XXVI SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS

COMPARISON OF COULOMB-BASED RHEOLOGICAL MODELS IN HEC-RAS AND RIVERFLOW2D FOR TAILINGS DAM BREAK SIMULATION: A CASE STUDY OF STAVA-ITALY (1985)

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Abstract: This study presents a comparative analysis of Coulomb-type rheological models applied to the simulation of the Stava tailings dam failure (Italy), which occurred in 1985 and mobilized approximately 180,000 m³ of tailings, with an estimated initial volumetric concentration close to 50%. Two numerical models were used: the Clastic Grain Flow – Coulomb model in HEC-RAS 6.6 and the Turbulent Coulomb model in RiverFlow2D 8.12.05. The use of these models was motivated by the entrainment of approximately 50,000 m³ of debris and vegetation into the downstream valley, intensifying the granular behavior of a flow already characterized by high solid content. The simulations were evaluated based on their ability to reproduce the observed data for the inundation extent, arrival time, and final maximum depths. Internal friction angles ranging from 2.5° to 15.0° were tested, with the best performance observed for values of 2.5° and 5.0°. The results suggest that Coulomb-based models, combined with bottom friction, may serve as a complementary tool in sensitivity analyses for events with similar characteristics—such as high initial solid concentration, sediment granulometry in the dam and reservoir ranges from silt to sand and significant debris entrainment in the downstream flow.

Resumo: Este estudo apresenta uma análise comparativa de modelos reológicos do tipo Coulomb aplicados à simulação da ruptura da barragem de rejeitos de Stava (Itália), ocorrida em 1985 e que mobilizou aproximadamente 180.000 m³ de rejeitos, com concentração volumétrica inicial estimada próxima a 50%. Foram utilizados dois modelos numéricos: o modelo *Clastic Grain Flow – Coulomb* no HEC-RAS 6.6 e o modelo *Turbulent Coulomb* no RiverFlow2D 8.12.05. A utilização desses modelos foi motivada pela entrada de aproximadamente 50.000 m³ de detritos e vegetação no vale a jusante, intensificando o comportamento granular de um escoamento já caracterizado por alto teor sólido. As simulações foram avaliadas com base na capacidade de reproduzir os dados observados para a extensão da inundação, o tempo de chegada e as profundidades máximas finais. Ângulos de atrito interno variando de 2,5° a 15,0° foram testados, sendo que o melhor desempenho foi observado para os valores de 2,5° e 5,0°. Os resultados sugerem que modelos baseados em Coulomb, combinados com a tensão cisalhante de fundo, podem servir como uma ferramenta complementar em análises de sensibilidade para eventos com características semelhantes — como alta concentração inicial de sólidos, granulometria dos sedimentos na barragem e reservatório variando entre silte e areia, e significativa entrada de detritos no escoamento a jusante.

Palavras-Chave – HEC-RAS; RIVERFLOW2D; COULOMB.

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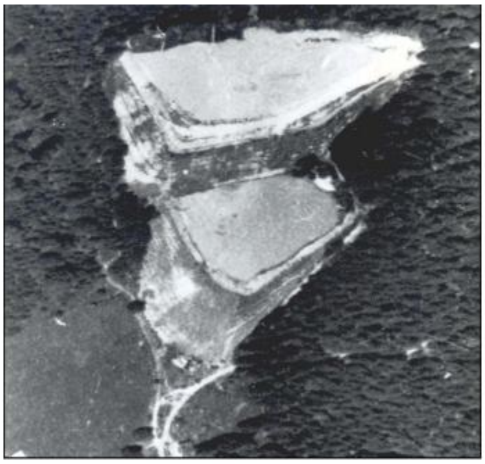
CASE STUDY

This subsection was prepared based on the characterization by Chandler and Tosatti (1995) and Luino and Graff (2012) of the fluorite tailings dams located in Stava, Italy (Figure 1), at the following UTM 32N coordinates: (691,976.48 m E; 5,132,592.62 m N) for the lower reservoir and (691,863.26 m E; 5,132,548.88 m N) for the upper reservoir.

Figure 1 – Fluorite tailings dams located in Stava, Italy (Source: Luino and Graff, 2012)



Construction of the basins began in 1962 with the Lower Reservoir. A significant number of conifer trees were removed from the area, which contained springs and surface water. The soil was soft, and wooden piles were used as a rudimentary method of ground reinforcement for the reservoir's dam foundation. No additional foundation improvements were made. The dam was constructed using the upstream raising method. In 1969, construction of the Upper Reservoir began, initially intended to recycle tailings from the Lower Reservoir to recover previously discarded fluorite.

