Iber as a Flood Nowcasting and Forecasting Software Suite for Mine Managers

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Abstract

Iber is a two-dimensional numerical tool for the simulation of free surface water flows. Widely used for numerical modelling of environmental flows, Iber has been recently enhanced to simulate non-water flows such as mudflows and debris flows by implementing rheological models oriented to compute the resistance forces. This new extension is freely distributed, fully integrated into a user-friendly guided interface, and enables practitioners to analyze mine-tailings spill propagation, providing valuable information for assessing flood hazard and risk in the event of tailing storage facilities failure. This work shows the new features and capabilities of Iber.

Keywords: Risk management, hazardous situations, mine-tailings, numerical modelling, Iber

Introduction

Mine tailings, a by-product of mine activities, are commonly stored, temporally or permanently, in Tailing Storage Facilities (TSF). The failure or malfunctioning of TSF can release large amounts of water containing high concentrations of pollutants into the environment, which often behave as non–Newtonian fluid flows. Preventing and mitigating these hazardous situations is challenging for the mining industry for both active and closured TSF (Klose 2007).

The complexity and scale of tailings disasters present enormous challenges for emergency services, environmental regulators, mine managers, and affected communities (Penman *et al*. 2001). Efforts to provide effective response and recovery require a thorough understanding of the behaviour of tailings materials, including their transport mechanisms, dispersion patterns and the potential for further environmental degradation over time. Advances in numerical modelling tools, together with improvements in computational capacity, allow for the development of strategies to reduce the risk to the environment and population based on more accurate predictions of mine tailings behaviour and propagation (Hungr 1995; Adewale *et al*. 2017).

Numerical modelling tools allow simulating the dynamics of non–Newtonian fluids by solving mass and momentum conservation equations. This is an essential step in flood risk management, providing reliable flood information for mine planning in existing or new facilities (e.g. maximum flood extent, depth, and flow velocity). Iber is a software suite widely extended –but not limited– for simulating hydrodynamic processes of water flows (Bladé *et al*. 2014), and particularly to simulate dam-break scenarios (Sanz-Ramos *et al*. 2023b). This two-dimensional hydrodynamic numerical tool has been recently enhanced to simulate non–Newtonian shallow flows (Sanz-Ramos *et al*. 2023a, 2024a), especially those related to mine tailings by incorporating rheological models that reflect the fluid's properties (e.g. Bingham).

The purpose of this work is to demonstrate the new features of Iber for simulating shallow non–Newtonian flows, such as mine tailings spill propagation. The code integrates several rheological models to consider different flow behaviours and a specific numerical scheme that achieves the fluid detention according to the rheological properties of the fluid. It is fully integrated in a user-friendly guide user interface and freely distributed for practitioner in general, and specifically for mine managers. (www.iberaula.com). The performance of the numerical tool is shown throughout a benchmark, showing good results and the valuable information to assess flood hazard and risk in mine-tailings spill propagation scenarios.

A software suite for mine managers

Numerical tool: IberNNF

Iber is a two-dimensional software for the simulation of hydrodynamics originally developed for shallow water flows (www.iberaula.com). The application fields of Iber also extend to transport processes, morphodynamics, hydrological processes, soil erosion in watersheds, urban drainage and eco-hydraulics. Fig. 1 depicts a schematic inter-relationship of the different calculus modules, being the hydrodynamics the main module. IberNNF is a new calculation module that works as hydrodynamic module separated from the rest of modules of Iber. It integrates a specific numerical scheme and rheological models for the numerical modelling of non–Newtonian shallow flows, or non-water shallow flows. A detailed description can be found in Sanz-Ramos *et al.* (2023a).

Rheological models

Rheology is the science in charge of studying the deformation and flow of matter under variations in temperature, pressure and shear stress (Adewale *et al.* 2017). Omitting the temperature and pressure terms, fluid behaviour is only a function of shear stress, which is proportional to the shear rate through the viscosity. Non–Newtonian fluids can be classified into 4 large groups: Newtonian (constant viscosity), Dilatant (viscosity increases when shear stress increases), pseudoplastic (viscosity reduces when shear stress increases), and Bingham-type (the fluid movements starts when the shear stress is greater than the yield stress).

From the simplest Potential law to the full –and complex– Bingham model, several rheological models exist in the literature, the development of each one being oriented to achieve the particular reproduction of a fluid behaviour. The aim of IberNNF is not to include as rheological models as possible—or exist—; however, it implements the flowing 8 rheological models to attempt representing the resistance forces that act against flow motion of non–Newtonian flows.

