Water Inflows Into Tailings Ponds

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ABSTRACT

This paper describes the characteristics of tailings ponds highlighting situations and events that favour water penetration into such structures, with the consequent reduction of their resistance. By making reference to real cases, the various ways in which water of different origin makes its way into these ponds are examined as well as their underlying causes and the effects they produce. The water flowing over the deposits of materials causes over all an erosion and transport of material, whereas seeping waters worsen the mechanical characteristics of such deposits. In the cases in which the action of flowing water prevails, the deposited material is progressively removed and spread out, whereas if seepage prevails, landslides of dams usually with violent mudslides rushing downhill causing devastating mechanical effects can happen. Such actions are examined in detail emphasising on the mechanical effects of water in the tailings ponds. An extreme effect is liquefaction of the material contained in the ponds and of the material constituting the dams with failure of the latter. The consequences of the rushing mud are also taken into account by making comparisons between the mud pressures exercised on the structures and the pressures required to cause them to collapse. Some precautionary measures and safety works that must be got ready to avoid failure of the dams or to limit damages if failure, which may be likely in the case of abandoned ponds, were to occur, are proposed. Given the similarity between the landslides of tailings ponds and the landslides of natural slopes, mention is made of the desirability of applying the measures suggested here also to natural slopes.

INTRODUCTION

Given the nature and state of the tailings deposited in tailings ponds, it is well known that in the presence of water they will turn into mud which would rapidly rush downhill if the dams were to fail, destroying anything in their way. It is therefore imperative to evaluate the risks of such events and seek to identify all the possible negative circumstances that could cause mud inrushes so as to prevent such circumstances or at least attenuate their effects if they were to be inevitable.

In other terms tailings plus water can be turned into "mud bombs" whose destructive energy is given by the potential energy of the mass of mud as to the height to which it would rush downhill. These bombs can be triggered by failure of the dams and less often by the sliding of slopes surrounding the ponds which may produce waves of mud that flow over the dams and rush downhill. Measures need to be designed to avoid that these bombs be triggered thus securing the stability of the dams and of the slopes surrounding the tailings ponds, and avoiding that the deposits turn into mud by the inevitable inflow of water. This virtually means making sure that consolidated tailings preserve their consolidation status.

The action that water has on tailings is similar to its action on the incoherent or weakly cemented soils found on natural slopes since both materials are similar in nature and state. Therefore, the analyses and inferences presented here on the mechanical effects produced by water where it seeps into tailings ponds may also apply to the cases where water permeates natural slopes. In this regard mention is made of the violent mudflow of 19 July 1985 following liquefaction and failure of the two tailings dams of the Prestavel fluorite mine near Stava, North-eastern Italy, which caused the death of 263 people living in the nearby hamlets (Genevois and Tecca, 1993), and of the violent mudslides of 5 and 6 May 1998 that overflowed into the country towns of Sarno and Quindici, in Southern Italy, killing over 200 people. These last slides occurred after heavy and prolonged rain : the large amounts of water violently carried downhill with it, in the form of slurry, the volcanic ash that had been erupted by the Vesuvius in the past and that had deposited on nearby hillslopes.

Now while in terms of mechanical effects there are similarities between the two types of mudslides, one major difference, in terms of polluting effect, is that the tailings are much more toxic than the mud from natural slopes.

CHARACTERISTICS OF TAILINGS PONDS

Up to recently tailings were dumped into the sea, rivers and lakes, but now they are usually deposited in confined areas on the ground when they are not used to fill underground mines or put to other uses. By using special techniques, the tailings in the form of slurry are pumped into ponds whose dams are gradually erected with the coarser particles being heaped up the edges. The water used to carry the tailings is removed from the side opposite to the dam by pumping or by spillways flowing into canals previously prepared underneath the ponds. In this way the water is desilted which in fact is the very purpose of tailings ponds.

The ponds are built close to the mine and for reducing the length of the embankments in valleys that are closed off by erecting dams. The valley beds are usually crossed by streams which are deviated so as to prevent them from coming into contact with the pond, or they are made to flow through pipes or drainage tunnels inside the valley beds that are then buried underneath the tailings. Through the spillway towers these canals also collect the desilted water from the ponds (Rossi, 1973). The tailings consist of host rock and gangue. The nature of these materials varies from mine to mine and may even vary appreciably from one excavation site to another of the same mine. Very often the tailings come from flotation plants, and so it is likely that when they are deposited they consist of sands and silts of varying types mixed with clays (Kelly and Spottiswood, 1982).

The tailings are almost always deposited through hydrocyclones which convey the coarser fractions along the embankment and the finer fraction into the pond thus raising the embankment and filling the pond at the same time. In the pond, sedimentation is differentiated which means that the grainsize decreases in the direction of the spillways. Because the hydrocyclones put on the tailings pond from fixed points of the crest of the embankment the material deposited upstream forms advanced tongues towards the pond. This could be eliminated if the hydrocyclone were automatically shifted in uniform and continuous way along the crown of the dam. The aim of this technique is to produce dams that are permeable to water but not to solids, while in the ponds it produces silts that can be compacted by removing the water on the pond and by filtering away the water inside the deposit through the dam (Ciccu and others, 1987). Actually, the filtering hardly ever occurs because there are always clays and/or very fine-grained materials in the pond that prevent water seepage and the dam may become impermeable for the presence of clay or may undergo processes of "regressive erosion" for piping.

