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Computational modelling of final covers for uranium mill tailings impoundments

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Abstract

To properly design a final cover for uranium mill tailings impoundments the designer must attempt to find an effective geotechnical solution which addresses the radiological and non-radiological potential impact and prevents geochemical processes from occurring within the tailings. This paper presents a computer-based method for evaluating the performance of engineered final covers for the remediation of uranium mill tailings impoundments. Three hypothetical final covers were taken from scientific literature to investigate the proposed method: (i) a compacted clay liner (CCL); (ii) a composite liner (CL) and (iii) a capillary barrier (CB). The processes investigated: (i) the saturated hydraulic flux; (ii) the unsaturated hydraulic flux (exclusively for the capillary barrier) and (iii) the radon exhalation to the atmosphere. The computer programs utilised for the analyses are: (i) Hydrologic Evaluation of Landfill Performance (HELP); (ii) SEEP/W and (iii) RADON. The site considered for the development of the research presented herein was the uranium mill tailings impoundment located at the Brazilian city of *Poços de Caldas*, in the *Minas Gerais* State.

Keywords: Final covers; Geotechnical modelling; Tailings impoundments; Soil remediation; Uranium mill tailings

1. Introduction

A complete assessment of the efficiency of final soil covers applied to uranium mill tailings impoundments must take into account the several particular aspects concerning non-radiological and radiological potential impacts. In this sense, final covers have to prevent water infiltration into underlying tailings as well as prevent radon gas emission from the underlying tailings into the atmosphere. In addition, when pyrite is present in the tailings composition, the final covers have to prevent infiltration of gaseous oxygen into the tailings in order to avoid acid mine drainage formation.

The long-term efficiency of final covers is a major important concern when designing final covers for uranium mill tailings impoundments. Shackelford [1] writes that "the costs associated with the assessment of the variety of materials, conditions and applications in environmental geotechnics are often prohibitive such that detailed testing and analysis is not always possible. In this regard, when laboratory and field data are available, modelling represents a promising approach due to the relative ease of implementation and the potential for universal application of a given model to a given type of problem".

The approach presented herein for the assessment of the efficiency of final covers utilises different computer models in an integrated manner. Therefore, output data from one program is utilised as input data for another program. Laboratory investigations were performed in the Laboratory of Geotechnics at COPPE/UFRJ as well as in the laboratory for radiological investigations at IRD/CNEN. Field investigations were performed at the *Poços de Caldas* mill tailings impoundment. The results were used as input and background information. The uranium mill tailings impoundment of *Poços de Caldas* was taken as the reference site under assessment.

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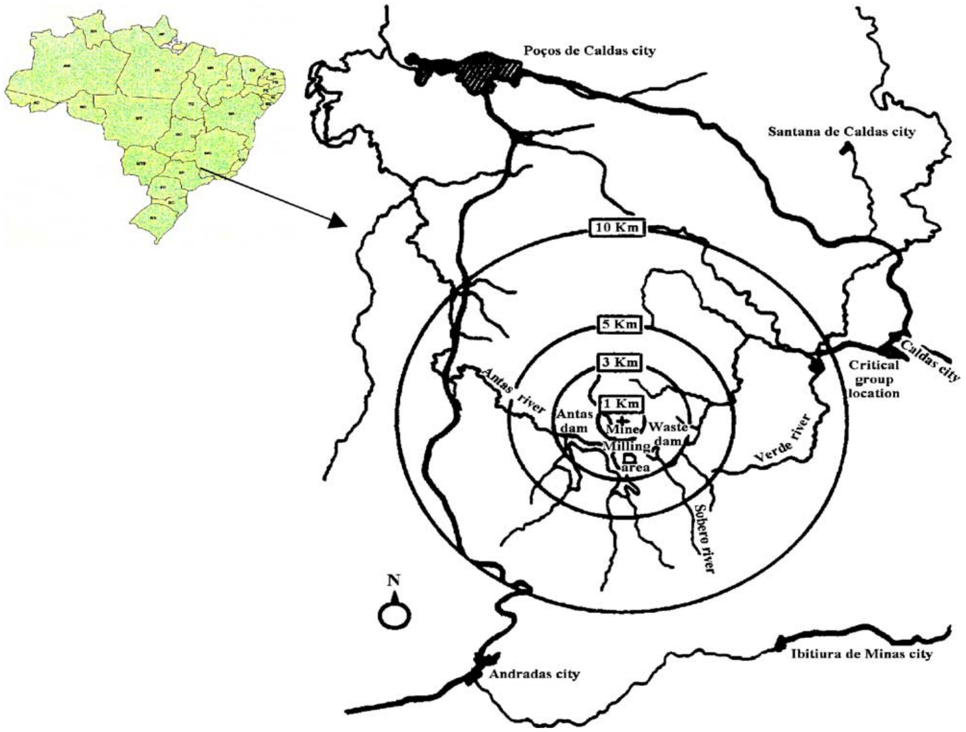

Fig. 1. Site location of the UMMF of *Poços de Caldas*.

