Evaluation of the tailings basins pollution potential

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SUMMARY: Tailings basins within mining areas may represent potential sources of environmental contamination for soil and underground water. In fact, the disposed muds are typically characterized by high concentration of heavy metals and other possibly dangerous compounds. The tailings basins built in Europe before the legal implementation of the EU Directive on the landfill of waste (Directive 99/31) were not provided with impermeable barriers. In such conditions, during the initial period of the basin life the liquid phase in the disposed residue filtrates throughout the solid phase under a unit vertical hydraulic gradient, reaching the soil underneath; afterword, when the accumulated mud forms an impermeable layer at the bottom of the basin, the same mud, under the load of the superimposed new strata, consolidates, ejecting liquids throughout the bottom. The article discusses the implementation criterion aimed at evaluating the conformity of old tailing basin to the new regulation on landfill of waste and a method for the calculation of the rate of polluted liquids released through the bottom of a tailing basin during its operative life and after its closure.

Keywords

Tailing basin, EU Directive 1999/31, criterion for conformity

1. Introduction

Residues resulting from mineral processing have been traditionally stored in basins or lagoons typically created by damming valleys or by constructing complete perimeter embankments. To allow the progressive reduction of the residues water content and thus increase the life of such basins, their bottom was left permeable; consolidation, facilitated by filtration through the bottom as well as by evaporation at the surface, led to better stability conditions and allowed the raising of the basin by the construction of secondary embankments partly founded on the consolidated muds (upstream method). In this way the basin grew in height in the shape of a truncated pyramid, the top of which was the lagoon in which the slurry was deposited.

European Community Directive number 99/31 on landfill of waste [1], which came into force in 1999 throughout the European Union, required that all new landfills were provided with a sealed bottom aimed at protecting soil and ground waters from contamination and that old waste deposits had to be updated to match the introduced requirements. The majority of tailing basins resulted to be not conform to the Directive 99/31 since they lacked the bottom impermeable barrier and this could not be realised under the existing deposits [6].

The prolongation of the disposal in such basins was, then, subjected to an environmental impact assessment mainly focused on the evaluation of the contaminated flow throughout the basin bottom.

This modification of the European Regulation has fallen in a period of important evolution of the residues filtration and disposal technologies; many industries have provided their mineral processing plants with sections where the residues are dehydrated by filtration devices (typically filter presses) and have changed the tailings disposal method from lagooning to dry stacking or dry disposal. In such cases, in the volume of the waste deposit a horizontal discontinuity forms between the lower layer, disposed prior to the switching of the disposal method, and the upper layer of dehydrated muds deposited afterwards. The lower layer, if suitable, can be used as bottom barrier of the new waste deposit. Suitability can be established on the basis of a comparison between the overall flow that cross the basin bottom and the flow through a barrier constructed in accordance with the regulations. To this concern it has to be considered that the contaminated flow throughout the basin bottom depends on processes that develop only in the lower layer: the vertical filtration due to gravity and the consolidation of the mud induced by the weight of the upper layer.

In the following, after citing the characteristic elements of the main disposal technologies and the Community Directive 99/31 concerning the landfill of waste, we will illustrate a criterion aimed at evaluating the conformity of tailing basins with the Directive 99/31 and a case of study concerning a tailing basin where the existing layer of mud has to be used as the bottom barrier of a new accumulation of wastes.

2. Lagooning and Dry disposal

Lagooning consists of pumping the slurry (25 – 30% solids) into fully constructed basins or ponds formed within natural depressions using earth dams [2] [3]. In such basins the liquor content is reduced from 75 - 70% to 35 – 30%, either by evaporation or consolidation of the mud under its own weight. Lagooning basins are developed starting with a retention embankment that makes it possible to store a volume proportional to the area and the height of the embankment. When this volume has been completely filled, a secondary embankment is built partially on the dry mud, thus creating a new volume for storage but with a smaller evaporating area. In such a way the basin increases in height with the construction of a succession of secondary embankments (upstream method).

This method requires low capital cost if low-value land is available and natural depressions can be utilized with the construction of small embankments; it does not require additional thickening of the slurry prior to disposal, it requires no dust control because of the presence of the supernatant liquor. On the other hand, it calls for the availability of large amounts of land and involves a number of environmental hazards, including contamination of soil and ground waters by leaching of caustic liquor and toxic metals, especially in the case of non-neutralized residue. It requires planning and allocation of funds for long-term closure and remediation which are problematic due to the presence of the large amount of entrained liquor and long-lasting impacts deriving from leaching. Basin construction and elevation need to be carefully monitored and managed to avoid catastrophic failure of the embankments and the consequent threats to the environment and the population: construction and maintenance costs may be quite high. Finally, closure and site remediation may result in an indefinite legacy due to the difficulty of meeting statutory environmental standards.

When areas for storage are limited or costly, basins develop vertically. In such cases, the mud production rate is limited by the speed with which the muds consolidate, since a second retention embankment can be built only when the mud has reached suitable bearing capacity.

In dry disposal, the slurry is transported via pipeline from the refinery to the filtration plant. Here it is filtered to a dry cake (65 – 70% solids) and washed with water or steam to recover soda and minimize alkalinity. The dried mud is transported to the disposal area on trucks or conveyors and is disposed of with traditional earth moving machines [2] [3].

