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Rheology matters: simulating dilute-to-dry tailings dam breaks

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Abstract

Mine tailings dam failures generate complex flows composed of water, multiple solid phases of varying sediment sizes, organic matter, chemical solutes, and metals. These flows can rapidly entrain soil from surrounding terrain, and under lower-energy conditions, deposit material or even come to a halt.

Accurately predicting affected areas requires models that incorporate rheological formulations capable of representing both dilute suspensions and dry tailings. In many cases, these models must also capture interactions between tailings flows and existing water bodies such as rivers or reservoirs.

This paper presents a practical application of a two-dimensional model for tailings dam risk assessment that integrates rheological formulations for non-Newtonian fluids, spanning dilute-to-dry tailings. The model accounts for variability in soil properties of both the terrain and tailings, as well as the spatiotemporal evolution of fluid properties, including density, viscosity, and yield stress during flow and interaction with the environment.

Results highlight the critical role of selecting appropriate rheological formulations and accounting for dynamic interactions with terrain and water bodies. The findings provide valuable insights for professionals involved in risk assessment and the design of mitigation measures for tailings dam failures.

Keywords: *tailings rheology, dam break modelling*

1 Introduction

Flows of high-density mine tailings are one of the most challenging and complex to assess gravity-driven flows in environmental processes. In this kind of flow, the fluid in motion consists of a mixture of water and multiple solid phases of different natures, such as different sediment size classes, organic materials, and heavy metals, rushing downstream through steep terrain. Typically, slurries and debris are considered highly solid-laden fluids, with the mixture density exceeding twice or three times the water density, and the bulk solid phase accounting for 40–80% of the flow volume (Iverson 1997). Tailings flows can include hyperconcentrated flows and dry materials avalanche. Most of the numerical models reported for highly solid-laden flows use a single-phase approach, neglecting the mixture density in the shallow-flow mass and momentum conservation equations (Murillo & García-Navarro 2012). Two-phase approaches consider the depth-averaged mass and momentum conservation for the liquid and solid phases separately (George & Iverson 2011). Note that some tailings flow models consider 2 layers of different flow behaviour, such as upper alluvial sediment flow and an underlaying layer of uniform material mud flow. These models, inaccurately called two-phase models, establish a non-physically based interaction between the layers and

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can therefore not be considered realistic two-phase models, and are not tested against experimental results or real event data.

The mass exchange between the flow layer and the erodible bed involves complex physical processes, and the understanding of the theoretical basis remains unclear. Experiments in large-scale channels (Iverson et al. 2011) and field observations in real events (McCoy et al. 2012) indicate that the entrainment volume in steep beds can be in the same order of magnitude of the initial volume mobilised. Tailings flows can gain significant mass and momentum as they move over steep slopes because of the material entrainment from the erodible bed before deposition begins on flatter terrain downstream. One of the biggest challenges for the application of depth-averaged models to realistic, large-scale, long-term mud/debris flows is the computational effort required. This kind of unsteady flow usually occurs along very steep and irregular terrain, which requires the use of a refined non-structured spatial discretisation to capture the terrain complexity, exponentially increasing computational time. Furthermore, the complexity of the numerical solution and the computational cost of the solvers increase considerably with the number of equations, and the coupling between flow variables adds additional features to the mathematical model. Most numerical models designed for mud/debris flow are one-dimensional, or their resolution procedures use square-structured meshes in 2D models. There is a lack of efficient, robust two-dimensional numerical models specifically designed for mud/debris flows that can work with unstructured triangular meshes. In the last 5 years, the use of graphics processing units (GPUs) as hardware accelerators for sequential computation has been shown to be an efficient and low-cost alternative to traditional multi central processing unit strategies (Lacasta et al. 2015).

This paper presents a two-phase two-dimensional model for multi-grain tailings flows over nonuniform erodible beds. We first present the fundamental equations and then summarise the results of simulations of a real tailings dam break event using the quadratic rheological formulation, suitable for relatively dilute tailings, and the granular formulation, appropriate for dry stacks.

