Original Article

Sensitivity Analysis of Debris Flow Simulations Using Kanako-2D

Maurício A. PAIXÃO ¹, Masato KOBIYAMA ², Masaharu FUJITA ³ and Kana NAKATANI ⁴

¹ Institute of Hydraulic Research, Federal University of Rio Grande do Sul, Brazil
(9500 Bento Gonçalves Avenue, Porto Alegre/RS-91501-970, Brazil)
E-mail : mauricio.paixao@ufrgs.br

² Institute of Hydraulic Research, Federal University of Rio Grande do Sul, Brazil
(9500 Bento Gonçalves Avenue, Porto Alegre/RS-91501-970, Brazil)
E-mail : masato.kobiyama@ufrgs.br

³ Disaster Prevention Research Institute, Kyoto University, Japan (Gokasho, Uji, Kyoto 611-0011, Japan)
E-mail : fujita.masaharu.5x@kyoto-u.ac.jp

⁴ Graduate School of Agriculture, Kyoto University, Japan (Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan)
E-mail : nakatani.kana.4z@kyoto-u.ac.jp

Due to the complexity and difficulty of observing debris flow in the field, computational modeling has been used to investigate this geological phenomenon. One of the computational simulators for this purpose is Kanako-2D. In order to understand the phenomenon itself and the model, the present study performs a sensitivity analysis of the Kanako-2D simulator in relation to runout distance, reached area, and flow width. The values of the input parameters were individually changed in a physical-based criterion while the others were kept at standard values. Real slope-site with a history of debris flow and a hypothetical slope-site with similar characteristics were utilized. The sensitivity analysis was quantified from three methods : screening, regionalized, and variance analysis. The results show high sensitivity to Kanako-2D for the angle of internal friction, sediment diameter, the mass density of the fluid phase, and the mass density of bed material.

Key words : debris flow, sensitivity analysis, sediment disasters, Kanako-2D

1. INTRODUCTION

Debris flow is a natural phenomenon with high destructive power, governed by gravity, composed of a mixture of water, air, and sediments [Takahashi, 2007], and considered one of the most dangerous mass movement types due to its high flow velocity and long travel distances [Jakob and Hungr, 2005]. Disasters related to debris flows have been causing serious damages to society, impacting human lives, houses, infrastructure, and the environment worldwide.

Though science and technology have been significantly advanced in terms of understanding the debris flow occurrence mechanism throughout last decades [Coussot and Meunier, 1996 ; Iverson, 1997 ; Vandine and Bovis, 2002 ; Jakob and Hungr, 2005 ; Takahashi, 2007 ; Cui et al., 2013 ; Takahashi, 2014 ; Wu, 2015 ; Wendeler, 2016 ; Suzuki et al., 2018], such understanding is still not satisfactory for the prediction of debris flow [Zhou et al., 2019] and consequent reduction of such disaster. Therefore, society needs more studies on this phenomenon to implement adequate countermeasures that can be classified into

two types : structural and non-structural.

Independent of a type of disaster and countermeasure, computational modeling has been commonly used in the world. Observing recent works such as Jakob and Hungr (2005) and Takahashi (2007) and van Asch et al. (2014), it can be said that this comment is still valid for reducing debris flow disasters. Because of the important role of computational simulation for such disaster reduction, various models and software have been proposed. Richit et al. (2017) reviewed several software programs that simulate debris flows and classified them in different criteria, such as DFLOWZ, FLO-2D, FLOW-R, Hyper-Kanako, Kanako-2D, MassMov 2D, r. avafLOW v 1, RAMMS, RASH 3D, TRENT 2D (WG), and UBCDFLOW.

The Kanako-2D model developed by Nakatani et al. (2008) is a physically-based model, with free access, user friendly, and GUI-equipped. According to these authors, the initial objective was to evaluate the influence of different types of SABO dams on flow propagation. However, this model has been used to map susceptible areas to debris flow and other

objectives, for example, *Liu et al.* (2013), *Yanagisaki et al.* (2016), and *Nakatani et al.* (2016).