The fundamental methods for erecting the dams are the following (Klohn, 1972):

- Upstream method: this is the most cost-effective but also the least safe among those listed here; as the height of the tailings dam rises, each successive dyke moves further upstream, and so overlay an unstable bed of unconsolidated tailings (Figure 1a).
- Downstream method: this is an obvious improvement over the former from the static point of view (Ciccu and others, 1987). With this method each successive layer of coarse particles from the tailings is deposited on a base of coarse, free-draining particles (Figure 1b).
- Downstream method with mine waste rock (Klohn, 1972): the downstream face of the dam consists of mine waste rock (Figure 1c).
- Centerline method (Gipson, 1998): the crests of the layers of coarse particles are aligned along the same vertical line (Figure 1d).

WATER IN TAILINGS PONDS: WHERE IT COMES FROM, INFLUENCING FACTORS AND EFFECTS

From the above remarks it is clear that owing to the nature and state of the materials that make up the ponds and of those that constitute the dam, the presence of water could considerably worsen the mechanical characteristics of the pond materials and in time the stability of the dam especially if it was erected using the upstream method. Indeed, in this case the dam could be almost quite included in aquifers that saturate the pond (Figure 1a).

The presence of water in a tailings pond could be due to a number of reasons:

- water may be trapped inside the pond because surrounded by impermeable layers (Kesseru, 1997); this is water used to convey the tailings into the pond and/or water that flowed in subsequently and was never removed;
- rainwater falling directly onto the surface of the tailings pond;
- water may seep into the pond from the bottom and/or from the buried walls of the valley which houses the pond if the bed is not fully impermeable;
- water may flow in from the slopes of the valley above the pond for the absence or inefficacy of drainage canals;
- water may flow in from the hydrogeological basins that converge onto the valley which houses the tailings pond and remain trapped because of the absence or inefficacy of drainage systems which would drain away the water without it flowing into the pond.

Apart from the water coming from considerable depths (Sammarco, 1994), the inflows of water depend on rainfall frequency and amount. The violence of the waters flowing into a tailings pond from the slopes of hydrogeological basins will depend on slope steepness, and the amount of water will be greater the larger the catchment basins.

The factors regulating the inflow and trapping of water inside the deposited material are a great many and very complex. Undoubtedly, high permeability at the surface and inside the body of the pond during rainfall facilitates the seepage of water into the tailings layers, whereas the subsequent consolidation for drying at the surface prevents evaporation of the water which is thus trapped especially if there are no drainage facilities at the bottom of the pond that together with the spill water could remove also the seeping water. The dam as well is incapable of securing the passage of water in time.

The consequences of the action of the water on the tailings ponds can be schematised as follows. Such effects may coexist in the same pond even though one may prevail over the others, depending on the situation at hand:

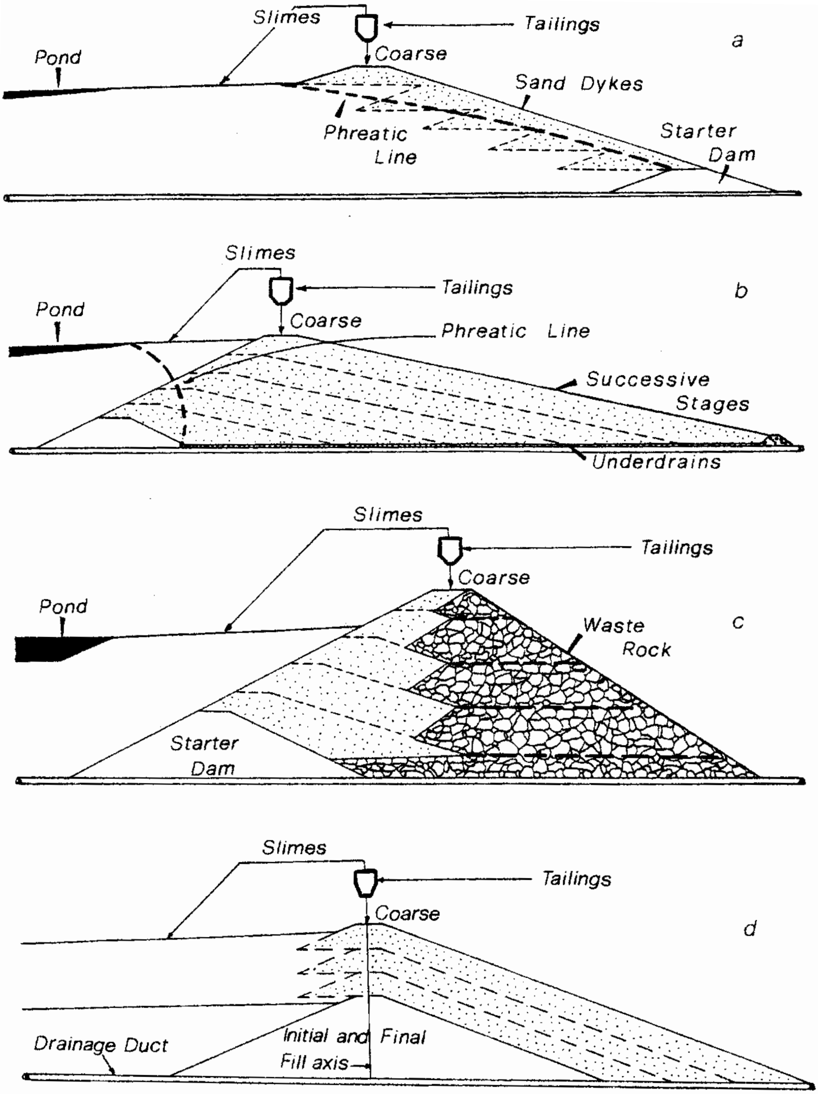

Figure 1: Basic methods of tailings dams construction: Upstream method, a; Downstream method, b; Downstream method with mine waste rock, c; Centerline method, d.