The *Manning* equation can be applied for both water and non-water flows, since it was utilised by several authors for simulating hyperconcentrated flows (e.g. Takahashi 1985; Syarifuddin *et al.* 2018). Macedonio and Pareschi (1992) considering constant sediment concentration and uniform flow, derived the following expression: $\tau = \tau_y + \mu_1 (dv/dz)^{\alpha}$, where τ_y is the yield stress,

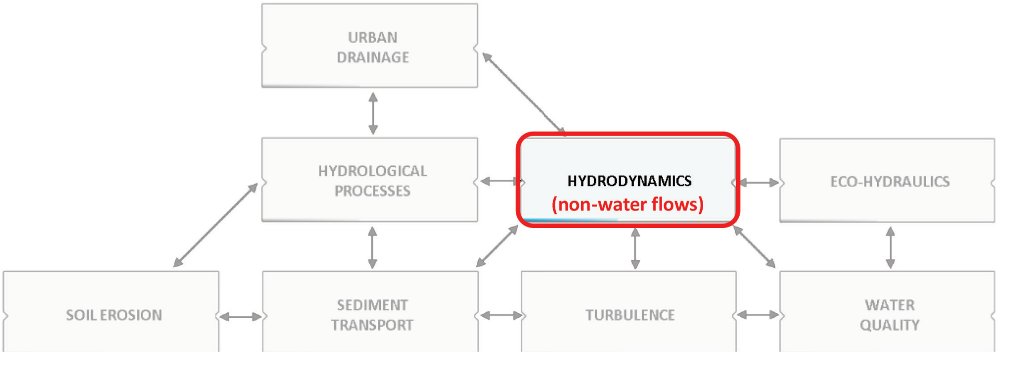

***Figure 1** Calculation modules of Iber for (a) water flows, and (b) non-water flows (IberNNF).*

μ_1 is a proportionality coefficient and α is the flow behaviour index. When α = 1 a model for *Viscous* flows is developed; while α = 2 a *Dilatant* flow behaviour is expected.

O'Brien and Julien (1988) derived an expression for the representation of the shear stress of mudflows, being a quadratic equation that integrates the Mohr–Coulomb term, the viscous term and the turbulent term through the Manning equation. In this sense, the formulation of Herschel and Bulkley (1926) is a generalization of various expressions in which e.g. dilatant, viscous or plastic behaviours can be derived depending on the value of the coefficient α.

Since the proposal of the Bingham (1916) rheological model, several approaches have been introduced to deal with the difficulties on directly obtaining the shear stress proportional to the flow velocity (Pastor *et al.* 2009). IberNFF implements a Bingham simplified model (O'Brien and Julien 1988; Pitman *et al.* 2003), which is a explicit equation that considers the viscous and the Mohr–Coulomb contributions.

The rheological model of Voellmy (1955) considers the Mohr–Coulomb and the turbulent contributions, being this last one equivalent to the Manning model. Finally, the Bartelt model (Bartelt *et al.* 2015) accounts for resistance generated by the cohesion, a physical property of the fluid. This rheological model is commonly used together with the Voellmy model.

Workflow

The utility and practical application of any numerical code necessarily requires its integration in a graphical user interface (GUI). This facilitates the model build-up, setup and results visualization. Iber is fully integrated in the multi-dimensional pre- and post-process GUI software called GiD. The interface is adapted for Iber to make a simple, easy and user-friendly experience for a 2D-hydrodynamic modelling process. Three main steps define the workflow of Iber, and thus IberNNF: the first step (pre-process) is where the user creates the model and implements all conditions; the second step (calculation) is the place for time parameters definition, calculation module selection and simulation run; and finally (post-process) is when all results can be analysed in the GUI or/and export to third party software.

The activation IberNNF (Fig. 2a) adapts the GUI to show the particular tools and options to carry out a simulation considering the fluid as non–Newtonian. A new tab on the Problem data appears allowing the selection of the different rheological models, the fluid properties, and additional options (Fig. 2b). Depending on the rheological model selected, different parameters must be imposed, particularly those related to the friction slope which follow the same definition of Land uses concept (Fig. 2c). This provide identical benefits as for Newtonian fluids, allowing to assign it manually in the model geometry/

