinzhuang Landslide, Taiwan (2009)	2,820,000	2	0.42	2,000	RAMMS was applied to assess the potential impact area and accumulation depths after a potential failure of a large-scale landslide. Maximum DF velocities up to 62 m/s in the upper part, and 18 m/s in the lower part.
De Finis et al. (2018)	Sernio fan (anomalous basin-fan system), Alps, Italy	10,000 m^3	NA	0.05; 0.05; 0.05; 0.12; 0.12; 0.12; 0.2; 0.2; 0.2	200; 400; 600; 200; 400; 600; 200; 400; 600	Sensitivity analysis was carried out, observing the changes in DF velocity and runout distance. A decrease of **μ** led to an increase in the DF velocity and in the runout distance, but not a significant widening of the DF path. An increase in DF velocity was observed for reducing **ξ**. The runout completely changed if the entrainment was considered. It led to a significant increase in DF volume (by a factor 14–23) due to channel debris yield rate of 50–100 m^3/m.
Frey et al. (2018)	Huaraz GLOF, Peru (1941)	Up to 3,000,000	5	0.08 (viscous DF); 0.04 (hyperconcentrated flow)	500; 500	RAMMS was applied for the case of eventual GLOF, where no surges were expected. Erosional processes were considered within predefined zones. Friction coefficients were adopted from Schneider et al. (2014).
Iribarren Anacona et al. (2018)	Manflas GLOF, Andes, Chile (1985)	5,000,000	30	≤0.001	500	RAMMS was applied to simulate large GLOF that travelled for 110 km; peak discharge was 11,000 m^3/s, velocity up to 12 m/s in the upper reaches, decreasing to 4 m/s in the lower reach. Coarser DEM caused DF runout to stop prematurely. Only very small **μ** values yielded reasonable runout estimates.
Kaltak (2018)	Stože DF, Slovenia (2000)	~700,000	4	0.075	200	Model was calibrated using information about affected area. Sensitivity analysis was also conducted for artificial terrain. Smaller numerical grid increased the deposition area. **μ** Had a larger impact on the DF deposition area than **ξ**.
Krušić et al. (2018), (2019)	Selanac DF, Serbia (2014)	~125,000	30; 5	0.05; 0.11	500; 500	Validation of DF models was made using: i) The runout distance data observed in the field, ii) by a comparison between DEM before and after the DF. Two DEMs were used, better results were obtained using 5 m DEM.
Tsao et al. (2018)	Hualien DF, Hualien County, Taiwan (2014)	5,000	5	0.225	150	RAMMS and its block release was used for back calculation of a real DF using hydrograph data and data on inundation area. The results were used to establish a hazard map of the area.

