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Debris flow hazard assessment of abandoned tailings ponds in Friuli Venezia Giulia, Italy

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Introduction. As other European countries, in the last decades, Italy has experienced a steady decline of the exploitation of mineral resources. About three thousands mines were producing between 1870 and 2006 (Berry et al. 2009), nowadays only a few tens of mines (sensu strictu) are still working. In such context, there are many abandoned mines which may induce some hazards to human life and environment. Previous studies (Berry et al. 2009) describe the potential instability risks of disused mining sites, related only to phenomena which are referable to discontinuous subsidence, but no mention is done about the hazard introduced by the collapse of flotation basins or tailings dams and waste heaps. The tailings have small grain size and usually high water content, and contain a certain amount of the extracted material, also heavy metals, and chemicals added during the milling process. The tailings ponds are constructed by raising levees using various mining wastes, including tailings and unprocessed ore, lifting them progressively during the process of filling. This method, although inexpensive, implies a specific prejudice to the stability of the banks, especially in case of heavy rain or earthquakes. Unfortunately, the lack of evaluation and monitoring during the disposal and dismission as well, has led to hundreds of banks failures, some with disastrous consequences. Collapse of tailings dams and mining waste heaps, due to natural hazards such as earthquakes or intense hydrological events may result in the release of large amounts of tailings threatening both human lives and environment: Kolontàr (Hungaria, 2010), Taoshi (China, 2008), Aberfan (UK, 1966). The major percentage of incidents is related to meteorological causes (Rico et al. 2008). The tailings management practice in Italy has commonly identified difficulties: many structures suffer problems with seepage and dust pollution. Italy has recently had the sort of catastrophic tailings failure: in Stava (Eastern Italian Alps), on 19th July 1985 the bank of the upper basin failed and collapsed onto the lower one, which, too, collapsed. 200,000 cubic metres of tailings poured out of the dams, flowing at a speed up to 90 km/h, killing 268 people and destroying 62 buildings. These and other past experiences show that emphasis should be put on prevention. The aim of this study is to evaluate the hazard of four tailings ponds located on the left side of the Rio del Lago, next to the dismissed blende and galena mine of Cave del Predil (Tarvisio, UD, North-Eastern Italy). The tailings might be involved in a liquefaction process that occurs in saturation conditions, following a possible high intensity hydrological events or seismic shocks. The outflow that would be released in case of the basins collapse, threatens the hamlets of Riofreddo and Plezzut and the city of Tarvisio, sited 10 km downstream.

Geomorphological setting. The four tailings ponds are founded on the underlying alluvial deposits consisting of silty sands and coarse gravels, and on the late Holocene colluvial deposits which cover Triassic calcareous-dolomitic formations. These ponds were placed in morphologically favourable locations, requiring the minimum earthworks. They were set along the Rio del Lago valley, confined between a rock and debris slope on one side, and the

embankments constructed using the coarser soil material resulting from the mine excavations on the other side (Fig. 1). Table 1 displays areas and volumes of the four tailings ponds and Figure 2 is a section across the basin 2, showing the typical structure of a tailings pond.

Table 1. Area and volume of the tailings ponds.

	Pond 1	Pond 2	Pond 3	Pond 4
Area (m^2)	18375	30521	29096	17444
Volume (m^3)	257945	925920	789240	303096

Figure 1. Aerial view of the old flotation plant area and the tailings ponds.

