

A Tool for Modeling Slope Instability Triggered by Piping

Paola Gattinoni, and Vincenzo Francani

Abstract—The paper deals with the analysis of triggering conditions and evolution processes of piping phenomena, in relation to both mechanical and hydraulic aspects. In particular, the aim of the study is to predict slope instabilities triggered by piping, analysing the conditions necessary for a flow failure to occur. Really, the mechanical effect involved in the loads redistribution around the pipe is coupled to the drainage process arising from higher permeability of the pipe. If after the pipe formation, the drainage goes prevented for pipe clogging, the porewater pressure increase can lead to the failure or even the liquefaction, with a subsequent flow slide. To simulate the piping evolution and to verify relevant stability conditions, a iterative coupled modelling approach has been pointed out. As example, the proposed tool has been applied to the Stava Valley disaster (July, 1985), demonstrating that piping might be one of triggering phenomena of the tailings dams collapse.

Keywords—Flow failure, liquefaction, modeling, piping, porewater pressure.

I. INTRODUCTION

RECENT research has revealed that natural soil pipes provide important pathways for subsurface movement of water and solutes, as well as contributing to landslide initiation, because of the build-up of porewater pressure.

Piping is a natural phenomenon of erosion caused by the groundwater flow, that removes the finest grains creating tubular hollows [1] or low strength layers [2]. Few Authors have studied subsurface erosion phenomena and they have identified the growing model, generally named piping [3], tunnel erosion [4], suffusion [5]. Among the different names, the “true” piping (in engineering sense) occurs when water seeping through a porous medium produces drag force to entrain material at the outlet through liquefaction or Coulomb failure.

The process of pipe initiation can be connected to specific geologic conditions, such as the grains size [6], [7], the morphology [8], pedologic [9] and chemical [10] factors, climatic characteristics [4]; moreover, for pipe initiation the groundwater flow has to achieve a critical gradient [11]. Therefore, morainic terraces, river banks and tailings dams, where localised flow can take place, are typical situations where piping is significant.

Recent advances in computer technology have facilitated

the evaluation of seepage and deformation, but computational methods for evaluation of piping potential are currently limited [12]. Recent works have been conducted with respect to estimating the time of development of piping [13] and to describe water dynamics in a piped hillslope. In particular reference [14] proposes a simple method to simulate pipe flow, assuming that characteristics of pipe flow can be modelled by introducing an equivalent soil layer having larger saturated hydraulic conductivity values than the surrounding soil matrix [15]. On the contrary, there is very little work that has been completed with respect to constitutive models of piping [16], [17], and even less has attempted to develop a constitutive model of piping that could be used in a continuum model to predict the piping behaviour of a slope.

Reference [18] demonstrated, through experimental studies, that when high roughness characterizes the lower end of a pipe, piezometric levels are highest and pipeflow is lowest relative to matrix flow. This analogy can be extended to a hillslope where clogging, sedimentation, or a restriction may occur in a natural soil pipe, involving a porewater pressure increase which has been suggested as contributing factor to landslide initiation [19], [20].

In the applied research the above cited aspects are very important as failures caused by piping may occur, leading to slope instabilities and mass movements, even characterized by large dimensions [21], [22]. In spite of that and although there were early reports of significant subsurface erosion, the role of piping in land slips and bank failures is still an under-researched topic [4], maybe because it is often very difficult to decide whether the piping was a cause or an effect of the failure [23]. Nevertheless, some progress has since been made on the links between hillslope landslides and piping [24], [19], especially in defining thresholds for piping failure in river banks [1], [25] and in earth dams [26].

Reference [24] demonstrated, applying a finite element modeling approach, that the multiple peat slide occurred on 1998 on Cuilcagh Mountain (Northern Ireland) was triggered by subsurface pipes. The Authors provided a first quantitative indication of the importance of subsurface piping in slope failures.

Reference [27] shows examples of flow failures in tailing impoundments (such as Merriespruit failure, South Africa 1994), in which the increment of porewater pressure and the loss of shear strength led to liquefaction.

