XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

UNSATURATED FLOW ANALYSIS FOR THE DESIGN OF A MULTILAYER BARRIER

ANALYSE D'INFILTRATION DANS UNE BARRIERE MULTICOUCHE

A. Lloret ***E.E. Alonso***

Department of Geotechnical Engineering
E.T.S. Ingenieros de Caminos, Universitat Politècnica de Catalunya
Barcelona, Spain

SYNOPSIS: An important element of a proposed scheme for the isolation of harmful wastes is a multilayer soil barrier exposed to the atmospheric environment on its upper surface. The imperviousness of the barrier is guaranteed by a compacted clay layer, extended over a drainage layer to control infiltration flows.The upper part is integrated by a top soil and biologic layer overlying a sand layer in direct contact with the upper boundary of the clay. All the layers are compacted "in situ" in an unsaturated state. An infiltration analysis of this barrier has been performed. Drainage outlets have been modelled by means of a simple and effective procedure involving the introduction of sink terms in the governing equation. A sensitivity analysis, in which several parameters of the barrier have been changed over an average reference case has been carried out. A relevant conclusion of the analysis is the independent behaviour of the upper and lower parts of the barrier. A simple procedure has also been proposed to compute the long term drainage flow rates and the response time of the clay layer.

INTRODUCTION

A proposed isolation scheme to protect hazardous wastes sealed in concrete structures, relies in the imperviousness of clay layers. A layer of 1 to 2 m thick of compacted low permeability clay may ensure very low infiltration flows over the years. In order to control the small inflow quantities, the compacted clay barrier is extended over a layer of pervious sand which, in turn, is placed against a plastic membrane which covers the concrete structure to be protected. It is also important to protect the clay barrier against environmental effects (wetting and drying cycles, rainfall erosion, frost penetration, privileged infiltration paths caused by vegetation or living animals, etc). A protective biologic layer should therefore be placed over the impervious clay. This layer will support, at the surface, a vegetation cover which will enhance evapotranspiration effects. It seems also appropriate to eliminate most of the infiltration waters before they reach the surface of the clay layer. One way to achieve this goal is to locate an intermediate sand layer connected to a drainage outlet between the protective upper layer and the clay barrier.

The preceding ideas lead to a multilayered barrier concept in which the different layers have widely different water retention characteristics and permeabilities. In addition, the materials are extended and compacted 'in situ' in an unsaturated state. The transient flow processes induced by infiltration waters is a key consideration in the design of the barrier and the selection of appropriate materials.

Fig. 1 shows a representative cross section of the lower end of a proposed multilayered barrier in which all the layers dip uniformly a small angle towards the collecting drain ditches. In this particular case two materials are distinguished within the protective upper layer: a surface organic layer which holds the vegetation and the protective biologic layer.

CONDITIONS AT DRAINS

The analysis reported in this paper has been performed with the program NOSAT. This program solves in a coupled way the simultaneous flow of water and air in an unsaturated soil (Alonso et al., 1988). NOSAT may simulate seepage boundaries. When a node belonging to this boundary reaches a water pressure equal to the atmospheric value, suction is specified as zero from then on.This numerical procedure was specifically designed to study the impoundment process in earthdams. In this case, the water pressures rises monotonically in the boundary nodes. If this is not the case the procedure may lead to errors. In addition, in order to obtain precise solutions the node separation along the surface should be relatively small compared with the expected length of the seepage surface. In the particular infiltration problem described here, the height