2 Two-phase tailings flow model

The model for mud/tailings flow is based on the RiverFlow2D MT model (Hydronia 2026) whose formulation, described in detail in Martínez-Aranda et al. (2022), involves the following assumptions:

- Shallow two-phase solid-water flow approach.
- Multicomponent flow: the mixture of water and sediment particles is described by using the continuum approach and assuming the same velocity for the liquid and the solid phase.
- The different sediment size classes present in the flow are distributed uniformly in the flow column.
- The reference coordinate system is horizontal-vertical, but the pressure and stress forces act along the direction tangential to the bed surface.
- Dynamic pore-fluid pressures can be developed in the liquid phase, affecting the frictional shear stress between solid grains.
- The model formulation is physically based and has been thoroughly validated with experimental data and real events (Martínez-Aranda et al. 2022).
- The two-dimensional mud/tailings flow model over an erodible bed consists of 3 + N + 1 partial differential equations, including the depth-averaged equations for the water–sediment mixture mass and momentum conservation:

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho hu)}{\partial x}+\frac{\partial(\rho hv)}{\partial y}=-\sum_{p=1}^{N}\rho_{b,p}\frac{D_p-E_p}{1-\xi_p} \tag{1}$$

$$\frac{\partial(\rho hu)}{\partial t}+\frac{\partial}{\partial x}\left(\rho hu^2+\frac{1}{2}g_\psi\rho h^2\right)+\frac{\partial}{\partial y}(\rho huv)=-g_\psi\rho h\frac{\partial z_b}{\partial x}-\tau_{bx} \tag{2}$$

$$\frac{\partial(\rho hv)}{\partial t}+\frac{\partial}{\partial x}(\rho huv)+\frac{\partial}{\partial y}\left(\rho hv^2+\frac{1}{2}g_\psi\rho h^2\right)=-g_\psi\rho h\frac{\partial z_b}{\partial y}-\tau_{by} \tag{3}$$

The continuity equation for each sediment size class p = 1,...,N, expressed as:

$$\frac{\partial(h\phi_p)}{\partial t}+\frac{\partial(hu\phi_p)}{\partial x}+\frac{\partial(hv\phi_p)}{\partial y}=-(D_p-E_p) \tag{4}$$

Additionally, the mass conservation equation for the bed layer, considering N sediment size classes is:

$$\frac{\partial z_b}{\partial t}=\sum_{p=1}^{N}\frac{D_p-E_p}{1-\xi_p} \tag{5}$$

where ρ is the bulk mixture density, h is the flow depth, (u, v) are the components of the depth-averaged flow velocity vector u along the x and y coordinates respectively, ϕ_p represents the depth-averaged volumetric concentration of the p^{th} sediment size class, being N the number of sediment size classes transported, and (τ_{bx}, τ_{by}) are the components of the basal resistance vector τ_b along the x and y coordinates respectively. Moreover, z_b is the bed elevation, ξ_p is the deposition porosity for the p^{th} sediment class and $\rho_{b,p}$ is the associated bulk density in the bed layer, D_p and E_p are the size-specific deposition and entrainment exchange rates, respectively, and $g_\psi = g \cos^2 \psi$ is the bed-normal projection of the gravity, being g the gravitational acceleration and cos ψ the direction cosine of the bed-normal with respect to the vertical axis (Juez et al. 2013). Accordingly, the normalised bulk density r is given by:

$$r=\frac{\rho}{\rho_w}=1+\phi^\chi \quad \text{with:} \quad \phi^\chi=\sum_{p=1}^{N}\frac{\rho_{s,p}-\rho_w}{\rho_w}\phi_p \tag{6}$$

where ϕ_χ is the buoyant solid concentration, ρ_w is porewater density and $\rho_{s,p}$ is the density of the sediment particles for each sediment size class.

3 Rheological formulations

A detailed explanation of the depth-averaged non-Newtonian basal resistance models used for the RiverFlow2D MT model (Hydronia 2026) can be found in (Martínez-Aranda et al. 2022), and here only the most important points are summarised in Table 1.