Several studies have shown the Kanako-2D assertiveness [Nakatani et al., 2010; 2011; Michel et al., 2015; Paixão and Kobiyama, 2017; Kobiyama et al., 2018; Kobiyama and Michel, 2019; Michel et al., 2019]. Because of the above-mentioned characteristics, Kanako-2D has a high potential to predict areas prone to debris flow occurrences. However, this debris flow simulator has not been evaluated in terms of sensitivity yet. In general, studies using numerical simulations for the reproduction of debris flow only present the best fit results, while differences between models and key parameters are not sufficiently clarified. Thus, the present study aims to address these deficiencies. The objective of the present study is to execute a sensitivity analysis of Kanako-2D using debris flow that occurred in a small catchment in southern Brazil and virtual debris flow occurrence in a hypothetical catchment, aiming the reduction of disasters related to debris flow through computational modeling.

2. MATERIAL AND METHODS

2.1 Kanako-2D theory

The Kanako-2D simulator consists of integrated 1D and 2D models, approaching the debris flow from its entrance into the channel with one-dimensional equations and its propagation and deposition on the alluvial fan with two-dimensional equations. The equations are based on previous studies by *Takahashi and Nakagawa* (1991) that considered the debris flow as a dilatant fluid model and included equations for momentum, continuity, riverbed deformation, erosion/deposition, and riverbed shear stress. Since the present study focus only on runout distance and reached area of debris flow for a sensitivity analysis, we do not analyze the SABO dam equations that are inserted in Kanako-2D.

The continuity equation for the total volume is described as :

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = i \quad (1)$$

The continuity equation for the material volume of debris flow :

$$\frac{\partial Ch}{\partial t} + \frac{\partial Chu}{\partial x} + \frac{\partial Chv}{\partial y} = iC_* \quad (2)$$

The momentum equations in x (main flow direction) and y -axis (cross flow direction) are, respectively :

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = g \frac{\partial H}{\partial x} - \frac{\tau_x}{\rho h} \quad (3)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = g \frac{\partial H}{\partial y} - \frac{\tau_y}{\rho h} \quad (4)$$

The bed surface alteration is described as :

$$\frac{\partial z}{\partial t} + i = 0 \quad (5)$$

For the deposition velocity ($i < 0$) along the riverbed :

$$i = \delta_d \cdot \frac{C_\infty - C}{C_*} \cdot \frac{q}{h} \quad (6)$$

For the erosion velocity ($i \geq 0$) along the river bed :

$$i = \delta_e \cdot \frac{C_\infty - C}{C_* - C_\infty} \cdot \frac{q}{d} \quad (7)$$

Here, the equilibrium concentration (C_∞) can be calculated as :

$$C_\infty = \frac{\rho \cdot \tan \theta}{(\sigma - \rho) \cdot (\tan \phi - \tan \theta)} \quad (8)$$

The riverbed shearing stresses in x -axis direction for stony type ($C \geq 0.4C_*$), immature ($0.01 < C < 0.4C_*$), and bed load transportation or turbulent-muddy-type ($C \leq 0.01$ or $h/D \geq 30$), Kanako-2D uses the equations (9), (10), and (11), respectively. The riverbed shearing stress in y -axis direction is determined when u is replaced by v in Eqs. (9)-(11) :

$$\frac{\tau_x}{\rho^h} = \frac{u \sqrt{u^2 + v^2} d^2}{8h^3 \left\{ C + (1-C) \frac{\rho}{\sigma} \right\} \left[\left(\frac{C_*}{C} \right)^{1/3} - 1 \right]^2} \quad (9)$$

$$\frac{\tau_x}{\rho^h} = \frac{1}{0.49} \frac{u \sqrt{u^2 + v^2} d^2}{h^3} \quad (10)$$

$$\frac{\tau_x}{\rho^h} = \frac{g n_m^2 u \sqrt{u^2 + v^2}}{h^{4/3}} \quad (11)$$

where h is the flow depth ; z is the bed elevation ; H is the flow surface elevation ; u is the velocity in the x -axis ; v is the velocity in the y -axis ; g is the gravity acceleration ; C is the sediment concentration by volume in debris flow ; t is the time ; C_* is the sediment concentration by volume in movable bed layer ; ρ is the mass density of the interstitial fluid ; i is the sediment erosion/deposition velocity ; τ_x and τ_y are the riverbed shearing stress in x and y directions, respectively ; q is the discharge of debris flow per unit width ; d is the mean particle size ; C_∞ is the equilibrium concentration ; δ_d is the coefficient of deposition velocity ; δ_e is the coefficient of erosion velocity ; ϕ is the internal friction angle ; σ is the density of material ; and n_m is the Manning's roughness coefficient.

