ESTIMATING THE DRAWDOWN OF LEACHATE IN A SATURATED LANDFILL: 3D MODELING BASED ON FIELD PUMPING TESTS

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SUMMARY: In this paper, the question of leachate pumping in a saturated landfill is addressed. In order to optimise the pumping strategy, a methodology based on field pumping tests and numerical simulation is presented. The classical methods of Theis and Cooper-Jacob are used to analyse the pumping tests. It leads to an assessment of the average values of the hydraulic conductivity and the storage coefficient of the waste body. Visual Modflow-Surfact is then used to simulate pumping operations in complex 3D landfill cells. It also enables to develop pumping abacuses that can be used as decision tools in order to define the optimum pump locations and pumping flow rates with respect to the drawdown objectives. Finally, in order to evaluate the limitations of the 3D numerical model, the delayed flow phenomenon is approached based on a theoretical study of leachate flow in the unsaturated zone.

1. INTRODUCTION

Modern sanitary landfills are designed to have a double barrier (passive + active) at their base. This barrier includes an underdrain system which collects leachate at the lower point of the cell where it is evacuated by gravity (buried pipes) or by forced purge (buried pumps) depending on the geometry of the cells and the situation of the storage / treatment ponds. In the short run, this system is sufficient to prevent the building up of an hydraulic head exceeding the thickness of the drainage layer. However, as a result of pipe failure or biotic / mineral clogging of underdrains with time, leachate may progressively accumulate in the landfill. This could potentially represent serious implications in terms of emissions to the ground, gas recovery and slope stability (for cells elevated above the ground surface). Moreover, although it still has to be confirmed, the process of waste biodegradation may finally result in the release of great quantities of leachate due to the diminution of its water retention capacity, an important part of the water (constitutive / adsorbed) being retained by organic matter.

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As a matter of fact, whatever type of landfill installation is concerned (closed / in operation, unlined / lined), one finds that the extraction of leachate generated by the storage of waste may become a difficult task for landfill owners facing unexpected environmental and economic issues (lack of post-closure provisions). In order to prevent such problems, it is therefore important to be able to control the flow of water entering landfill cells both during operation and post-closure care periods (Marcoux et al., 2009). But the problem is complex: if excess water entails significant quantities of leachate to be treated, an insufficient recharge may leave the waste in a dry state, incompatible with the objective of its bio-stabilization within the scope of one generation (30 years).

Now, once a leachate mound develops in the cell, its drawdown is generally difficult to achieve because of the low hydraulic conductivity of the waste which can dramatically decrease reaching values as low as 10^{-7}m/s or even less due to loading effects (compression from the overlying waste and the cap cover) and time (combined effects of ravelling and clogging).

In order to respond to this issue, a methodology involving field pumping tests and numerical simulations is presented, further continuing research works conducted by Oweis et al. (1990), Rowe and Nadarajah (1996), Cossu et al. (1997), Joseph (1997), Giardi (1997) and Al-Thani et al. (2004).

2. STUDY CASE: A LANDFILL CELL SUBJECT TO LEACHATE SATURATION AS A RESULT OF UNDER-DRAIN CLOGGING

2.1 Description of the experimental landfill cell

Established in northern France, the landfill cell that has been investigated extends over 4 hectares with an average depth of 16 m. Equipped with an impermeable barrier at the base (clay + geomembrane), the cell operated from 2001-2003 received a mixture of industrial and commercial waste (52 %), household waste (32 %), sewage sludge (8 %) and inerts (8 %) compacted using a 30 tons sheepfoot compactor. The final cover comprising a non-sealed synthetic liner added to clay and organic soil layers was placed 2 years after the end of cell operation which resulted in the infiltration of large quantities of rain water into the cell. Moreover, the leachate could not be collected by gravity due to rapid clogging of the leachate drainage layer at the bottom of the cell.

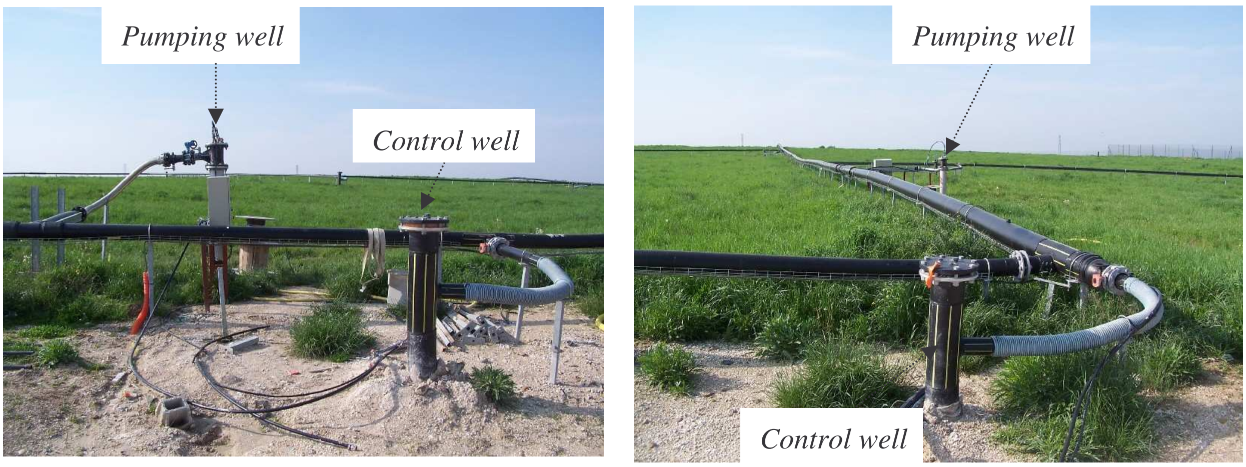

Figure 1. Associated pumping and control wells on the experimental cell.