Table 1 Rheological basal resistance formulations used in RiverFlow2D MT

ID	Model	Basal resistance†	Flow type
1	Turbulent Manning	$\tau_b = \tau_f + \rho g_\psi \left(n^2 \lvert u \rvert^2 / h^{(1/3)}\right)$	Turbulent Newtonian
2	Full Bingham	$2\tau_b^3 - 3\left(\tau_y + 2\mu_B \lvert u \rvert / h\right)\tau_b^2 + \tau_y^3 = 0$	Cohesive viscoplastic
3	Simplified Bingham	$\tau_b = (3/2)\tau_y + 3\mu_B \lvert u \rvert / h$	Cohesive viscoplastic
4	Turbulent Coulomb	$\tau_b = \tau_f + \rho g_\psi h \lvert u \rvert^2 / h^{(1/3)}\ with$ $\tau_f = \left(\rho g_\psi h - P_b\right) tan\delta_f$	Frictional turbulent
5	Turbulent Yield	$\tau_b = \tau_f + \rho g_\psi \left(n^2 \lvert u \rvert^2 / h^{(1/3)}\right)$	Cohesive turbulent
6	Turbulent Coulomb/Yield	$\tau_b = min\left(\tau_y, \tau_f\right) \rho g_\psi \left(n^2 \lvert u \rvert^2 / h^{(1/3)}\right)\ with$ $\tau_f = \left(\rho g_\psi h - P_b\right) tan\delta_f$	Frictional/cohesive turbulent
7	Quadratic	$\tau_b = \tau_y + (k^0/8)\mu_B \lvert u \rvert\ /$ $h\ \rho g_\psi \left(n^2 \lvert u \rvert^2 / h^{(1/3)}\right), with\ k^0 = 24$	Cohesive viscous/turbulent
8	Granular	$\tau_b = \rho g_\psi h tan\delta_f$	Dry pure-frictional
9	Viscoplastic Coulomb	$\tau_b = \tau_f + \left((2m+1)/m\right)^m \mu_P (\lvert u \rvert / h)^m, with\ \tau_f$ $= \left(\rho g_\psi h - P_b\right) tan\delta_f$	Frictional shear-thinning (m < 1) or shear-thickening (m > 1)
10	Voellmy	$\tau_b = \mathcal{A}\ \rho g_\psi h + \rho g_\psi \frac{\lvert u \rvert^2}{\mathcal{B}}; \mathcal{A} \approx \tan\delta_f\ and$ $\mathcal{B} \approx h^{1/3}/n^2$	Frictional with negligible pore pressure

4 Numerical solution

The equations described in the above section are solved by a fully conservative finite-volume method detailed in (Martínez-Aranda et al. 2022). The spatial domain is divided into triangular computational cells using an unstructured mesh. The time step is limited by the Courant–Friedrichs–Lewy condition. The numerical computation can take advantage of multiple-core GPUs that allow reducing model runs up to 1,000 times with respect to non-parallelised models.

† μ_B is the mixute dynamic viscosity, δ_f is the basal friction angle.

5 Results

This application aims to illustrate the importance of selecting the rheological formulation that better captures the non-Newtonian behaviour of the tailings we would need to deal with. Using a formula that is not appropriate for the type of tailings would ignore key fluid behaviour characteristics that govern the tailings flow, and in order to approximate real events would require using values of the key parameters (e.g. viscosity and yield stress) that could be unrealistic and completely out of reasonable range. In this test, we compare results for 2 different rheological formulas (quadratic and granular) while keeping the same parameters for both cases. On 25 January 2019 (12:28 pm), Dam I at the Córrego do Feijão Iron Ore Mine, located 9 km northeast of Brumadinho in the state of Minas Gerais, Brazil, suffered a sudden catastrophic failure, resulting in a highly violent mud flow which travelled downstream more than 10 km and reached the Paraopeba River. The initial failure extended across the dam's face, and the slope collapse was complete in less than 10 seconds. Most of the dam material flowed out of the dam in less than 5 minutes. The tailings in the dam showed a sudden and significant loss of strength and rapidly became a heavy liquid that flowed downstream at a high speed (about 120 km/h in some zones. The data used to characterise the tailings and the main parameters used in the test are summarised in Table 2. Tailings were composed of a mixture of water, sediments, and heavy metals, mainly iron (Fe) 264.9 mg/g, aluminium 10.8 mg/g, manganese 4.8 mg/g, and titanium 0.5 mg/g (Vergilio et al. 2020). The size distribution consisted basically of a mineral sand fraction (38%) and a fines fraction (62%), accounting for mineral silt–clay and metal particles. The water content before the failure was estimated to be around 50% by volume with a specific weight of 22–26 kN/m^3 (Robertson et al. 2019).