- Slow effects: erosion, dissolution, transport, sedimentation and precipitation. These effects are due to the actions exercised initially at the surface of the pond and then at greater and greater depths, by the runoff waters that flow into the pond directly and from the surrounding slopes. Cuts for erosion of the dam caused by the water allow debris and particles in solution to be transported downstream from the dam and deposited at distances that are greater the higher the speed of the water. In time these mechanisms occur repeatedly and this causes the scattering of toxic materials over wider and wider surface areas. It is self-evident that the more frequent and the harder the rainfall, the greater the speed at which the dams are destroyed. In substance, the action of water on a tailings pond produces processes that are quite similar to those involving rivers. Figures 2 and 3 show the morphology produced by the action of water on the surface of a tailings pond (Figure 2a), at depth (Figure 2b), along the dam (Figure 3a) and in areas where the terraces and shelves that have formed enable to reconstruct the dynamics of the erosion-sedimentation mechanism that caused them, a dynamics according to which the subsequent flow of water erodes not only the alluvial material deposited by the previous waterflow but also the deeper material (Figure 3b).
- Violent effects: downrush of deposited material as a result of the failure of a dam or of some of its portions. This failure is the ultimate cause which in turn is the result of other triggering actions which evolve slowly unlike the failure which occurs rapidly (Sammarco, 1993). For instance, the water that flows into the pond over long periods of time is the initial cause, it, liquefying and progressively making the material in the pond heavier, causes the slow increase of the pressure exercised on the dam, and, seeping through this last, decreases gradually its resistance until the dam suddenly yields. Obviously in order for the deposited material to rush down the valley it has to be in the form of mud and the dam must give in. The most frequent causes of yielding of dam are: seismic action, piping, overtopping, liquefaction, and slope instability. There may however be several causes, acting simultaneously and do not that lead to dam failure. For instance in Figure 4a a small hole can be seen in the dam of an old tailings pond of the Boccheggiano mine caused by an earthquake; the hole was later widened by overtopping (Figure 4b). At first the seismic action caused the collapse of two square metres at the surface of the dam slope above a cavity which had formed previously; this cavity had formed because the sand had been dragged away by water inflowing into a pipe located underneath the pond through its broken part; later the pond surface was flooded during a storm and the water flooded the pond and flowed out through the small hole running along it from the bottom upwards and thus widening its size hole.

  Another effect that can be considered to be violent is sudden failure caused by an occasional overloading of a portion of the surface of a pond where consolidation is only superficial.

In the following an analysis is made of the action of water on the materials making up tailings ponds, and of the effects produced by the violent mudslide rushing downhill when these materials are liquefied by water by comparing the forces exercised on these occasions by the rushing mud and the maximum strength that structures can withstand.

INFLUENCE OF WATER ON THE RESISTANCE OF DEPOSITED MATERIALS

The materials deposited in the tailings ponds generally consists of sands, silts and/or clays. As a conseguence their mechanical characteristics depend essentially on the presence or absence of water and on the forms in which the latter is present forms, which in turn depend on the percentage of water present. As the percentage of water increases, the water passes from the state of absorbed water to capillary water and to ground water which may either be quiescent or flowing, thus modifying the characteristics of the strength of the material.

Figure 2

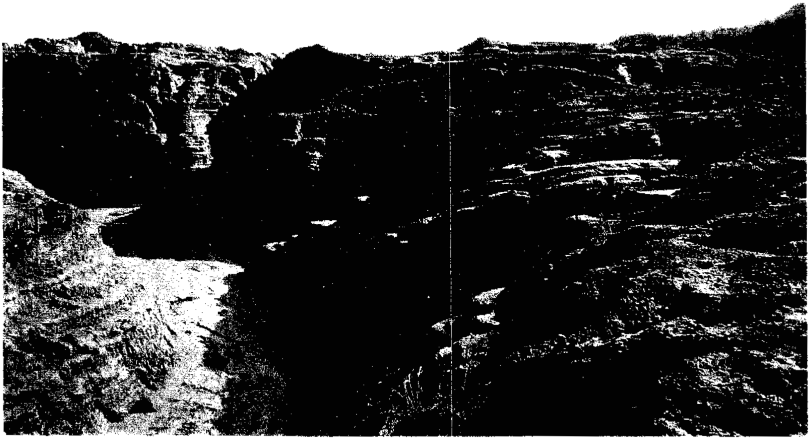

Figure 3

Figures 2 and 3: Tafone Mine, Central Italy. Morphologies characteristic of water action on the tailings pond.

