Forecast of emergency situations owing to excessive water inflows into tailings ponds

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ABSTRACT

This paper refers to the first results of a study, which aims at analysing and evaluating situations which precede and cause tailings flow slides. The most frequent situations before mud inrushes, their evolutions and their action manner in causing these inrushes are analysed. Heavy rainfall is a relevant circumstance, which often occurs before these events. For this reason, the effects of the rainfall, and as a rule, of the water flowing into tailing ponds, on the stability conditions of the material stored in the ponds and of the dams erected to retain it, are deepened.

Factors, which mainly affect emergency situations and their action mode, are studied, in order to find out some useful hints to forecast and face these situations. This is done by observing the events in two ponds of Southern Tuscany, almost in an emergency situation: on one hand, we have a pond with too much water and which is crossed by high water flows; on the other hand, a pond that has some particular parts, which may fail after some heavy rains and pour onto others.

In particular, the trends of piezometric surfaces, as well as their variations, in the above-mentioned ponds and mainly their dams, are observed at regular intervals and after some particular events. Trends and their variations are related to previous rainfall, in order to find out rainfall, which mainly affects them, and to identify probable existing emergency situations and, in any case, possible emergencies, which might occur after heavier rainfall than the usual ones. This procedure allows us to find some quite high piezometric surfaces, which are strongly affected by rainfall, as well as some tailings ponds parts more at greater risk of "liquefaction" than some other ones.

Some measures are also suggested according to our present knowledge: they refer to carrying out some works to prevent these emergency situations and/or reduce their effects, and to controls and interventions be taken to find out and effectively face these situations.

INTRODUCTION

Sixteen of the seventy-eight incidents reported in a list on the major tailings dam failures, which occurred from 1960 to 2001 (Wise 2002), are clearly due to the heavy rains soon after which they occurred (Wagener 1998, Fourie 2000). Of other 16 incidents are also listed causes like next ones: insufficient perviousness of filter drain, internal dam erosion, too high pond level, pipe blocking, which imply water action (Chandler and Tosatti 1995, Lucchi 1995). As to other incidents, of which is reported a cause, such as dam failure from foundation giving in, also water may have caused them (Douglas G. Feasby and others 1995) .

As a matter of fact, water may:

- Reduce resistance of the stored material;
- Increase the thrusts on the dams, reduce the resistance of the same dams, and
- In case of their failure, make it possible tailings flow slides downstream.

If the dam of a completely dried up tailings pond fails, the tailings that would come out, as there is not water which could fluidify and drive them, would confine theirselves to set out downstream according to their granulometry and the soil morfology.

On the contrary, if too much water is present in a tailings pond, it can not only cause liquefaction of tailings, weakening and failure of dams, but also supply the material that should come out, and which partly makes it, the conditions for its inrush downstream.

And just these dynamic consequences, may on their turn cause actual disasters. In order to avoid such consequences it is necessary to prevent water presence in tailings ponds by obstructing water inflows into them and by favouring outflows out of the same ponds. But nor disciplinable situations can occur, and in these cases one must be able to identify possible states of emergency, or rather, not to allow their rising by observing, over all, the piezometric situations either in the tailings or in the dams (Sammarco 2003a).

This paper is going to give its own contribution in this direction. It refers to the results of a study, which is being carried out to analyse and evaluate situations preceding and causing tailings flow slides due to exaggerate water inflows into tailings ponds. This study is based on some field tests, which were carried out in two tailings ponds in Tuscany. These ponds are under some circumstances in emergency situations, and for this reason they can provide us with useful hints to make a thorough analysis of these situations. This study follows a similar one on the dynamics and effects of flow slides (Sammarco 1993, 1998), even if it would have had to be carried out before from a chronological point of view. Thus, the whole study might be defined a follows: emergency situations that precede tailings flow slides, dynamics and effects of the mud inrushes.

EVENTS DYNAMICS: FROM WATER INFLOW INTO TAILINGS PONDS TO MUD INRUSHES

The tailings, which generally consist of sands, silts and/or clays, in the form of slurry are generally pumped into ponds, whose dams are gradually erected with the coarser particles that are heaped up the edges. For this reason, both the settled materials and the materials of dams, which were built to retain them, are soft and at times clayey. Therefore, their resistance and hydraulic characteristics mainly depend on water and on modes with which it is present.

On their turn, these modes depend on water percentage: by increasing such percentage, we may schematically suppose that water is not absorbed any longer, but it becomes capillary and finally phreatic water. And this last is a case that often occurs both in tailings ponds and dams which sometimes are crossed by high, even if slow, water flows. These water flows may cause, erosion, which contributes to reducing the overall system resistance and modifying its permeability.

Water, which may inflow into tailings ponds, can

- Inflow together with the tailings themselves, which it conveys;
- Come from deep formations, sometimes as thermo-mineral water;
- Due infiltration and/or overflowing, come from water courses, that at first flowed on the valley bottom, but which were then diverted to prevent their flowing through the tailings. Water may also come from water pipes that were built on the ponds floor before tailings inflow, due to the pipe break or obstruction;
- Come from plants, which are located upstream, due to some system faults or wrong operations;
- Flow due to rains and/or, in some locations, snow melting.