Economically, it has important advantages connected with the reduction of areas needed for storage and the need for mud containment structures: the plan of the deposit calls for the building of a main retention embankment starting from which the deposit rises in height without the need for secondary embankments. However, it does require the building and running of a filtration plant. Compared with the method previously described, it has fewer impacts and a lower risk for the environment: the reduced number of voids and thus the amount of fluids contained in them limits the risks for soil and ground water contamination; on the surface of the deposit there are no caustic lakes which are a source of environment and health risks; the intrinsic geotechnical stability of the deposit minimizes the risk of collapse and the consequent impacts on the environment, health and production activities. It thus requires the setting up of less extensive and cheaper monitoring and control systems. However, the dried surface of the deposit may produce dust and thus requires the adoption of systems of dust control.

3. EU Regulation on the Landfill of Waste

For the purposes of Directive 1999/31/EC on the landfill of waste, the following categories of waste are defined:

- municipal waste: waste from households, as well as other waste that, because of its nature or composition, is similar to waste from the household;
- hazardous waste: any waste that is covered by Article 1(4) of the EU Directive on hazardous waste [1];
- non-hazardous waste: waste that is not covered by Article 1(4) of the EU Directive on hazardous waste [1];
- inert waste: waste that does not undergo any significant physical, chemical or biological transformations; inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health; the total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant and, in particular, not endanger the quality of surface water and/or groundwater.

The European List of Waste (LoW) established by [4] provides a common terminology throughout the European Union with the purpose of improving the efficiency of waste management activities. The LoW serves as a common encoding of waste characteristics in a broad variety of purposes, such as classification of hazardous wastes, transport of waste, installation permits, decisions about the recyclability of waste or as a basis for waste statistics.

As regards landfill classification, the Directive on the landfill of waste establishes that each landfill shall be classified in one of the following categories:

- landfill for hazardous waste;
- landfill for non-hazardous waste;
- landfill for inert waste.

The general requirements for each class of landfill are established in Annex I of the Directive and refer, in particular, to landfill location (Paragraph 1), water control and leachate management (Paragraph 2), protection of soil and water (Paragraph 3), gas control (Paragraph 4), nuisances and hazards (Paragraph 5), stability (Paragraph 6) and barriers (Paragraph 7).

As mentioned above, Annex I of Directive 1999/31/EC establishes the requirements for all classes of landfills. With reference to the protection of soil and water (Annex I, Paragraph 3), the Directive states that the landfill must be situated and designed so as to meet the necessary conditions for preventing the pollution of soil, groundwater or surface water and ensuring efficient collection of leachate. The Directive specifies that the protection of soil, groundwater and surface water is to be achieved by the combination of a geological barrier and a bottom liner, during the operational/active phase, and by the combination of a geological barrier and a top liner, during the passive phase/post closure (Annex I, Paragraph 3.1).

The Directive also establishes the possibility of completing artificially and reinforcing the natural barrier when the geological and hydrogeological conditions, below and in the vicinity of a landfill, do not provide sufficient attenuation capacity to prevent a potential risk to soil and groundwater (Annex I, Paragraph 3.2).

In addition to the geological barrier (natural or artificially reinforced), a drainage layer and an artificial sealing liner is required for both landfill categories (hazardous and non-hazardous waste), so as to ensure that leachate accumulation at the base of the landfill is kept to a minimum (Annex I of Directive 1999/31/EC, Paragraph 3.3).

According to the requirements of Annex I, in absence of a natural geological barrier, the protection of soil and groundwater can be guaranteed by a 1-m thick layer of clay at the bottom of the landfill, combined with a drainage layer of 0.5 m above a High Density PolyEthylene geomembrane (landfill for non-hazardous waste).

4. Criterion for conformity and determination of the reference flow

As anticipated in the introduction, tailing basins built prior to the coming into force of EU Directive 99/31 are, for the most part, not provided with bottom barrier for the protection of the soil and the groundwater. Despite this, the muds deposited in them, owing to their low permeability, may be considered a barrier against the runoff of leachate. To assess whether such a barrier is equivalent to the provisions of Annex 1 of the Directive 99/31 and thus if the basin can be considered as compliant with this regulation, the flow through it can be compared with the flow that cross the bottom of a landfill provided with the barrier required by the Directive. For a landfill of non-hazardous wastes (assumed as reference for the following discussion) the Directive requires a barrier composed by a one-meter layer of clay with a permeability below $1 \cdot 10^{-9}$ m s^{-1}, above which is an impermeable geomembrane of HDPE and a draining layer with a thickness of 50 cm.

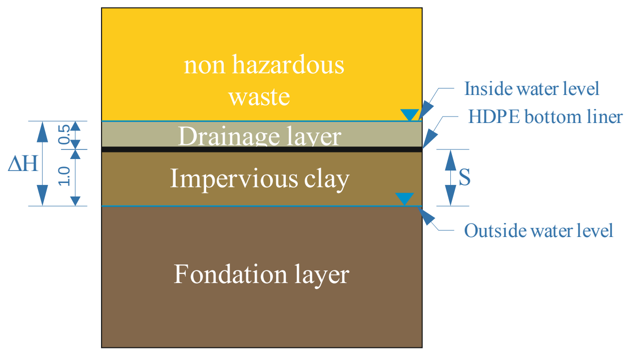

Figure 1. Bottom barrier according with the EU Directive 99/31 for a landfill of non-hazardous waste

The flow crossing this barrier, assuming that the internal hydraulic head may reach a height of 50 cm above the clay (coincident with the upper limit of the draining layer) and neglecting the contribution of the geomembrane, is generated by a vertical hydraulic gradient i = 1.5 m m^{-1}, as results from the following calculations (Figure 1):

i = ΔH/S in which ΔH = 1.5 m is the total head and S = 1 m is the thickness of the clay layer

The flow rate through the unit area of layer surface (flux) results to be:

$\Phi = k \cdot i \cdot A = 1 \cdot 10^{-9} \cdot 1.5 \cdot 1 \ m^2 = 1.5 \cdot 10^{-9} \ m^3 \ s^{-1} \ m^{-2}$

This value represents the reference for the verification of the viability of the mud layer to be considered as barrier for the runoff of the leachate.

