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Numerical simulation of ash-spills induced by dike failure on ash tailings impoundments – a case study

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ABSTRACT: A model developed for simulation of both discontinuous clear-water flows and hyper-concentrated discontinuous flows is validated on a real dike failure event, which happened on an ash-tailings impoundment site. Numerical model is based on the MacCormack finite-difference scheme and involves constitutive equation in a form of the general yield-power law (the Herschel-Bulkley's rheological model). The influence of the solid phase volumetric concentration on the propagation characteristics of the dike-break wave is analysed. Rheological properties of ash-water mixtures are determined in the laboratory using a tube viscometer. Definition of the corresponding constitutive equations is based on the test results. In that respect, the rheological properties of ash may be described by the Bingham model.

1 INTRODUCTION

Ash spills induced by dam-break or dike-break on ash tailings impoundments present a severe danger to the environment. Numerical simulation of ash spills helps, therefore, predicting a size of endangered area and estimating hydraulic and environmental consequences of such an event.

A considerable attention has been paid so far to the analysis of unsteady free-surface flows of highly concentrated solid–liquid mixtures, which have a non-Newtonian character. The studies include both analytical solutions, and examples of numerical and physical modelling. A review of the investigated fluids, the constitutive relationships and the numerical schemes applied, can be found in the paper by Komatina & Đorđević (2004). A number of non-Newtonian dam-break flow experimental analyses have been performed, too (Aguirre-Pe et al. 1995, Jeyapalan et al. 1983, Komatina 1998, Komatina & Jovanović 1997, Laigle 1996, Laigle & Coussot 1997), the basic parameters of which have been summarized in Komatina (2000). The investigations refer mostly to mud and debris flows, however there are a few analyses of dam-break flow of liquefied mine tailings (Jeyapalan et al. 1983, Komatina 1998).

While earth dam engineering has evolved in theory and practice, little attention, from the hydraulic engineering point of view, has been paid to the design and construction of dikes on ash tailings impoundments. Common weaknesses in design of such dikes and working practices of impoundments include steep downstream dike slopes, inadequate emergency outlet structures, keeping high water levels (with potential for easy overtopping the dike crest), cracks appearance and sloughs occurrence, poor maintenance, etc. Failures of dikes are characterised by liquefaction of ash, and flow spreading over substantial distance, with potential for severe damage to life and property.

In this paper, ash spills induced by dike-break on ash tailings impoundments, are considered. The paper is continuation of the paper by Komatina & Đorđević (2004). It deals rather with the practical aspect of the problem and demonstrates the application of the numerical model, proposed in the preceding paper. A real dike failure event, which happened on the ash tailings impoundment site situated on an alluvial plain of the Danube River in Serbia, is used to illustrate the application of the model.

2 NUMERICAL MODEL

The 1D unsteady free-surface hyper-concentrated flows are described by the De St.-Venant equations in conservative form:

$$\mathbf{U}_t + \mathbf{E}_x = \mathbf{S} \tag{1a}$$

$$\mathbf{U} = \begin{bmatrix} A \\ Q \end{bmatrix}, \qquad \mathbf{E} = \begin{bmatrix} Q \\ \dfrac{Q^2}{A} + g I_1 \end{bmatrix}, \qquad \mathbf{S} = \begin{bmatrix} 0 \\ g A(S_o - S_f) + g I_2 \end{bmatrix} \tag{1b}$$

where x and t are space coordinate and time, respectively; A – the flow area; Q – the discharge; g – gravitational acceleration; S_0 – the bottom slope and S_f – the friction slope. The terms I_1 and I_2 are related to the hydrostatic pressure force (the second one being $I_2 = 0$ in prismatic channels).

In determining the friction slope, it is usually assumed that for unsteady flow, the bottom shear stress at a specific point is equal to the value of the uniform flow with a corresponding flow discharge and depth (Aguirre-Pe et al. 1995, Laigle & Coussot 1997). Consequently, it is possible to apply a simple rheological relationship, such as the Herschel-Bulkley's model, employed in this case.