The general view of the Kanako-2D interface is

shown in **Fig. 1**. In the Kanako-2D model, there are nine input parameters: the mass density of bed material, the mass density of fluid phase, the concentration of movable bed, Manning's roughness coefficient, the coefficient of erosion rate, the coefficient of deposition rate, sediment diameter, internal friction angle, and sediment concentration.

Due to the difficulty of establishing a parameter distribution, we did not perform a GSA. According to

$K2$ values can be positive or negative, denoting how intense a change in the result is due to the relative change in the parameter. Positive values indicate positive variations between input and default parameter results. Comparatively, negative values mean that the result becomes smaller in comparison with the previous step. The $K2$ method allows for the identification of the largest response variation within the analyzed parameter range and indicates the parameter value for which the model is most sensitive. This analysis is important because it can provide a baseline for the modelers to choose values to be used in simulations, reducing the time spent in calibration and validation of the model. In other words, the $K2$ method analyzes the relative variation of a model response with the immediately following response, acting as a derivative function that the model's behavior involves in a given analysis point.

Table 1 Input parameters of Kanako-2D model.

Parameter	Range of values	Tested values	Reference	Default (Kanako-2D)	Typical Values
AIF (ϕ)	22 to 45	22, 25, 30, 35, 37, 40, 45	ASTM (1985) Iverson (1997)	37	25 to 45
CDR (δ_d)	0.0001 to 1.00	0.0001, 0.0010, 0.0100, 0.0500, 0.1000, 0.2000, 0.3000, 0.4000, 0.5000, 0.6000, 0.7000, 0.8000, 0.9000, 1.0000	Takahashi (2007)	0.05	-
CER (δ_e)	0.0001 – 0.1000	0.0001, 0.0007, 0.0010, 0.0100, 0.0300, 0.0400, 0.0500, 0.0800, 0.0900, 0.1000	Takahashi (2007)	0.0007	-
CMB (C^*)	0.50 – 0.80	0.50, 0.65, 0.80	Takahashi (2007)	0.65	0.65
MDB (σ)	2100 – 2700	2100, 2150, 2300, 2450, 2650, 2700	Rio de Janeiro (2016) Iverson (1997)	2650	2100
MDF (ρ)	1000 – 1500	1000, 1100, 1200, 1300, 1400, 1500	Fernando (2013) Iverson (1997)	1000	1000 to 1200
MRC (n_m)	0.025 – 0.300	0.025, 0.030, 0.050, 0.100, 0.150, 0.200, 0.300	Chow (1959) Jin and Fread (1999) Rodriguez et al. (2006)	0.030	0.030
SDI (d)	0.01 – 3.00	0.01, 0.05, 0.10, 0.30, 0.45, 0.50, 1.00, 2.00, 3.00	Iverson (1997)	0.45	up to 10

where AIF is the internal friction angle ($^\circ$), CDR is the coefficient of deposition rate, CER is the Coefficient of erosion rate, CMB is the concentration of the movable bed (m^3/m^3), MDB is the mass density of bed material (kg/m^3), MDF is the mass density of the fluid phase (kg/m^3), MRC is the Manning's roughness coefficient, SDI is the sediment diameter (m).

$K3$ values are always positive and denote how far the results are from an expected result, i.e., the default results. The results are evaluated by the variance, whose values around zero indicate low sensitivity, because the results do not largely change when the parameters are changed. The bigger the $K3$ value, the greater the sensibility. The $K3$ method adds robustness to the sensitivity analysis trying to identify how much the response goes away from a central value of the samples, in this case, the results are obtained by default parameters. It means that the more the results of a parameter deviate from the default response, the greater the sensitivity that this parameter causes in the model. Thus, the sensitivity should be evaluated considering the three proposed methods together, not individually. In other words, the combination of these three methods allows for comparing the results even that some parameters vary widely in magnitude order.

2.3 Parameter variations and evaluation method

Kanako-2D has been used for debris flow prediction, however, we observe in the literature that the simulator's parameters have been used to settled as or considerably close to default by many authors and users. Based on a literature review, we determined the range of each parameter variation and parameters used for simulations (Table 1). It is important to highlight that the default value of each parameter in Kanako-2D does not mean, necessarily, its recommended or typical value. Furthermore, some parameters cannot be freely

changed, because they depend physically on interactions with others, such as sediment diameter and Manning's roughness coefficient. However, the present paper aims to analyze the sensitivity of Kanako-2D when its parameters are changed, trying to identify for which one the simulator shows sensibility. For this reason, we changed the input parameters individually without further considerations.