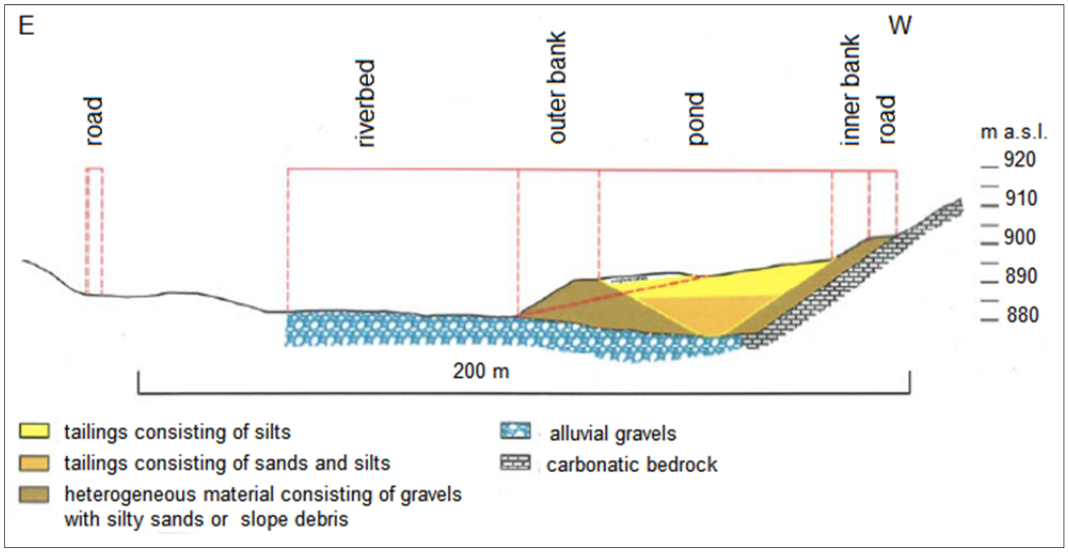

Figure 2. Cross section of the tailings pond 2.

Geotechnical properties of the tailings. The ponds collect the calcareous-dolomitic sediments resulting from the enrichment process of the minerals. The basins are filled of silty and sandy-silty sediments (silty fraction between 45 and 70%); the outer banks, with an average slope of 30°, are made primarily of gravel with silt and sand (gravel fraction between 45-80%, sandy fraction varies between 20-40%); the inner banks are generally made of coarse debris slope.

Geotechnical problems. The maximum height of the embankments, today, varies from 15 to 22 m. Taking into consideration the construction practices when the tailing ponds were created, several geotechnical issues arise, among which: (a) the ponds were founded without any measures to protect the aquifers; (b) the stability of the embankments is questionable as they are made of loose granular material susceptible to liquefaction; (c) the location of the tailings ponds along the valley permits, in case of heavy rain, the water to accumulate in the abandoned ponds, causing a possible mud overflow to the valley stream by erosion channels cut through the embankments (Figs. 3, 4) or banks erosion caused by the main stream itself.

Figure 3. Erosion channel cut through the embankment of a tailings pond.
Figure 4. Extensive erosion ditches through the embankment of a tailings pond.

Debris flow hazard evaluation. In order to assess the hazard associated with a debris flow along the Rio del Lago-Slizza, generated by the collapse of the tailings ponds, a numerical simulation of some possible event scenarios was undertaken using the two-dimensional model FLO-2D. This finite difference routing model reproduces the effects, in terms of inundation area, flow velocity and runout, of a debris flow by solving the continuity equation and the two-dimensional equations of motion (O'Brien et al. 1993) and combining yield, viscous, collision and turbulent stresses in the quadratic rheologic equation for the total friction slope. For a complete discussion of the model, see the User's Manual (FLO-2D Software Inc. 2006). Simulations were carried out assuming that the debris flow propagates along the Rio del Lago immediately downstream of the pond 4, for all the embankment failure scenarios occurring across the study area, including the failure of single embankments as well as the simultaneous failure of more embankments. The whole duration of the process was assumed to be equal to 2 hours.

Table 2. Routed sediment volumes.

Collapse of pond(s)	1	2	3	4	1+2	2+3	3+4	1+2+ 3+4
Volume (10^3 m^3)	424	1510	1283	489	1932	2790	1770	3698

Missing specific investigations, the rheological properties of the flow have been chosen from the values reported in the literature concerning materials similar in particle size distribution and calculated for an average sediment concentration of 0.36; Table 3 lists rheological properties together with the other simulations' input parameters.

Table 3. Input parameters of numerical simulations.

viscosity η (Pa s)	yield stress τ_y (Pa)	specific gravity γ_m (kN/m^3)	Resistance parameter for laminar flow K
0.96	9.4	2.65	2285

Results and conclusions. The results of numerical simulations of the most hazardous events can be summarized as follows:

(a) The hamlet of Rio Freddo can be affected by the debris flow also even in the case of the less severe occurrence, represented by the collapse of the single pond 1: the mass would flow through the settlement with a thickness of about 4 m and an average speed of 2.3 m/s, reaching the village after about 11 minutes from the collapse failure. In the case of the heaviest scenario, represented by the collapse of all the four tailings ponds, the flow would reach Rio Freddo after approximately 8 minutes from the flow onset, with an average speed of 3.4 m/s and the remarkable thickness of 14 m (Figure 5).