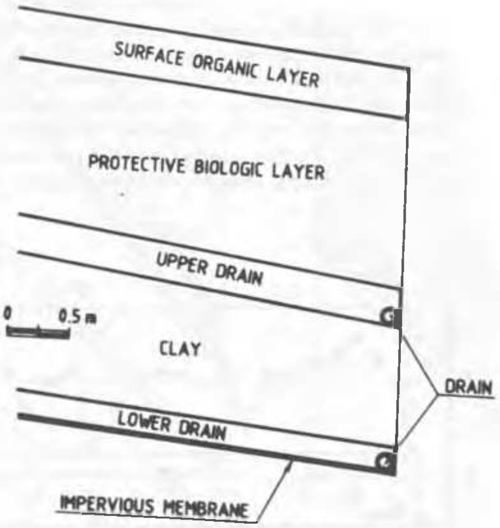

Fig.1. Cross section of multilayer barrier

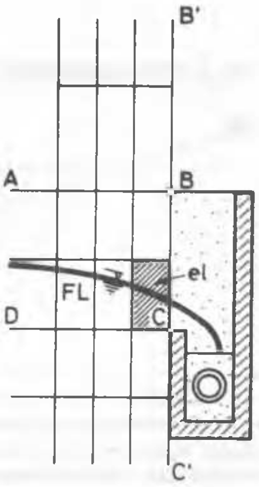

Fig.2. Outflow conditions at drains

of water in the drains (specially in the lower one) is very small, sometimes in the order of fraction of a centimeter. Extremely fine meshes would therefore be required to handle this situation.

An alternative formulation to the drainage process was therefore developed. The idea was to simulate the drained water as a sink term in the corresponding element. The condition to be satisfied is to guarantee that the nodes in the boundary sand-drain do not exhibit pore water pressures in excess of the atmospheric value.

In practice the following procedure is adopted: Consider (Fig. 2) a downstream boundary B'C' of the multilayer barrier. The sand layer is represented by ABCD. Also indicated in the figure is the finite element mesh and the phreatic line established in the sand layer. The boundary BC of the sand layer discharges into the tube drain represented in the figure. In the procedure a node is selected to specific the zero pore water pressure condition. A convenient choice for the case plotted in Fig. 2 is node C which belongs to the boundary element "*el*". Before the sand layer acts effectively as a drain node C will have a negative pore water pressure (Fig. 3). Calculation proceeds assuming that the boundary B'C' is impervious. As water infiltrates, the pressure in C will increase and eventually it will reach a zero value. A small tolerance ($p* = 1.5Pa$) has been established so that when $p_{wc} > p*$ the sink in the element *el* is activated. This occurs, for instance, when the water pressure in *C* reaches the value $p_{wc}^{(2)}$ (Fig. 3). The magnitude of the sink is controlled in the program to ensure that p_{wc} remains within the limits ± $p*$.

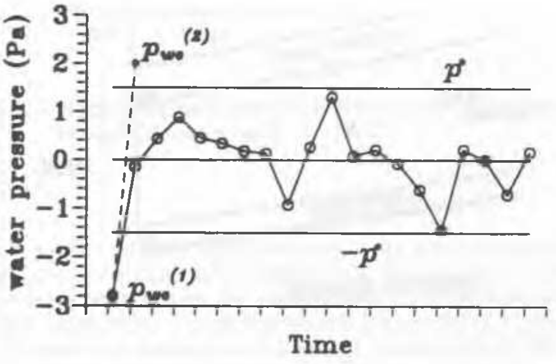

Fig.3. Evolution of pore water pressure at drainage node

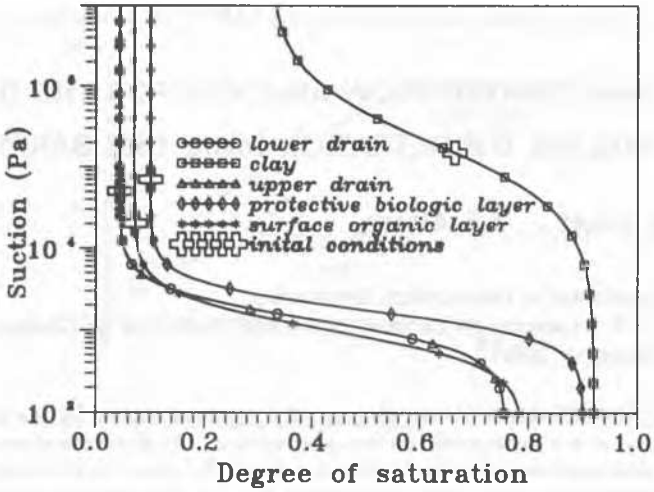

Fig.4. Water retention curves and initial conditions

MODELLING THE MULTILAYER BARRIER

The main soil properties which control the hydraulic behaviour of the multilayer structure are the water retention characteristics and the variation of permeability to water with degree of saturation or soil suction. Fig. 4 shows the water retention curves adopted for the four soils involved. Also indicated in the figure are the initial (as compacted) conditions. The curves show a reasonably well defined air entry value and a limiting irreducible degree of saturation. The materials are installed in a rather dry condition. The variation of permeability to water and degree of saturation are shown in Fig. 5. It is observed that the permeability drops substantially when the degree of saturation reaches values close to the irreducible state. On the other hand the permeability changes slowly for a wide range of values of S_r approaching satuation.