The input parameters data need to be assessed for uncertainty to identify the parameter range variation that is physically based [EPA, 2009]. Furthermore, it is important to correctly establish the input parameters and their combinations to avoid physically unreasonable results. The variation for each parameter was chosen based on the range of possible values (Table 1), considering values close to each other to permit the analysis of the simulator's behavior when some parameters had been changed. As the typical values were inserted in the considered range, they were also indirectly analyzed. Some considerations should be made about the tested values of the parameter.

The AIF is the internal friction angle ($^\circ$) and parameter ϕ often applied for simulations, varies depending on the particle's composition. Typically, they vary from 22 (silt composition) to 45 degrees (granular compacted sand composition) [ASTM, 1985]. Thus, the considered range in the SA contemplates all possibilities of AIF.

The CDR is the coefficient of deposition rate and

the CER is the coefficient of erosion rate. Parameters δ_d and δ_e are often applied for simulations. *Takahashi* (2007) commented that both the CER and CDR should be more empirical and theoretically discussed because they comprehend uncertainties related to erosion and deposition during debris flow occurrences. There is still a lack of knowledge on ways to measure or estimate these parameters either in the field or laboratory. Meanwhile the former is an experimental value, the latter is an empirical value. Thus, introducing such parameters causes difficult technical problems. In addition, they vary in a large order of magnitude, depending on the relief, mechanical, and runout properties. Such technical problems increase the difficulty of performing debris flow simulations.

The CMB is the concentration of the movable bed (m^3/m^3) and parameter C_s is often applied for simulations. According to *Takahashi* (2007), the CMB is usually lower than $0.65 \text{ m}^3/\text{m}^3$ but higher than $0.10 \text{ m}^3/\text{m}^3$, and values lower than $0.50 \text{ m}^3/\text{m}^3$ are considered small. Hence, typical values are around $0.65 \text{ m}^3/\text{m}^3$ for CMB. *Suzuki et al.* (2020) found CMB around $0.8 \text{ m}^3/\text{m}^3$. Also, from previous studies on actual riverbeds and from some models presenting riverbed packing, minimum porosity was found 0.2, that is, maximum CMB was $0.8 \text{ m}^3/\text{m}^3$ [*Sulaiman et al.*, 2007; *Takebayashi et al.*, 2012]. Although *Sulaiman et al.* (2007) and *Takebayashi et al.* (2012) focused on gentle slope river not directly related to the debris flow CMB, we decided to range from 0.5 to 0.8. Kanako-2D adopts one grain-size in the simulation, however, for the riverbed conditions and for SA the use of maximum CMB can be useful.

The MDB is the mass density of bed material (kg/m^3) and parameter σ is often applied for simulations. Although the MDB may vary between 1600 to $2700 \text{ kg}/\text{m}^3$, the lower limit is rarely found, except in specific regions such as volcanic areas. Typical values for the MDB are close to $2100 \text{ kg}/\text{m}^3$. Thus, the range between 2100 and $2700 \text{ kg}/\text{m}^3$ is used for the present sensitivity analysis.

The MDF is the mass density of the fluid phase (kg/m^3) and parameter ρ is often applied for simulations. The MDF ranges from 1000 to $1500 \text{ kg}/\text{m}^3$ according to *Fernando* (2013), however, typical values range from 1000 to $1200 \text{ kg}/\text{m}^3$ [*Iverson*, 1997]. In order to evaluate its influence on simulation results, the full range was considered.

The initial sediment concentration can be obtained and tested according to *Takahashi et al.* (2001), depending on the MDB, the MDF, and the AIF. Such concentration influences the peak discharge of debris flow and consequently the hydrograph condition and the simulated results. Nonetheless, several studies discussed an appropriate shape of the debris flow

hydrograph [*Rickenmann*, 1999; *Quisca*, 2002; *Shen et al.*, 2018]. As we have already determined the inflow hydrograph by using the *Rickenmann* (1999) and the estimated volume, the initial sediment concentration cannot be changed. Therefore, the initial sediment concentration was not evaluated in this SA.