Investigations showed that the dams were built over heterogeneous glacio-fluvial deposits. As a result of the method of construction of the tailings basins the material is extremely heterogeneous. The sand material predominates near the dam, but it becomes more silty towards the centre of the basins. The sandy and silty materials are often interlayered.

The disaster occurred at 12:22:55 PM on July 19, 1985, when two fluorite tailings dams failed just upstream of the village of Stava, in the municipality of Tesero, Italy, resulting in the loss of 268 lives.

On the valley margins, mud marks reached the tops of trees up to 25 meters high. The total amount of displaced material was estimated at 180,000 m³, with an additional 40,000 to 50,000 m³ resulting from the erosion of trees and debris along the valley. Due to this increase, the option to test frictional rheological models was considered.

Takahashi (2014) reported that the initial volumetric concentration of solids in the Stava tailings flow was 47.6%.

The flow reached the confluence area of the Stava and Avisio rivers (Figure 2), where it stabilized, forming a dam and a lake 500 meters long.

Figure 2 – Confluence area of the Stava and Avisio rivers (Source: CNR-IRPI Torino apud Luino and Graff, 2012)

RHEOLOGICAL MODELS

O’Brien and Julien (1984) present a classification of hyperconcentrated flow types based on the volumetric concentration of the flow (Table 1).

Table 1 – Classification of hyperconcentrated flows (Source: O’Brien and Julien, 1984)

Flow type	Concentration by volume (%)	Flow Characteristics
Landslide	*53-90*	Will not flow, failure by block sliding
	50-53	Block sliding failure with internal deformation during the slide, slow creep prior to failure
Mud flows	*48-50*	Flow evident, slow creep sustained mud flow, plastic deformation under its own weight, cohesive, will not spread on level surface
	45-48	Begins spreading, cohesive
Mud flood	*40-45*	Mixes easily, show fluid properties in deformation; spreads on horizontal surface but maintains a inclined fluid surface, large particle settling, waves appear but dissipate rapidly
	35-40	Marked settling, spreading nearly complete on horizontal surface, liquid surface, two phases appear. Waves travel substantial distance.
	30-35	Separation of water on surface, two phases. Waves travel easily. Most sand and gravel has settled out.
	20-30	Distinct wave action, fluid surface, all particles resting on bottom in quiescent fluid condition.
Water flood	*<20*	Water flood with bed and suspended loads.

In flows with coarse particles where friction has a significant influence on the movement, the Mohr-Coulomb rheological model may be necessary.

One of the rheological models available in RiverFlow2D is the Turbulent-Coulomb model (Hydronia, 2025), which is based on the Coulomb approach, with the addition of a turbulent shear stress term derived from the Manning roughness coefficient, as defined in Equation (1).

$$\tau_b = (\rho g_\psi h - P_b)tan\delta_f \; + \rho g_\psi \frac{n^2|u|^2}{h^{\frac{1}{3}}} \qquad (01)$$

Where τ_b is the total shear stress, ρ is the density, g_ψ is the component of gravity normal to the bed, $|u|$ is the magnitude of velocity, P_b is the pore pressure, h is the flow depth, and δ_f is the basal frictional angle.

In HEC-RAS 6.6 (USACE, 2020), the Clastic Grain Flow Mohr-Coulomb model is available and defined by the following equations, where c is the cohesion or cohesive strength, μ is the Coulomb friction coefficient, σ is the normal stress at the base of the mixture, θ is the bed slope angle, h is the vertical flow depth, and ϕ is the internal friction angle. Equations 2 to 4 show this relationship.

$$\tau_y = c + \mu\,\sigma \qquad (2)$$

$$\sigma = (\rho m - \rho w)\ ghcos^2\theta \qquad (3)$$

$$\mu = tan.\ \Phi \qquad (4)$$

It should be emphasized that the bottom turbulent shear stress (τ) is always enabled in HEC-RAS 6.6, where g is the gravitational acceleration, ρ_m is the water-solid mixture density, V is the magnitude of the velocity vector, R is the hydraulic radius and τ is the bottom turbulent shear stress (Equation 5).

$$\tau = \rho_m \; \frac{gn^2}{R^{\frac{1}{3}}}|V|^2 \qquad (5)$$

The basal friction angle is typically only a fraction of the Coulomb angle (McDougall and Hungr, 2006, as cited in Naef, 2006).