Reference [12] presents a review of published literature on piping phenomena involved in dam failures, citing 40 case

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histories of foundation related piping failures, 133 case histories of internal erosion piping failures, 83 case histories of backwards erosion and suffusion piping failures and, finally, 11 case histories of piping failures induced by biologic activity. The aim of this study was to create a tool for modeling the piping evolution process, with particular attention to the conditions leading to flow slides or to liquefaction that are mostly linked to the coupling of the hydraulic and mechanical behaviour. More in detail, both the porewater pressure distributions and the loss of soil materials arising from subsurface piping was incorporated into the stability analysis. The applicability of the method was tested on a case study, the tailings dams collapse of Stava (July 1985), for which some Authors consider the piping among triggering phenomena [28].

Tool for modeling the piping evolution and its effects on slope stability

The groundwater flows along main directions (generally having high permeability), according to a piezometrical gradient that often achieves the highest value near the foot slope (groundwater exit point). If the piezometrical gradient achieves a critical threshold, localized piping phenomena can initiate, with the removal of finest materials and the consequent further increase of permeability. Evidently, the process grows by itself: once soil particles are removed by erosion, the magnitude of the erosive forces increases due to the increased concentration of flow. The phenomenon can be described as a backwards erosion, starting from the foot slope and evolving in a progressive widening of the pipe and his spreading towards the upper end. The piping growing brings about the loss of soil materials and then the make-up of a weak layer, involving more and more broad zones of the ground till the slope collapses.

A tool for modelling the above described processes is pointed out (Fig. 1).

A. Model of Piping Evolution

The primer condition of piping was analysed through the Zaslavsky and Kassif's model [11]. To this aim, the critical threshold of the piezometrical gradient was calculated:

$$j_{CR} = \frac{(G-1) \cdot (1-n) \cdot \cos \alpha}{a_1} \quad (1)$$

where G is the specific yield of grains, n the porosity, α the dip of the land surface, a_1 a corrective factor. To simulate the pipe initiation and evolution, a groundwater flow model was developed, according to the following iterative scheme:

- 1) starting from the initial condition (without pipe), for each cell of the domain, the simulated piezometrical gradient is compared with the above cited critical threshold [11] to identify those cells where processes of pipe initiation take place;
- 2) in these cells, pipes are inserted in the model, as an equivalent material having higher permeability and porosity and lower density and strength than the

surrounding soil matrix [15];

- 3) the simulation is carried out in the new conditions, obtaining new piezometrical gradients that were compared with the critical threshold to identify the cells interested by the pipe widening.

A repetitive simulation is carried out, changing each time the shape and the size of pipes. For each simulation, the corresponding groundwater flow conditions are pointed out. In this way it is possible to simulate the evolution of the piping phenomenon: a pipe, even if very small, brings about an increase of the piezometrical gradient in the nearby area; the consequent drainage generates a further erosion of fine grains and, then, a continuous widening of the pipe. The process goes on till a change in piezometric gradient takes place or failure occurs.

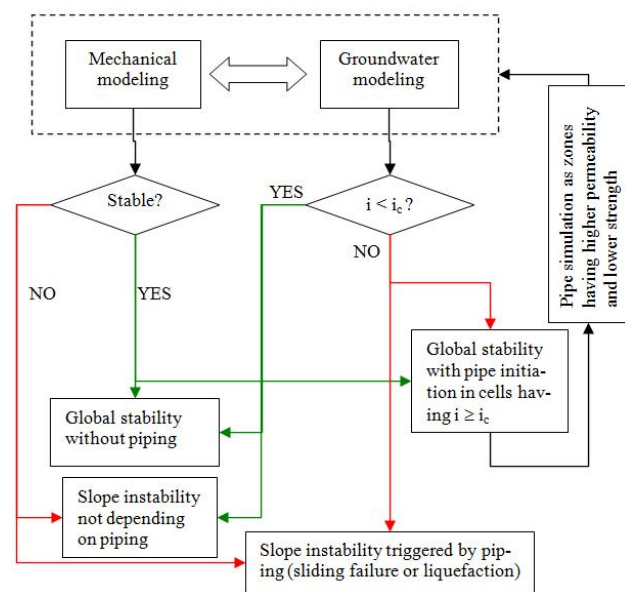


Fig. 1 Flow diagram of the tool used for modeling the slope instability triggered by piping (i is the piezometrical gradient and i_c its critical threshold)