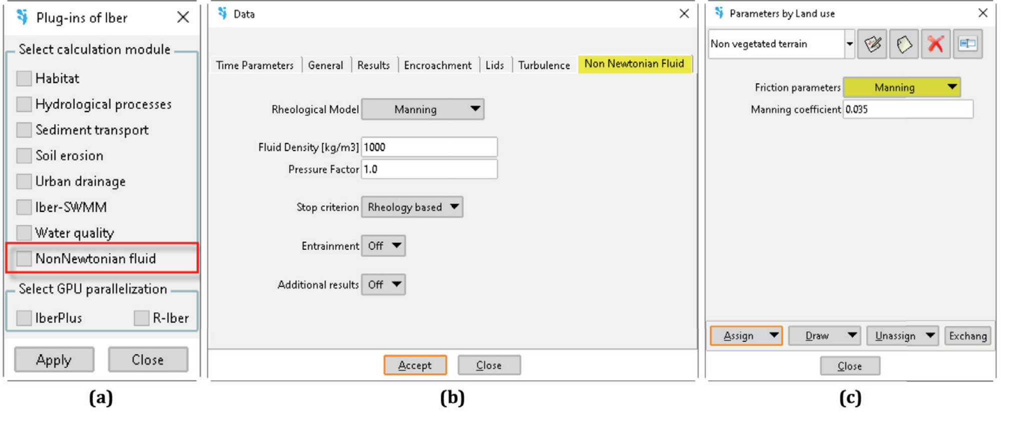

Figure 2 *GUI of IberNNF: (a) activation of the module; (b) definition of main parameters; and (c) definition of non-dependent parameters of the rheological model.*

mesh or automatically to the mesh by importing raster files. Nevertheless, the Land uses database has been particularised to this module removing land uses typically used for flood analysis or hydrological processes, e.g. "river", "concrete" or "urban fabric".

Evaluating past, present and future hazardous situations

Since 1961, more than 150 major TSF failures have been reported (WISE 2024), with an average of 2.5 failures per year and 82 of them occurring between 2000 and 2024. This highlights the strong need for enhance and comprehensive management, monitoring, prevention, and planning strategies to mitigate the flood risks associated with mining activities.

IberNNF can be applied to simulate mine-tailings spill propagation after a TSF failure (Sanz-Ramos *et al.* 2024b, a) and, thus, it can be a useful tool for mine managers to analyse past events, plan and design actions to mitigate hazardous situations of existing or future TSF. To that end, IberNNF couples the hydrodynamics with a specific option that implements the breach formation in the simulation process (Sanz-Ramos *et al.* 2023b), the dam-break process and the subsequent fluid propagation being simulated jointly. This allows mine managers to identify and assess the potential flood extent and environmental damages

The numerical tool provides the evolution of hydrodynamic variables (e.g. depth, velocity, and fluid elevation) at each element of the calculation mesh, the base to assess the flood hazard and risk at each element at risk (EaR) of computational domain. The results can be analysed directly in the GUI or can be exported to other software to provide additional features and greater versatility for the users. This can help to apply the specifications and verify criteria of guidelines of each country or region worldwide to prevent dangerous situations for people and the environment (Penman *et al.* 2001; Klose 2007; Kheirkhah Gildeh *et al.* 2021).

Application & results

The performance of the numerical tool was exemplified through, first, the idealised dam-break of a visco-plastic fluid ($\rho = 1835$ kg/m^3) presented by Bryant (1983), which consists in a stored fluid (30.5 m in height and 305 in length) immediately released over a fully flat terrain with a runout distance of 1896 m. The parameters of the different rheological models implemented into IberNNF were defined according to Naef *et al.* (2006) with the aim of reproducing the results of the analytical solution of Hungr (1995). According to Hungr (1995), a simulation considering a total steady-state shear strength of 2390 Pa was carried out.

Table 1 summarises the values of the rheological models, and the maximum runout and fluid elevation at the end of the simulation, together with the detention time. In all simulations the fluid was released instantaneously and stopped a few seconds later. The fluid motion, runout and detention

Table 1 *Maximum runout and height at the end of the simulation and detention time according to the values of the rheological models of Bingham (simplified), O'Brien & Julien, and Voellmy. *Bingham simplified with a factor of 1.5 in the yield stress contribution (Naef et al. 2006).** Bingham simplified with a factor of 1 in the yield stress contribution (O'Brien and Julien 1988). ***Bingham simplified model was forced to a total steady-state shear strength of 2390 Pa.*

Model	Bingham* (simplified)		Bingham** (simplified)		Bingham*** (simplified)	O'Brien & Julien				Voellmy	
Parameter	$1.5\cdot\tau_y$	μ_B	τ_y	μ_B	$\rho g h S_{rh}$	n	τ_y	η	K	μ	ξ
Value	1500	100	1500	100	2390	0.02	1500	100	24	0.02	2500
Runout [m]	1748		2066		1875	1893				1738	
Time [s]	126		148		130	146				168	
Height [m]	9.59		8.14		9.69	8.25				12.75	

τ_y: yield stress; μ_B: viscosity; ρ: density; h: depth; n: Manning coefficient; η: O'Brien's viscosity; K: resistance parameter.

time were according to the rheological properties of the fluid.