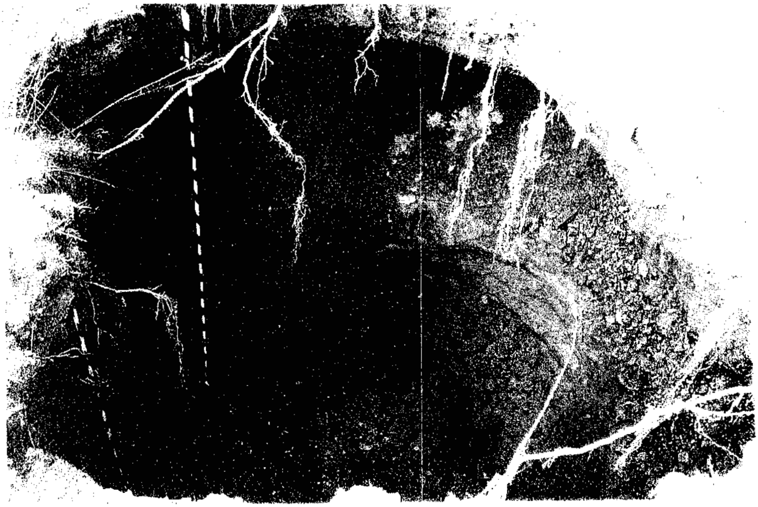

Figure 4: Boccheggiano Mine, Central Italy. Cavity inside the dam of the tailings pond that is appeared in consequence of the breakdown of its roof during the 1998 earthquake, above, and that has been on purpose filled, after its widening for overtopping, below.

Let the shear strength per surface unit, τ, of the material be expressed through the Coulomb relationship

$$\tau = c + (p_t - p_w) \tan \varphi \qquad (1)$$

where p_t is the total pressure exercised by the weight of the soil and of the water it contains, p_w is the hydrostatic pressure, p_t-p_w is the effective pressure, p_e, φ and c approximately represent respectively the internal friction angle and cohesion.

The shear strength parameters in eq. (1) vary strongly with water concentration.

When the water is in a state of static equilibrium, the effective pressure on a horizontal section immersed in a sand layer at depth z from the surface of the layer and at depth z' from the water level, is

for $z \geq z'$

$$p_e = \gamma_s(1-n)\,z-\gamma_w(1-n)z' \qquad (2)$$

and for $z<z'$

$$p_e = (\gamma_s - \gamma_w)(1-n)z \qquad (3)$$

where γs is the specific weight of the solid particles, γ w is the specific weight of the water and n the porosity of the layer (Terzaghi, 1951).

There ensues that the effective pressure is smaller the higher the level of water in the layer, when the latter coincides with the surface of the layer it takes on a minimum value which is maintained whatever the level of the water above the layer.

In the case of flowing water the stresses and the thrusts depend on the geometry of the piezometric surfaces. Furthermore, fairly fast outflows will not only appreciably influence the stress distribution, but will also determine the shifting of large amounts of material over long periods of time.

As an example Figure 5a shows the trends of the shear resistance parameters c and φ versus the percentage of water, w, in a clayey-marly consolidated deposit of the Neogene obtained through laboratory tests (Todorovic and others, 1985).

The failure lines for different percentages of water were obtained from such trends (Fig. 5b). It's evident that the resistance of the material decreases as the amount of water increases. At equal variation of the latter the decrease would be greater for a less coherent material. For percentages of water much higher than those used during these tests, the material submitted to the tests would have had an extremely reduced resistance.

It is not possible however to precisely quantify the contribution to the shear resistance variations for each parameter of equ. (1), which is moreover an approximated expression of that resistance.

In any case the water that seeps into a material consisting of sand and/or clay modifies the mechanical properties of the material and hence the failure lines that are usually used to characterize such properties, and hence the states of stress that are admissible in the presence of little or no water at all are certainly no longer admissible when the presence of water modifies those lines so much that they become tangent or secant to Mohr's circles which represent the effective states of stress in the various points of the mentioned material; the Mohr circles may in turn vary appreciably also as a result of the deformation and transport of the material resulting from the water that penetrates into the deposited material.