These last waters can reach a tailings pond according to the following modes:

- Falling directly on its surface (Swanson and others 2000);
- After falling to the slopes of hydrographical basins that converge onto the valley, which houses the tailings pond;
- After infiltrating into the subsoil of these basins and of hydrogeological basins which too, inflow into the same pond.

Obviously, the wave, which stands for the water level in time, and within the pond and dam, may look very different from the rainfall-related one for the following reasons:

- Some other water may flow into the pond, along with the rainfall related one;
- Same specific rain-related water does not reach the pond at the same time, but through different paths according to different time lags. These paths may also change in time (Sammarco 1994);
- Permeability may change considerably in the various pond parts, due to all waters flowing into it (Scheidegger 1961).

And these ones are the reasons which make difficult the correlation between the cited two waves.

The water inflowed into a tailings pond can pass through the pond or be retained if it should come to be surrounded by impermeable layers (Kesseru, 1997) or because of the absence or inefficacy of drainage works. This gives rise to a system, which is made up of some water stagnation zones, out of which water flows according to the Darcy mode generally.

Should water inflow increase, the draining system permeability be reduced (Fernandez-Rubio 2002) and/or evaporation from the pond surface be prevented, thus leading to too much water in the same pond, the following events may occur:

- Liquefaction of tailings (Fourie and others 2000);
- Pressure increases on the dam, because water quantity in the pond would increase and the tailings capacity to sustain themselves would decrease;
- Dam weakening, because the flow-rate of the water flowing through its draining parts and therefore the erosion action would increase and, as water pressure is higher, its capacity of intiltrating into the dam itself and its foundation would also increase.

If the last two mentioned events should be such as to lead to the dam failure, the tailings would flow out of the pond and inrush downstream along with water, which turned them into mud.

The circumstances which give rise to too much water quantity in a pond must be valued and controlled. This can be done by observing, over all, their effects on the piezometric situations periodically and after some particular events.

PIEZOMETRIC SITUATIONS AND THEIR DEPENDANCE ON RAINFALL IN PONDS ALMOSTO IN EMERGENCY

Rainfall is one of the leading causes of too much water quantity in tailings ponds.

Its effects were and are being investigated by observing piezometric situations and their variations in the area of dams and of some particular points in two ponds. These quantities were then related to previous rainfall and the flooding conditions in a pond, flooding which may occur sometimes.

Gavorrano and Fenice Capanne mines tailings ponds are being monitored. Both these tailings ponds may come to be in unstable situations due to the following reasons (Sammarco 2002a, 2002b):

- High water content in and high water flow through the pond in the first and
- Particular topographic conditions of its parts and dams reduced resistance in the second one.

GAVORRANO MINE TAILINGS POND

During the mine production period, between 1943 and 1981, a system of 9 different bordering ponds (Mineraria and Mining 2002), which may be considered as one single pond, was built in a valley, with a 5÷10% slope of a hilly land, made up of llimestones, marls and shales of the Ligurian Flysh. This pond has the following features:

Total volume of the stored material:	$>2.4\text{x}10^6$	m^3
Volume of the material stored only in the pond more downstream	$>0.9\text{x}10^6$	m^3
Total area	=510,000	m^2
Area of the pond more downstream	=110,000	m^2
Particles size of the stored material in this pond	<0.15	mm
Maximum height of the pond more downstream	=~20	m
Average slope of the ground surface in the first two km downstream	=1.1	%

The stored material is supported, to SW and SE, by the hills upstream, while to NE and NW by a dam raised using the “upstream” construction method. As to stability, this method is the least reliable of the usually adopted other ones (Figure 1).

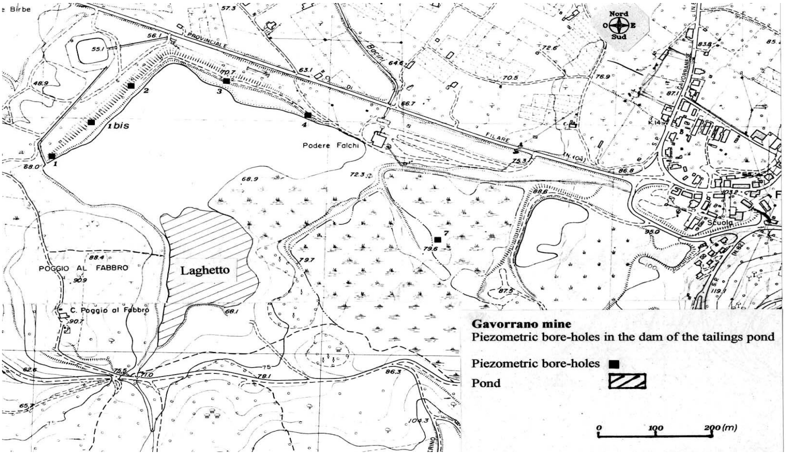

Figure 1. Tailings pond of the Gavorrano mine

Water can flow into the pond:

- Falling directly as rain water on its surface:
- From slopes flowing into the pond, if the channels, designed to intercept and convey it, are filled up with earth or broken;
- From unforeseeable infiltrations from valley bottom and slopes under the tailings;
- From a diverted stream, by canalizing it into a channel and a small tunnel in order to may build the pond in its valley, should it, in time, start following its original path due to missing maintenance;
- By thermo mineral water immissions from the pond floor or walls, which once showed themselves as intermittent springs. This would occur if the flood of the close underground mine should make it possible these water go up again and come out into the stored material.