2. Site description

The uranium mine and mill site is located on the *Poços de Caldas* plateau, in the Southeast Brazil (Fig. 1).

The plateau has a diameter of 35 km and covers an area of 1000 km^2. The total drainage area of the tailings impoundment is 0.86 km^2 and the total final volume of tailings discharged is approximately 2.39 million m^3.

3. Methodology

3.1. Conceptual approach

In general terms, a complete evaluation of final covers for the closure of uranium mining and milling tailings impoundments should take into account both geotechnical and geochemical aspects.

Geotechnical investigations are concerned with the capacity of the systems to minimize water and oxygen percolation towards the bulk of tailings. In addition, the effectiveness of the gas barrier layer of the covers to reduce radon exhalation towards the atmosphere is considered. Thus, geotechnical investigations comprise (i) water balance analyses; (ii) assessment of the saturated and unsaturated flux of water through final covers and (iii) evaluation of radon flux attenuation across the gas barrier layer.

Radon emission occurs due to the radioactive decay of elements such as^{226}Ra, ^{228}Ra and ^{232}Th present within the tailings composition.

3.2. Methodology adopted for the modelling

The geotechnical and geochemical aspects of the closure of uranium mill tailings impoundments were investigated through the integration of computer models. The following computer models were used and the sequence proposed for evaluating final cover systems is presented in Fig. 2.

The Hydrologic Evaluation of Landfill Performance (HELP) computer model, version 3.07 [2] was firstly employed for this simulation. The radon attenuation capacity of the gas barrier of the covers was investigated using the RADON program, version 1.0 [3]. The limit value of exhalation ratio was adopted in terms of flux and followed the default value established by USEPA for uranium mill tailings impoundments closure, equal to 20 pCi m^2 s^{-1} [4].

HELP model has a simplistic approach for estimating unsaturated flow. In particular, HELP cannot reasonably model

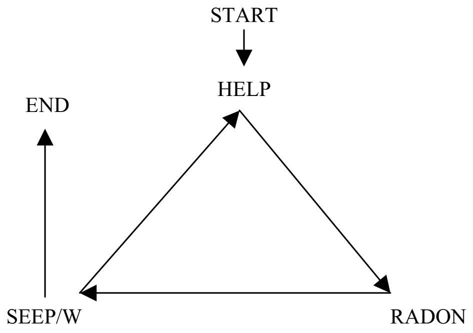

Fig. 2. Computational approach for evaluating final covers.

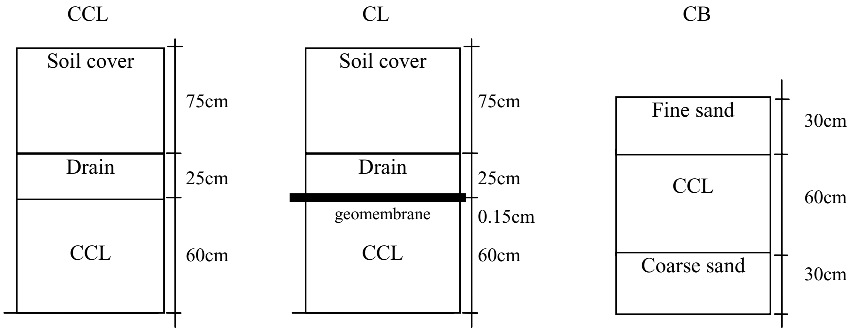

Fig. 3. Hypothetical final covers evaluated (cm; not to scale).

the behaviour of capillary barriers (CBs) [2]. In this regard, the model herein employed to analyse unsaturated flow was the SEEP/W program, version 4.20 [5].

The sequential modelling approach adopted in this work consists in utilising the infiltration results predicted in the near-surface HELP modelling as the top boundary condition for the unsaturated flow modelling.

Computational modelling finishes if saturated and unsaturated fluxes as well as radon flux are lower than a defined threshold and if water infiltration is adequate to help preserving the initial saturation degree of the compacted barrier layer. Otherwise, new layer thickness should be established for the cover systems or alternative cover designs should be modelled in order that hydraulic and gas fluxes as well as cover properties are properly controlled.

3.3. *Hypothetical final covers studied*

Fig. 3 shows a schematic representation of the different hypothetical final covers simulated in this work. The designs were taken from scientific literature.

The compacted clay liner (CCL) and composite liner (CL) cover designs were taken from Melchior et al. [6]. The compacted clay and lateral drainage layer, material properties of these covers were taken from Woyshner and Yanful [7]. The soil cover layer material properties and the characteristics of the 1.5 mm thick HDPE geomembrane were taken from HELP default database. The CB cover design as well as its material characteristics were taken from Woyshner and Yanful [7].

As the soil parameters for the three proposed cover designs were assumed identical concerning common layers, the behaviour of the layers comprising of identical materials can be compared under the different cover designs. Each proposed cover was separately analysed and comparisons between the different covers were accomplished. Table 1 lists the parameters adopted.