The friction slope in Equation 1b is determined on the basis of the previously calculated value of the bottom shear stress τ_0, using the relationship (ρ fluid density, R – hydraulic radius):

$$\tau_o = \rho g R S_f \tag{2}$$

The calculation procedure of the bottom shear stress has been illustrated in detail in the paper by Komatina & Đorđević (2004).

The system of partial differential, hyperbolic-type equations (1) is numerically solved using the MacCormack explicit finite-difference scheme which is explained in detail elsewhere (e.g. Đorđević 2000, Garcia-Navarro & Saviron 1992). The scheme is second order accurate in both the space and time. In order to provide numerical stability of the scheme, the Courant-Friedrichs-Lewy's criterion is used to determine the time step Δt.

3 CASE STUDY

The model was applied for the analysis of a real dike failure event, which happened on an ash tailings impoundment site, located on an alluvial plain of the Danube River in Serbia. The impoundment is bounded by the river in the north, by road in the south, and by two canals in the east and west (Group of authors 2004). The breach of the surrounding 5 m high impoundment dike occurred on the west boundary, at a "spot" situated on the right bank of the prismatic canal of compound trapezoidal cross-section. The breach opening was 26 m wide with almost vertical sides (Fig. 1). It was located 345 m upstream from the inflow of the canal to the Danube River.

Available field data from the event included: a surveyed breach opening; a surveyed ash hole formed after the ash-water mixture had flowed out from the impoundment to the canal; trails of the ash-spill on the canal banks (Fig. 2); stage in the Danube River on the date of the failure event (70.10 m a.s.l.); the discharge flow of 4 m^3/s in the canal and samples of the material taken from the ash tailings impoundment site.

Material properties were obtained from the laboratory tests. Granulometric characteristics are given in Table 1, where d denotes the particle diameter, and p is the corresponding percentage of occurrence. The material density is 1900 kg/m^3, and its chemical composition: 50% SiO_2, 10.5% Fe_2O_3, 21% $Al_2O_3 + TiO_2 + P_2O_5$, 7% CaO, 5% MgO, 1.5% SO_3 and 2% $Na_2O + K_2O$, the loss of ignition being equal to 3% of the total mass.

Rheological properties were analysed for several ash-water mixtures, in which the volumetric concentration of the solid phase C_V varied between 0% and 48%. The measurements have been

Figure 1. Dike-break site (breach opening).

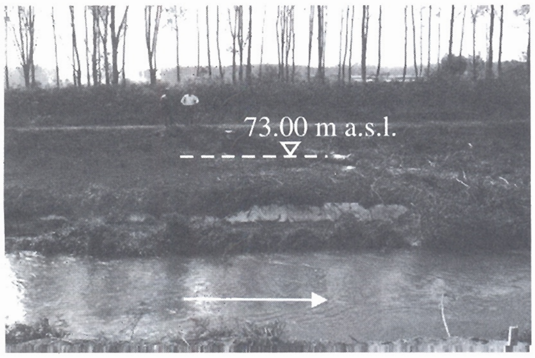

Figure 2. Trails of ash-spill on the canal banks.

Table 1. The ash granulometric composition.

d (mm)	0.500	0.400	0.300	0.200	0.100	0.074	0.053	0.045	0.038	0.001
p (%)	100.0	99.2	96.7	90.2	67.9	52.3	42.1	37.1	34.5	0.0

performed using a tube viscometer, similar to that used by Chang et al. (1988), and the experimental procedure was identical to that described by the same authors. This type of viscometer has been successfully used in the analyses of kaolinite clay (Komatina 1999), copper mine tailings (Komatina 1998) and red mud slurry (Chang et al. 1988).

Homogeneity of the mixtures has been provided by performing the experiments using the fine ash particles only. Afterwards, the rheological parameters of these mixtures were recalculated (in a way described by Wan & Wang 1994), to represent the whole grain size distribution. In order to achieve steady and laminar flow of the ash-water mixtures during the measurements, two tubes, having a sufficiently high length-to-diameter ratio (L/D), have been used ($D = 7.5$ mm, $L = 1247$ mm and 1537 mm, giving values of the L/D ratio equal to 166 and 205).