The shape of the fluid at the end of the simulation was non-horizontal (Fig. 3a), the elevation in Bingham and O'Brien & Julien approaches being higher at intermediate distances (1250-1750 m) than upstream (500-1250 m) and decreasing almost vertically at the leading edge. The results of Voellmy were smoother than the others, being necessary to use a very low value of the Coulomb friction coefficient. Tn terms of runout, two approaches provided the best fit in comparison with the analytical solution: considering a total steady-state shear strength of 2390 Pa (Bingham***) and O'Brien & Julien. Only differences in the maximum height at the upstream part of the channel are remarkable due to velocity-dependent terms of the O'Brien & Julien rheological model. The results were also compared with DAN model (Hungr 1995), showing a good performance of IberNNF in representing an idealised dam-break scenario with non-Newtonian flow.

The second example is the gypsum TSF failure presented by Jeyapalan *et al.* (1983), which geometry was idealized according to Wu *et al.* (2020). A constant height of 11 m, released instantaneously, was imposed as initial condition considering a Bingham type fluid (τ_y = 1000 Pa and μ = 50 Pa·s). A mesh density of 5500 els./ha was used to discretize the computational domain. Fig. 3b shows a 3D view of the free surface at the end of the simulation, revealing a non-horizontal shape with the fluid at rest. The simulated runout was 300 m and the fluid front detention was produced at 50 s, in agreement with Jeyapalan *et al.* (1983). The fluid was fully stopped at 102 s.

Although the freezing time aligns with the observations, uncertainties in the breach formation –such as the breaking time and the evolution of the breach shape– along with the potential fluidization of the stored fluid (Ayala-Carcedo 2004), could result in an incomplete representation of the fluid behavior during both the dynamic and static phases (Sanz-Ramos *et al.* 2022).

Conclusions

New capabilities of Iber, particularly through the hydrodynamic module IberNNF for non-water flows, provide practitioners and mine managers a free distributed software to assess flood hazard and risk scenarios. This module is fully integrated in a user-friendly guide user interface (GUI) allowing the analysis of mine-tailings spill propagation over the environment, whether in its own GUI or exporting the results to other software.

Both dynamic and static phases of the fluid are result only of the rheological model, obtaining a free surface with the fluid at rest. The current version of IberNNF implements the equations of Bingham (simplified), O'Brien and Julien, Manning and Manning-like formulas (Viscous and Dilatant fluid behaviours), Voellmy, Bartelt and Herschel-Bulkley, providing practitioners a wide range of formulations to properly represent particular fluid behaviors.

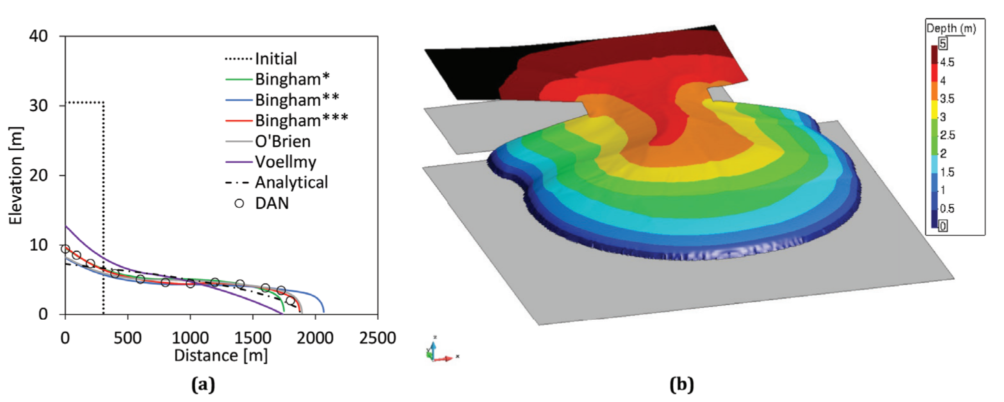

Figure 3 *Results of the numerical simulations: (a) idealized dam-break presented by Bryant (1983), and (b) gypsum TSF failure presented by Jeyapalan et al. (1983).*

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