4. Help modelling—saturated flow

4.1. *Input data*

The data utilised for the HELP modelling are presented in Table 1. These same values are used as input data for the different models when required.

Table 1
Input data utilised in the HELP modelling [7,2]

Parameter	Soil cover	Drainage layer	Geomembrane	Compacted clay layer	Coarse sand
Layer type	Vertical percolation	Lateral drainage	Geomembrane liner	Barrier liner	Vertical percolation
Layer thickness (cm)	CCL/CL = 75	CCL/CL = 25 CB = 30	1.5 mm	60	CB = 30
Porosity	0.417	0.33	0	0.445	0.39
Field capacity	0.045	0.08	0	0.43	0.05
Wilting point	0.018	0.03	0	0.35	0.025
Initial water content	0.045	0.08	0	0.445	0.05
Saturated hydraulic conductivity (cm s^{-1})	1.0×10^{-2}	2.6×10^{-3}	2.0×10^{-13}	1.0×10^{-7}	8.4×10^{-3}
Slope (%)	0				
Maximum length of drainage (m)	10				
Cover area (m^2)	400				
SCS runoff curve number	CCL/CL = 75.8 CB = 81.0				
Depth of the evaporative zone (cm)	30				
Maximum leaf area index	0 (bare ground)				
Initial snow water content (mm)	0				
Growing season	Whole year				

Input data for the geomembrane of the CL final cover design: pinhole density in geomembrane liner = 1 per hectare, geomembrane liner installation defects = 6 per hectare and geomembrane liner placement quality = good.

Table 2
Average annual results obtained from HELP modelling

Parameter	CCL		CL		CB	
	%	mm a^{-1}	%	mm a^{-1}	%	mm a^{-1}
Evaporation	37.2	593	37.2	593	38.6	615
Runoff	8.34	133	8.36	133	30	479
Lateral drainage	51.8	825	54.2	864	29	463
Percolation	2.45	39	0.005	0.08	2.22	35

Geotechnical parameters of the soils to the suggested CB (i.e., lateral drainage, CCL and coarse sand layers) were taken from Woyshner and Yanful [7].

Both soil cover and geomembrane parameters were taken from the HELP default soil properties database. Precipitation and average temperature values used in the modelling were user-input for a 20-years period and were measured in the INB meteorological station located within the uranium mine and mill facilities of *Poços de Caldas*.

4.2. Results and discussion

The summary of the annual average results of the hydrologic evaluation with HELP model is shown on Table 2.

Fig. 4 presents the graphic results obtained with the HELP model for the three suggested designs.

Approximately 2.45% of the total annual average precipitation of the site percolates through the compacted clay layer of the CCL cover. It corresponds to about 39 mm of percolated water per year. The same analyses were carried out to the CL and CB final cover designs.

The average annual percolation value obtained for the CL clearly shows the importance of the geomembrane to avoid water seepage across the final cover. Only 0.005% of the total annual precipitation percolates the compacted clay layer annually which represents 0.08 mm of the total average annual precipitation of the site.

Concerning the CB design, the estimated average annual amount of water that percolates the cover was of 2.22%, equivalent to 35 mm a^{-1}. In this situation a quantity of approximately 3.5 mm a^{-1} of accumulated water can be expected to overlay the compacted clay layer.

Analyses were carried out taking into account the average monthly results of the HELP modelling due to the dry period of the site. The dry months occur from April to September and during these months the water percolation through the covers will tend to be lower. The results of the CCL analyses (Fig. 5a) showed that the predicted values of water