Considering only direct rain water on the tailings pond surface and supposing an annual rainfall in an average amount equal to the one, which occurred in the period between 1995 and 2001, calculated from the rainfall data, which were gathered near the pond itself, and an evapotranspiration rate of 600 mm/year, 108,000 m^3 of water would penetrate into the pond yearly with a mean flow rate of 3.5 l/s.

The above-mentioned amounts, which are lower than the actual ones, are enough to point out at the high risk we would run if the system draining capacity were reduced further. The pond material is not at all consolidated actually. Its low viscosity degree is due to the high inflow of water and reduced permeability of the dam downstream. This last circumstance is stressed by the high piezometric level in the dam itself, where water finds itself at a slightly lower depth than two metres (Sammarco 2003a).

The following relevant incidents occurred in the years listed below:

- 1958: failure of the dam of the pond downstream during its initial filling step;
- 1997: flooding of the southern eastern part of the pond.

Considering circumstances and events that could occur, some specific suggestions have been given to improve the pond stability and prevent disastrous consequences in case of dam failure. Some of these are the following (Sammarco 2002b).

1. If possible, and with due care, take away the piezometric surface from the external dam or at least lower it, by replacing the material on the dam floor with some draining material.
2. Improve the external dam stability by increasing its size up to having a base, which is at least twice as large as the present one.
3. Prearrange effective drains behind and on the floor of the parts of dam, to be assembled over the existing dam.
4. Shape the dam slope in such a way as to have some terraces, designed to carry out piezometric controls. This also aims at enabling some pumpings in order to lower the piezometric surface, in case of need and even after the mine abandoning.
5. Realize some suitable anchorage system for restraining firmly the dam to the soil.
6. Control the conditions of the internal dams and, if necessary, implement some measures to increase their stability (Sammarco 2003b).

FENICE CAPANNE MINE TAILINGS POND

In the period between 1957 and 1984, 4 adjoining ponds, on a land made up of shales and limestone layers of the Ligurian Flysh, were filled. Two of them, ponds 1 and 2, are located in a valley, in WNW-ESE direction, with an average slope of 3.3%. The two remaining ones, ponds 3 and 4, are located in a valley, in N-S direction, with an average slope of 6%. A dam upstream and a dam downstream enclose the first two ponds. They are 10 m and 35 m high respectively and were both built according to the upstream method. The remaining ponds, are on slightly higher quota than the first ones and are supported downstream by weak dams (Figure 2).

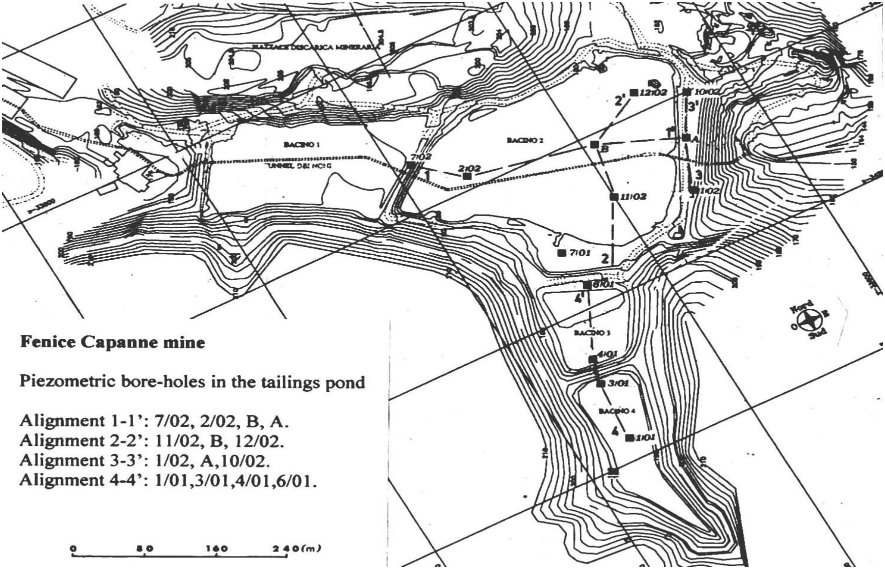

Figure 2. Tailings pond of the Fenice Capanne mine

- This system has the following features:

Total volume of the stored material:	>0.98x10^6 m^3
Volume of the stored material only in the pond downstream	>0.6x10^6 m^3
Total area	=100,000 m^2
Area of the pond downstream	= 55,000 m^2
Particles size of the material stored in this last pond	<0.25 mm
Average slope of the ground surface in the first two km downstream	=2.3 %

Water can flow into the above-mentioned ponds according to the following modes:

- Falling directly on their surface as rain water;
- From slopes flowing into them if the peripheric channels are filled up with earth or broken;
- Suddenly seeping from the bottom and slopes of the valley, now under the tailings, as, by bore-holes carried out near the ponds, some water was found in a higher altitude than the ones of the ponds floor. We also have to bear in mind that there are some flooded galleries of the Fenice Capanne mine below the more upstream pond. The water pressure in these galleries may become enough as to allow water infiltration into the pond, if the drainage tunnel of this mine were occluded;
- From a preengineered tunnel, on two ponds floor, before their filling. Over all rain water falling upstream the ponds and on their surface, may flow, this last after having crossed spillways, into this tunnel. In case of tunnel overflow and/or obstruction, water could flow from the tunnel into the ponds.