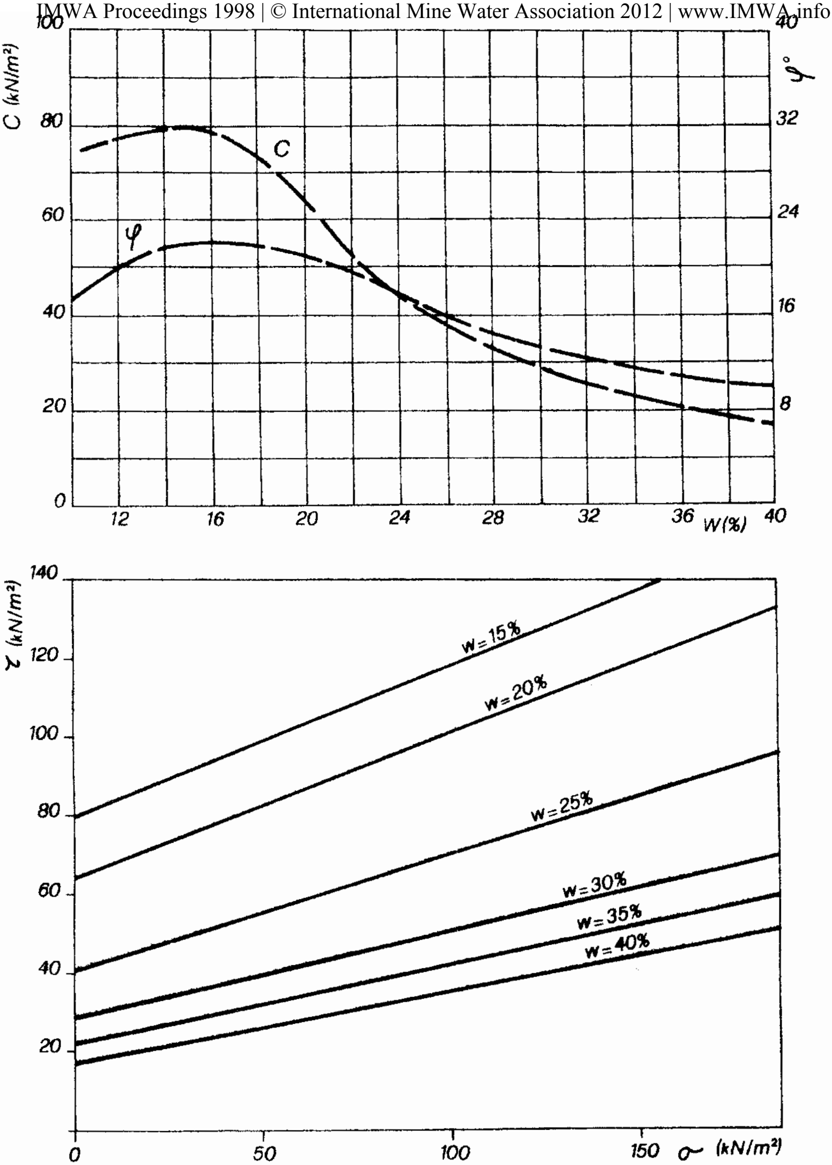

Figure 5: Neogen clay-marl deposit. Cohesion and angle of internal friction versus water concentration, above; limiting shear stress lines relating to various water concetrations, below.

FAILURE OF THE DAMS AND MUD IRRUPTIONS: AN ASSESSMENT OF THE CONSEQUENCES

If the amount of water in a tailings pond were to increase to levels that would cause liquefaction of the material it contains and would make its dams unfit to balance the thrusts, the dams would fail and the mud would burst out. The violence with which the mud would flow downhill would be greater, the larger the amounts of mud, the higher the elevation at which the pond is located, and the steeper the slopes of the hillside.

In order to calculate the destructive capacity of such mudslides it is necessary to quantify their action on manmade structures. The effects of the mud rushing downhill from a tailings pond can be schematized as follows:

1. effects that do not depend directly on the energy released upon failure of the dam
2. effects caused by such energy.

The former, which are produced also when the latter occur, consist in the burying of extensive areas and the entity of the damage caused depend on the uses made of the areas covered by the mud. The latter, namely the effects caused by the energy of the mud, consist mainly in the transformation of the potential energy of the mud that rushes down the slope into kinetic energy, on which depend the stresses that the mud exercises on all the obstacles it meets. To calculate the ultimate consequences of the action of the mud it is necessary to determine such stresses and compare them with the maximum stresses that the man-made structures can withstand.

A stream of mud that bursts out of a tailings pond and flows downstream and hits at velocity V, a fixed obstacle consisting of a plane that is perpendicular to the direction of the flow , will hit the obstacle with a force that can be inferred from the approximated expression that relates momentum variation to impulse

$$MdV = Fdt \qquad (4)$$

where M is the mass whose velocity varies, dV, over time, dt, and F is the force acting on the obstacle that causes the velocity variation.

Now supposing that the velocity V of the mudstream is cancelled out upon impact with the obstacle, by using γ to indicate the specific weight of the mud, A the surface area of the cross-section of the stream and g the gravity acceleration, (4) may be written as:

$$F = \gamma A V^2 g^{-1} \qquad (5)$$

so for instance, if the specific weight of the mud, its cross-section and the velocity of the stream were to be equal respectively to 1,300 kg m^{-3}, 1 m^2 and 10 ms^{-1}, the force acting on the obstacle would be

$$F = 1{,}300 \times 1 \times 10 \times 10 \times 9.81^{-1} = 13251.78 \text{ kg} = 130 \text{ kN}$$

Figure 6 shows the forces versus the velocity of the mudstream, obtained from (5), acting on the obstacle consisting of a plane surface orthogonal to the direction of the mud stream, where the density of the mud is assumed to be 1,300 kg m^{-3}, the cross-section of the mud equal respectively to 0.50, a, 1.00, b, 2.00 m^2, c, and the velocity is offset upon impact. If the mud stream were not to hit the obstacle perpendicularly, leaving aside the shear stresses on the surface of the obstacle, it would exercise a force given by:

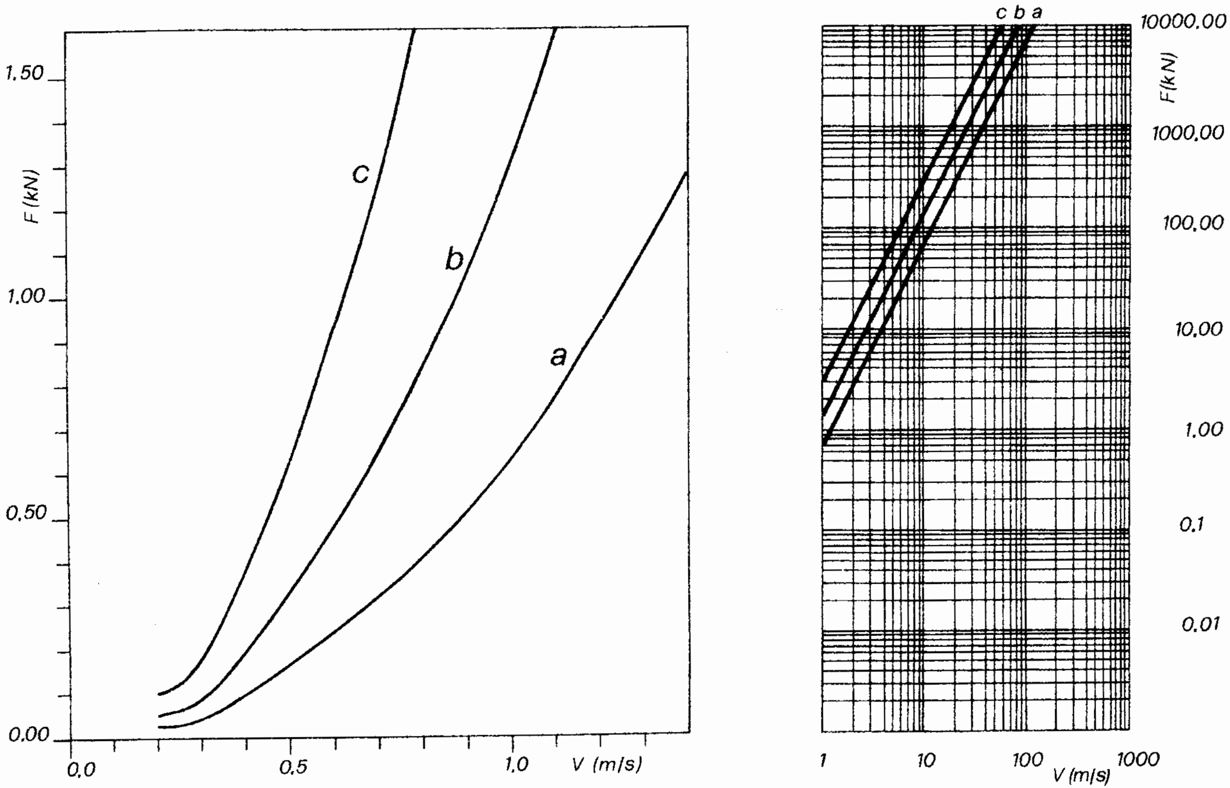

Figure 6: Force of a mud flow on a perpendicular to the flow obstacle versus flow speed, V, for values of the mud flow section of 0,50, a 1.00, b, 2.00 m^2, c, and supposing that the flow speed cancels out with the impact.

$$F = AV^2g^{-1} \cos \theta \qquad (6)$$

where θ is the angle between the direction of the mud stream and the normal to the surface of the obstacle. Therefore, assuming a unidirectional flow, diagrams could be drawn up to analyse the risks, to which an obstacle would be exposed in dependence of its orientation at a given velocity and cross-section of the mudstream.

The method suggested to infer the abovementioned forces presupposes that the velocity of the mud at the time of impact is known and that the velocity is offset as a result of the impact. The velocity at which the mud hits the obstacle can be inferred only with approximation because besides the difference in height between the pond and the obstacle, it is necessary to take into account also the energy attenuation, which however is difficult to measure, to which the mudstream is subject as it flows because of its viscosity, of the deformations that it and the surface on which it flows undergo, and of the braking action of vegetation. Furthermore, the velocity of the mud will not be offset upon impact and consequently the forces calculated will be greater than the effective forces because there will always be residual kinetic forces, not considered as such in the calculations, that will not contribute to determining the forces at which the obstacles will actually be hit. The forces thus calculated will undoubtedly be approximated but they will always have provide an order of magnitude of the effective forces and as such they will in any case be useful for making a gross evaluation of the effects of the latter on the structures that could be involved.

To determine the resistance of man-made structures, 1 m high mudstreams have been assumed with a specific weight of 1,300 kg m^{-3}, that hit a portion of the structures in the perpendicular direction; approximate pressure values and velocities of the mudstream required to make such structures fail have been found. Such values are shown in Table 1.

The forces and velocities thus obtained, capable of causing such failures are actually possible if the dams of tailings ponds were to fail. This is fully confirmed by the effects produced by the mud that on 19 July 1985 burst out of the tailings pond of the Prestavel mine (Figures 7 and 8): 240,000 m^3 of mud rushed down a slope for 5.000 m with an average inclination of 10%, destroying the villages of Stava and Tesero and killing 269 people.

Figure 7: Prestavel Mine, North-Eastern Italy. The mud, that came auto from the tailings ponds, poured into the Fiemme Valley, crossed the Stava Torrent, on the left, and destroyed and buried the village of Stava which had been built in the lower on the right area of the figure.

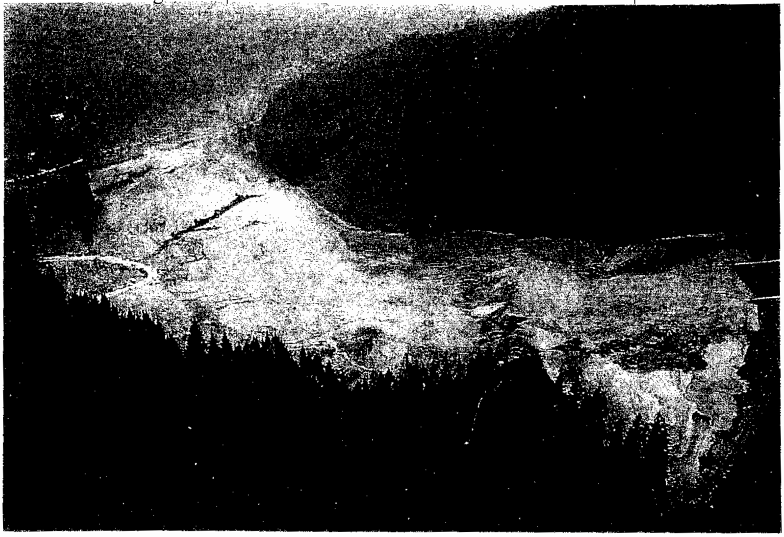

Figure 8: Prestavel Mine. The mud that devastated the Fiemme Valley flowed violently from the tailings ponds, on the right in the upper photo, to the Avisio River, at the bottom of the lower photo: the half-destroyed house and the flooded house, visible in this second photo, evidence in substance the last effects of the irruption (Anon, 1985).