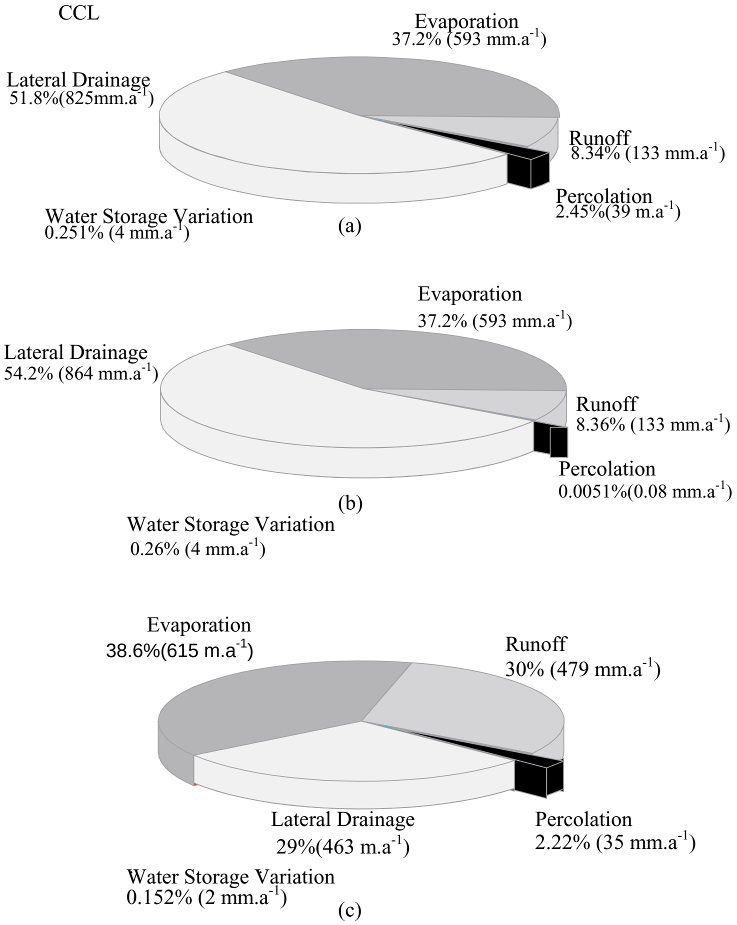

Fig. 4. Annual average results of the hydraulic balance obtained from HELP modelling for (a) compacted clay liner (CCL); (b) composite liner (CL) and (c) capillary barrier (CB).

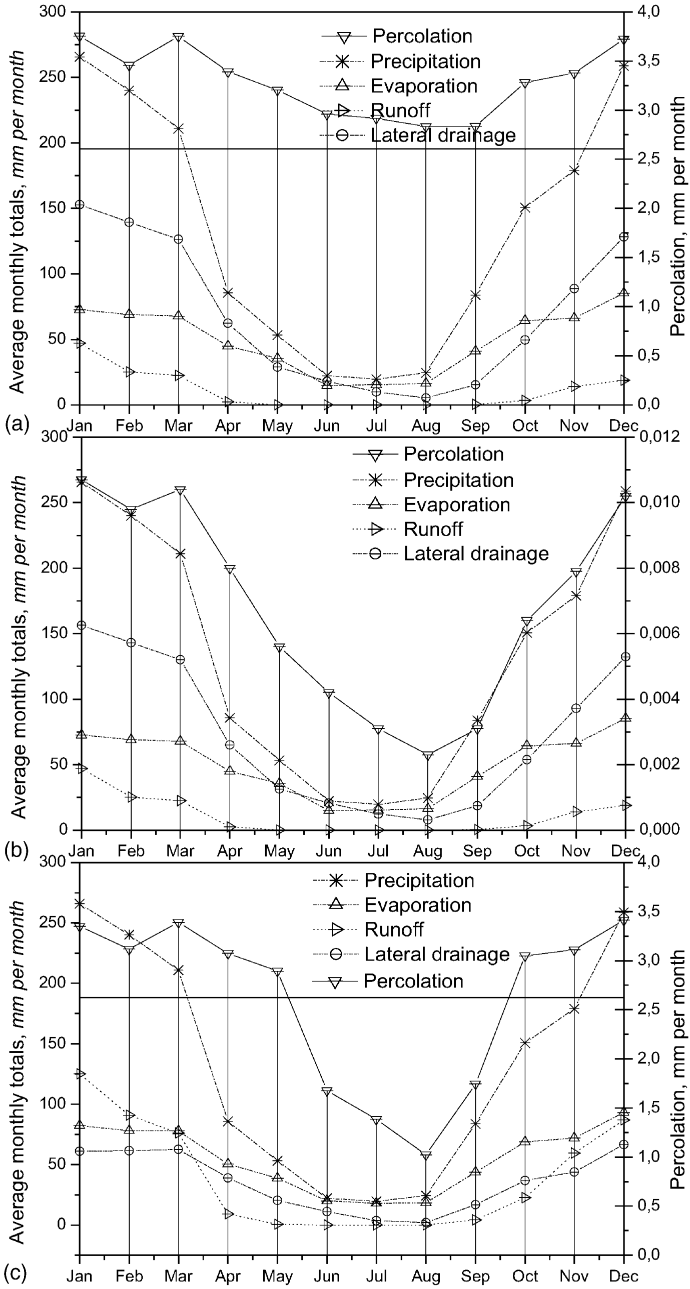

Fig. 5. Monthly average results of the hydraulic balance obtained from HELP modelling for composite liner (CL).

percolation across the compacted clay layer ranging from 2.8 to 3.7 mm per month. This analysis demonstrated that even in the dry months the flux of water migrating into the clay layer is superior to the hydraulic conductivity of the material, equivalent to 2.6 mm per month which, in turn, is equivalent to the hydraulic conductivity of 1×10^{-7} cm s^{-1}. Therefore, the average monthly results show the availability of accumulated water at the surface of the clay occurring for all months, including the months within the dry period. These conclusions, therefore, corroborate the conclusions obtained from the average annual results.

Fig. 5b presents the average monthly results obtained from the HELP modelling of the hypothetical CL cover design. The percolation values ranged from 0.002 to 0.01 mm per month with an average percolation value of 0.007 mm per month. The lower rates occur within the dry period.