In order to remedy the situation, two biogas wells were equipped with leachate pumps placed at the lower points of the cell (Figure 1). Immediately before the pumping tests carried out in 2008 (i.e. 5 to 7 years after the placement of waste), the leachate levels in the cell, as indicated by the 16 control wells regularly monitored, suggested that a continuous leachate layer had developed over 10 to 12 m from the base of the cell, that is more than half of its height.

2.2 Modus operandi and details of the pumping tests

The measurement of leachate head in a cell is not sufficient to determine the volume of leachate that can be extracted from the waste. It depends indeed on the storage coefficient and the hydraulic conductivity of the waste. In order to evaluate those parameters, pumping tests can be implemented.

On the experimental site described earlier, pumping tests were conducted in 2008. They consisted in monitoring simultaneously the flow of leachate extracted from pumping wells and the drawdown of leachate level in the control wells (used as piezometers). Six tests were conducted using two pumping wells and three control wells located between 5 and 18 m from the pumping wells. After a rapid determination of the optimal pumping rate (0.4 – 0.6 m^3/hour), tests were undertaken including the monitoring of leachate levels every 2 minutes during the first 60 minutes, then every 5 minutes for 5 hours.

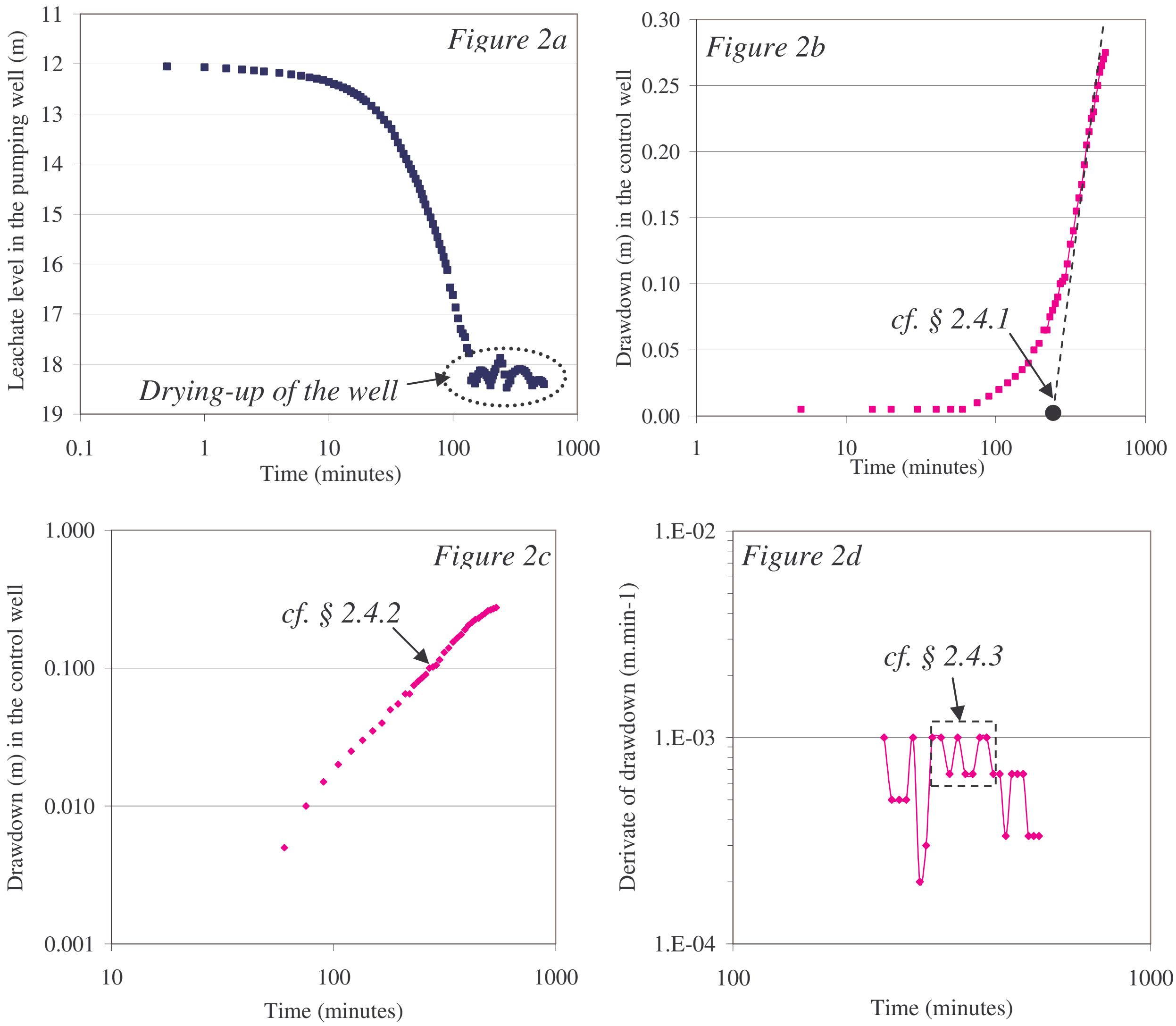

Figure 2. Experimental results from pumping tests (2a: pumping well; 2b/c/d: control wells).