Table 1 - Man-made structures and the dynamic characteristics of mudstreams required to make such strutures collapse

Structure	Type of collapse	Values sufficient for collapse	
		Pressure (kPa)	Velocity ($m\ s^{-1}$)
Roof	Break trhough	0.98	0.87
Curtain walls	Knocking down	1.47	1.06
Reinforced concrete pillars with section $0.30x0.30\ m^2$	Failure mainly resulting from bending	21.90	4.10
Two floor stone dwellings with horizontal section of $20x10\ m^2$ and long side normal to flow direction of the mudstream	Overtuning	8000.00	78.45

CONCLUSIONS

To avoid the disastrous effects that have just been inferred at the theoretical level, it is imperative to prevent that the tailings should turn into mud and that the resistance of the dams be reduced as a result of the erosive action of water and/or of other factors such as earthquakes and abusive extraction of sand from the embankments. It is therefore necessary to prevent that water may flow into such ponds, and where this were to be impossible, then the water needs to be diverted and drained soon as possible. The inflow of water can be avoided by making the valley slopes and beds, to be covered by the tailings impermeable, if they are not naturally impermeable, constructing drainage canals to collect and drain away the water glowing down the slopes around the ponds, by making impermeable the surface of the latter, tilting them adequately towards the spillway and building canals underneath the tailing ponds, to collect the waters that flows into the spillways, preventing the waters from the hydrogeological basins upstream from flowing into the tailings ponds. The water that might seep into the pond and that can be measured by piezometric borings can be drained away from the pond and especially away from the areas immediately upstream from the dams respectively by means of filtering pipings positioned on the bed of the ponds and by underdrains at the foot (toe) of the dams.

However, as the works to prevent water from seeping into the pond and those for preventing that the seeping waters should remain trapped inside the pond may become ineffective in time, especially for lack of maintenance, slides and outflows of mud are to be considered as possible events. It is therefore necessary to impose all the precautionary measures that are indispensable for avoinding that such events may turn into actual catastrophes. The measures being suggested essentially consist of:

- not authorizing houses to be built (Genevois and Tecca, 1993) or adits to underground mines (Rossi, 1975) downstream from the tailings ponds;
- exclusively in cases in which the impact energies would not be high, man-made structures could be allowed downstream from the ponds but their geometry and orientation would have to be such as to oppose sufficient low resistance against a mudstream, if any;
- if man-made structures that could be damaged by a mudslide are present, in order to protect them then canals and embankments are to be built so that in case of dam failure the mudstream would flow along a predefined route.

Mudslides with catastrophic effects have occurred not only because of failure of tailings dams but also as a result of the landslide of natural slopes made of incoherent materials as mentioned in the introduction. Given the striking similarity of circumstances, settings and mechanics of the slide events, the precautionary measures envisaged above for tailings ponds can apply also to areas of slope instability where a landslide could produce destructive effects for people and structures.

ACKNOWLEDGEMENTS

The author thanks Messrs C. Maida and S. Tassoni of this District for their active and kind collaboration.

REFERENCES

1. Anon. (1985). Dopo la tragedia di Val di Fiemme. Epoca. 2 Agosto, Anno XXXVI. In Italian.
2. Anon. (1998). La colata di fango che ha inghiottito Sarno. Panorama. 21 Maggio. In Italian.
3. Ciccu R., Manca P.P. and Massacci G. (1987). La stabilità dell'argine del bacino di decantazione della miniera di Mont'Ega (Sardegna occidentale). L'Industria Mineraria, n. 4, pp. 15-25. In Italian.
4. Ciccu R., Di Gregorio F., Manca P.P., Massacci G. e Massoli Novelli R. (1987). I bacini di contenimento degli sterili di flottazione in Sardegna : problemi di sicurezza e necessità di intervento. Atti Convegno Le Scienze della Terra nella Pianificazione Territoriale. Chieti. In Italian.
5. Genevois R. and Tecca P.R. (1993). The tailings dams of Stava (Northern Italy) : An analysis of the disaster. Proc. Environmental Management Geo-Water and Engineering Aspects. 8-11 February, Wollongon, Australia. Balkema A.A., Rotterdam, pp. 23-36.
6. Gipson A. H. (1998). Tailing disposal - The last 10 years and the future trends. Proc. of the Fifth International Conference on Tailings and Mine Waste '98. 26-28 January, Fort Collins, Colorado, USA. Balkema, Rotterdam. pp. 127-135.
7. Kelly E.G. and Spottiswood D.J. (1982). Introduction to Mineral Processing. John Wiley & Sons, New York, p. 490.
8. Kesseru Z. (1997). Argilliceous geological barriers, Multi-disciplinary view. Proc. 6th International Mine Water Association Congress : Mine Water and Environnment. 8-12 September, Bled, Slovenia, pp. 397-413
9. Klohn E.J. (1972). Design and Construction of Tailings Dams. CIM Bull., 65, April, pp. 28-44.
0. Rossi G. (1973). I bacini di decantazione dei rifiuti degli impianti di trattamento dei minerali. L'Industria Mineraria. Ottobre e Novembre, pp. 465-480 e 525-545, In Italiam.