The following relevant incidents occurred in the years listed below:

- 1984: Settling in the above-mentioned tunnel;
- 1987: Failure of the pond 4 dam part and
- 2002: Flooding of this pond and the one immediately upstream.

At present, the above-mentioned ponds stand for the greatest risk, due to the easiness with which water inflows into them and the reduced resistance of their dams. If these last fail after some heavy rains some tailings slurry waves might actually thus pour onto the pond part below, thus compromising the system stability (Sammarco 1993).

To reduce risks of tailings flow slides as much as possible, some works have been planned (Sammarco 2002 a) and are being carried out to reduce water inflow into the ponds, without preventing, but rather promoting, water outflow. Some solutions are also being searched, to improve the static situation of the most downstream dam as much as possible.

FIELD TESTS CARRIED OUT UP TO NOW AND RELATED RESULTS

The condition of both above-mentioned tailings ponds have been under control for more than two years, by monitoring water levels at regular intervals and after heavy rains both in the dams and the tailings of the same ponds. Water levels are related to rainfall, which is the only water inflow into these ponds that one can measure. Rainfall is recorded near both tailings ponds.

Water levels are gauged, in particular, in the following piezometric bore-holes wholes:

- P. 1, P. 1bis, P. 2, P. 3, P. 4, in the most downstream dam of the Gavorrano mine ponds (Figure 1);
- P. 1/02, P. A, P. 10/02, in the most downstream dam of the Fenice Capanne mine ponds, along the alignment 3-3’;
- P. 7/02, P. 2/02, P. B, P. A.;
- P. 11/02, P. B, P. 12/02;
- P. 1/01, P. 3/01, P. 4/01, P. 6/01; respectively, along the alignments 1-1’, 2-2’ and 4-4’ in the ponds of the last mentioned mine as well (Figure 2).

To try of highlighting some correlations we have drawn, in figure 3, water levels measured in the bore-holes in the most downstream dam of the Gavorrano mine tailings pond, daily rainfall, above, and monthly rainfall, below. This figure points out that these levels depend on the rainfall, but evident repercussions of single days rainfall on them do not occur.

After a period of heavy rainfall, the highest water level increases occurred in the piezometer 1 and mainly in the piezometer 4, both near the dam ends while in the piezometer 2, located in the dam central part, only slight increases occurred: water levels kept still high during some months after the above-said period.

In figure 4 we have drawn water levels in bore-holes located in the vertical section, which runs through the ponds 3 and 4 of the Fenice Capanne mine along the alignment 4-4’, daily rainfall, above, and monthly rainfall, below. We began monitoring these levels, which are still being monitored at present, soon afterwards the flooding of the aforesaid ponds which occurred in January 2001.

Also if it is evident the influence of the rainfall on the piezometric levels, one does not distinguish clearly the effects of the single days rainfall on that levels. This is obviously due to the irregularity with which the rainy days follow one another and to the different rainfall from one to another of these days. This with the exception of the level increases on the following dates: 27.06.01; 19.04.01; 27.11.02; 03.12.02; 22.01.03 and 31.01.03.

These increases are presumably due to heavy rains during in previous days. This is also shown in table 1, where a water level increase of 2.89 m in the piezometer 6, measured on 22.01.03, after 30.6 mm rain on the day before, can be seen.

The water level changing mode in one piezometer seems at times different from that in another (Figures 3 and 4). This is probably due also permeability variations that occur in these ponds owing to the same waters which flow through them.

The effects, on the water levels, of rainfall occurred during various periods before each measurement, were analysed by statistical method, also if it had not many data, in order to better understand how the rainfall affects the piezometric situation of these tailings ponds.

In particular, water levels in the piezometers located in the dam of the Gavorrano mine tailings pond (Figure 1) and in the ones located in the pond of the Fenice Capanne mine, whose mouths are on the alignments 3-3’ and 4-4’ (Figure 2), were gauged. The water level values, which were gauged in each piezometer, were then related to values of the rain quantities fallen during previous 9 periods, after relating the value of each water level to the rainfall occurred in the periods between the measurement day and the 15th, 45th, 75th, 105th and 135th day before measurement itself and to the rainfalls in the periods between the 15th and 45th, the 45th and 75th, between the 75th and 105th, the 105th and 135th day before each level measurement.

Supposing that the relationships between water levels and rainfalls are linear, the following elements were calculated: regression lines and correlation factors by means of Excel for Windows and SPSS for Windows respectively. They are included in table 2, 3 and 4, which also point out the deductions listed below.

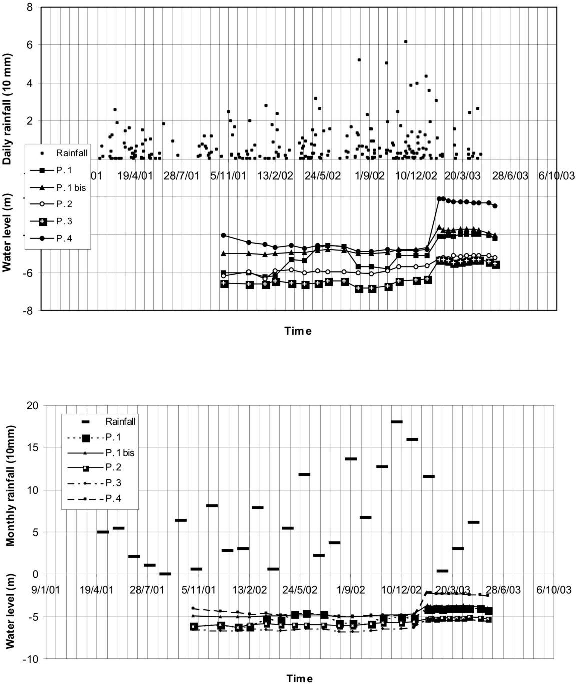

Figure 3. Gavorrano mine. Water level from the surface in piezometric bore-holes in the dam of the tailings pond, above and below, daily rainfall, above, and monthly rainfall, below.