The Bingham model was applied for description of the rheological properties of mixtures. Values of the two parameters, plastic viscosity η and the yield stress τ_c, have been well fitted by the widely used relationships (O'Brien et al. 1993):

$$\eta = a_1 \cdot e^{C_V/b_1} \text{ and } \tau_c = a_2 \cdot e^{(C_V - C_{V0})/b_2} \tag{3}$$

where a_1, b_1, a_2, and b_2 denote empirical coefficients obtained by laboratory experiments; C_{V_0} is the minimal volumetric concentration of the solid phase, necessary for establishment of the yield stress. Values of C_V and C_{V_0} are expressed in percents.

Table 2. Rheological properties of the mixtures.

C_V (%)	30	33	36	39	42	45	48
ρ (kg/m^3)	1270	1297	1324	1351	1378	1405	1432
η (mPas)	70.6	96.8	132.7	182.0	249.6	342.2	469.3
τ_c (Pa)	0.01	0.03	0.08	0.27	0.88	2.87	9.30

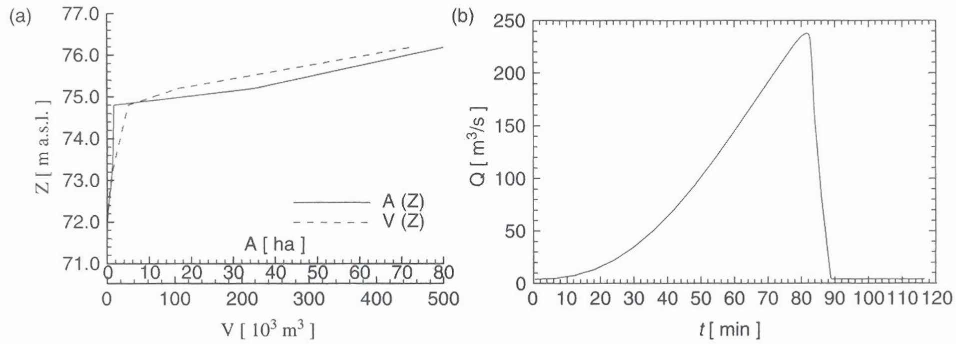

Figure 3. (a) Area and volume curves of the impoundment; (b) Outflow hydrograph from the impoundment.

In this study, the following values have been obtained: $a_1 = 3$; $b_1 = 9.5$; $a_2 = 0.008$; $b_2 = 2.55$; $C_{V_0} = 30\%$. For comparison, results reported by Shook & Roco (1991) for a coal slurry with a similar granulometric composition ($d_{max} = 0.3$ mm, $d_{33} = 0.044$ mm, compared to $d_{max} = 0.5$ mm, $d_{97} = 0.3$ mm, $d_{36} = 0.044$ mm in this study), correspond to the values: $a_1 = 4$; $b_1 = 9.5$; $a_2 = 0.35$; $b_2 = 7.2$; $C_{V_0} \approx 30\%$. Values of the rheological parameters, used in the numerical modelling, are listed in Table 2.

The volume curve of the ash tailings reservoir (Fig. 3a), necessary for estimation of the outflow hydrograph from the impoundment, was determined on the basis of the existing topographic maps of the impoundment and size of the surveyed ash hole. A linear evolution of the breach opening (both of the width and the height) was assumed in estimating the outflow hydrograph. This assumption is justified by previous laboratory analyses (Jovanović 1987).

4 RESULTS AND DISCUSSION

The outflow hydrograph from the impoundment site was estimated on the basis of: the known water level in the impoundment, the volume curve, assumed evolution law of the breach opening and trails of the ash-spill on the canal banks. Different durations of breach development were considered (15–90 min). By comparison of the calculated water level with the trails of the ash-spill on the canal banks, it was concluded that the breach fully developed in 90 minutes. The resulting hydrograph is shown in Figure 3b. The peak flow of 237 m^3/s occurred 1.36 hours (81 minutes) after the beginning of the process. The corresponding flow depth and velocity at the opening were 2.16 m and 4.5 m/s, respectively. It was estimated, on the grounds of the surveyed volume of the ash hole and the total volume of the outflow material, that the initial concentration of ash in the ash-water mixture was approximately 6%. This means that it did not exhibit non-Newtonian behaviour. Therefore, the De St.-Venant equations, without the additional term that accounts for rheological behaviour of the fluid, were used for the analysis of the dike-break induced wave propagation.