For each test, four graphs were plotted in order to analyze the data, as described in Figure 2:

- Evolution of the leachate level versus time in the pumping well (on semi-log scale): Figure 2a
- Evolution of leachate drawdown versus time in the control well (on semi-log scale): Figure 2b
- Evolution of leachate drawdown versus time in the control well (on log-log scale): Figure 2c
- Evolution of leachate drawdown derivatives in the control well (on log-log scale): Figure 2d

2.3 Hydro-dynamic parameters controlling the accumulation of leachate in waste

The circulation of leachate in the waste depends primarily on 2 hydrodynamic parameters, namely:

- the hydraulic conductivity (Kin $m.s^{-1}$) which is also expressed in terms of transmissivity (T in $m^2.s^{-1}$) (in § 2.4) where T = K*H (H: leachate level in the waste mass);
- the storage coefficient (S), which reflects the volume of voids really essential to the circulation of leachate.

The hydraulic conductivity (K) is defined as the ratio of the flow of fluid (volume flow rate per unit area) by the hydraulic gradient. In saturated conditions, it is a constant appearing in the classical Darcy's law (1856). The mode of placement and compaction of the waste lifts induce some degree of anisotropy in the material (horizontal stratification). As a result, most of the fluid transfers from the surface to the bottom of a cell develop along sub-horizontal plans connected by vertical short circuits. This anisotropy results in an horizontal hydraulic conductivity (K_h), generally 2 to 10 times greater than the vertical hydraulic conductivity (K_v) (Powrie and Beaven, 1999).

The storage coefficient (S) (unitless) represents the ratio of the volume of water released or stored per unit surface area to the variation of the hydraulic level. Irrespective of the specific storage (S_s) of the leachate (volume of water removed per unit volume of aquifer per unit decline of hydraulic head in saturated conditions), S (sometimes also refered as S_y in the literature) is equivalent to the drainage porosity (n_d) also called “effective porosity” or “cinematic porosity”.

When trying to modelize the drawdown of landfill cells, one can accurately represent the geometrical characteristics of the cell. On the other hand, hydrodynamic parameters K and S are characterized by a relatively high uncertainty. Indeed, for practical reasons, their adjustments from pumping tests are limited to a few monitoring points (control wells or piezometers). Consequently, K and S parameters represent mean values, not accounting for the vertical variability of waste hydraulic properties, nor stochastic distribution associated to the waste heterogeneity. Yet, laboratory studies [Powrie and Beaven (1999), Olivier et al. (2007)] have shown that K and S parameters tend to decrease with increasing load (or depth). This decrease results from the collapse of the structure of the waste as a result of the high pressure applied on the material as well as the migration of fines through the structure (fine particles produced by the disintegration of larger particles as a result of biodegradation). A realistic representation of the characteristics of the waste requires the consideration of this phenomenon by analogy with laboratory results. However, the effect of waste heterogeneities on K and S distribution are not considered in this study.

2.4 Determination of average hydraulic properties of waste by means of field pumping tests: principles and methods

Theis (1935) first developed the analytic expression representing the flow of groundwater towards a fully penetrating well in a transient regime in the presence of an homogeneous, isotropic and unlimited aquifer, limited by impermeable bedrock and roof. Theis has shown that the general equation of the hydraulic head could be expressed (in polar coordinates):

$$\frac{\partial h}{\partial r^2} + \left(\frac{1}{r}\right).\left(\frac{\partial h}{\partial r}\right) = \left(\frac{S}{T}\right).\left(\frac{\partial h}{\partial t}\right) \qquad [1]$$

with the boundary conditions: $h = h_0$ at initial time (t = 0) and $h \to h_0$ when $r \to \infty$.

The mathematical resolution of the equation [1] gives the expression of the drawdown (s) in a piezometer located at a distance (r) from the pumping wells:

$$s = \frac{Q}{4\pi.T} \int_u^\infty \frac{e^{-u}}{u}.du = \frac{Q}{4\pi.T}.W(u) \qquad [2]$$

$$\text{where: } u = \frac{r^2.S}{4.T.t} \qquad [3]$$

and the “Theis well function" given by the tables:

$$W(u) = -0{,}577216 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{2.2!} - \frac{u^4}{2.2!} + \ldots \qquad [4]$$