5. Use of the basins surface for the disposal of new residues

The use of the surface of the tailing basins for the disposal of new layers of residues is favoured by land-use optimization criteria according to which it is preferable to go on with the disposal upon an old basin surface instead of constructing a new landfill in a virgin area that can be used, if not, for other purposes [5]. This particular use of the of tailing basins surface is, in any cases, viable if the layer of the residues already in place in the basin acts as a bottom barrier for the new residues.

According to the criterion described in the previous paragraph, this verification can take place on the basis of the comparison between the flow crossing the layer of residues in the basin and that crossing the barrier of a landfill built according to the cited Annex 1 of Directive 99/31 (reference flow). It has been shown that, for a landfill of non-hazardous waste, this reference flow is $1.5 \cdot 10^{-9} \ m^3 \ m^{-2} \ s^{-1}$.

As regard the evaluation of the flow through the layer of residues contained in the basin, it has to be taken into consideration that it is caused by the superimposition of the flow generated by gravity (filtration flow) and the flow caused by the consolidation of the mud layer under the weight of the overlaid new residues (assuming that consolidation under its own weight has been completed).

The filtration flow can be calculated by applying Darcy's Law to the model illustrated in Figure 2. In this model the difference in total head ΔH between the start and the end points of the path followed by the fluid particles coincides with the length of the same path ΔS; the hydraulic gradient is, then, unitary. The flow rate through a horizontal section and the corresponding flux result respectively:

$Q = k \cdot A \cdot i = k \cdot A \cdot \Delta H/\Delta S = k \cdot A \ (m^3 \ s^{-1})$ and

$\Phi = Q/A = k \ (m^3 \ s^{-1} \ m^{-2})$.

Flux coincides with the value of the permeability coefficient.

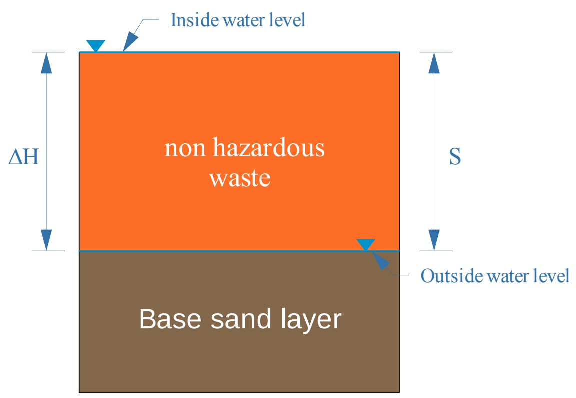

Figure 2. Reference model for the calculation of the filtration flow

The consolidation flow can be calculated by means of Terzaghi's one-dimensional consolidation theory [7]. According to this Theory the loading of a saturated porous material causes an immediate increase of the pressure of the water contained in the material pores (pore pressure) that, as a consequence, migrates towards zones where the pressure is lower. In the case of a horizontal layer loaded on its surface, these zones are the thin strata adjacent to the lower and upper boundaries. The exit of the water through these boundaries causes a reduction in the layer's volume that is equal to the volume of the water exited from the layer. The time over which the phenomenon develops depends on the permeability k and on the thickness of the layer. The reduction of the layer volume, and so the volume of water expelled, depends, for a given load, on the oedometric modulus M of the porous material under consolidation.

The application of Terzaghi's model to the mineral processing residues is complicated by the fact that the properties of this materials (in particular k and M) improve with depth and with time as a consequence of the advancement of the consolidation. Thus, the calculation of the consolidation flow must be carried out using models that take into account the evolution of the material properties with depth and over time.

6. Case study

The basin under consideration is composed of a main embankment and nine secondary embankments and contains a layer of mud 20 metres thick. It has been built on a sandy ground which permeability is 10^{-5} m s^{-1}. The plan of the Company is to dispose 20 metres of residues, previously dried by filtration (γ=20 kN m^{-3}), on the top of the basin and bring the overall height to 40 metres.

The geometric model of the basin is shown in Figures 3 and 4, in which the deposited mud is shown in yellow and that to be placed is in orange. The figures also illustrate the one dimensional models used to calculate the filtration and consolidation flows in the various areas of the basin. These models consists of columns which height represents the thickness of the mud layer already placed in the basin and the superimposed segment in red represents the thickness of the dehydrated mud to be disposed upon the basin surface.