The MRC is the Manning's roughness coefficient ($\text{s}/\text{m}^{1/3}$) and parameter n_m is often applied for simulations. In relation to MRC, the used values vary from 0.025 to 0.200 for natural streams according to *Chow* (1959), however, during a debris flow event, the roughness can be higher, as demonstrated by *Jin and Fread* (1999) and *Rodriguez et al.* (2006). *Suzuki et al.* (2018) described a set of physical models adopted in Kanako-2D, including the use of MRC values. However, it is important to note that: i) MRC values are not used in the Kanako-2D simulation unless the sediment concentration is smaller than 1%; and ii) when the ratio between flow depth and diameter become larger than 30, the riverbed shearing stresses implement n_m values also in high concentration. Such conditions can be seen in riverbed shearing stresses equations, especially in Eq. (11). Thus, depending on set conditions of hydrograph and sediment concentration, the MRC cannot be ignored although it is usually not well implemented in simulations.

The SDI is the sediment diameter (m) and parameter d is often applied for simulations. In relation to SDI, the particle size cannot exceed the flow depth as Kanako-2D employs a single-phase model of debris flow. By considering the given conditions in this analysis, the maximum diameter is set to 3 m. Since Kanako-2D can simulate a large range of sediment diameter, from small to large sediments, the range was set from 0.01 to 3.00 m. The considered range includes all types of debris flow that Kanako-2D can simulate.

The results of debris flow simulated with Kanako-2D were quantified in terms of runout distance, width, and reached area (**Fig. 2**). The runout distance was measured from the initiation center zone to the lowest deposition point on an alluvial fan. We considered the mean width and the debris flow patch. The deposit of

Fig.2 Debris flow measurements.

Fig.3 Real slope-site : (a) Bõni creek catchment, (b) debris flow scar of the 2000 event (source : provided by Boeni family).

sediments in the alluvial fan was counted as the reached area, not considering part of sediments that could be deposited in the transport zone.

2.4 Real Slope-site

The real slope-site is the Bõni creek catchment (**Fig. 3 a**) (2.27 km²) located in the Rio Grande do Sul State, south Brazil. Its altitudes vary from 356 m to 680 m. Though this region has a vast history of mass movements, the events that occurred in 1982 and 2000 are highlighted. The region is located between escarpments and plateau, showing a typical mountainous environment. **Fig. 3 b** shows the region where four shallow landslides took place in the event of 2000. According to *Michel* (2015), the events in 2000 are characterized by shallow landslides that became a debris flow when the landslides converged to the channel. Also, the maximum thickness of the movable layer in the study area is around 2 m, then used this value for both real and hypothetical slope-site.

Field surveys were conducted during the periods of

Fig.4 Hypothetical slope-site.

July 19th-21st and July 26th-28th 2016 to identify the 2000's landslides scars. Although the event occurred a long time ago, we could identify both scars and part of the debris flow course. The scar limits permitted to estimate the sediment volume that was dislocated during the debris flow event. The field-estimated scar area was 3750 m² and, according to *Michel* (2015), the maximum soil depth in this region is 2 m. Thus, the sediment volume considered was 7500 m³.

To establish the sediment hydrograph, we used the method described by *Whipple* (1992), which adopted a triangular form with a shorter rise time and a longer recession time. In the present study, the recession time was twice longer than the rising time. The estimated peak discharge was 160 m³/s based on the equations described by *Rickenmann* (1999). The used digital elevation model (DEM) with 2.5 x 2.5 m resolution of this catchment was provided by the Brazilian Geological Survey-CPRM. The created grid condition for the alluvial fan (2D) presents the same resolution of the DEM data. The domain size (157 x 482 meshes) of simulations is shown in **Fig. 3 a** for 1D and 2D.

The calculation conditions were the same for both the real and hypothetical slope-sites. For 1D, $\Delta x=10$ m, and for 2D, $\Delta x=\Delta y=2.5$ m, with time-step of 0.03 s.

2.5 Hypothetical Slope-site

Hypothetical slope-sites are ideal terrain with constant slopes along the hillslope and alluvial fan. This condition could avoid geomorphic terrain peculiarities that can influence debris flow dynamics. In order to analyze the topography influence on debris flow propagation, we used a hypothetical terrain with same general characteristics of hillslope (60 m of length and 18° of slope in transport zone - 1D) and alluvial fan (4° of slope in deposition zone - 2D) of the real slope-site (**Fig. 4**).

The sensitivity analysis was performed in the same manner that it was used for the case of the real slope-site, varying the parameters according to **Table 1**.