2.4.1 Determination of T and S parameters using the Cooper-Jacob method (1950)

Cooper and Jacob (1950) found that for small values of r and large values of t, u (equation [3]) becomes very small so that the series expansion of the well function can be approximated by $W(u) = -0{,}5772 - \ln u$ (provided u <0.1). After rearrangement of equation [2], one gets the following approximate expression:

$$s = \frac{0{,}183.Q}{T}.\log\frac{2{,}25.T.t}{r^2.S} \qquad [5]$$

One can therefore plot (s) as a function of the logarithm of time which, in the conditions of application of Jacob’s solution simplifies as a linear equation $s = c.\log t + t_0$ where the slope of the drawdown (c) during a logarithmic module and the abscissa to the origin (t_0) comply with:

$$c = \frac{\Delta s}{\Delta t} = \frac{0{,}183.Q}{T} \quad [6] \qquad \text{and} \qquad t_0 = \frac{r^2.S}{2{,}25.T} \quad [7]$$

that is:

$$T = \frac{0{,}183.Q}{c} \quad [8] \qquad \text{and} \qquad S = \frac{2{,}25.T.t_0}{r^2} \quad [9]$$

When several piezometers are available, it is interesting to plot every curve on one single graph as one should get in theory a family of parallel lines of similar slope c (equation [6]). Once solved [8] and [9], equation [5] can also determine the radius of influence of pumping wells (distance from which s = 0):

$$R = 1{,}5.\sqrt{\frac{T.t}{S}} \qquad [10]$$

This radius increases with time following a parabolic law and the rate of enlargement of the cone of drawdown decreases proportionally to $1/\sqrt{t}$. Considering the hydrodynamic properties of the waste material in the example presented earlier (§ 2.), a constant pumping rate of $Q = 0.42 m^3/h$ for instance induces a catchment area equivalent to a circle of radius 13 m after 6 hours of pumping, 26 m after 24 h of pumping or 69 m after 1 week of continuous pumping.

Finally, the formula of Cooper and Jacob may also be applied after termination of pumping tests during the recovery of the leachate layer, provided that it is fast enough to be monitored. It provides a fairly reliable estimate of transmitivity. Let t' be the time counted from the end of pumping, the leachate recovery (building up) equation is:

$$s' = \frac{0{,}183.Q}{T}.\log\frac{t+t'}{t'} \qquad [11]$$

2.4.2 Determination of T and S parameters using the Theis graphical method

From [2] and [3], on gets respectively:

$$\log(s) = \log\left(W(u)\right) + \log\left(\frac{Q}{4\pi T}\right) \qquad [12]$$

and

$$\log(t) = \log\left(\frac{1}{u}\right) - \log\left(\frac{4T}{r^2.S}\right) \qquad [13]$$

Using equation [4], one can plot W(u) as a function of (1/u) on a bilogarithmic paper, i.e. on gets log(W(u) versus log (1/u). We then plot for each piezometer the experimental curves of log(s) as a function of log(t) on a transparent paper (again on a bi-logarithmic scale). Lastly, by superimposition of the two papers so as to make the two curves coincide, it follows that:

- The axis of the abscissas is shifted vertically by a quantity equal to $\log(\frac{Q}{4\pi T})$;
- The axis of the ordinates is shifted horizontally by a quantity equal to $\log\left(\frac{4T}{r^2.S}\right)$.

One can therefore select a point anywhere along the experimental curve and note the values of its coordinates along both abscissas / ordonates axis to finally get:

$$T = 0{,}08.Q.\frac{W(u)}{s_A} \quad [14] \quad \text{and} \quad S = 4.\frac{T.t_A}{r^2.(1/u)} \quad [15]$$

In this way, hydraulic properties of the waste materials are derived from each piezometer. It is not recommended to apply the method to the pumping well itself as pumping tends to modify the porosity of the ground near the well whereas the high velocities of fluid percolation cause losses of local head (turbulent flow).

Also, Theis formulas assume that the radius of the wells is negligible. Obviously, this is not the case and therefore at the beginning of pumping, a substantial part of the flow is directly taken from the well without having percolated through the waste. This “capacity effect” modifies abnormally the beginning of the the curve. Accordingly, the duration of pumping should be long enough to exceed the effect of the well capacity (minimum 2 logarithm cycles).

2.4.3 Contribution of the differential analysis for validating Cooper-Jacob and Theis graphical methods.

Parks and Bentley (1996) have proposed a so-called “derivation technique” method that makes possible the isolation of parts of pumping tests for which the drawdown curve (versus time) satisfies the assumptions made by Theis regarding infinite radial fluid movements.

Although relatively unknown, this method is susceptible to validate (or reject) S and T values derived from the methods of Cooper-Jacob (§ 2.4.1) and Theis (§ 2.4.2), both methods potentially presenting multiple solutions. In particular, it helps to highlight the phenomena of capacitance (accumulation of leachate in the well and surrounding gravels) that can distort the beginning of pumping curves or the occurrence of parasitic effects related to the presence of impermeable lateral limits or singular waste layers (characterized by a non-representative behaviour). The derivation curve D=f(t), which represents the rate of the drawdown on bi-logarithmic scale, equals:

$$D(t+\Delta t)=\frac{\log[s(t+\Delta t)]-\log[s(t)]}{\log(t+\Delta t)-\log(t)} \qquad [16]$$

2.5 Calibration of hydraulic parameters from laboratory tests

2.5.1 Calibration of average values of K and S parameters

Using both the Cooper-Jacob and the Theis graphical method with the constraint proposed by Parks and Bentley, average values derived from field pumping tests were found to be as follows: $K \cong K_h = 2.8*10^{-6}$ m.s^{-1} and $S \cong n_d = 0.8$ %. When compared to other values published in the literature for similar levels of compression (desaturated zone: 80 – 150 kPa), the present value for K appears in the same order of magnitude (Table 1). On the other hand, the storage coefficient (0.8 %) is significantly lower compared to the n_d value derived from laboratory experiments. The difference can be explained primarily by the duration of the pumping tests (6 hours) in comparison to 1 week drainage (until complete stabilization) for laboratory tests conducted by Powrie and Beaven (1999), Olivier and Gourc (2007) and Olivier et al. (2007).