The geometry of the problem has been discretized by means of a finite element mesh. The left boundary corresponds to a symmetry axis and is considered impervious as well as the bottom boundary. On the surface a constant rate of infiltration ($Q_i = 10^{-8}$ m/s) has been assumed in all

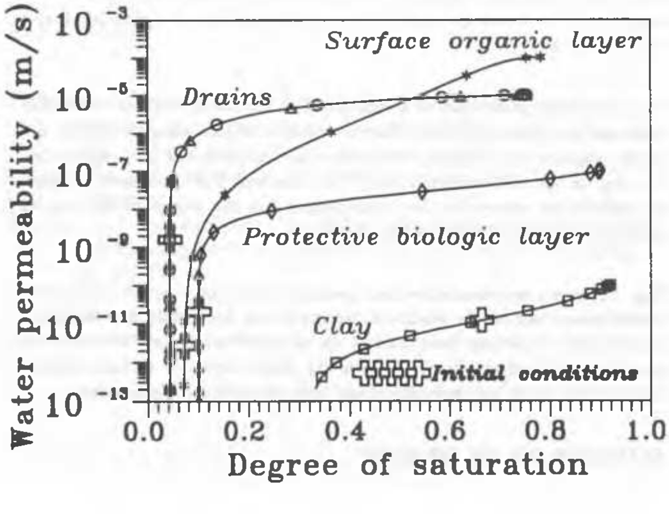

Fig.5. Permeability curves and initial conditions

cases. Downstream the boundary is also impervious except for the sand drains in which the condition described before has been implemented. To facilitate stability and convergence the size of the elements has been reduced in the proximity of the contact planes between materials of widely different permeability. The mesh had 364 four nodes lineal elements and 406 nodes.

Two important considerations in the design of the barrier are the long term flow drained through the clay layer and the time for the water to discharge through the lower drain. Fig. 6 provides this information for the particular problem described. Water first comes out of the lower drain 1789 days (4.9 yr) after the beginning of the infiltration. The computed flow rate is 0.27 l/day.m (for meter of horizontal length of the barrier). Water is drained through the upper drain 73 days after the beginning of the experiment and the flow rate is 21.43 l/day.m which is 98.5% of the total infiltration.

The assumed initial distribution of suction in the different layers (see also Figs. 4 or 5) is as follows: surface organic layer: 20kN/cm^2, protective biologic layer: 70 kN/m^2; sand layers: 50 kN/m^2; clay layer: 150 kN/m^2. A month later (Fig. 7a) important changes have taken place. The lower part of the clay layer maintains suctions close to their original values. Suction in the lower drain has increased due to the proximity of the clay. However suctions have been greatly reduced in the two upper layers. The maximum suction gradients are concentrated in the upper part of the clay layer where an infiltration front is progressing downwards. Eight and a half years later (Fig. 7 b) the infiltration process is in a steady state condition. Suctions have decreased to very low values and the circulation of water is quite regular: it is vertical in the "impervious" layers and subhorizontal in the sand layers.

SENSITIVITY ANALYSIS

In order to better understand the behaviour of the barrier, a sensitivity analysis has been carried out. Changes essentially affect the clay layer. Variations in its initial suction, permeability and thickness have been considered (Table 1). The initial suction has a direct relationship with the compaction water content. Cases (2) and (3), if compared with the reference case described above (case (1)), correspond to a drier compacted clay layer.