The monthly results (Fig. 5c) showed that water percolation varied from 2.1 to 3.4 mm per month and from June to September this value was lower than 2.6 mm per month. This implies that for these months the predicted quantity of water migrating into the compacted clay layer is lower than the hydraulic conductivity of the material. Consequently, it

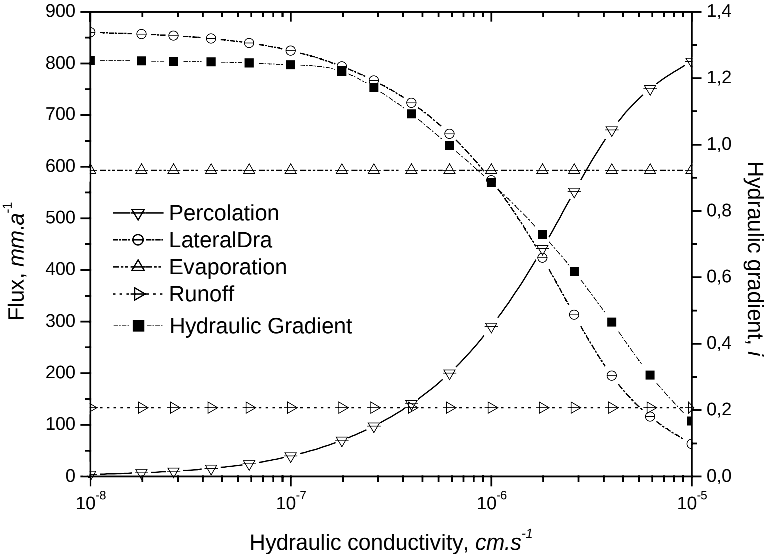

Fig. 6. Sensitivity analysis results obtained from the variation of the hydraulic conductivity of the compacted clay layer of the CCL.

clearly shows the potential to shrinkage and desiccation of the compacted clay layer in the dry months.

Sensitivity analyses of the compacted clay layers were analysed due to the great importance of saturated hydraulic conductivity to the percolation control. The analyses were accomplished by varying the hydraulic conductivity of the clay layers. The hydraulic conductivity values for the three final covers and its corresponding hydrologic parameters were taken from the annual average results obtained from the HELP modelling. Hydraulic gradient, *i*, was calculated from the relationship between hydraulic flow through the compacted clay layer and its corresponding hydraulic conductivity values, k_S.

The results obtained for the sensitivity analysis of the CCL clay layer are shown on Fig. 6. The percolation slightly varies until the hydraulic conductivity of the layer is equal to $1 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$. From this point on, percolation starts to increase at higher rates. Since runoff and evaporation values are unaltered as percolation increases, the lateral drainage decreases at inversely proportional rates. The hydraulic gradient is higher or equal to 1.0 until the hydraulic conductivity of approximately $7 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$ is achieved. In other words, hydraulic conductivity values equal or lower than $7 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$ indicate the presence of accumulated water within the layer right above the compacted clay. In a simplistic way it implies to the accumulation of water to maintain the degree of saturation of the compacted clay. On the other hand, hydraulic conductivity values higher than $7 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$ (hydraulic gradients lower than 1.0) imply a deficit of water flow throughout the compacted clay

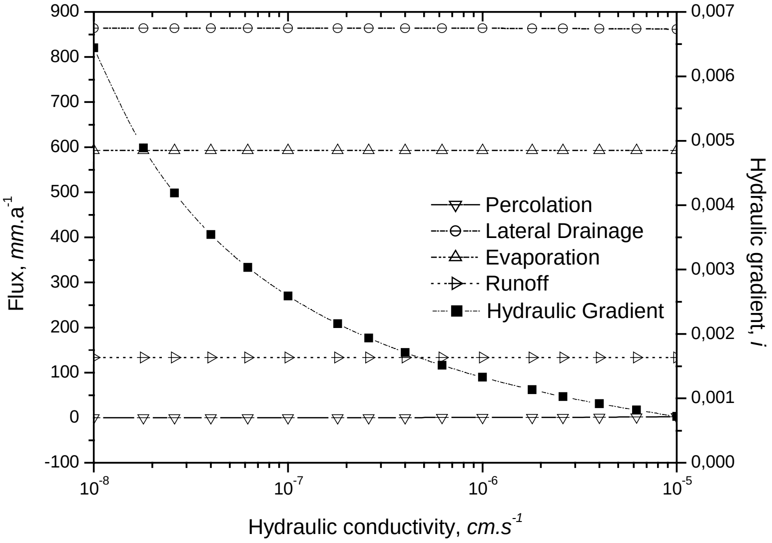

Fig. 7. Sensitivity analysis results obtained from the variation of the hydraulic conductivity of the compacted clay layer of the CL.