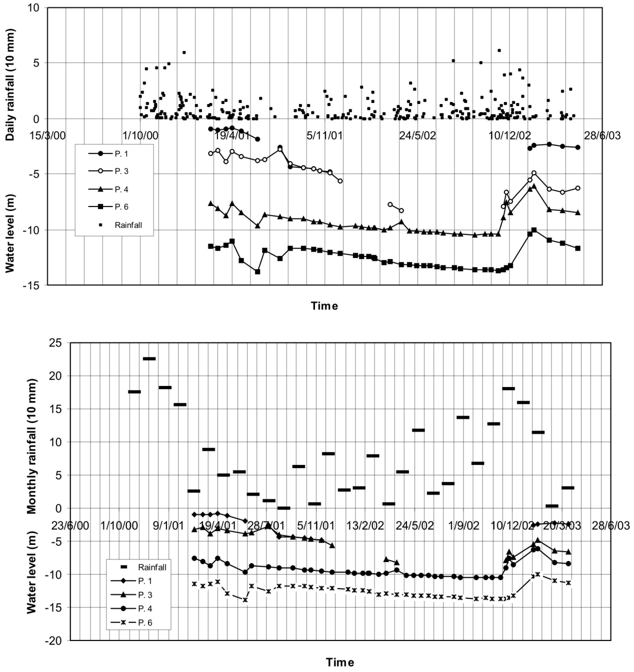

Figure 4. Fenice Capanne mine. Water level from the surface in piezometric bore-holes of the alignment 4-4', above and below, daily rainfall, above, and monthly rainfall, below.

Table 1. Fenice Capanne mine. Water level raisings in the ponds 3 and 4, along the alignment 4-4', and daily rainfalls

Raising time (Days)	Water level raisings (m)				>10 mm Daily rainfalls during a 15 days period before the measure (mm)
	P. 1	P. 3	P. 4	P. 6	
04.04.2001-19.04.2001	0.15	0.90	1.10	0.35	16.2 (06.04.2001)
13.06.2001-27.06.2001		0.10	1.00	2.00	18.2 (19.06.2001)
15.11.2002-27.11.2002			1.47	0.08	61.6 (18.11.2002); 12.0 (22.11.02)
27.11.2002-03.12.2002		1.24	1.36	0.18	61.6 (18.11.2002); 12.0 (22.11.2002); 39 (29.11.2002)
11.12.2002-22.01.2003		1.92	2.15	2.89	19.6 (08.12.2002); 30.6 (21.01.2003)*
22.01.2003-31.01.2003	0.21	0.60	0.20	0.36	30.6 (21.01.2003); 11.0 (23.01.2003)

**Rainfall during the day before the measures*

The water level in the dam of the Gavorrano mine pond is presumably affected by rains, which fell 4 or 5 months before. The most critical situation, due to overtopping might occur near piezometer 4, where an amount of rain, slightly higher than 380 mm, which should fall during one month, can, after 4 months, increase the water level up to the dam top (Table 2). This is confirmed by water level consistent increase in this piezometer, which actually occurred after a period of heavy rains (Figure 3).

Table 2. Gavorrano mine. Correlations between levels piezometric levels in the dam of the tailings pond and rainfalls in the course of different periods.

	Pearson correlation indeces and regression lines				
Before the measures rainfall periods (Before the measures days)	P.1	P.1bis	P.2	P.3	P.4
0 – 15	-0.138 Y=0.0036x-4.829	-0.043 Y=-0.0012x-4,6004	-0.097 Y=-0.0013x-5.65	-0.306 Y=-0.0058x-5.9503	-0.283 Y=-0.012x-3.5557
0 – 45	0.007	0.108 Y=0.0012x-4.7625	0.073 Y=-0.0004x-5.7297	-0.096 Y=-0.0007x-6.0597	-0.089 Y=-0015x-3.7828
0 – 75	0.285 Y=0.0019x-5.288	0.306 Y=0.0022x-5.0465	0.329 Y=0.0011x-5.8954	0.221 Y=0.0011x-6.3267	0.206 Y=0.0022x-4.3425
0 – 105	0.502* Y=0.0027x-5.6894	0.464* Y=0.0028x-5.3946	0.592** Y=0.0016x-6.1404	0.470* Y=0.0018x-6.6378	0.425* Y=0.0038x-4.9668
0 – 135	0.677** Y=0.0031x-6.0501	0.578** Y=0.0029x-5.6742	0.768** Y=0018x-6.331	0.664** Y=0.0022x-6.9184	0.592** Y=0044x-5.515
15 – 45	0.91 Y=0.0013x-5.0333	0.173 Y=0.0049x-5.1489	-0.107 Y=0.0025x-5.9685	0.014 Y=0.0024x-5.8181	0.029 Y=0.0044x-4.5084
45 – 75	0.498* Y=0.0059x-5.4153	0.420* Y=0.0078x-5.4618	-0.070 Y=0.0045x-6.1759	0.505* Y=-0.0029x-5.3765	0.469* Y=0.0133x-5.3475
75 – 105	0.637** Y=0.0082x-5.6818	0.504* Y=0.0067x-5.3242	0.037 Y=0.0049x-6.185	0.578** Y=0.0073x-6.1683	0.608** Y=0.0121x-5.172
105 – 135	0.709** Y=0.0089x-5.7105	0.524** Y=0.0071x-5.2608	0.561** Y=0.0049x-6.1166	0.749** Y=-0.0068x-5.1524	0.653** Y=0.0133x-5.0963