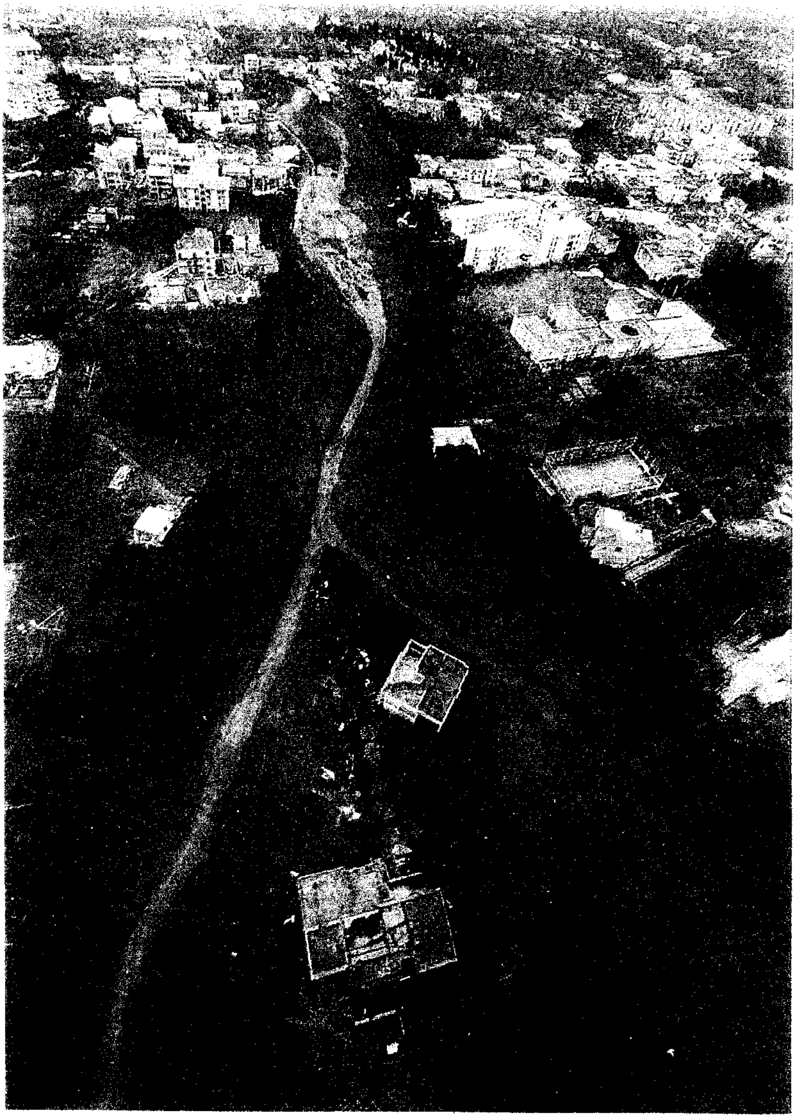

Figure 9: Flow slide of Sarno, Southern Italy. Mud flows which have destroyed and buried a quarter (Anon, 1998).

11. Sammarco O. (1993). Delayed water irruptions : Events and circumstances. Proc. Environmental Management Geo-Water and Engineering Aspects. 8-11 February, Wollongong, Australia, Balkema A.A., Rotterdam, pp. 651-656.
12. Sammarco O. (1994). Sull'utilizzazione di miniere in sotterraneo abbandonate per stoccaggio d'acqua. Acque sotterranee. Fasc. 44 Anno XI, Dicembre, pp. 57-65. In Italian.
13. Sammarco O., Tassoni S., Ovi M. e Bini F. (1997). Sfornellamento in corrispondenza del gradone centrale dell'argine del bacino di decantazione fanghi della miniera Boccheggiano. Internal Reports I. BuMines 30, 130 e 49, Corpo delle Miniere, Distretto di Grosseto, p. 43. In Italian.
14. Terzaghi K. (1951). Mécanique Théorique des Sols. Dunod, Paris, p. 474. In French.

CAPTIONS OF THE FIGURE

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Figure 6 : Force of a mud flow on a perpendicular to the flow obstacle versus flow speed, V, for values of the mud flow section of 0.50, a, 1.00, b, 2.00 m^2, c, and supposing that the flow speed cancels out with the impact.

Figure 7 : Prestavel Mine, North-Eastern Italy. The mud, that came out from the tailing ponds, poured into the Fiemme Valley, crossed the Stava Torrent, on the left, and destroyed and buried the village of Stava which had been built in the lower on the right area of the figure.

Figure 8 : Prestavel Mine. The mud that devastated the Fiemme Valley flowed violently from tailings ponds, on the right in the upper photo, to the Avisio River, at the bottom of the lower photo : the half-destroyed house and the flooded house, visible in this second photo, evidence in substance the last effects of the irruption (Anon, 1985).

Figure 9 : Flow slide of Sarno, Southern Italy. Mud flow which have destroyed and buried a quarter (Anon, 1998).