Table 2 Parameters used in the simulations (Robertson et al. 2019; Vergilio et al. 2020)

Model parameters						
Liquid density ρ_w (kg/m^3)	1,000					
Initial mixture density ρ (kg/m^3)	2,247.5					
Internal stability angle ϕ_b(∘)	5					
Manning roughness coeff. n (s m −1/3)	0.003					
Pore press. excess coeff. γ_{pp}	2.05					
Global critical Shields stress θ_c	0.03					
Transport capacity parameter β_T	0.5					
Number of solid phases	6					
Solid phase material	**Sand**	**Silt**	**Fe**	**Al**	**Mn**	**Ti**
Medium diameter d_p (mm)	0.4	0.075	0.075	0.075	0.075	0.075
Initial volume concentration ϕ_p (–)	0.19	0.224	0.075	0.009	0.0015	0.0003
Solid density ρ_p (kg/m^3)	2,700	2,700	7,874	2,700	7,210	4,506
Bed fraction $F_{b,p}$ (–)	0.38	0.62	0.0	0.0	0.0	0.0
Deposition porosity p_p (–)	0.35	0.45	0.45	0.45	0.45	0.45
Critical Shields stress $\theta_{c,p}$ (–)	0.020	0.067	0.067	0.067	0.067	0.067

Figure 1 shows an aerial image of the mine site after the dam collapse, including the dam location and the original tailings elevation in metres above sea level.

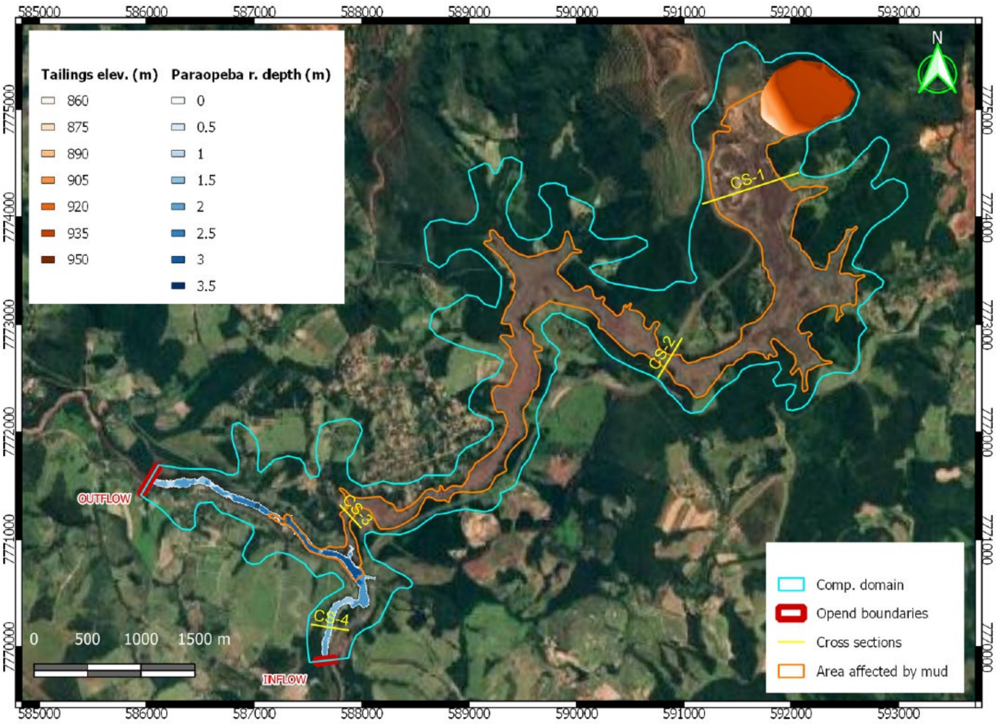

Figure 1 Aerial image of the area affected by the mud and the computational domain used in the simulation

The area affected by the mud was 3.3 × 106 m^2, without including the original dam area. In order to perform the simulations, a spatial domain of 10.396 × 10^6 m^2 is discretised using an unstructured triangular mesh with the RiverFlow2D MT model containing approximately 20,000 cells ranging from 15–50 m in size.