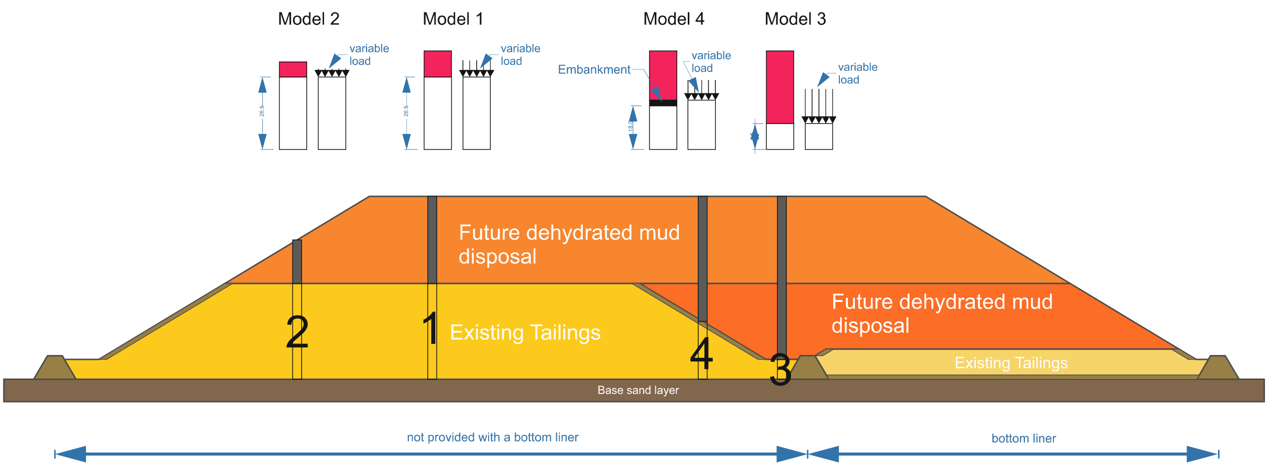

Figure 3. Section A of the basin with the indication of the calculus models

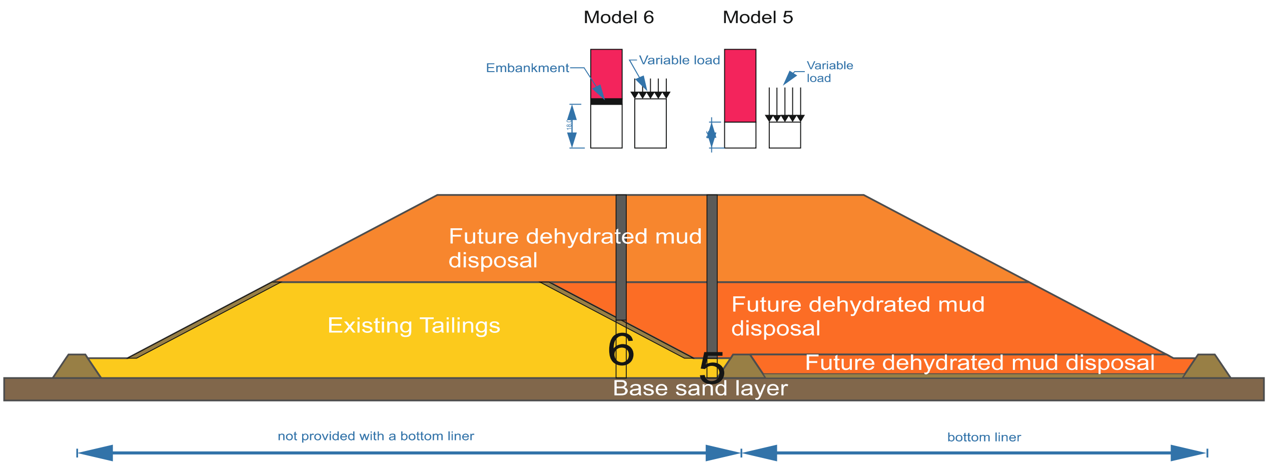

Figure 4. Section B of the basin with the indication of the calculus models

The feasibility of the project is subordinated to the evaluation of the flow generated by filtration and consolidation of the existing mud under the load of the superimposed new layers; as mentioned earlier, the consolidation flow depends on permeability (k) and on oedometric modulus (M) of the lower layer and also on the velocity of the load application (velocity of raising the height of the basin).

The geotechnical parameters (k and M) used to perform the analysis were obtained by laboratory and in situ tests while the velocity of raising the basin was deduced from the Exploitation Plan of the landfill.

6.1 Geotechnical investigation

The permeability (k) depends on the density of the mud and thus on the depth within the layer (z). It was investigated by means of oedometric tests carried out on undisturbed samples taken at different depths. Through these tests the permeability coefficient was measured at increasing values of the effective vertical stress (σ'_v) and then of the depth(z). In the following diagrams the points represent the measured values of coefficient k for different depths (Figure 5) and for different effective vertical stress values (Figure 6) while the lines represent the fitting curves which equations have been assumed to describe the dependences k = k(z) and k = k (σ'_v).

The first diagram identifies the present distribution of the permeability (k) within the layer; the second diagram describes the evolution of the permeability (k) induced by the load of the new layers disposed on the basin top.

The oedometric modulus was measured both by oedometric tests on undisturbed samples and in situ CPTU (cone penetration test with additional pore pressure measurement) tests performed in two boreholes (Figure 7). The result of the in situ and laboratory tests are represented in the following two diagrams together with the fitting curve that describes the relation between the oedometric modulus (M) and the depth (z).