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Bezak et al. (2019)	Suhelj fan, Slovenia	62 potential DFs: 100–20,000 totaling to 225,000	4	Eight cases were investigated: 0.1; 0.1; 0.2; 0.2; 0.4; 0.4; 0.4; 0.5	Eight cases were investigated: 100; 1,500; 150; 600; 100; 400; 1,500; 400	Sensitivity analysis: a random sequence of DFs did not have a significant impact on the final fan characteristics after 60+ DF events with variable **μ** and **ξ** values. DF fan height increased with **μ** increase, and slightly increased with **ξ** increase, if **μ** was held constant.
Dietrich and Krautblatter (2019)	Roßbichelbach DF, Alps, Germany (2015)	9,550 ± 1,550	1	0.16	200	Three-point discharge hydrograph was used as input. Material entrainment was included. Calibrated friction parameters were typical for mud-rich DF.
dos Santos Corrêa et al. (2019)	Serra do Mar DFs, Brazil (1967)	Release height 1 and 1.3 m	8	0.05	100; 130; 160; 190; 200	Back-analysis of numerous DFs in 1967 using RAMMS. The simulations were not able to adequately reproduce the geometry of the DF deposits despite testing multiple combinations.
Gan and Zhang (2019)	Luzhuang gully DF, China (2014)	254,531	2	0.07	1,500	RAMMS without entrainment module was applied. It was calibrated considering DF volume, deposition heights and velocities. Friction coefficients were further estimated by applying a physical model (flume test in scale 1:100).
Nam et al. (2019)	Mt. Umyeon DF; Mt. Majeok DF, south Korea (2011)	1,931; 2,086	5	0.1; 0.1	950; 950	RAMMS was used for mud-flow simulations with sediment concentration set at 0.4 (sediment density was 2,600 kg/m^3). Validation was done with regard to flow velocities and sediment volume in the deposition area. Flow velocity was 8 m/s.
Rodríguez-Morata et al. (2019)	Sahuanay creek, Abancay, Andes, Peru (2012)	55,000	4 (channel) and 12 (fan)	0.2 for dry phase; 0.1 for wet phase	200; 400	The friction parameters **μ** and **ξ** were defined based on field observations of depositions, (i.e. area and maximum heights observed in each phase and DF volume).
Tsao et al. (2019)	Heliu Community DF, Taiwan (2015)	27,000	2	0.24	300	RAMMS was used for back-calculation of a real DF using live video (flow velocities), inundation area and deposition depth to validate the model.
Abraham et al. (2020)	Kurichermala DF, India (2018)	NA	12.5	0.01 (varied from 0.005 to 0.5)	100 (varied from 10 to 2000)	Back analysis of a devastating DF using geotechnical investigation. Runout modeling using block release option in RAMMS. Calibration of friction parameters using digital image processing to compare the shape of the actual DF and the simulated one.
Bezak et al. (2020)	Brezovški and Lukenjski graben, Slovenia (2018)	Debris flood: 48,000, out of that 7,000–10,000 of coarse deposits	1	0.13 for Brezovški graben, 0.2 for Lukenjski graben	400 for Brezovški graben, 900 for Lukenjski graben	Best fit parameters were determined using the inundation area. RAMMS was successfully applied for a debris flood modelling.

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Calista et al. (2020)	Marane DF, Abruzzo, Italy (2018)	NA	2	0.17	150	The friction parameters were calibrated using the inundation area and DF heights.
Franco-Ramos et al. (2020)	Pico de Orizaba Volcano Lahar, Mexico (2012)	~33,000	3.6 cm?	0.15	400	Combination of tree-ring based lahar reconstruction and process modeling with RAMMS was the first of this kind. The calibration of RAMMS was made exclusively on scar heights on trees (compared to modeled maximum lahar depths) and the extension of fresh deposits in the field. The estimated lahar peak discharge was 78 m^3/s. Lahar density 1,400 kg/m^3 was used. **μ** was determined based on the slope of the deposition zones.
Zimmermann et al., (2020)	19 hillslope DFs, Switzerland (2002–2012)	60; 130; 800; 378; 280; 918; 960; 392; 175; 1,050; 153; 2,800; 380; 100; 112; 91; 42; 108; 655	NA	0.23; 0.4; 0.3; 0.21; 0.13; 0.11; 0.46; 0.4; 0.49; 0.33; 0.35; 0.24; 0.33; 0.2; 0.37; 0.05; 0.05; 0.4; 0.29	200; 200; 200; 300; 240; 190; 150; 285; 300; 550; 1,250; 700; 1,100; 400; 175; 300; 200; 900; 700	In the modelling of hillslope DF, the back-calculated parameters **ξ** follow a narrower bandwidth than parameters **μ**. The study results showed a correlation between the back-calculated **μ** and the percentage of clay content of the mobilized soils. Considering cohesive interaction, the performance of all DF simulations improved in terms of reduced overestimation of the observed deposition areas.