For the simulations, the tailings mixture is considered fully saturated with an initial global volumetric concentration of solids $\phi_0 = 0.5$, leading to a mixture density ρ = 2,247.5 kg/m^3. The specific initial volumetric concentration for each solid phase ϕ_p is estimated from the available literature (Robertson et al. 2019).

Figures 2 and 3 provide a clear illustration of the strong influence that the selected rheological formulation exerts on the predicted dynamics, runout, and internal structure of the tailings flow. Despite using identical initial conditions and parameter values, the quadratic and granular formulations lead to fundamentally different flow behaviours, highlighting the sensitivity of tailings dam break simulations to rheological assumptions.

Figure 2 shows the spatial distribution of flow depth at 5, 10, and 35 minutes after the dam failure. Under the quadratic formulation, the numerical results indicate a rapid mobilisation of the tailings mass, with most of the initial volume released from the impoundment within the first 5 minutes. The flow front advances quickly downstream, forming a highly energetic surge with flow depths locally exceeding 25 m during the early stages. As the wave propagates, the flow spreads laterally and longitudinally, maintaining significant thickness over several kilometres. Even at later times (35 minutes), the simulation predicts sustained motion and widespread inundation, consistent with a fluid-like behaviour dominated by viscous and turbulent stresses.

In contrast, the granular formulation produces a markedly different response. The initial release is followed by a rapid dissipation of momentum, and the flow depth decreases sharply within a short distance from the dam. The granular resistance, governed primarily by frictional interactions, limits the mobility of the tailings, causing the flow to decelerate and come to rest within a few hundred metres of the original deposit. At all simulated times, the affected area remains confined, and no significant downstream propagation is observed. This behaviour reflects the dominance of dry, friction-controlled mechanics, which are unable to reproduce the long runout observed in the real event.

Figure 3 complements this analysis by showing the evolution of the volumetric concentration of solids within the flow. For the quadratic formulation, the concentration fields reveal substantial spatial and temporal variability. During the initial stages, high solid concentrations are maintained within the core of the flow, while dilution occurs near the flow margins and downstream due to spreading and interaction with the terrain. This heterogeneous structure is characteristic of liquefied tailings, in which porewater pressures and viscous stresses maintain solids in suspension over long distances. The persistence of elevated concentrations downstream supports the interpretation of a highly mobile, water-rich mixture.

Conversely, the granular formulation exhibits relatively uniform and persistently high volumetric concentrations near the source area, with little evidence of downstream dilution. The lack of significant spreading or entrainment results in a compact deposit that rapidly stabilises. This concentration pattern further confirms that, under granular rheology, the tailings behave as a dry or quasi-dry mass with limited capacity for sustained motion or internal reorganisation.

The application demonstrates that the quadratic formulation can reproduce the rapid release, high velocities, long runout distances, and evolving internal structure characteristic of the Brumadinho tailings flow. The granular formulation, while appropriate for dry-stack failures, fails to capture these essential features for a liquefied tailings scenario. These results emphasise that using an inappropriate rheological model can lead to severe underestimation of affected areas and hazard intensity, even when all other model parameters are kept unchanged.