Table 2 Summary results of the sensitivity analysis.

Real Slope-site	K1			K2			K3		
	Runout Distance	Reached Area	Width	Runout Distance	Reached Area	Width	Runout Distance	Reached Area	Width
AIF(φ)	-0.96	-3.04	-1.54	8.5	4.18	4.66	747.97	3360.58	695.08
CDR(δd)	-0.01	-0.34	-0.04	-0.91	4.86	3.36	257.24	1646.16	636.34
CER(δe)	0	0.02	0.01	0.15	0.16	0.95	388.83	12849.23	5602.82
CMB(C^*)	0.36	0.64	0.21	0.36	0.64	0.21	34.41	109.76	12.64
MDB(σ)	-2.25	-2.06	-0.06	-4.95	-2.57	5.4	442.75	273.1	13.7
MDF(ρ)	1.39	2.48	-0.09	4.91	4.08	-0.74	1100.96	2159	13.67
MRC(n_m)	0.02	0	0	0.34	-0.06	0.4	250.43	9.46	92.7
SDI(d)	-1.25	-1.05	0.55	13.05	2.34	5.1	3661.64	3025.05	584.92
Hyp. Slope-site	K1			K2			K3		
	Runout Distance	Reached Area	Width	Runout Distance	Reached Area	Width	Runout Distance	Reached Area	Width
AIF(φ)	-0.73	-1.57	-0.49	1.14	2.27	2.22	199.87	921.99	86.34
CDR(δd)	-0.12	-0.17	-0.07	0.32	2.74	1.41	415.15	11519.7	1725.74
CER(δe)	0	0	0	-0.04	0.01	0.19	16.3	391	36.72
CMB(C^*)	0.65	1.17	-0.58	0.91	1.63	-0.75	200.44	640.03	153.48
MDB(σ)	-0.81	-1.86	0.04	9.56	22.75	10.66	80.58	439.89	16.17
MDF(ρ)	0.59	1.4	0.03	5.4	2.15	1.47	589.87	763.64	39.41
MRC(n_m)	0	0	0	0.04	0.03	-0.72	0.77	0.86	56.89
SDI(d)	0.03	0.12	0.01	2.5	2.34	-5.1	110.56	385.74	348.44

3. RESULTS AND DISCUSSION

The sensitivity analyses of debris flow using Kanako-2D were performed using screening ($K1$), regional ($K2$), and variance analysis ($K3$) methods. A total of 124 simulations were run to perform the SA. **Table 2** presents the results of the real and hypothetical slope-site. The results present the maximum relative values obtained by the three different methods for each parameter allowing us to infer that the parameter that implied more sensibility to Kanako-2D presented the highest value in the same analysis method.

3.1 Screening Method ($K1$)

The $K1$ method provides a general understanding of the model when parameters vary between their two extreme values. According to the results obtained by this method, we observed that the sensitivity of some parameters was similar both to real and hypothetical slope-sites.

The CER did not show variation within its range, which indicates that this parameter is not sensitive to the model. It can be said that there is a need to theoretically and empirically define the CER because there is still a lack of information on the way to execute its measurements in the field or laboratory. This current situation has been causing uncertainties to define the values of CER even within the range

proposed by *Takahashi* (2007). Similarly, the CDR presented a slightly negative variation for runout distance, reached area, and width of debris flow, both in the real and hypothetical slopes.

The results of the SA implemented here do not show significant variation for *MRC*. This reason can be thought by the limited conditions for applying the Eq. (11) as the sediment concentration (C) is smaller than 1% or when $h/d \geq 30$. This coefficient is only contributed to the riverbed shear stress when the sediment concentration is these conditions. However, its contribution cannot be ignored

The coefficient is considered when the sediment concentration is smaller than 1% or when $h/d \geq 30$, which can be observed at a specific condition of the debris flow. However, its contribution cannot be ignored.

The parameters that presented high sensitivity to the model are *MDB*, *MDF*, *SDI*, *AIF*, and the *CMB* for runout distance, reached area, and width in both the real and hypothetical slope-sites.

The bed where the debris flow is running out is a potential zone to generate sediments, especially by remobilization of the bed material. According to Eq. (6), the higher the *CMB*, the lower the deposition velocity. Thus, the runout distance, reached area, and width become larger. The *MDB* directly influence on the equilibrium concentration, C_∞ (Eq. (8)), affecting

the deposition (Eq. (6)) and erosion (Eq. (7)) patterns. As larger the MDB, smaller the equilibrium concentration according to the Eq. (8). Such condition can affect the incorporation of sediments to the flow. Thus, this parameter is especially important for the modeling of debris flow using Kanako-2D.