(b) The hamlet of Plezzut, about 2 km downstream of Rio Freddo, begins to be interested by the flow in the occurrence of the pond 3 collapse. In this case a part of the inhabited area would be crossed by a debris flow with a thickness of up to 8 m, which reaches the hamlet in about 25 minutes, with an average speed of about 2.6 m/s. In the event of the collapse of all the four ponds, the debris flow would cross Plezzut with thicknesses up to 15 m, about 19 minutes after the collapse of the four ponds, covering the distance at an average speed of 3.4 m/s.

(c) The outskirts of Tarvisio might be affected by the flow produced by the simultaneous collapse of the ponds 3 and 4 as well as by the collapse of the all four ponds (see Table 2). In such cases, the village of Tarvisio would be reached by the debris flow in about 30 minutes, with thicknesses varying between 6 m and 13 m.

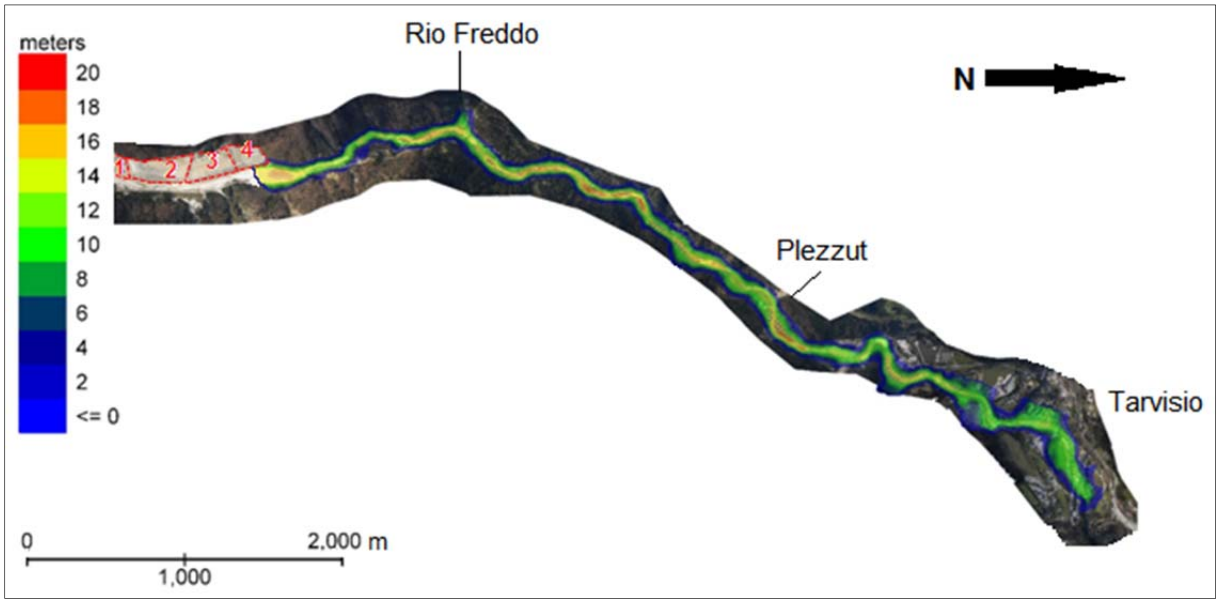

Figure 5. Maximum flow depth map on the occurrence of a simultaneous collapse of ponds 1, 2, 3 and 4.

The four abandoned tailings ponds located 10 km South of Tarvisio may represent a severe hazard for the valley due to the flows that would generate from an embankments failure. As the fine grained materials deposited in the ponds retains a quite high proportion of Pb, Zn and other flotation chemicals, a possible failure or a continuing leaching and erosion of these

materials would extend the contamination over a large inhabitated area. After the risk assessment, the issue is to undertake measures to protect the embankments from erosion and possible failure.

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