Simulations were conducted with the following data: the bottom canal slope $S_0 = 0.087\%$, the Manning's coefficient value $n = 0.024\,\mathrm{m}^{-1/3}\,\mathrm{s}$, distance between cross-sections $\Delta x = 15$ m. The time step was calculated from the Courant-Friedrichs-Lewy's condition. The initial conditions

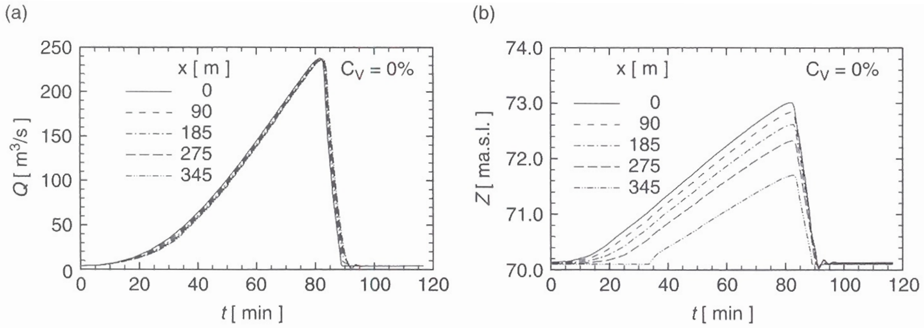

Figure 4. (a) Hydrographs and (b) Stage hydrographs at chosen locations along the canal.

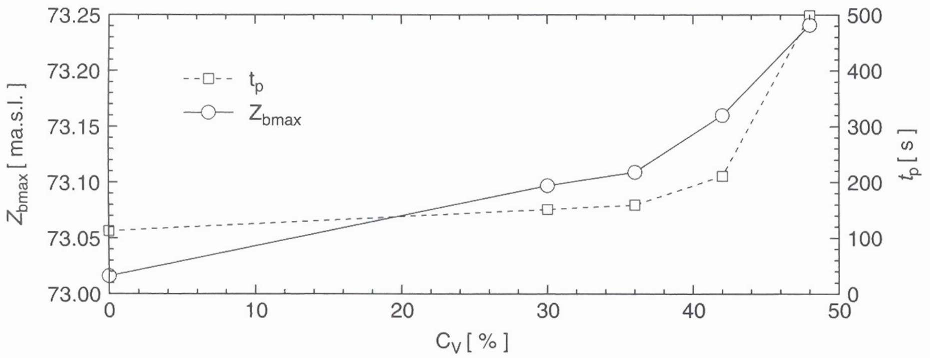

Figure 5. Influence of the concentration of solids on the maximal stage in the cross-section near the breach opening and the dike-break wave travelling time to the downstream cross-section where canal meets the Danube River.

were constant discharge of 4 m^3/s in the canal and corresponding water level profile. The calculated outflow hydrograph was used as the upstream boundary condition, whereas the constant water level in the Danube River was used as the downstream boundary condition. The later is due to the fact that the Danube River is a large alluvial stream with the discharge two to three orders of magnitude greater than the canal discharge, which means it could receive discharging flows from the canal without significant changes in the water level.

Results have shown that the total volume of the outflow ash-water mixture was received by the canal and conveyed to the river, which is in agreement with the field observations. As it was expected, there was no significant attenuation of the dike-break induced wave, due to very limited expansion space (Fig. 4).

In addition, a sensitivity analysis was conducted in order to illustrate the influence of the solid particles concentration on the propagation characteristics of the dike-break wave, as in Jovanović (1991). Therefore, in this analysis, the De St.-Venant equations included terms, which account for rheological properties of the flowing fluid. Settling of the particles during propagation was neglected, the propagation time being an order of magnitude shorter than the settling time of the coarsest particle.