Based on Eq. (8), it is noted that an increase in MDF elevates the C_{∞} value, which affects the erosion/deposition patterns. Keeping constant the other parameters of Eqs. (6)-(7), an increase in MDF intensifies erosion, allowing the flow to have larger runout distances.

SDI is an important input parameter that presents sensitivity to Kanako-2D. The results are in accordance with *Uchida et al.* (2013), which commented that patterns of erosion, deposition, and runout distance are strongly affected by SDI. Sediment erosion/deposition velocity and riverbed stresses equations are depending on SDI. In case of erosion, when SDI reduces, the erosion velocity increases. Furthermore, in riverbed shear stress, a reduction in SDI implies in lower values of shear stress to motion the debris flow for stony-type, and immature debris flow. Thus, as SDI becomes smaller, the runout distance and reached area are larger. On the other hands, for bedload transport or turbulent-muddy-type, the shear stress does not depend on SDI, but roughness and flow conditions

The AIF is also an important parameter, which increases and decreases the runout distance, reached area, and width of the debris flow. The AIF depends on particles conditions, and higher values are related to angular and larger sediments, such as compacted sand and gravels. The motion of these type of sediments more easily generates shear stress. Such condition may impact reached area and width of the debris flow.

Experiments conducted by *Takahashi* (1977) showed a relationship between terrain slope and CMB. The experiments showed that the CMB is strongly influenced by terrain conditions, maintaining the relation approximately constant. This parameter presented sensitivity to the Kanako-2D model, especially for the width of the debris flow. It indicates that the spread of the debris flow is strongly related to topographic and soil conditions.

3.2 Regional Method (K2)

In terms of runout distance, the parameters that generated the highest sensitivity to the model for both slope-sites were the SDI, AIF, MDB, and MDF.

For reached area, the parameters that generated the highest sensitivity to the model for both slope-sites were the CDR, AIF, MDF, MDB, and SDI. These parameters also generated the highest sensitivity to debris flow width in both slope-sites.

The results of *K2* indicate that SDI induces higher variations in runout distance, reached area, and width of the debris flow. It should be noted that the SDI range varies in several orders of magnitude. According to Eq. (7), the erosion velocity increases as the diameter reduces. Such condition may explain the importance of SDI in the runout distance, reached area, and width of the debris flow. Thus, we strongly recommend the measurement of this parameters in the field. As Kanako-2D employs a single-phase model, it is necessary to discuss what is the representative SDI to be measured in the field and considered for better-performing simulations. In these cases, we recommend the comparison between measured and calibrated values.

According to the dilatant fluid theory [*Bagnold*, 1954], an increase or reduction in the number of particle collisions influences on the energy dissipated in the fluid. Such a condition allows particles to go further or closer. Consequently, parameters capable to perturb characteristics of the fluid mass, such as MDF and sediment concentration, are expected to be more sensitive to the model. The differences between real and hypothetical slope-sites for runout distance, reached area, and width suggest that relief characteristics may exert an important role in the debris flow propagation. During the running of the debris flow in the model, the accentuated interaction between flow and terrain caused by the rough surface in real slope-site can provide sediments to the flow. On the other hand, in the case of the hypothetical slope-site, the terrain is flat, reducing the interaction between flow and terrain. This specific situation may reduce the importance of some parameters in real slope-site, especially in the reached area and width due to entrenchment characteristics of the channel.

3.3 Variance Method (K3)

The *K3* method showed considerable differences between the results in both slope-sites. Also, the variance for real slope-site was larger than that of the hypothetical slope-site, demonstrating a larger dispersion around the expected result, i.e., the default result. In terms of runout distance, SDI, MDF, and AIF generated more sensibility to the model for the real slope-site. For the hypothetical slope-site, MDF, CDR, and CMB were more sensitive. The common parameter to both slope-sites was MDF. As previously commented, this parameter is important since it is related to the flow capacity and competency.

In the case of the reached area, CER, AIF, and SDI caused more sensitivity to the model for the real slope-site. However, the CDR, the MDF, and the AIF caused more sensibility to the model in the hypothetical slope-site. Similarly to *K1* and *K2*, the parameters that

make significant changes in sediment delivery to debris flow are more sensitive.