B. Flow Failure Conditions

As far as the effects of subsurface pipes on slope stability are concerned, in addition to the mechanical effect of loads redistribution induced by the pipe opening, also the water drainage caused by the increase in permeability along the pipe has to be considered. Actually, pipes can be described as zones having higher permeability and lower strength than the surrounding materials. According to the experimental and numerical studies carried out by [14], groundwater simulations in presence of piping showed that:

- 1) the porewater pressure is the smallest around the upper ends of pipes, for both open and closed pipe conditions;
- 2) if the pipe outlet is connected to the land surface (open pipe), the porewater pressures greatly decrease in the whole slope with reference to "no pipe" conditions;
- 3) if open pipes clog, they may behave as closed pipes (not

connected to the land surface), then the porewater pressures at the pipe outlet become higher than under “no pipe” conditions and they increase with the increase of the pipe length (Fig. 2).

From a mechanical point of view, if the drainage at the slope foot is prevented after the pipe formation (for example in consequence of pipe clogging), the following porewater pressures increase can trigger the slope instability. So, to verify the slope stability conditions resulting from piping, the groundwater flow model previously described was coupled with a mechanical one (Fast Lagrangian Analysis of Continua, [29]), able to simulate the strain deformation response of the soil. Two hydrogeological states for the pipe can be modelled:

- 1) a freely draining condition (open pipes), which will result in a drainage of the slope and thus reduced porewater pressure;
- 2) a hydrostatic pressure condition, in which water can be assumed to flow freely into the pipe further upslope, but if effectively unable to flow out at the lower end (closed pipes).

Although free drainage is probably the most common condition for piping, if the failure is to be explained, then the second hydrogeological state is more realistic, giving rise to localized artesian effects. Actually, in this latter case, the porewater pressure increase associated to the loss of soil materials brings about a decreasing shear strength, thus leading to Coulomb failures. Also, in undrained conditions, if the increment in porewater pressures is very high, it can even set the effective stresses to zero, with the consequent soil liquefaction.

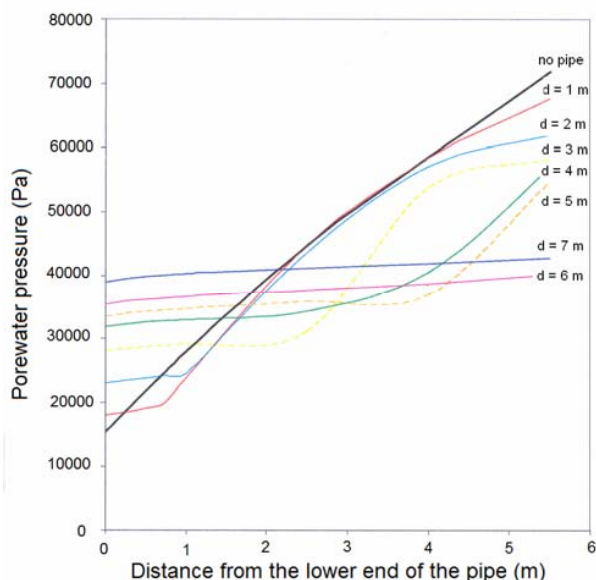


Fig. 2 Porewater pressures versus the distance from the lower end of the pipe, when the pipe size changes (d is the pipe diameter)

II. THE STAVA EXAMPLE

In the Stava Valley (Trento, Northern Italy) two fluorite tailings dams were constructed on baggy and weakly resistant glacio-fluvial deposits lying on dolomitic rocks.

The dam of the lower basin was erected on a porous starter dam anchored to the foundation soil, using the “upstream” method, which is the least reliable method with respect to stability. The dam of the upper basin (Fig. 3) was constructed without prearranging either drainage systems or anchorages, using first the “centerline” method, so that as the dam grew higher its base partly rested on the lower basin tailings, and after that the “upstream” method was also used. The area occupied by the two basins and the volume of the stored material were respectively 30000 m² and 300000 m³, which included 15000-20000 m³ of free water [31].