Table 1. Comparison of K and S values derived from pumping tests with literature data

Parameter	Waste material (type)	Loading (kPa)	K (m.s^{-1})	S (or n_d) (%)
Field tests	Industrial / commercial waste + household waste	80 – 150	$2.8*10^{-6}$	0.8
Powrie and Beaven (1999)	Fresh raw household waste	87 – 165	$3.1*10^{-6}$ to $8.2*10^{-5}$	6.5 to 12.5
Olivier and Gourc (2007)	Degraded reconstituted household waste	130	$5*10^{-6}$ to 10^{-5}	2.4 to 2.9
Olivier et al. (2007)	Pretreated degraded household waste	80 – 130	$1.2*10^{-7}$ up to $2.7*10^{-7}$	1.5 to 2.5

Moreover, for a waste layer of 0.6-0.7 m thickness, the porosity evaluated after 6 hours of drainage (identical to field tests) was evaluated as one third of the effective (or ultimate) drainage porosity calculated after complete end of percolation (Olivier and Gourc, 2007) (including delayed flow phenomenon). Consequently, as a first approach, the storage coefficient derived from field measurements was multiplied by a factor of 3, hence giving an average value of 2.4 %.

2.4.2 Distribution of K and S parameters versus depth

The distribution of the horizontal hydraulic conductivity (K) versus depth (or similarly versus the overburden pressure) can be evaluated using functions proposed in the literature. It offers different distribution curves following power and exponential laws. Presently, a power law was considered, as follows:

$$K(z) = \alpha \cdot z^{-\beta} \qquad [17]$$

where α and β are constants (not detailed here as each calibration is site-specific).

The second parameter (S) is badly documented in the literature, in particular if a large range of load has to be considered. In order to override this limitation, a permeability – porosity relationship known as the Kozeny-Carman equation, has been used [Kozeny (1927), Carman (1937)]. Applicable to laminar flows in saturated granular media, it states that the hydraulic conductivity can be estimated as a function of the storage coefficient (S), the dynamic viscosity of the fluid (η) and the average diameter of material particles (D), as follows:

$$K = \alpha \cdot \frac{S^3}{(1-S)^2} \cdot \frac{1}{\eta} \cdot D^2 \qquad \text{with } \alpha = \text{constant} \qquad [18]$$

If one makes the assumptions that the waste is almost fully saturated below the leachate table and that (η) and (D) do not vary very significantly versus depth, on gets at a given level (z) from the top of the waste body:

$$K(z) = A \cdot \frac{S(z)^3}{[1-S(z)]^2} \qquad \text{with } A = \frac{\alpha \cdot D^2}{\eta} = \text{constant} \qquad [19]$$

Finally, equation [19] is equivalent to the following third degree equation: $A * S^3 - K * S^2 + 2 * K \cdot S = K$. Its resolution, although complex, was made possible using Cardano's method.

3. MODELING LEACHATE DRAWDOWN WITH A 3D NUMERICAL MODEL (MODFLOW-SURFACT)

3.1 Introduction

In the presence of landfill cells of complex geometry, the simulation of waste fluid pumping requires the use of a three-dimensional transient numerical model. In this context, the U.S. Agency for the Environment (EPA, 2000) suggests the use of such models for that matter when pumps are located at a distance inferior or equal to d_{lim} from an hydrogeological limit:

$$d_{\lim} = 2\sqrt{K_h / K_v} * H \qquad [17]$$

where K_h and K_v are the horizontal and vertical hydraulic conductivity of the waste and H the piezometric height (saturated height). A quick calculation considering H = 10 m and a ratio K_h/K_v of between 2 and 10 gives a distance $d_{\lim}$ of between 28 and 65 m. In practice, a 3D numerical modeling is required whenever pumps are located close to the edge of landfill cells.

3.2 Description of Modflow-Surfact model

Several commercial software exist, usually based on the finite element method (Feflow, Simuscopp) or finite difference methods (Modflow, Modflow-surfact). Provided a prior calibration of hydrodynamic parameters of waste material is undertaken by means of pumping tests, they can help to anticipate conditions of drainage through repeated pumping. Currently, Modflow-Surfact which is integrated into the Visual Modflow 3D interface was used to simulate the drainage of the experimental cell.

3.2.1 Principle of Modflow-Surfact model

The Modflow Surfact model is one of the most successful hydrodynamic models to date (Al-Thani et al., 2004) and as such is incorporated into a number of commercial softwares like Visual Modflow.

The general equation controlling fluid flow in Modflow Surfact model is the equation of Richards (1931). It was obtained by combining:

- The continuity equation (expressing the conservation of mass);
- The dynamic equations (generalized Darcy law);
- The equations of state (assuming an isothermal flow of incompressible fluid at constant density).