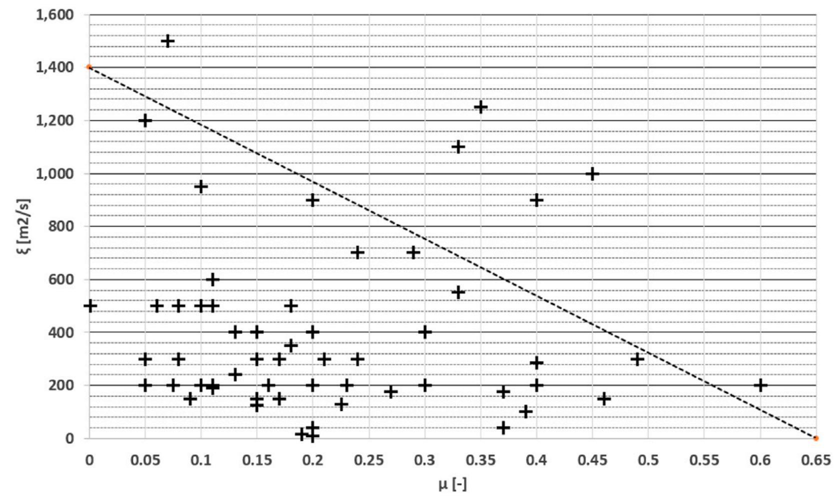

FIGURE 1 | Range of the Voellmy-fluid friction parameters (μ and ξ) used in the analyzed studies shown in **Table 1**, excluding one study with very large ξ parameter, (i.e. Chung et al., 2018).

engineering measures to reduce the risk (Rickenmann et al., 2006; Simoni et al., 2012; Bezak et al., 2020). Additionally, debris flow modelling can also be used for several other applications such as definition of risk maps. For these purposes, different types of debris flow models can be used (Rickenmann et al., 2006; Cesca and D'Agostino, 2008). This study reviews more than 30 past worldwide applications of the Rapid Mass Movement Simulation (RAMMS) model and its debris flow module (RAMMS-DF). This software is one of the available tools that can be used for debris flow modelling (Christen et al., 2012; RAMMS, 2017).

RAMMS AND DEBRIS FLOW MODELLING

The RAMMS model uses depth-averaged shallow water equations for granular flow in the single-phase model for debris flow modelling (RAMMS, 2017). The model employs the Voellmy-fluid friction model that includes two parameters, (i.e. the dry-Coulomb type friction μ (Mu) and the viscous-turbulent friction ξ (Xi)). These two parameters are usually calibrated, although other parameters such as stop parameter or simulation resolution also have an effect on the modelling results (Bezak et al., 2019). However, some of these are limited by data availability. A detailed description of the model's theoretical background and key equations are provided in the user's manual. **Table 1** provides a review of more than 30 past studies that used RAMMS software for debris flow modelling. It can be seen that RAMMS model has been frequently applied in Europe, (i.e. for the Alpine region) while applications in South America and Asia were also included in the review (**Table 1**). Furthermore, it can be also seen that RAMMS was used for modelling relatively small debris flows, (i.e. 1,000 m^3 or less) to extreme ones where their magnitude exceeds a couple of million m^3 (**Table 1**). The simulation resolution was in most cases very high, especially considering large debris flow magnitudes with resolution ranging from less than 0.5 m to 20 or 30 m (**Table 1**). In most cases, the resolution was between 2 and 5 m (**Table 1**). Moreover, the Voellmy-fluid friction parameters covered wide ranges (**Figure 1**). Low values for the both parameters are prevailing, and only a few case studies used the parameters above the line connecting the end points: ($\mu = 0$, $\xi = 1{,}400$ m/s^2) ($\mu = 0.65$, $\xi = 0$ m/s^2). Nevertheless, they mostly stayed within the ranges indicated by Scheidl et al. (2013) as typical for debris flows (**Table 1**). More specifically, Dry-Coulomb type friction parameter μ (Mu) ranged from less than 0.001 to 0.7. Most often, the value of this parameter was around 0.1 or 0.2 (**Table 1**). The Viscous-turbulent friction parameter ξ (Xi) ranged from 10 m/s^2 to 2,000 m/s^2. Its value was most often between 200 and 500 m/s^2 (**Table 1**). The debris flow magnitude slightly decreases and increases with increasing μ and ξ, respectively. Nevertheless, no significant correlation could be detected (**Table 1**). As illustrated, the RAMMS model was used for a variety of different applications, including modelling of the glacial lake outburst flood (**Table 1**). **Figure 2** shows a result of a typical application of the RAMMS model in an alpine environment.