On 19 July 1985, a violent flow slide with catastrophic effects (268 deaths, extensive damage to property and environment) occurred, following the failure of the two tailings dams described above.

The triggering event of the collapse was identified by several Authors in the liquefaction of the right side of the upper tailings dam, attributed to leakages from a decant pipe passed under the dam. Subsequently the central part of the tailings dam would collapse, pouring sand, unconsolidated silt and water into the lower reservoir, bringing about his rupture [31].

Among the main factors that contributed to the upper tailings dam instability, the following have to be mentioned:

- 1) the high water content of the tailings ponds [32] and the high piezometrical surface within the dam: actually, in addition to water that was retained by the decanting tailings, water flowed systematically into the ponds from surrounding slopes and from the groundwater intercepted;
- 2) the lack of bottom drainage systems [33];
- 3) the constructive method [28];
- 4) the unconsolidated condition of silt [34];
- 5) the action of loads and vibrations [28];
- 6) the lake level that, being straight in contact with the sandy tailings dam, allowed the water flow and then the piping [28].

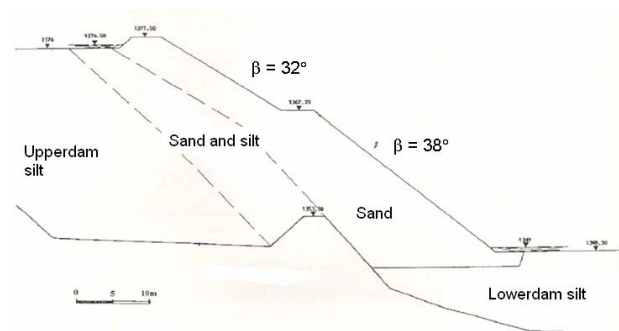


Fig. 3 Scheme of the upper tailing dam of Stava (height: 29 m), resting right on the silt of the lower reservoir, without bottom drainages (from [30], modified)

Among mechanisms that could prime the failure, the liquefaction triggered by piping was analysed in the present study, pointing out the related sequence of events.

A. Pipe Initiation

To apply the previously described tool, the grain size distribution data of the upper tailings dam [33] was used to obtain 50 equiprobable grain size distribution curves (Fig. 4). The Kenney and Lau's method [7] was applied to these grain size distributions to consider the susceptibility to piping in the examined soil. Fig. 5 shows the application of the method to one of the 50 grain size distribution curves simulated: F is the percentage of grains having diameter D ; H is the percentage increment of grains having diameter $4D$, with reference to the ones having diameter D ; the dotted line divides the stability zone (above) from the instability zone (below); the continuous line is the $H(F)$ curve for the case examined. Results pointed out that 49 grain size distribution curves out of 50 can be interested by piping phenomena. Considering a specific yield of grains $G = 24.5 \text{ kN/m}^3$, the porosity $n = 40\%$, the dip of the land surface $\alpha = 38^\circ$ (corresponding to the upper tailings dam) and a corrective factor $a_1 = 1$, according to the Zaslavsky and Kassif's model [11], the critical piezometrical gradient j_{cr} became equal to 0.676.

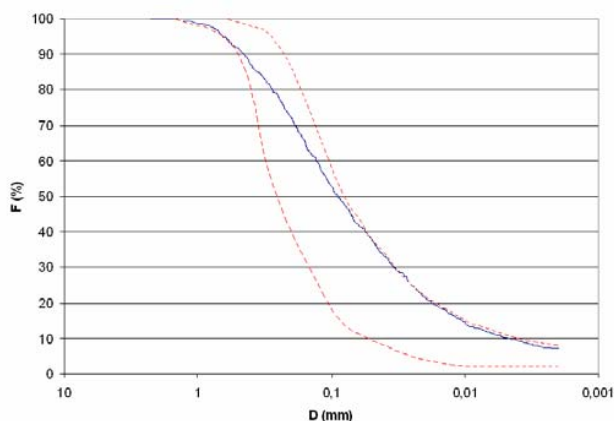


Fig. 4 Dotted line: distribution curves fitting grain sizes of the upper tailings dam sand; continuum line: an example of the 50 equiprobable grain size distribution curves generated through Monte Carlo simulation

B. Piping Evolution Modeling

After verifying the primer conditions of the piping phenomenon, the pipes evolution was simulated through a coupled modeling (mechanical and hydraulic) of the upper tailings dam (Fig. 6). The geotechnical properties of the tailings dam (Table I) were obtained from in situ and laboratory tests performed after the collapse [35], [36].