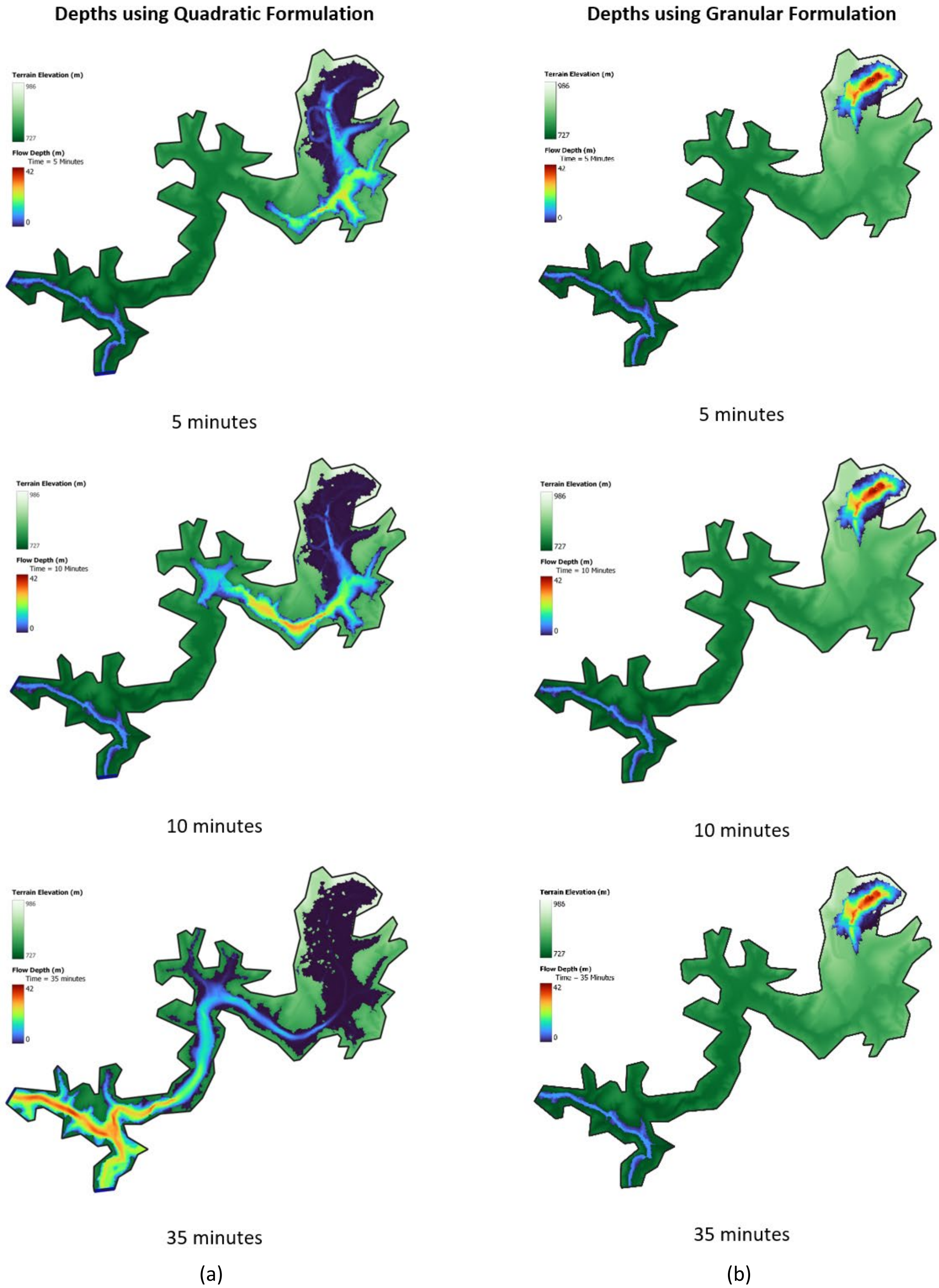

Figure 2 Flow depth maps at different times obtained using the (a) quadratic and (b) granular formulations