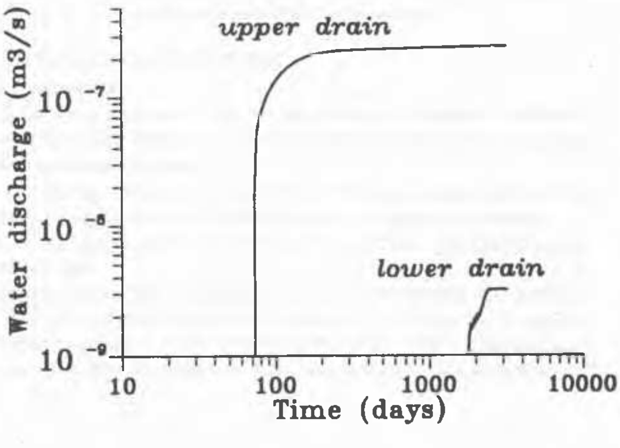

Fig.6. Discharge flows in upper and lower drains

Table 1. Results of sensitivity analysis

CASE DEFINITION	(a) t_u (d)	(b) t_l (d)	(c) Q_u (l/d.m)	(d) Q_l (l/d.m)	(e) Q_u/Q_i (%)	(f) Q_l/k_{wsat}
(1) REFERENCE (Described in the paper)	73.03	1788.9	21.43	0.27	98.66	1.25
(2) Lower initial clay suction (s_i=80 kN/m^2)	63.49	866.9	21.38	0.28	98.53	1.29
(3) Lower initial clay suction coarser biologic layer	21.63	859.7	21.41	0.27	98.66	1.25
(4) Clay thickness reduced in 0.5 m	73.62	930	21.38	0.32	98.53	1.48
(5) Lower clay permeability $k_{wsat} = 10^{-12}$ m/s	54.07	> 200 yrs	21.68	-	$\simeq$ 99.87	-
(6) Clay permeability and thickness reduced,(6)=(4)+(5)	54.07	> 100 yrs	21.68	-	$\simeq$ 99.87	-

Case (3) differs from case (2) in the water retention and permeability characteristics of the biologic layer. In (3) this layer is assumed to be coarser. Case (4) corresponds to an uniform reduction of the clay thickness in 0.5 m and case (5) corresponds to a reduction of two orders of magnitude of the permeability of the clay layer. Both changes define case (6). In Table 1 the exit time of water through the two drains ,upper and lower (t_u and t_l) and the flow rates (Q_u and Q_l) (steady state condition) have been indicated for each case (Columns (a) through (d)). In column (e) the ratio of Q_u to the infiltration rate (Q_i) has been indicated.

The results presented in Table 1 lead to several considerations:

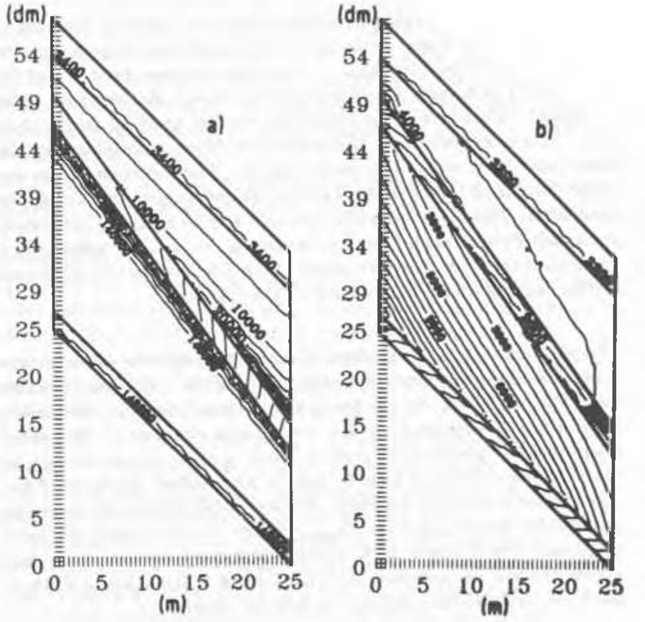

Fig.7. Suction map in Pa: a) t= 1 month; b) t= 8.7 years

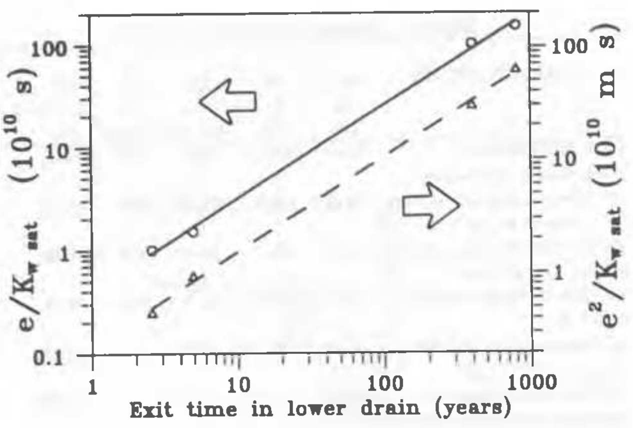

Fig.8. Relationship between exit time of water through lower drain, clay thickness and permeability

- The upper drain collects, in all cases, more than 98% of the infiltrating water (at long term). This is explained by the small flow drained through the lower drain which is a small fraction of the infiltration. This latter flow is directly related to the permeability of the clay and only marginally to other conditions.

- The multilayer barrier described is, in fact, a superposition of two systems, upper and lower, rather independent from each other. The upper systems is integrated by the first two layers and the upper drain and the lower one by the clay layer and the lower drain. This independence is manifested in a double sense: a lower thickness of the clay layer or a different initial suction does not affect the behaviour of the upper drain (flow rate, time to drain liquid water). On the other hand, a change in water retention properties of the biologic layer does not modify the flow through the lower drain (compare cases 2 and 3).

- The last column in Table 1 indicates the ratio between the steady state flow of the lower drain (per unit length) and the saturated permeability of the clay k_{wsat}. This dimensionless ratio would be essentially 1 in a vertically directed flow under a unit gradient. The computed values indicate a long term vertical gradient larger than one. This is explained by the positive suctions maintained by the lower sand layer at the clay-sand contact. These suction values are somewhat larger than the samll suction values computed in the upper sand layer. This result provides a simple way to compute the steady state unit flow through the clay barrier: $Q = i\ k_{wsat}$, where i is a gradient larger than one but smaller than 1.5, irrespective of several factors, among them the thickness of the clay layer.

- The exit time of the first drop of water through the lower drains depends on many factors: the permeability of the clay layer, its water retention properties, its thickness and its intial suction. The latter dependence is explained by the strong nonlinearities of the water retention and permeability curves. For a given initial suction of the clay, the computed time t_l may be represented in terms of the clay thickness and permeability. Natural combinations of these two parameters are e/k_{wsat} or e^2/k_{wsat}, where e is the mean clay layer thickness. Fig 8 shows such a plot which may be used, as a first approximation, to estimate the time for the water coming through the lower drain in the analysed multilayer barrier.

CONCLUSIONS

This paper presents the methodology and results of a study of unsaturated flow through a multilayer barrier of soils of widely different permeability and water retention characteristics. A novel feature of the procedure is a simple and effective way of modelling the behaviour of drains by means of sink terms. Some computed results of a proposed multilayer barrier under a constant infiltration at the surface have been presented. This case serves as a basic model for a sensitivity analysis performed. The main results of this analysis have also been discussed. Relevant conclusions are:

- The particular design of multilayer barrier described may be conceptually treated as a superposition of two independent systems.

- The long term infiltration flow through the clay barrier depends only on its saturated permeability. A simple procedure to compute the infiltrated water has been proposed. It implies that the long term overall vertical gradient in the clay is somewhat larger than 1 due to the maintained positive suctions in the lower sand layer.

- The time response of the clay layer depends on its pemeability and water retention characteristics, its thickness and initial suction. It is not therefore amenable to be described in simple terms. For a given type of variation of permeability and water content with suction and for a given initial suction, a relationship between clay thickness, saturated permeability and time to drain liquid water through the drain has been obtained as a simple and rough guide.

ACKNOWLEDGEMENTS

The support provided by the *Agence Nationale pour la gestion des déchets radioactifs* de France (ANDRA) is gratefully acknowledged.

REFERENCES

Alonso, A., Batlle, F., Gens, A. and Lloret, A. (1988). Consolidation analysis of partially saturated soils. Application to earth dam construction. *Numerical Methods in Geomechanics.* G. Swoboda ed. pp. 1303-1308. Balkema.