The 3D calculation domain representing the waste body is meshed with parallelepipedic elements. The non-linearities of the Richards law are taken into account using a fixed point iterative method. A local mesh refinement can be performed near the pumping wells in order to describe accurately the drawdown cone around the well. Finally, if an effective drainage of the waste is expected, calculations shall be carried out in conditions of transient flow rather than in conditions of steady flow. Otherwise, if the objective is only to maintain a certain piezometric level in the waste in the presence of percolation through the cap cover of the landfill cell, one should refer to the practical method proposed by Rowe et al. (1996) before undertaking modelisation works.

3.2.2 Parameters of the model

The model is governed by 4 sets of parameters:

- <u>Geometric parameters</u>: surface and height of waste, presence of lateral boundaries.
- <u>Transfer parameters (input-output flows)</u>: intensity of recharge water, type and number of wells, leachate extraction flow rates.
- <u>Hydro-physical parameters in the saturated zone</u>: piezometric height, storage coefficient, hydraulic conductivity.
- <u>Hydro-physical parameters in the unsaturated zone</u>: although Van Genuchten model (1980) is integrated into Visual Modflow, its application in the context of our study has proved to bring drastic convergence problems. It appeared more reasonable to apply the so-called Pseudo-Soil

model that corresponds to the following assumptions: no flow in the unsaturated zone, constant K_v value and a linear decrease of K_h on the cells located at the interface between the saturated and unsaturated zones. An over-weighting of S value following laboratory adjustments (§ 2.5.1) has been applied to take into account delayed flows.

3.3 Estimation of the key output parameters: pumping duration, volume and remaining height versus the number of wells and the selected flow discharge.

Using the hydraulic parameters derived from the pumping tests, the numerical calculation gave a satisfactory description of the pumping operation in the landfill cell presented in § 2.1. More generally, it can be used to design pumping schemes for any given landfill cell. Figure 3 presents an example of calculation based on a realistic 3D geometry including an internal embankment. Even if a rigorous optimisation of the location of pumping wells is not carried out, this kind of simulation can help to compare different engineering solutions. For a given pumping flow rate, the radius of influence is clearly put in evidence (Figure 3.b). Thus, the duration of each pumping stage (before drying-up of the well) may be evaluated.

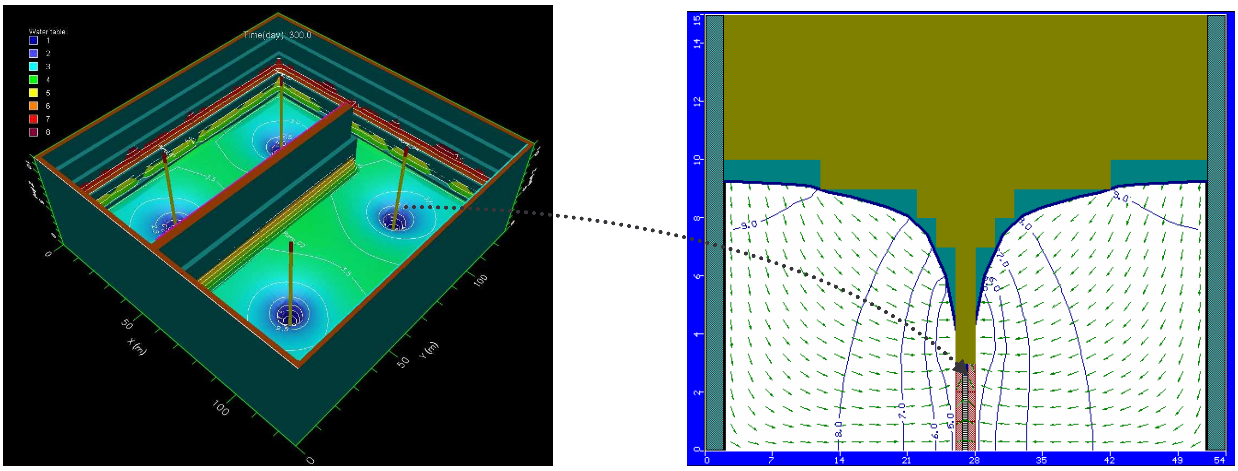

Figure 3. (a) Modeling the evolution of the leachate head using Visual Modflow 3D (Modflow-Surface flow model). (b) Flow directions (arrows) and hydraulic equipotential lines during a pumping exercice.

Another example of efficient use of Modflow-Surface numerical tool is the development of pumping abacuses (Figure 4) [Mugnier (2007), Olivier (2008)] that make possible a rapid evaluation of the efficiency of a pumping strategy in a saturated landfill. A simplified square-shaped domain with a centered pumping well was considered as a first approach. The abacuses are used to summarize a complete set of numerical simulations realised in a large range of variation of physical properties such as the height of the waste body, the initial height of the water table and the hydraulic properties (K and S) referred to as type 1, 2, 3 and 4 in Figure 4.a. The range of these hydraulic parameters was defined arbitrarily after compilation of the literature data (Mugnier, 2007) in order to cover all types of waste material potentially landfilled. As a matter:

- the composition of the waste stored;
- the possible pretreatment of the waste prior to landfilling;
- the intensity of compaction;
- the age of the waste material.