The domain (150 m in length by 43.5 m in height) was split through a grid having variable cells size: min 0.25 m x 0.25 m for the tailings dam, max 2.5m x 6 m for the foundation soil.

Following boundary conditions were considered for the modeling:

- 1) a hydrostatic load of 0.5 m above silt of the upper reservoir;
- 2) a groundwater flow in the foundation soil;
- 3) porewater pressure equal to zero on the surface of the tailings dam.

TABLE I
GEOTECHNICAL PROPERTIES OF DIFFERENT MATERIALS SHOWN IN FIG. 4

Material	Spec. yield kN/m^3	Cohes. kPa	Frict. angle $^\circ$	Bulk mod. MPa	Shear mod. MPa	Hydraulic conduct. m/s
Sand (1)	18.60	0	42	13.50	29.20	10^{-6}
Sand and silt (2)	17.65	0	35.5	7.41	22.20	$4 \cdot 10^{-8}$
Bottom and lowerdam silt (3)	18.6	35	0	4.44	13.30	10^{-9}
Upperdam silt (4)	15.87	15.7	0	2.22	6.67	10^{-9}
Substratum (5)	20.60	0	40	60	100	10^{-8}
Pipes	8.10	0	0	1.35	2.92	10^{-4}

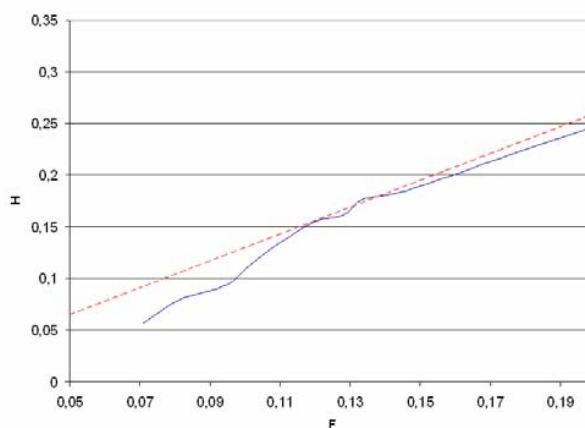


Fig. 5 Application of the Kenney and Lau's method [7] to one of the 50 grain size distribution curves simulated

Using FLAC (Fast Lagrangian Analysis of Continua, [29]), following features were obtained:

- 1) porewater pressures within the tailings dam and piezometrical level (Fig. 6);
- 2) initial in situ stress conditions.

The piezometrical gradient was calculated for each cell. The values obtained were compared with the j_{cr} to point out the area interested by piping (Fig. 7a). According to the previously described iterative tool, the pipes evolution was simulated (Fig. 7b).

A. The Collapse

Finally, effects of the piping on the slope stability of the Stava tailings dams were studied. To this aim, the porewater pressures in the upper tailings dam were simulated, as a consequence of the piping evolution previously analysed.

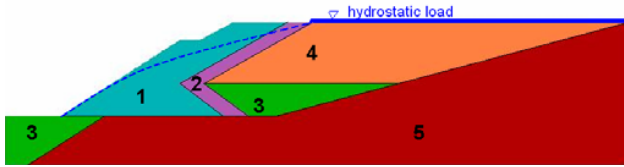


Fig. 6 Sketch of the upper tailing dam in the area prone to piping phenomena: 1) sand; 2) sand and silt; 3) silt of the lower reservoir; 4) silt of the upper reservoir; 5) foundation soil. The hydrostatic load above the upper basin and the relevant piezometrical level within the tailing dam (dotted line) are showed