CONCLUSION

No clear pattern can be observed in the reviewed studies regarding the frequency of the most suited friction parameters μ and ξ. Evidently, the RAMMS model parameters clearly depend on local debris flow characteristics such as topography, rheological properties, and hydro-meteorological conditions. Therefore, as already suggested in the RAMMS manual (RAMMS, 2017), model calibration should be the optimal way to determine the

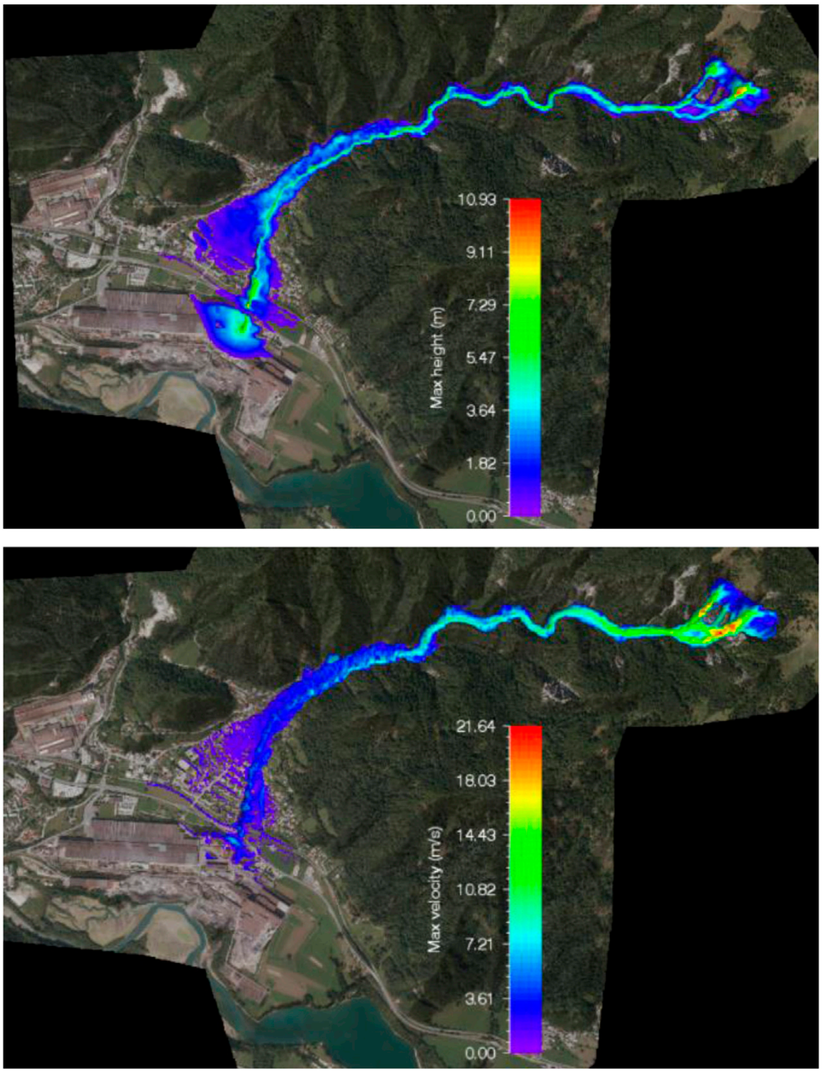

FIGURE 2 | A typical RAMMS modelling results for the Urbas landslide (Koroška Bela Municipality, Slovenia) in a case of potential debris flow triggering. Maximum debris flow height and velocity are shown. Results using μ = 0.075 and ξ = 200 m/s^2 and a hydrograph volume of 200,000 m^3 and a peak discharge of 2,680 m^3/s are presented.

friction parameters that clearly have a significant impact on the modelling results (**Table 1**). Moreover, further research could focus on a better connection of the RAMMS model parameters with the physical features of an area or debris-flow material.

AUTHOR CONTRIBUTIONS

MM prepared the first version of **Table 1**. NB made an update and verification of the table. Both authors contributed to the writing and editing of the article and approved the submitted version.

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