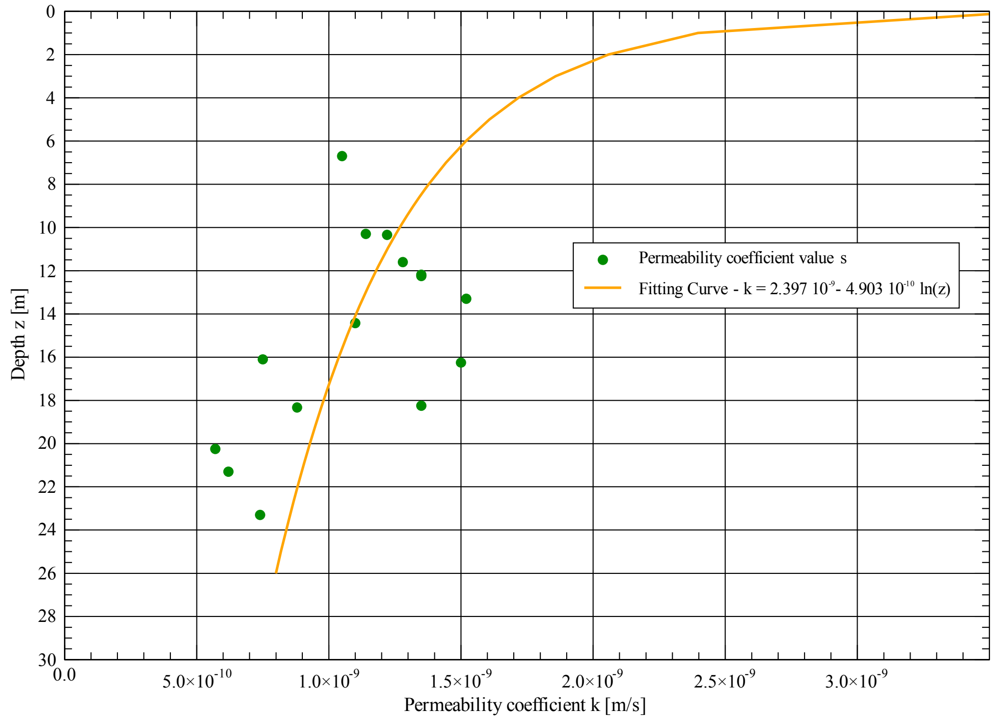

Figure 5. Relation between permeability coefficient k and depth z

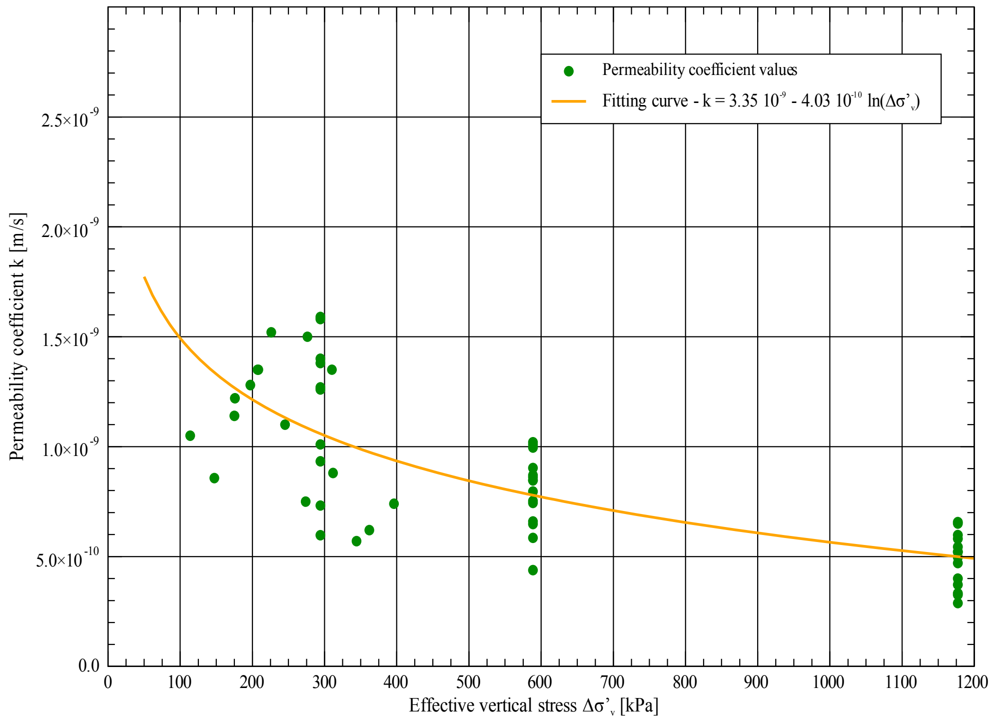

Figure 6. Trend of the permeability coefficient k as a function of the effective vertical stress σ'_v