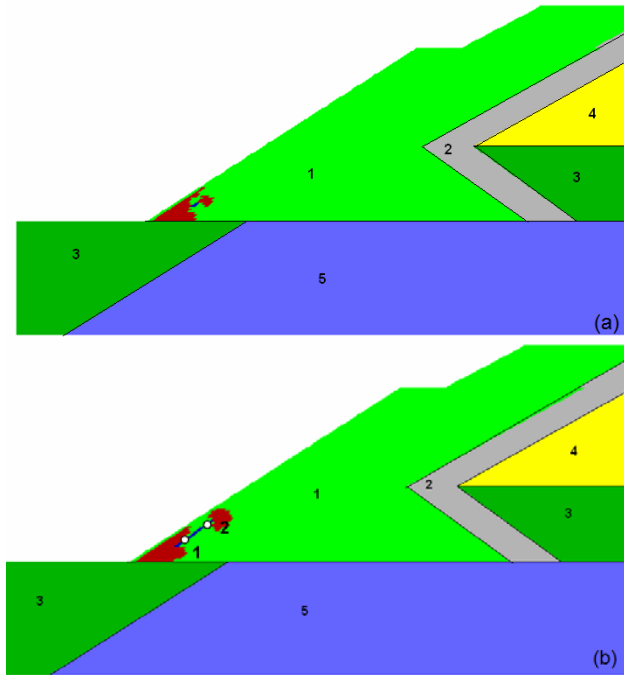


Fig. 7 The cells having piezometrical gradient equal or higher than j_{cr} are showed at the foot of the slope in a deep colour: a) starting phase; b) pipes widening. 1 and 2 are the porewater pressure monitoring points (Fig. 8)

Particularly, nearby the lower end of the pipe an increase in the porewater pressures was pointed out (Fig. 8): the larger is the pipe, the bigger is the increase. Such an increase in the porewater pressure at the foot slope, where collapse took place, brought about a decrease in effective stresses (Fig. 9) leading to the soil liquefaction.

Based on modelling results, the collapse would occur according to the following scheme:

- 1) liquefaction of the bottom of the upper tailings dam (Fig. 10a) and consequent flow-off of silt;
- 2) piping widening towards the upper part of the tailings dam (Fig. 10b);
- 3) increase in displacements (Fig. 10c) and widening of the instability area, till the collapse of the whole tailings dams (Fig. 10d).

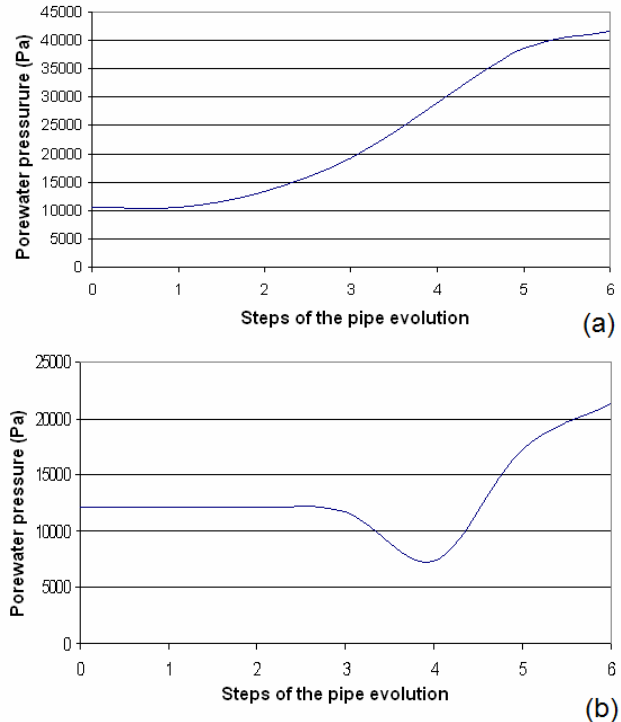


Fig. 8 Porewater pressures during the different evolution steps of the pipe: a) in point 1 (Fig. 7), b) in point 2 (Fig. 7)