USACE (2020) comments that the internal friction angle depends on the mixture, but its values are typically between 2.5° and 15°.

Hydronia (2025) indicates that in order to simulate mud flows of coarse materials, it is recommended to use the Turbulent-Coulomb or Turbulent-Coulomb-Yield, and in the Granular formulation, the friction angle is the stability basal angle of the material which is equivalent to the free surface angle once the material stops flowing. This stability basal angle varies for different materials, but to obtain runouts similar to those of mudflows they should be in the range of 1° to 8°, and never greater than 15◦ for materials with a low tendency to flow. Using friction angles around 30° makes mobilization almost impossible with the granular formulation.

INPUT AND OBSERVED DATA

In the numerical HEC-RAS model, a breach hydrograph was chosen according to Ghahramani et al. (2022) and Takahashi (2014), who estimate a triangular-shaped hydrograph with a peak flow of 28,160 m³/s (at the onset of failure) and a duration of 13.2 seconds. Since HEC-RAS allows a minimum discretization of 1 second, the hydrograph base was adjusted to 13.0 seconds and the peak flow to 28,593.23 m³/s.

The numerical RIVER-FLOW2D model allows the input of the mobilized volume as a matrix file. This methodology was applied by Ghahramani et al. (2022) in the Stava-ITA simulations using the DAN-3D and MAD-FLOW numerical models. In line with this, for the Stava-ITA case study, a matrix file and an adaptation of the Digital Terrain Model in its primitive form were developed, based on pre- and post-failure data presented by Chandler and Tosatti (1995), adapted to approximate the mobilized volume of 185,200 m³ according to the database compiled by Adria et al. (2023) and crest elevations of 1,350.50 m and 1,377.5 m, as described by Ghahramani et al. (2022).

The roughness coefficient used were 0.04 $m^{\frac{-1}{3}}s$.

The bulk unit weight of the flow mixture was taken as 19 kN/m³, based on Ghahramani et al. (2022), who used a specific gravity of 2.89 as reported by Chandler and Tosatti (1995).

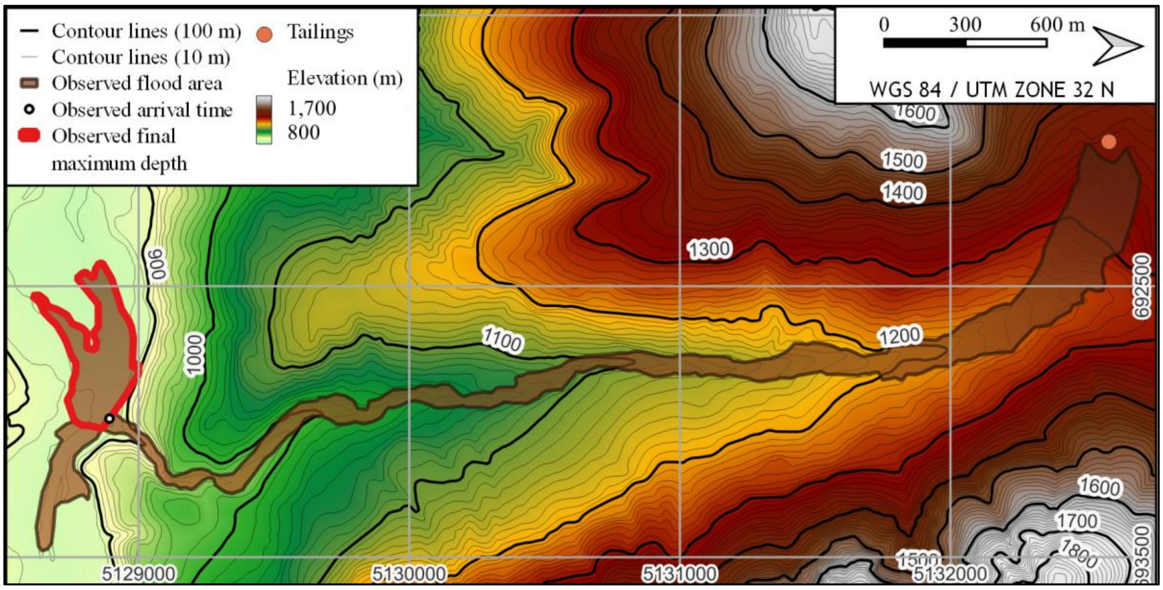
The topography of the downstream valley for this study is based on TINITALY with a 10-meter resolution from the Istituto Nazionale di Geofisica e Vulcanologia (Tarquini et al., 2007).