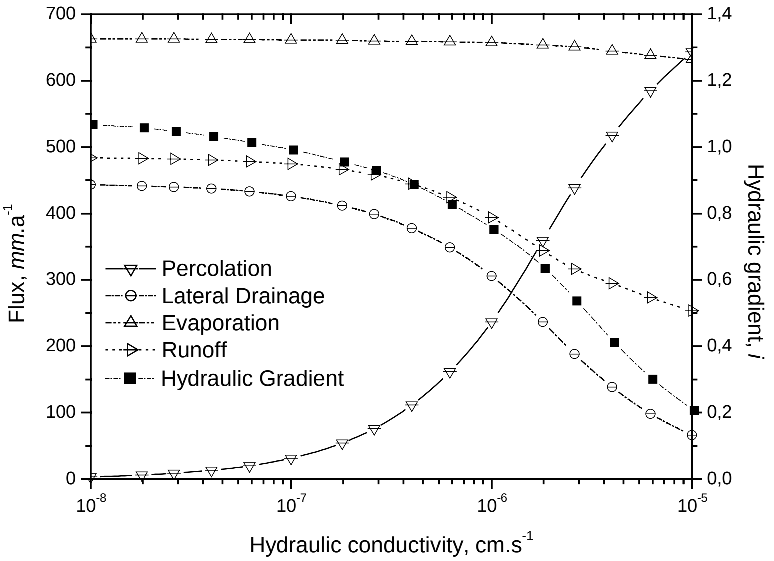

Fig. 8. Sensitivity analysis results obtained from the variation of the hydraulic conductivity of the compacted clay layer of the CB.

layer that suggests the increase of the potential for desiccation and, consequently, the reduction of service life of the cover.

Fig. 7 shows the results of the sensitivity analysis carried out from the variation of the hydraulic conductivity of the compacted clay layer of the CL cover. The results clearly indicate that the hydraulic flow throughout the cover is governed by the very low values of hydraulic conductivity of the geomembrane. Runoff and evaporation are kept constant whereas lateral drainage slightly decreases as soon as hydraulic conductivity increases. The hydraulic gradient is constantly lower than 1.0 and the percolation values are negligible. This indicates that there is no water flow coming from the top layer migrating downwards and the total volume of inflow water migrates through lateral drainage of the upper layer.

The results of the sensitivity analysis carried out from the variation of the hydraulic conductivity of the compacted clay layer of the CB cover are shown on Fig. 8. Hydraulic gradients lower than 1.0 result when hydraulic conductivity values are higher than $1 \times 10^{-7}\,\mathrm{cm\,s^{-1}}$. The risk of desiccation of the compacted clay layer therefore increases as hydraulic conductivity becomes higher than this value.

5. SEEP/W modelling—unsaturated flow

5.1. Input data

The geotechnical parameters of the soil materials that compose the CB final cover, including the soil–water characteristic curves (SWCC) were taken from Woyshner and Yanful [7]. For the uranium mill tailings, the SWCC was taken from the default material properties database of the SEEP/W program [5] and typically represents this material. Fig. 9 presents the hydraulic conductivity functions utilised in the unsaturated flow modelling of the CB and were generated by a sub-routine of the SEEP program. The hypothetical CB final cover was modelled as a two-dimensional system and under steady-state conditions. The top boundary condition was defined as the amount of water infiltration obtained from the annual average results from the HELP modelling and was set as $502.4\,\mathrm{mm\,a^{-1}}$. The sides of the finite elements mesh were considered as a constant head boundary. The bottom of the water flux domain was supposed impermeable.

5.2. Results and discussion

The SEEP/W modelling results for the proposed CB design are graphically presented in terms of hydraulic head in Fig. 10.

The head contours indicated within the clay layer suggest a low vertical saturated hydraulic conductivity. Nevertheless, Fig. 10 shows that this condition is not observed in the sand base. This suggests that the sand layer shows no contribution for dissipating hydraulic head. The results from SEEP/W modelling indicated that no capillary barrier is formed under the climate conditions found at the site considering the proposed design. The adopted hypothetical CB final cover design, therefore, acts as a CCL cover instead of a proper capillary barrier. In addition, the results indicated an average percolation flux through the sand base equivalent to $38.7\,\mathrm{mm\,a^{-1}}$, which is consistent with the annual average flux obtained from the HELP modelling, equal to $35\,\mathrm{mm\,a^{-1}}$ (Table 2). It should be noticed that the flux of water across the CB was low as a consequence of the presence of the compacted clay layer and its hydraulic conductivity,