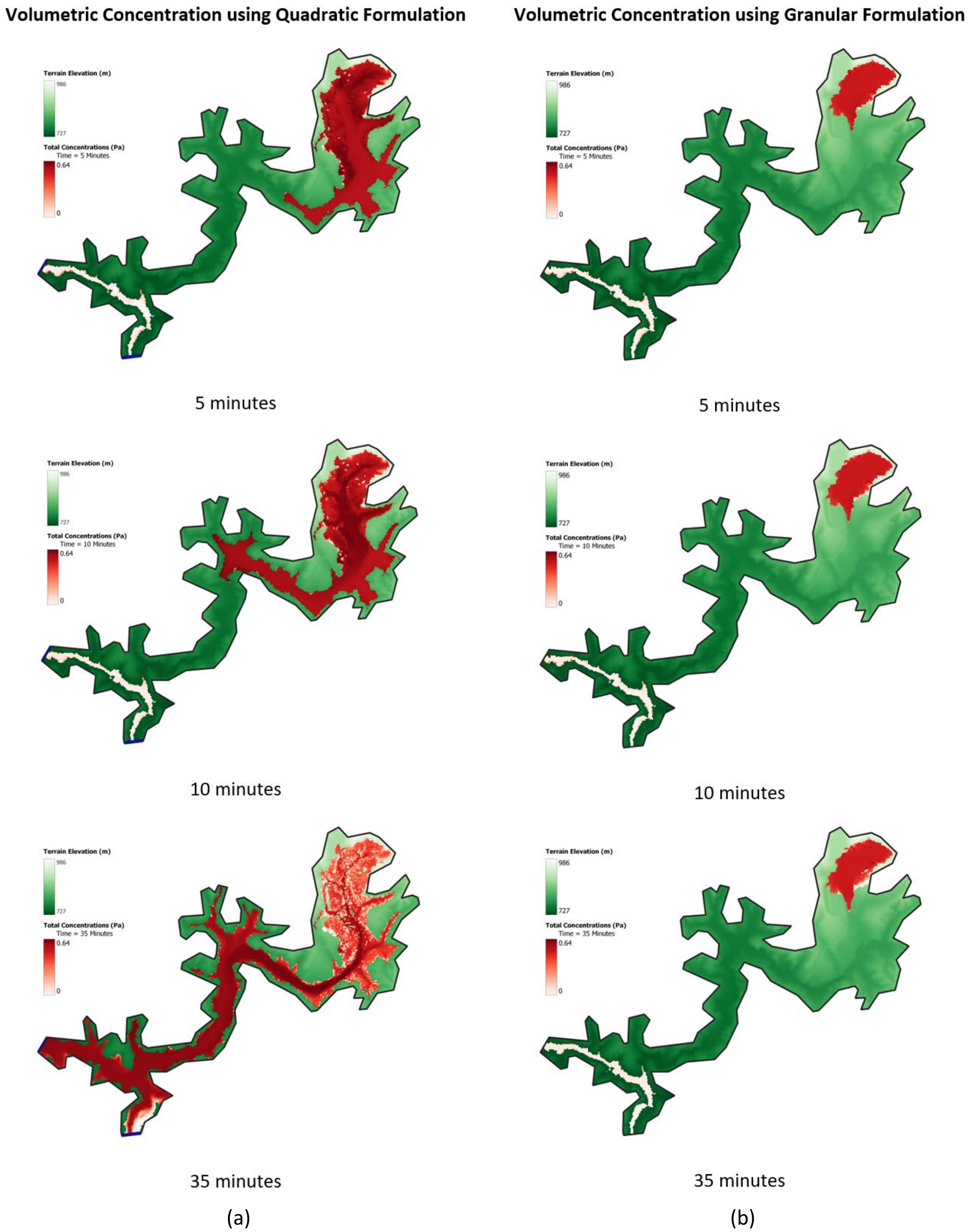

Figure 3 Material volumetric concentration maps at different times obtained using the (a) quadratic and (b) granular formulations

6 Conclusion

After mine tailings dam failures, the flowing fluid often consists of a mix of water and multiple solid phases with different sediment size classes, organic materials, chemical solutes, metals, and numerous sediment types in the dam itself. In turn, the high-speed flow can entrain soil from the existing terrain and, under low energy conditions, can deposit or stop altogether.

To determine areas that could be affected by tailings, it is critical to use models that account for rheology formulations that accurately represent the dam materials and tailings, whether dilute or dry. Also, if required, the model should be able to incorporate interactions between the tailings flow and existing water bodies, such as reservoirs or rivers.

This paper presents a practical application of the RiverFlow2D MT two-phase model for tailings dam risk assessments, using the case of the Córrego do Feijão dam break in Brazil in 2019 as base data. The simulations were performed with a quadratic and a granular rheological formulation applicable to non-Newtonian fluids. The first one can be used to represent initially dilute tailings, while the latter can be used for those originating from dry stacks. The model considers the variability of the soil characteristics in the initial terrain and tailings, as well as how the fluid properties, such as density, viscosity, and yield stress, change in time and space as the materials flow and interact with the terrain soils and other water bodies.

The application presented demonstrates the importance of considering an appropriate rheological formulation for the tailings deposit and the dynamic interaction between the tailings and their surrounding environment. Assuming the quadratic formula, the tailings flow several kilometres downstream from the dam location. By contrast, in the granular formulation, the tailings flow only a few hundred metres from the initial deposit before coming to a complete stop.

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