This study used the observed inundation area, the final maximum depth of 6 m at the confluence of the Stava and Avisio rivers, and the arrival time at the Avisio River (breach initiation at 12:22:55 h and arrival at the Avisio River at 12:30:40 h, totaling 465 seconds), according to the dataset compiled by Adria et al. (2023) based on Takahashi (2014) and Luino and De Graff (2012).

The Figure 3 presents the observed flood area, digital elevation model, and the area with observed final maximum depth and arrival time.

Figure 3 – Observed flood area, digital elevation model, and area with observed final maximum depth and arrival time

(Source: Adria et al. (2012))



The index used to evaluate the similarity between the observed and simulated flood envelopes is the FIT METRIC, as shown in Equation 6. Melo and Eleutério (2023) employed this parameter to calibrate a non-Newtonian hydrodynamic model for the event that occurred in Brumadinho, MG. In this equation, A represents the observed inundation area, and B represents the simulated inundation area. A Fit Metric value close to 1 indicates a good fit.

$$F = \frac{100\,\%\,(A \cap B)}{(A \cup B)} \tag{6}$$

Table 2 presents the scenarios with the rheological models CLASTIC GRAINFLOW COULOMB in HEC-RAS and TURBULENT COULOMB in RiverFlow2D.

Table 2 – Simulated scenarios

Internal friction angle (°)	**2.5**	**5.0**	**8.0**	**12.0**	**15.0**
Clastic-Grainflow Coulomb – HEC-RAS	RAS-1	RAS-2	RAS-3	RAS-4	RAS-5
Turbulent-Coulomb – RiverFlow2D	RF-1	RF-2	RF-3	RF-4	RF-5

RESULTS

The Figure 4 and Figure 5 show the flood inundation area from the numerical simulations in HEC-RAS and RiverFlow2D, respectively, compared to the observed inundation extent. The simulated flood inundation extents for the same internal friction angles were similar between the HEC-RAS and RiverFlow2D models. In both the RiverFlow2D and HEC-RAS models, only simulations with internal friction angles below 8° were able to reach the Avisio River.