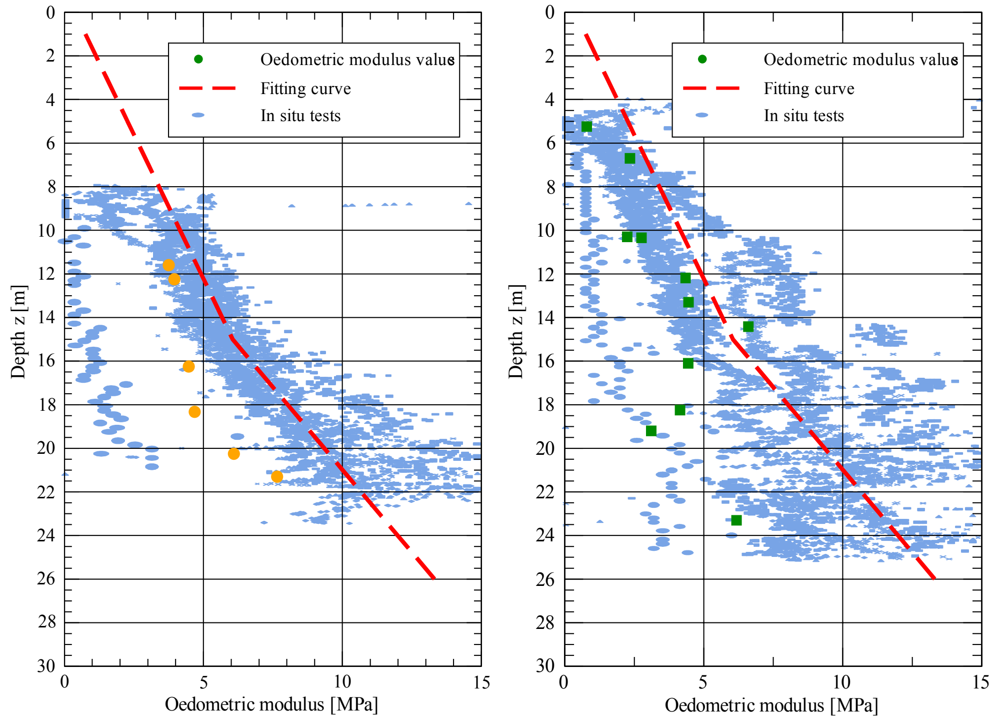

Figure 7. Trend of the oedometric modulus within the basin (CPTU test and oedometer test). Left: borehole A; Right: borehole B

The diagram in Figure 8 represent the variation of the oedometric modulus with the effective vertical stress (σ'_v) and will be used to describes the evolution of the modulus (M) when the basin surface will be loaded by the weight of the new layers.

In synthesis, from the data illustrated in the previous figures the following results were found:

- the laws $M = M(z)$ and $k_v = k_v(z)$ in the present basin condition;
- the laws $M = M(\sigma'_v)$ and $k_v = k_v(\sigma'_v)$;
- the laws $M = M(t)$ and $k_v = k_v(t)$ obtained by combining the previous relations with the $\sigma'_v = \sigma'_v(t)$ that describes the velocity of the basin rising.

These laws, represented by continuous curves in the previous diagrams, are:

$k_v = 2.397\ 10^{-9} - 4.9029\ 10^{-10} \ln(z)$

$M = 378.33\ z + 375\quad z<15$

$M = 660\ z - 3850\quad Z>15$

where z is the depth measured from the basin surface.

$k_v = 3.3507\ 10^{-9} - 4.0326\ 10^{-10} \ln(\Delta\sigma'_v(t))$

$M = 48.876\ (\Delta\sigma'_v(t))^{0,7841}$

The evolution of the load due to the mud disposal in the various areas of the basin is represented in the following Figure 9.

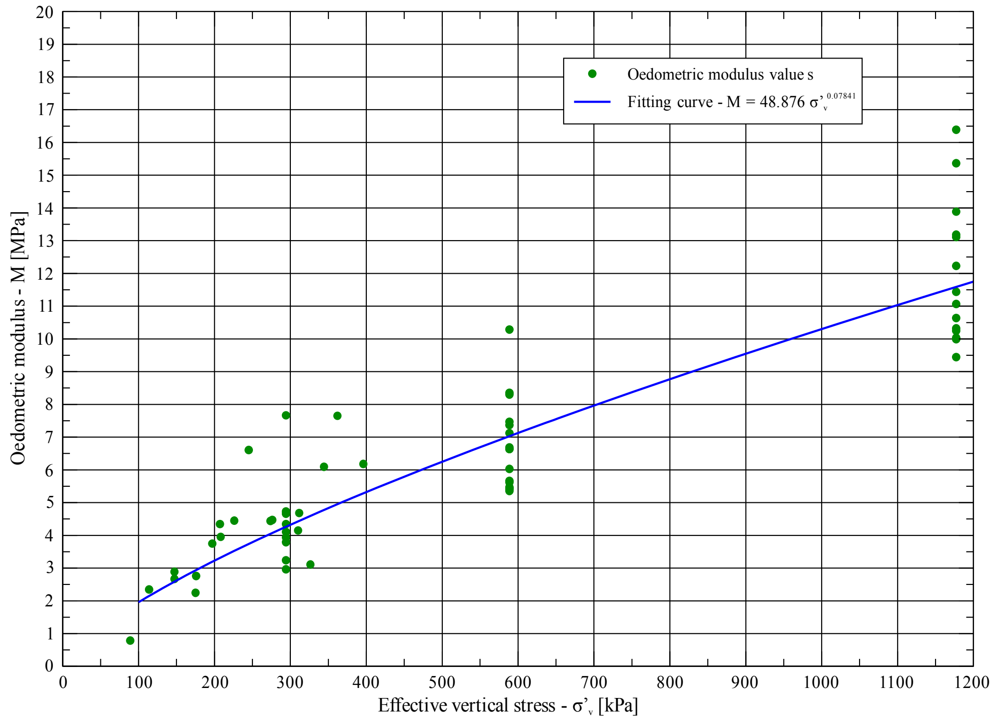

Figure 8. Evolution of the oedometric modulus as a function of the effective vertical stress (σ'_v)