Y= Water level x = Rainfall

** Correlation is significant at the 0.01 level (2 – tailed)

* Correlation is significant at the 0.05 level (2 – tailed)

Table 3. Fenice Capanne mine. Correlations between piezometric levels along the alignment 4-4' in the tailings pond and rainfalls during different periods.

	Pearson correlation indeces and regression lines			
Rainfall periods before the measures (before the measures days)	P.1	P.3	P.4	P.6
0 – 15	0.109 Y=0.0083x-2.8357	-0.070	-0.091 Y=-0.0152x-7.8118	-0.218 Y=0.0084x-12.101
0 – 45	0.288 Y=0.0063x-3.1804	0.517 Y=0.0063x-7.7371	0.036	-0.546** Y=0.0077x-12.497
0 – 75	0.401 Y=0.0045x-3.3849	0.706* Y=0.0057x-8.3013	0.117 Y=0.0038x-8.768	0.607** Y=0.0044x-12.535
0 – 105	0.620* Y=0.0053x-4.0187	0.785* Y=0.0058x-8.9062	0.271 Y=0.0066x-9.6954	0.633** Y=0.0035x-12.676
0 – 135	0.768** Y=0.0053x-4.5702	0.790* Y=0.0053x-9.2749	0.425* Y=0.08x-10.655	0.609** Y=0.0026x-12.681
15 – 45	0.306 Y=0.0081x-3.1205	0.667* Y=0.0092x-7.8699	0.691** Y=0.0142x-9.4086	0.558** Y=0.0075x-12.326
45 – 75	0.436 Y=0.0083x-3.3069	0.913** Y=0.0175x-9.0857	0.761** Y=0.0094x-9.2372	0.545** Y=0.0035x-12.137
75 – 105	0.751** Y=0.0156x-4.0437	0.380 Y=0.0086x-7.5751	0.518** Y=0.00788x-9.2117	0.417* Y=0.0043x-12.328
105 – 135	0.725** Y=0.0135x-4.0395	0.190 Y=0.0035x-7.1275	0.496* Y=0.0044x-8.9892	0.313 Y=0.0005x-11.94

Y= Water level x = Rainfall

** Correlation is significant at the 0.01 level (2 – tailed)
* Correlation is significant at the 0.05 level (2 – tailed)

The water levels in the piezometers along the alignment 4-4' of the Fenice Capanne mine pond do not seen to be affected by previous rainfall in the same way: by moving from upstream, P. 1, to downstream, P. 6, the sensitivity to the most remote and most recent rains seems to decrease and increase respectively. Water level would rise up to the surface near piezometer 1, if 260 mm rain fell three months back. This is confirmed by the following event: water, which flooded the above-mentioned pond in January 2001, grew higher than the mouth of piezometer 1. On this particular occasion, rainfall amounted to 182.8, 225.8 and 175, 2 mm in December, November and October 2000 respectively.

The relationships between water levels along the alignment 3-3' and rainfall look much less significative. In this latter case, there would not be possible rainfalls, which could cause water level raisings up to the pond surface, unless permeability reductions occurred as to make it possible these raisings. Water level variations in piezometer 7/02 seem quite anomalous: this level would increase when rainfall decreases. This case, which has to be confirmed and investigated further, might depend on interacting permeabilities and hydrostatic heads variations (Table 4).

The results of our statistical analysis are just indicative, because there have not been enough data available and important factors, like the characteristics and, in particular, the duration of single rains, could not be considered.

The different way with which rainfalls, of the same intensity in substance, affect two unlike tailings ponds and their dams is pointed out in figure 5, 6 and 7.

Some isochrones of the piezometric levels in the most downstream dam of the Gavorrano mine pond and in the one of the Fenice Capanne mine pond are drawn in figure 5 and in figure 6, respectively. The bottom of both dams is also drawn in these figures. The difference between the two situations shows up: in the first case, 72% of the dam is under the ground water, while in the latter just 11% of the dam is under the ground water. In other words: the dam failure risk is very higher in the first case (Sammarco 2003b). This different risk rate is also related to the tailings, as the piezometric situations in the dams indicate, in these cases, the ones in the tailings, which are just upstream the dams themselves.

Some isochrones of the piezometric levels along the alignment 4-4’ and 1-1’ of Fenice Capanne mine tailings pond are drawn in figure 7. The tailings pond bottom along the above-mentioned alignments in also drawn. By confronting the two cases the differences between the two piezometric, and therefore static, situations are very clear. The actual differences between these last situations will be even greater than the ones that in this way have been pointed out because they are increased by the different resistance of the dams, which is very low in the former case.