Figure 4 – Simulated inundation area at HEC-RAS

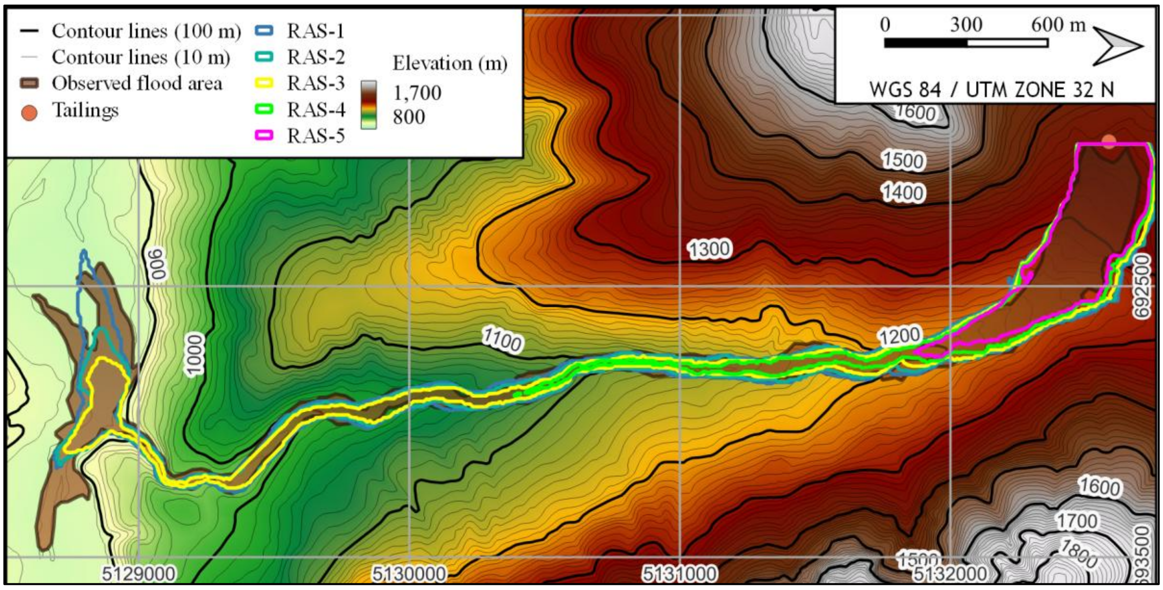


Figure 5 – Simulated inundation area at RiverFlow2D

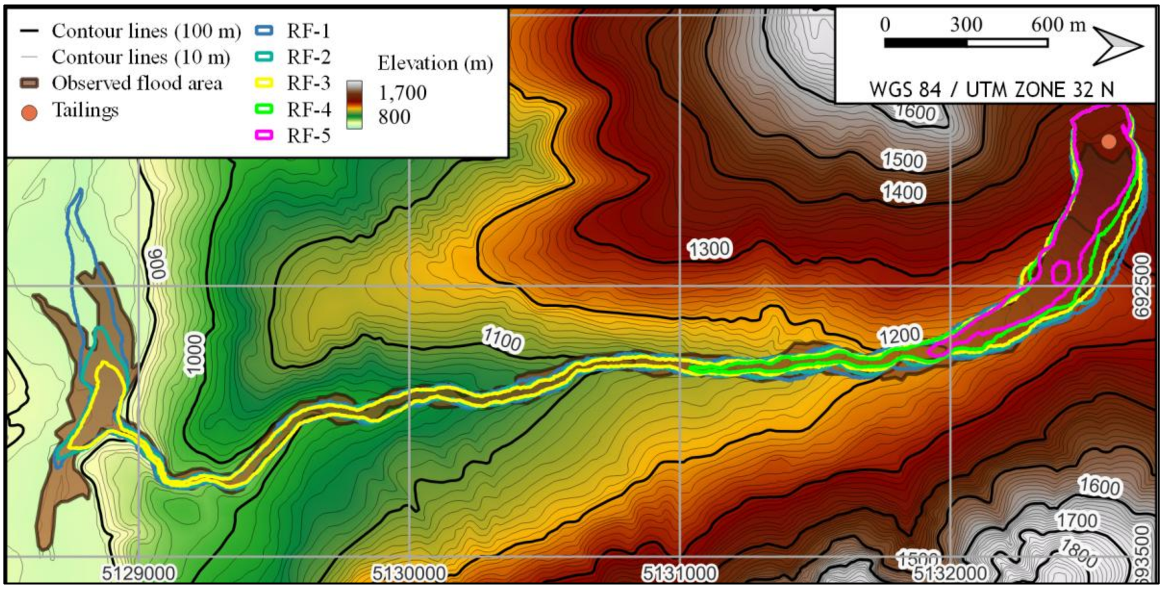


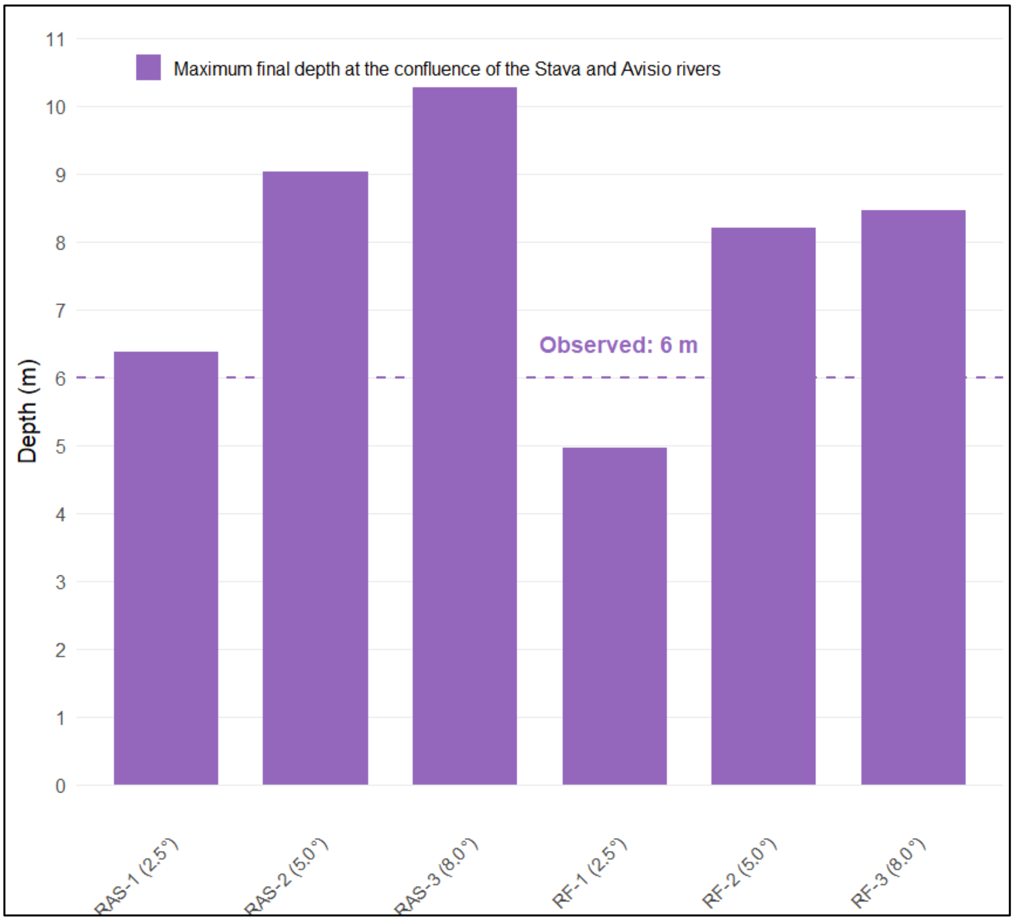
Table 3 presents the fit metric for the simulated inundation areas, with the internal friction angle of 2.5° exhibiting the highest values.

Table 3 – Fit metric of the simulated inundation area

Internal friction angle (°)	**2.5**	**5.0**	**8.0**	**12.0**	**15.0**
Clastic-Grainflow Coulomb – HEC-RAS	66.43	63.59	56.59	37.36	28.86
Turbulent-Coulomb – RiverFlow2D	62.17	59.43	50.91	28.33	17.75

Regarding the maximum final flow depth at the confluence of the Stava and Avisio rivers (Figure 6), simulations with internal friction angles of 2.5° and 5° produced depths closer to the observed value of 6.0 m. Specifically, at 2.5°, depths of 4.96 m (RiverFlow2D) and 6.37 m (HEC-RAS) were obtained, while at 5°, depths of 8.20 m (RiverFlow2D) and 9.03 m (HEC-RAS) were simulated.

Figura 6 – Maximum final depth at the confluence of the Stava and Avisio river



Finally, the observed arrival time of 465 seconds at the confluence of the Stava and Avisio rivers showed better agreement with simulations using an internal friction angle of 5°, while simulations with higher angles yielded fewer conservative values, as shown in Table 4.

Table 4 – Arrival time at the confluence of the Stava and Avisio river (Observed = 465 seconds)

Internal friction angle (°)	2.5	5.0	8.0	12.0	15.0
Clastic-Grainflow Coulomb – HEC-RAS	335	391	599	-	-
Turbulent-Coulomb – RiverFlow2D	317	422	910	-	-

FINAL CONSIDERATIONS

During the event, approximately 50,000 m³ of trees and construction debris were carried downstream, which were not represented in the current modeling, considering only the initial volume. The dam has a granulometric characterization with two distinct regions, ranging from silt to sand. The scenarios performed did not consider the heterogeneous variation of the dam material.

The best fits were obtained with internal friction angles between 2.5° and 5°, while values above 8° resulted in premature stopping of the flood inundation. The results from the numerical models HEC-RAS and RiverFlow2D were similar, despite different methods of volume insertion.

The use of a rheological model combining bottom shear and Mohr-Coulomb stresses may be a viable approach for sensitivity analyses in cases with initial volumetric concentrations near 50%, especially when sediment granulometry in the dam and reservoir ranges from silt to sand, and when dense vegetation and possible debris are likely present in the downstream valley.

This study aimed to compare HEC-RAS and RiverFlow2D using Coulomb-based rheological models to simulate a tailings dam failure. To isolate model behavior, simplifications were made, such as excluding the entrainment of approximately 50,000 m³ of debris and trees, bridge structures, bed erosion, material heterogeneity, and natural flow in the Avisio River. Future work could address these aspects, explore probabilistic methods, and apply advanced modeling or machine learning techniques. These steps, however, go beyond the comparative focus of this research.

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