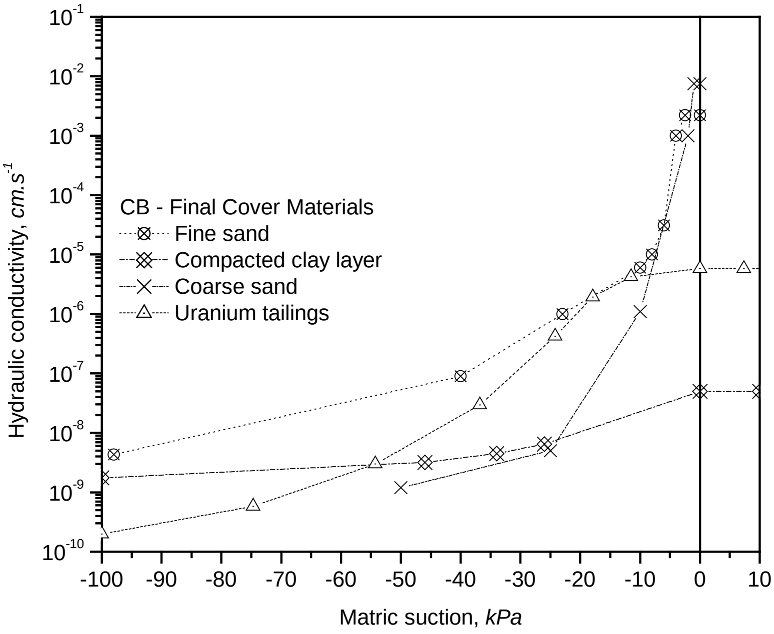

Fig. 9. Hydraulic conductivity functions utilised in the SEEP program for modelling unsaturated flow through the CB.

equivalent to 31.5 mm a^{-1}. Nevertheless, as it was observed in the results obtained from the HELP modelling for the CB design, during the dry months (i.e., from June to September) both hydraulic head and hydraulic gradients decrease. Thus, a favourable condition for the capillary barrier to work properly is suggested and this new scenario was investigated in a subsequent modelling. In this analysis the same finite elements mesh was used. The top boundary condition was set according to the annual average infiltration flux recorded from the HELP modelling for a dry year, equal to 100.4 mm a^{-1}. The remaining boundary conditions were maintained unaltered.

The results obtained from this analysis showed that even during the dry season the chosen CB design would not behave effectively as a capillary barrier. Flow modelling results indicated a flow of 29.4 mm a^{-1} percolating the cover but the sand base showed no contribution to dissipating hydraulic head. The graphical results were similar to the results previously presented in Fig. 10.

Accordingly, the adopted CB design showed no capillary barrier behaviour in both scenarios evaluated under the particular climate conditions of the studied site.

Many authors [8,9] agree that capillary barriers are generally considered plausible only in regions of arid and semi-arid climates. Nevertheless, this does not imply that capillary barrier designs should be totally discarded for the site of *Poços de Caldas* in future analyses.

A proposal is to increase the slope of the final cover in order to increase runoff and decrease water infiltration into the cover.

6. Radon exhalation modelling

6.1. Input Data

Table 3 shows the input data requested by the RADON program for the modelling of diffusion exhalation rates of ^{222}Rn across the compacted clay barrier of the hypothetical final covers.

In order to perform a conservative analysis the compacted clay layer was uniquely considered in the modelling. In addition, since thicknesses and material properties of the compacted clay layer are exactly the same for the three proposed final covers, the results are assumed to be the same for all designs evaluated in this work.

The porosity of the clay was the same as adopted in the HELP modelling. Gravimetric water content of the compacted clay varied from 0 to 30% with an increment of 5%. Since no field measurement of radon emanation coefficient was carried out a conservative value of 0.35 was assumed [10]. The relaxation length was also taken from the literature and is supposed equal to 200 cm, typical of uranium tailings impoundments [10].

Radon diffusion coefficients were calculated by the RADON program and varied as a function of both saturation degree and porosity values. The specific activities of ^{226}Ra in the tailings was set equal to 100 pCi g^{-1} and this value was obtained from previous field and laboratory measurements performed by Fernandes et al. [11]. Although small concentrations of radioactivity in soils are frequently present, the clay material of the cover was supposed to be free of any.