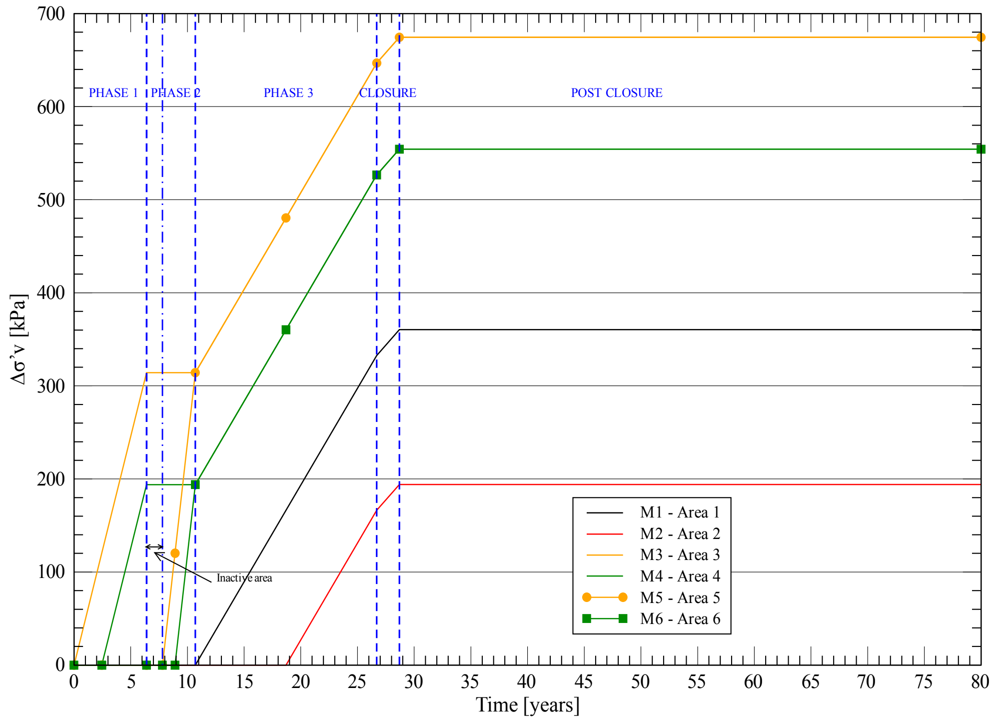

Figure 9. Evolution of the load applied on the areas of the basin

On the basis of these data six models were generated, each one representing an area of the basin. These models consist of vertical columns of mud having geotechnical characteristics assigned by the aforementioned laws and heights and load diagrams depending by their positions (Figures 3 and 4 and Figure 9 respectively).

6.2 Results

The result of the filtration and consolidation analysis is represented by the evolution of the flow through the bottom of the basin represented in the diagram of figure xx. This flow has been calculated as:

$$\frac{\sum_{i=1}^{6} v_{ti} A_i}{\sum_{i=1}^{6} A_i} \qquad [m/s]$$

in which v_{ti} represents the value of flow in the i^{th} area at time t (diagrammed in Figure 10) and A_i the extension of the same Area.

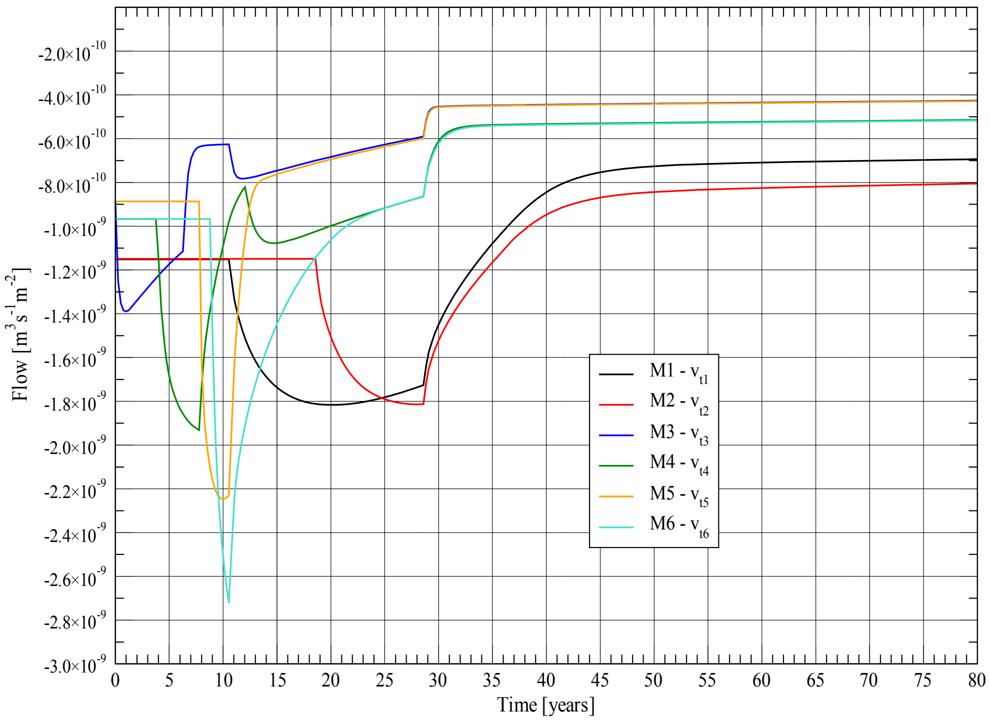

Figure 10. Behaviour of the flow in the basin areas

The evolution of the average flow v_t is represented in Figure 11 together with the initial value of the filtration flow (horizontal green line).