A set of abacuses is composed of three graphs used successively following three steps, as follows:

- Step 1 (Figure 4.a): evaluation of the duration of pumping versus the pumping discharge
- Step 2 (Figure 4.b): evaluation of the volume of leachate extracted
- Step 3 (Figure 4.c): evaluation of the remaining leachate height (after stabilization following a resting period in order to remove the pumping cone)
- And back to Step 1 for a second iteration and then possibly a third one,… until satisfactory drainage of the leachate.

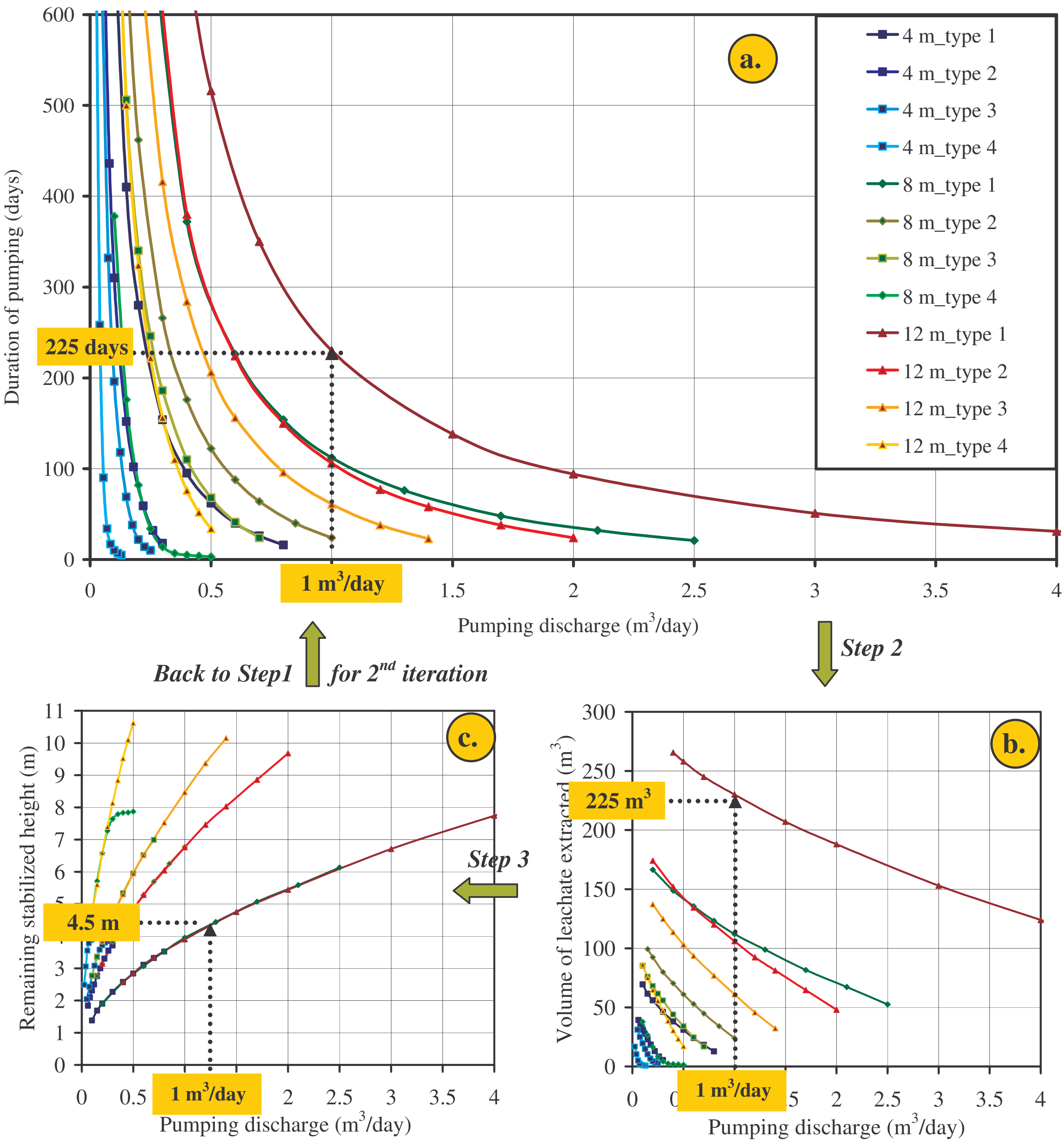

Figure 4. Example of abacuses developed using Modflow-Surfact (Study case: width = 50 m * 50 m; pumping well centered at the middle of the domain; initial level of saturation: 4, 8 or 12 m; other parameters: waste height + type of waste: unpublished).

4. QUALITATIVE ASSESSMENT OF THE DELAYED FLOW: INFLUENCE OF CAPILLARY EFFECTS

The pumping simulations using Visual Modflow are suitable to describe the experimental results of pumping tests and could be a useful tool to define pumping strategies in complex 3D cell geometries. However, the validity of the pseudo-soil flow model should be discussed. In this model, the effect of capillarity is neglected: It is only taken into account through the effective drainage porosity that exhibits a very low value ($n_d < 5\%$). It is significantly lower than the water content of saturated MSW even if a substantial part of this water is trapped in unconnected pores (irreductible water content). In this section, the problem of unsatured flow is simulated in a simplified 1D geometry in order to illustrate the phenomenon of delayed flow. This could be achieved by considering the the capillary effects that influence the water distribution in the waste during a pumping operation (Oxarango, 2008).