The results are presented in the form of diagrams showing dependence of two variables on the concentration C_V: the maximal value of the stage in the upstream cross-section corresponding to the breach opening (Z_{bmax}) and travelling time of the dike-break wave to the downstream cross-section where canal meets the Danube River (t_p) (Fig. 5). Linear relationships for $C_V < 36\%$ confirmed non-Newtonian character of these mixtures. Considerable delay and rise in level for mixtures with

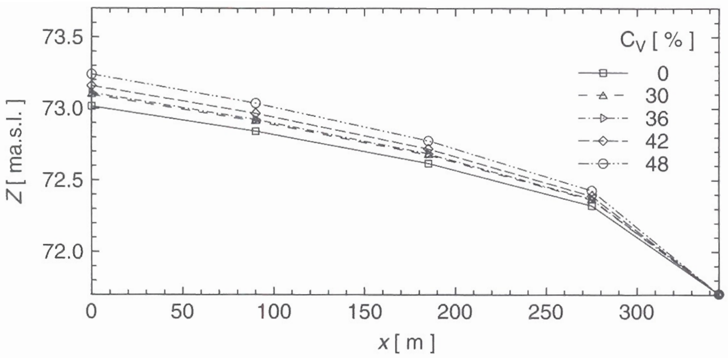

Figure 6. Envelopes of maximal stages for different volumetric concentrations of solids.

Table 3. Influence of C_V on the travelling time of the dike-break wave and the rise in maximal stage at the breach.

	$\Delta t_p/t_p$ [%]				$\Delta Z_{bmax}/Z_{bmax}$ [%]			
C_V [%]	30	36	42	48	30	36	42	48
0	34.1	41.2	87.1	342	1.74	1.99	3.05	4.77
30	0.0	5.3	39.5	230	0.00	0.25	1.29	2.98
36	–	0.0	32.5	213	–	0.00	1.04	2.72
42	–	–	0.0	136	–	–	0.00	1.67

$C_V > 36\%$, with respect to clear water and those ones with $C_V < 36\%$, illustrate strong influence of the yield stress on the propagation characteristics of the dike-break wave. This can be readily seen both in Figure 6, showing envelopes of the maximal stages along the canal and Table 3. However, capacity of the canal is not exceeded for any of considered hyper-concentrated ash-water mixtures (canal bank ground level is 73.50 m a.s.l.). The stage differences decrease as the considered cross-section becomes closer to the Danube River, which is in agreement with the fact that the water level in the river is not influenced by the canal outflow rate.

5 CONCLUSIONS

Dam-break or dike-break flow computation is a complex task, affected by a number of factors, such as availability and reliability of boundary and initial conditions, and capability of a numerical scheme to reproduce steep front without introduction of additional algorithms for bore tracking. The computation becomes even more complicated when modelling unsteady flows of highly concentrated solidliquid mixtures. In such a case, estimation of rheological parameters of the mixture, as well as calculation of the friction slope, appear as new sources of errors.

In this paper, a 1D numerical model for hyper-concentrated dam-break or dike-break flows was validated using field data from the real dike failure event. It was estimated that the initial concentration of ash in the ash-water mixture on the site had been 6%. Additionally, experimental investigations of the material taken from the impoundment, have shown that the minimal volumetric concentration of solids, necessary for establishment of yield stress is $C_V = 30\%$, which justifies utilisation of the De St.-Venant equations for clear water in prediction of dike-break wave propagation. Simulation results have shown that the total volume of the outflow ash-water mixture could be received by the canal, which is in agreement with the field observations. As it was expected, there was no attenuation of the dike-break wave.

Apart from reproducing the real dike failure event, additional analysis has been conducted in order to estimate what would have happened if the concentration of ash had been greater. The results have shown that despite deceleration of the front wave, no significant rise in stages (less than 5%) and consequently no overflowing of canal banks would have happened.

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