In the graph four points can be highlighted:

1. initial time (t = 0) at which the flow is caused only by filtration;
2. time t_{fmax} = 24.8 years when the flow (filtration plus consolidation) reaches its maximum value;
3. time t = 28.7 years in which the loading stage ends;
4. time t = ∞ in which the consolidation phenomenon is completed and the overall flow coincides with the final value of the filtration flow.

Instant t=0 is significant of the condition that precedes the basin loading phase: the flow coincides with that calculated with the filtration model and thus amounts to 1.04·· 10^{-9} m s^{-1}

The first part of the curve, between initial time and t = 28.7 years, represents the loading phase during which consolidation takes place. The behaviour of the overall flow is determined by two opposite effects: form one side consolidation causes the increase of the flow expelled through the bottom and from the other induces the improvement of the geotechnical parameters (M and k_v) that tends to reduce the same flow. In this stage the overall flow increases up to the maximum value of 1.312·· 10^{-9} m s^{-1}, which is reached after 24.8 years. Starting from that time a slight reduction is observed which is due to the prevailing effect of the geotechnical parameters improvement. In the post-closure period, the mud continues to consolidate and the flow decreases progressively, moving towards a stationary value of 0.808·· 10^{-9} m s^{-1}, which represents the filtration flow in the final conditions of the basin.

The analysis demonstrates that the overall average flow through the bottom of the basin is always lower than the reference flow (of 1.5·· 10^{-9} m s^{-1}). The impact on soil and ground water caused by the use of the basin for the disposal of new layers of wastes is, then, lower than that caused by a landfill of the same wastes provided with the barrier required by the regulation.

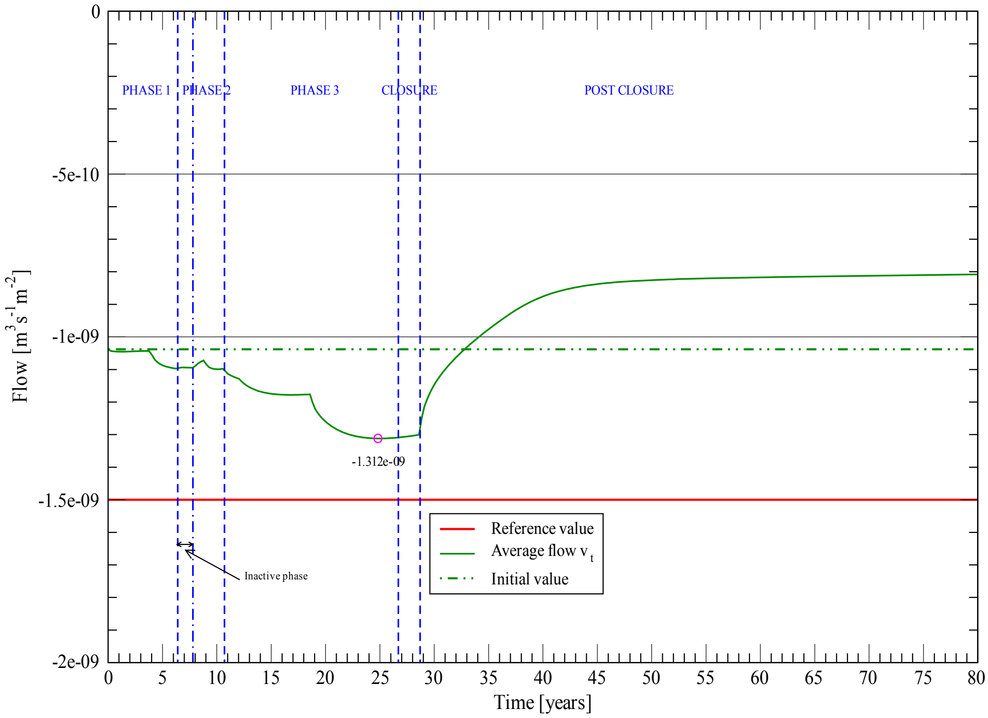

Figure 11. Average flow trend

7. Conclusions

The topics described herein demonstrate that tailing basins, even if realized without bottom barrier, can be used for the disposal of new layers of residues in compliance with the provisions of EU Directive 99/31. The criterion used for this evaluation is based on the comparison of the flow that crosses the basin bottom with a reference flow calculated for the barrier required by the EU Directive 99/31 (for a landfill of non-hazardous waste the reference flow is $1.5 \cdot 10^{-9}$ m^3 m^{-2} s^{-1}).

The calculation of the flow dispersed through the bottom of a tailing basin must take into account the filtration flow generated by the gravity and the consolidation flow induced by the weight of the new layers to be accumulated. The parameters that govern the phenomenon are permeability k, the oedometric modulus M and the thickness of the layer of mud present in the basin as well as the velocity with which the load above it increases. In general, the geotechnical parameters (k and M) improve with consolidation, thus as a first step it is necessary to define the mathematical laws that relate k and M to the vertical effective stress. These relations can be deduced from the analysis of data coming from oedometric tests and from in situ CPTU tests. As a second step, the obtained relations have to be combined with the function $\sigma'_v=\sigma'_v(t)$ to obtain the $k = k(\sigma'_v(t))$ and $M = M(\sigma'_v(t)$ that describe the evolution of the geotechnical parameters over the time. Finally these functions can be implemented in a one dimensional model aimed at simulating the filtration and consolidation phenomena during the life of basin and, in particular, at calculating the behaviour of the flow dispersed through the bottom over the time.

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Acknowledgments

Investigation carried out in the framework of projects conducted by CINIGeo (National Inter-university Consortium for Georesources Engineering, Rome, Italy).