For the width of the debris flow, the $K3$ method did not show large values, which indicates a weak relation between the parameters and the results. The spread of the debris flow for the real slope-site presented a high response for the CER, AIF, and CDR. For the hypothetical slope-site, the CDR, the SDI, and the CMB were sensitive. The $K3$ values for width were small on average when compared to real slope-site and also when compared to runout distance and reached area, confirming that the topography exerts a strong effect on the debris flow spread, as can be seen in the SA in the present study. Thus, we can affirm that the spread of the debris flow highly depends on the relief conditions. On the other hand, runout distance and reached area are more subject to flow conditions.

3.4 Model Sensitivity

Modelling is an attempt to reproduce real phenomena. Thus, it can be sensitive to the chosen simulator or also to the utilized parameters. As Kanako-2D was created to perform debris flow simulations, and it uses a well-established theory, we considered that the simulator is suitable. Thus, the model sensitivity was treated here as the response of the simulator to variation in the input parameters.

Thereby, parameters with the highest sensitivity to the Kanako-2D were those that presented the highest values of $K1$, $K2$, and $K3$ for runout distance, reached area, and width of debris flow for both slope sites.

Considering the general variation between the analyzed range of input parameters ($K1$), and considering the runout distance, Kanako-2D is sensitive to MDB for both real and hypothetical slope-sites. In relation to reached area, AIF plays an important role in real slope-sites, and MDB is sensitive for hypothetical slope sites. For debris flow width, AIF for real slope-site, and CMB for hypothetical slope-site.

When considering the most intense change in the result due to the relative change in the parameter's input ($K2$), and considering the runout distance, Kanako-2D is sensitive to SDI for real slope-site, and MDB for hypothetical slope-site. In relation to reached area, CDR plays an important role in real slope-sites, and MDB in hypothetical slope-site. For debris flow width, SDI for real slope-site, and MDB for hypothetical slope-site.

By considering the variance of the results, $K3$, and considering the runout distance, Kanako-2D is sensitive to SDI for real slope-site, and MDF for hypothetical slope-site. In relation to reached area, CER plays an important role in real slope-sites, and CDR in hypothetical slope-sites. For debris flow width,

CER plays an important role in real slope-sites, and CDR in hypothetical slope-sites.

Note that some of these parameters can be measured or estimated on the site and their values must be compared with calibrated ones. Such parameters are MDB, AIF, CMB, and SDI. On the other hand, some input parameters such as CDR and CER should be further studied, because there are still technical problems and difficulties for estimating their values.

Initial sediment concentration was not considered in the present SA because its variation would imply a change in the hydrograph. Furthermore, the debris flow hydrographs are still uncertain, demanding a specific study on the behavior of both inputs in Kanako-2D.

Furthermore, the SA developed in this study was designed for a specific case, i.e., for simulations with Kanako-2D. Thus, it cannot be extended or generalized to any other debris flow simulations without further considerations.

4. CONCLUSION

Computational modeling is an important tool in the prediction of areas prone to debris flow occurrence. Mapping such areas is one of the most important non-structural measures in disaster risk management. The present study executed a sensitivity analysis of debris flow by using the Kanako-2D model with the purpose to advance the knowledge of this simulator to help users to achieve a better prediction and also to support the natural disaster management. For such sensitivity analysis, a real slope-site with a history of debris flow occurrence (Böni creek catchment, Southern Brazil) and a hypothetical slope-site with same terrain characteristics (slopes and soil properties) were utilized.

The sensitivity analysis showed that the AIF, SDI, and MDB are the most sensitive parameters in the Kanako-2D model. We recommend the comparison between the measured and calibrated values of the sensitive parameters in future studies. Furthermore, a sensitivity analysis to other outputs such as flow depth, concentration, and velocity will be necessarily performed as well as different hydrographs formats, because debris flow runout is highly dependent on initial flow conditions.

ACKNOWLEDGMENT : This study was financed in part by the Coordination for the Improvement of Higher Education Personnel (CAPES)-Brazil via PDSE n°88881.179717/2018-1 during an internship of the first author at Kyoto University, Japan.

We also would like to thank the two anonymous reviewers for valuable comments that improved the quality of the manuscript, and the Boeni family for the

support during the field surveys.

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Received : 27 January 2020

Accepted : 10 March 2021