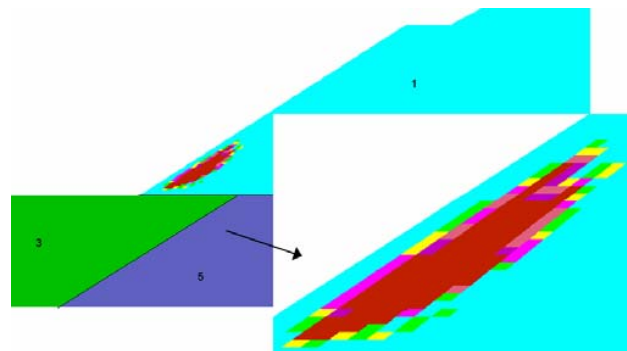


Fig. 9 Fall-off of effective stresses: red = 100%, violet = 90%, orange = 80%, pink = 70%, yellow = 60% and green = 50%

III. CONCLUSION

The paper presents a tool for the study of primer conditions of piping phenomena and the simulation of its evolutions, through a coupled (hydraulic and mechanical) modeling. Such an approach allowed to consider the increase in porewater pressures arising from piping widening and the consequent effects on the stability.

As an example, this tool was applied to the Stava case, to discover if the flow failure of tailings dams occurred in July 1985 might have been triggered by piping processes. Results showed that porewater pressures induced by piping at the bottom of the upper tailings dam could bring about a decrease in effective stresses, able to trigger the failure or even the soil liquefaction and then the collapse of the whole tailings dams.

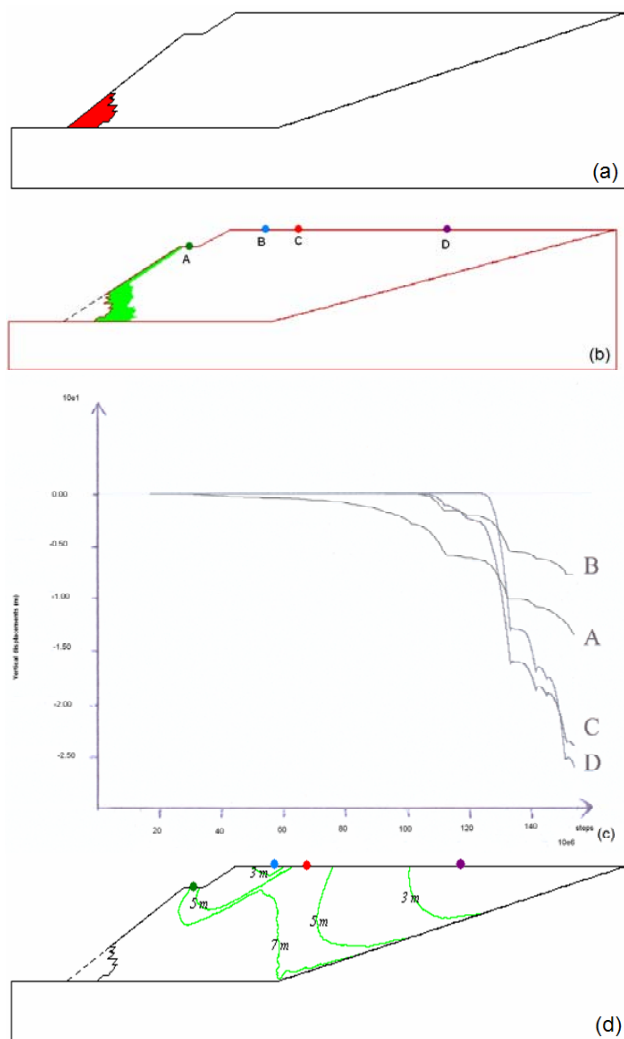


Fig. 10 Collapse scheme: a) liquefaction of the bottom of the upper tailing dam; b) piping widening towards the upper part of the tailing dam; c) increase in displacements in the monitoring points (Fig. 10b); d) collapse of the whole tailing dam

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Also, she has taken part in writing two textbooks on Applied Geology and two reference books concerning respectively the stability of rock slopes and the water circulation in rock masses.

She has taken part in several research program: MURST (1999): "Geological-technical characterisation of weak rocks, with reference to slope stability"; CNR-Agenzia 2000 (2001): "Hydrogeology of Milan: the groundwater use for the urban quality improvement"; INTERREG III B 2003 "Riscmass: Methodologies for the Landslide Risk Management with scenarios of Insurance Policy".