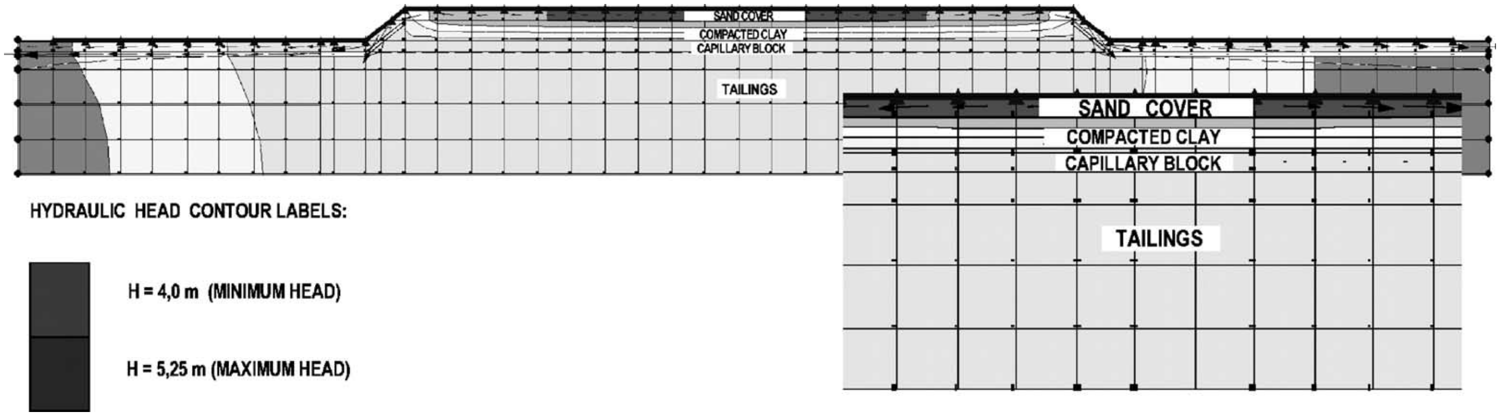

Fig. 10. Graphical representation of the hydraulic head contours within the compacted clay layer of the CB.

Table 3
Input data for the RADON model

Parameter	Uranium mill tailings	Compacted clay layer
Layer thickness (cm)	–	60
Porosity	0.30	0.445
Dry specific mass (g cm^{-3})	1.89	1.47
Specific activities of ^{226}Ra (pCi g^{-1})	100	0
Gravimetric water content (%)	10	0 to 30
Diffusion coefficient of^{222}Rn (cm^2 s^{-1})	4.67×10^{-3}	Function of gravimetric water content

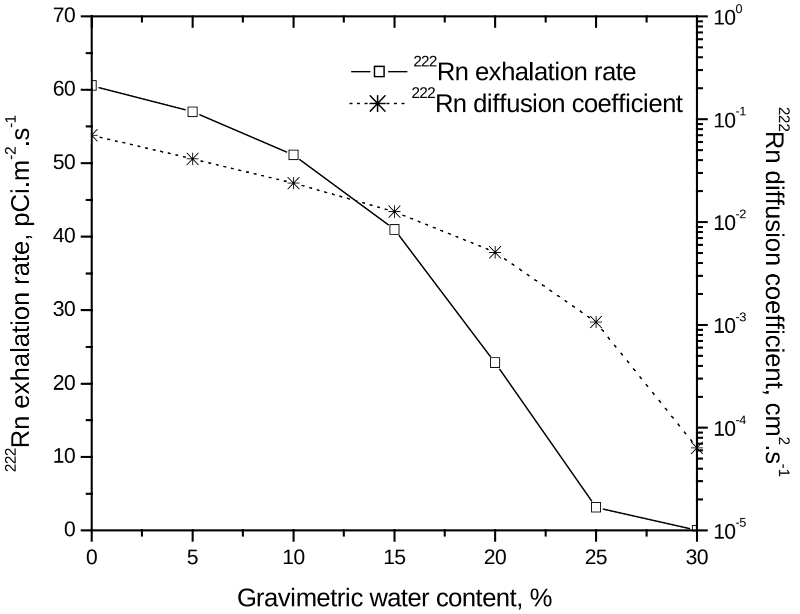

Fig. 11. Radon-222 exhalation rates as a result of the variation of the compacted clay layer (60 cm thickness) gravimetric moisture content.

6.2. Results and discussion

Fig. 11 shows the relationship between radon-222 exhalation rates, gravimetric water content and radon diffusion coefficient through the final cover.

Both exhalation rates and radon diffusion coefficient decrease with increasing water content of the compacted clay barrier. As it was observed, the ^{222}Rn exhalation flux limit of 20 pCi m^{-2} s^{-1} is only achieved when gravimetric water content of the compacted clay is equal to or higher than 21%. Below this value the radon exhalation rates can reach values twice or three times higher than the flux limit of 20 pCi m^{-2} s^{-1}. The ^{222}Rn diffusion coefficient through the compacted clay layer for gravimetric water content of 21% is approximately 5×10^{-4} cm^2 s^{-1}.

7. Conclusions

A computer-based method for evaluating final cover designs for the closure of uranium mill tailings impoundments has been used to model laboratory and field data.

(i) The results obtained from HELP modelling point out the importance of realising punctual analyses throughout the time when modelling final covers so to account climate variations that can get final covers to dry and fail due to soil desiccation and cracking.
(ii) Results obtained from HELP modelling suggest that, in the long-term, different covers showed distinct behaviours concerning potential to desiccation and cracking of the clay layers due to wet and dry cycles. The study of the CB clearly illustrate this fact since annual average results indicate that the cover was properly designed to tackle long-term wet–dry cycles, whereas monthly results show that the clay layer potential to desiccate and fail is considerably increased.
(iii) Results from HELP modelling of the CL showed that the very high efficiency of the system is predominantly caused by the geomembrane liner that separates hydrological environments in the drainage layer above from the compacted clay liner bellow.
(iv) For limiting ^{222}Rn exhalation rate of 20 pCi m^{-2} s^{-1} into the atmosphere, RADON modelling results indicated that gravimetric water content of the 60 cm clay

barrier should be either equal to or greater than 21%. This value corresponds to a degree of saturation of approximately 70% for the adopted clay material.

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