Excessive water quantities in the tailings ponds may unbalance the whole system. For this reason, not only we must identify them, controlling piezometric situations often, but also avoid them if possible. To prevent them, we think it convenient to adopt methods by which balances between meteoric water amounts that inflow into the pond and water amounts that outflow from the same pond, can be drawn. With these methods results as reliable as possible and related to longer possible previous periods must be obtained. The above-mentioned balances could be compared with the ones, which would be step by step deduced, in order to find out any possible significant deviation.

Our first approach. Figure 8 shows monthly rainfall and monthly average water levels in the piezometers 1 (Figure 8a), 2 (Figure 8b) and 4 (Figure 8c) in the dam of the Gavorrano mine pond. One can consider each of these levels to mean the monthly average flow-rate of the water flowing out the dam in the piezometer area and in the month, to which this level is referred. The sum relating to all the aforesaid piezometers, of the products, which are each calculed by moltiplying the water level in a specific month and in the area of each piezometer, by a suitable factor, can be compared with the rainfalls which are shown in the above-mentioned figure. A raising, of the water level in the dam, which is not justified by permeability decreases or by previous rainfall, could point out new not clearly meteroric water immissions in the pond or the increase of some previous. These immissions have to be born in the mind if heavy rains are foreseen.

Table 4. Fenice Capanne mine. Correlations between piezometric levels in the tailings pond along the alignment 1-1' and rainfalls during different periods.

Pearson correlation indeces and regression lines				
Before the measures rainfall periods (Before the measures days)	P.7/02	P.2/02	P.B	P.A
0 – 15	0,273 Y=0.0016x-16.482	0.043 Y=0.0024x-20.291	0.050 Y=0.0001x-23.085	0.295 Y=0.0039x-26.487
0 – 45	-0.044 Y=-0.0001x-16.397	0.021 Y=0.0005x-20.269	0.247 0.0004x-23.122	0.787** Y=0.0057x-27.026
0 – 75	-0.281 Y=-0.0004x-16.313	0.289 Y=0.0044x-21.329	0.365 Y=0.0003x-23.15	0.926** Y=0.0042x-27.195
0 – 105	-0.504 Y=-0.0007x-16.313	0.577 Y=0.0087x-23.343	0.374 Y=0.0003x-23.168	0.919** Y=0.0036x-27.334
0 – 135	-0.855** Y=-0.0011x-15.902	0.790** Y=0.0117x-25.48	0.442* Y=0.003x-23.187	0.901** Y=0.0031x-27.335
15 – 45	-0.186 Y=-0.0005x-16.36	0.001	0.286 Y=0.0011x-23.109	0.795** Y=0.0083x-26.947
45 – 75	-0.454 Y=-0.0011x-16.289	0.498 Y=0.0135x-21.71	0.385 Y=0.0007x-23.096	0.808** Y=0.0073x-26.912
75 – 105	-0.530 Y=-0.0018x-16.236	0.658* Y=0.0226x-22.493	0.151 Y=0.0009x-23.105	0.415 Y=0.0089x-26.961
105 – 135	-0.698* Y=-0.018x-16.255	0.395 Y=0.0102x-21.114	0.329 Y=0.0006x-23.076	0.348 Y=0.0048x-26.582

Y= Water level (m)   x = Rainfall (mm)

** Correlation is significant at the 0.01 level (2 – tailed)
* Correlation is significant at the 0.05 level (2 – tailed)

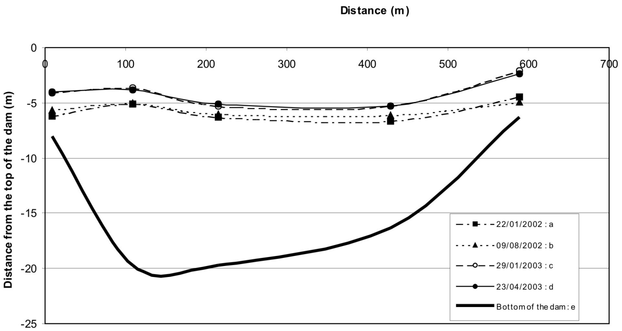

Figure 5. Gavorrano mine. Trends of isochronous piezometric levels in the dam of the tailings pond (a, b, c and d) and bottom of the dam (e).

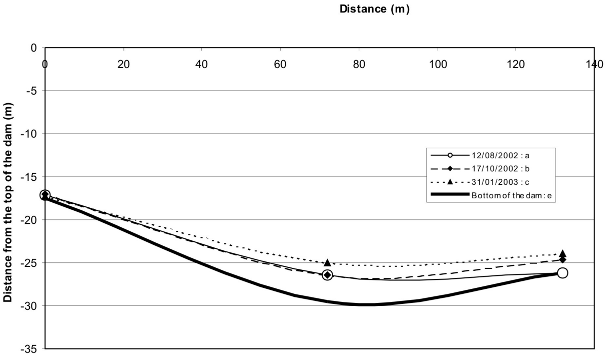

Figure 6. Fenice Capanne mine. Trends of isochronous piezometric levels in the dam of the tailings pond (a, b and c) and bottom of the dam (e).

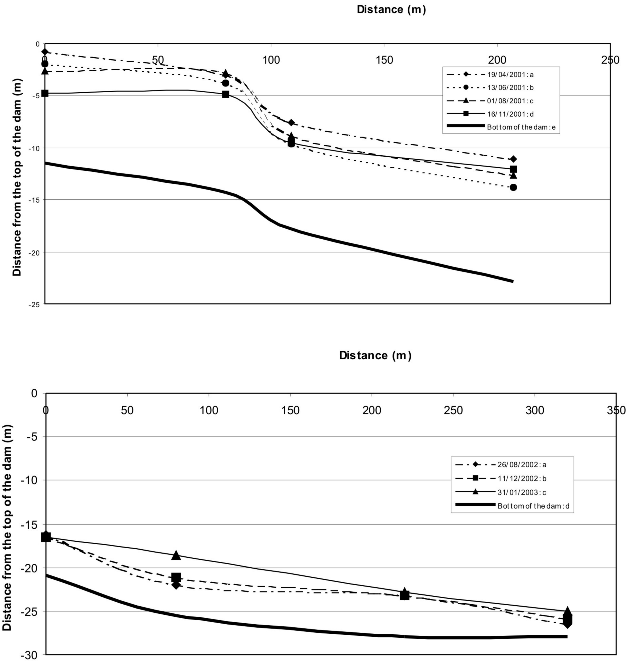

Figure 7. Tailings pond of the Fenice Capanne mine. Trends of isochronous piezometric levels (a, b, c and d) and bottom of the pond (e) along the alignments 4-4', above, and 1-1', below.

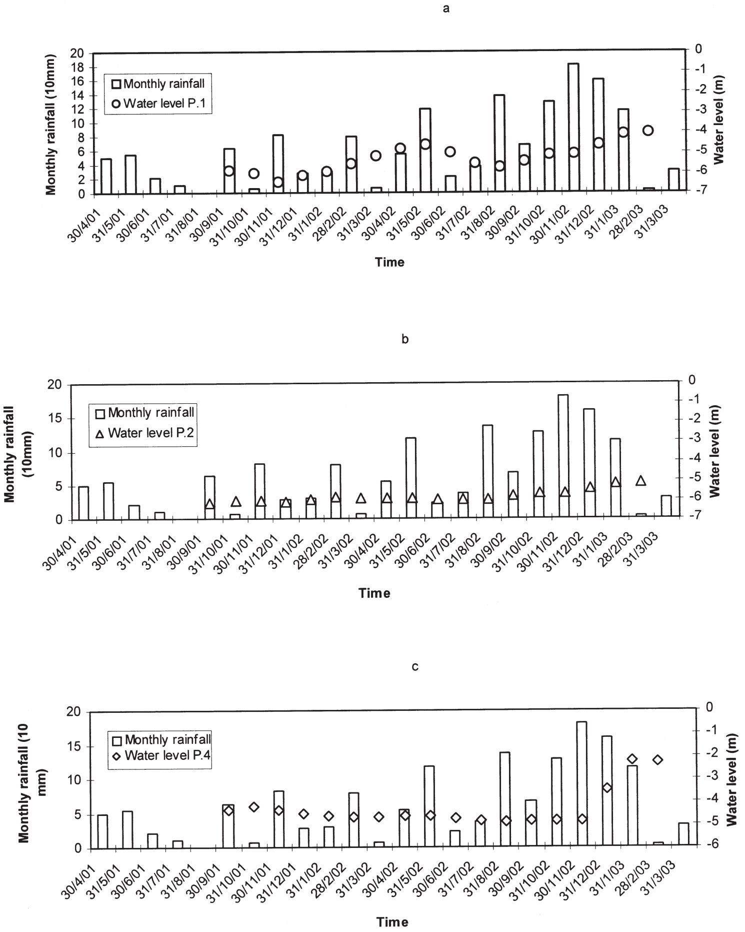

Figure 8. Gavorrano mine. Monthly rainfalls and monthly mean water levels in the piezometers 1 (a), 2 (b) and 4 (c) in the more downstream dam of the pond.

CONCLUSIONS

More field tests and a more thorough statistic approach can allow us confirming and better evaluating the results of our researches on the above-mentioned situations.

No doubt, they are not very different from actual emergency situations, which have to be forecast or at least be identified as soon as possible.

To prevent that these last can occur, or make them as short as possible, if they occur, the following measures have to be taken:

1. The dams have to be oversized, in order to reduce the probability of their failure and
2. Some controls, which are similar to the above-mentioned ones, have to be carried out to know at the right moment how and when to intervene.

These dams are actually soft ground structures that are often permeated by consistent water flows. Therefore they are subject to typical erosion processes and to consequent weakenings. For this reason, the dams' safety factors have to be increased by increasing their width.

This will allow having as well the breaking preferential surfaces which have been reduced by events, extended enough to offer the necessary resistance.

Controls have to be carried out permanently: when the mining activity is over, the tailings pond will somehow be still operating, because water will still flow into it, thus modifying its condition. These controls have to consist in measurements of piezometric levels mainly, to be carried out on a regular basis and whenever needed, to know the trends of piezometric surfaces in the dams. These last, on their turn, will have to be designed in such a way, as to make it possible the lowering of piezometric surfaces wherever and whenever necessary by means of submersible pumps.

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