4.1 1D capillary flow model and simulation tool

The unsaturated flow is described with the classical Richard's equation. This relation between the volumetric water content θ and the suction Ψ (with $\Psi = P_{liquid} - P_{gas}$ in Pa) reads as follows:

$$\begin{cases} \dfrac{\partial \theta}{\partial t} + \dfrac{\partial}{\partial z}\left[-K_s . kr_l(\theta) \left(\dfrac{\partial \Psi}{\partial z} + \rho g \right) \right] = 0 \\ \theta = f(\Psi) \end{cases} \qquad [18]$$

where K_s is the saturated permeability ($m.s^{-1}$), kr_l is the relative permeability to liquid, ρ is the liquid density ($kg.m^{-3}$), g is the gravity ($m.s^{-2}$) and z is the elevation (m).

In order to close this mathematical problem, a retention curve *f* is required. The classical Van Genuchten model is used to describe the suction/saturation relationship:

$$S_e = \frac{\theta}{n_0} = \left(1 + (\alpha \Psi)^{1/(1-m)}\right)^{-m} \qquad [19]$$

where S_e is the effective saturation of the medium, n_0 is the total open porosity and α and m are the fitting parameters.

Finally, the relative permeability function is modelled using the Van Genuchten-Mualem relation:

$$kr_l(S_e) = S_e^{1/2}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \qquad [20]$$

The boundary conditions associated with the one-dimensional vertical domain are a no-flux condition at the top and an imposed flux q at the bottom in order to model the pumping operation. This pumping condition corresponds to a flux through a unit surface located at the bottom of the 1D domain. One has to keep in mind that this model situation is not fully representative of the fluid flow in the vadose zone created during a real 3D pumping operation. However, it is suitable to illustrate the effect of capillarity in dynamic conditions. In this paper, two pumping fluxes are presented.

Initially, the water content (and thus the suction and pressure head) distribution above the chosen position on top of the saturated zone satisfies the capillarity/gravity equilibrium. The problem is solved using a dedicated software developed in the laboratory. It is based on a finite volume discretization of order 2 in space and time. The non-linearity of equation [19] is treated with a semi-implicit fixed point method. A very refined mesh with 5 000 nodes is used in order to insure a good numerical stability and an accurate water balance.

4.2 Simulation: domain and parameters

The parameters used in the simulations are summarised in Table 2. The domain size and initial height of the water table have been selected arbitrarily in order to be characteristic of a landfill dimension. The total open porosity (n_o) and the parameter of the Van Genuchten-Mualem relation have been deduced from the retention curves presented by Stoltz et al. (2007). This experiment was carried out on a drilled domestic waste compressed up to 200 kPa in an oedometric cell. The permeability at saturation was imposed arbitrarily. One should note that the capillarity effects become more sensitive as the permeability decreases. The pumping fluxes are selected to illustrate the effect of capillarity and remain small in order to ensure a good numerical stability.

Table 2. Parameters for the 1D simulation of water table drawdown with capillary effects

Parameter	Symbol	Values
Domain Height	H (m)	10
Initial height of the water table	H_w (m)	5
Permeability	K_s ($m.s^{-1}$)	10^{-6}
Total open Porosity	n_0	0.15 (15 %)
Van Genuchten parameter	α (m^{-1})	10
Van Genuchten parameter	m	0.33
Pumping flux	q ($m.s^{-1}$)	Low: 5.10^{-9} High: 5.10^{-8}

The Figure 5 presents the evolution of the moisture content spatial distribution with time. On Figures 5.a and 5.b, the evolutions of the moisture distributions exhibit significant variations according to the flow rate. For the low flow rate, the drawdown is operated in quasi-static conditions (the saturation decreasing under 0.45 in the vadose zone).

On the other hand, a large fraction of the mobile water is abandoned in the waste body at the high flow rate (the saturation hardly decreasing under 0.6 in such case). This effect is closely linked to the strong non-linearity of the relative permeability with the moisture content. Once the water table reaches the bottom of the domain, the pumping is stopped and the relaxation of the moisture content distribution can be studied (Figures 5.c and 5.d). In the case of low flow rate, the equilibrium level only rises up to 0.7 m while it rises up to 2.2 m for a high flow rate. This relaxation corresponds to a movement of the moisture driven by gravity from the pores that can not insure a capillary entrapment towards the saturated zone.

The monitoring of the water table level speaks for itself (Figure 5.e and 5.f). During the drawdown phase, the water table level H_w exhibits a linear trend versus time. This behaviour should also be obtained using the Pseudo-Soil model. However, the slope of this curve is linked with the pumping flux. If the data are analysed using the so-called drainage porosity (as defined in § 2.3), the dependency of this parameter n_d with the imposed flow rate must then be considered. Even if the total open porosity and the retention curve are kept constant, the drainage porosity varies from 0.057 (5.7 %) for the high flow rate to 0.09 (9%) for the low flow rate in the example presented here. On should note that the relaxation time is of the same order of magnitude as the drawdown time. However, this relaxation lasts longer in the case of high flow rate since the moisture distribution obtained at the end of the pumping operation is farther than the gravity/capillary equilibrium.

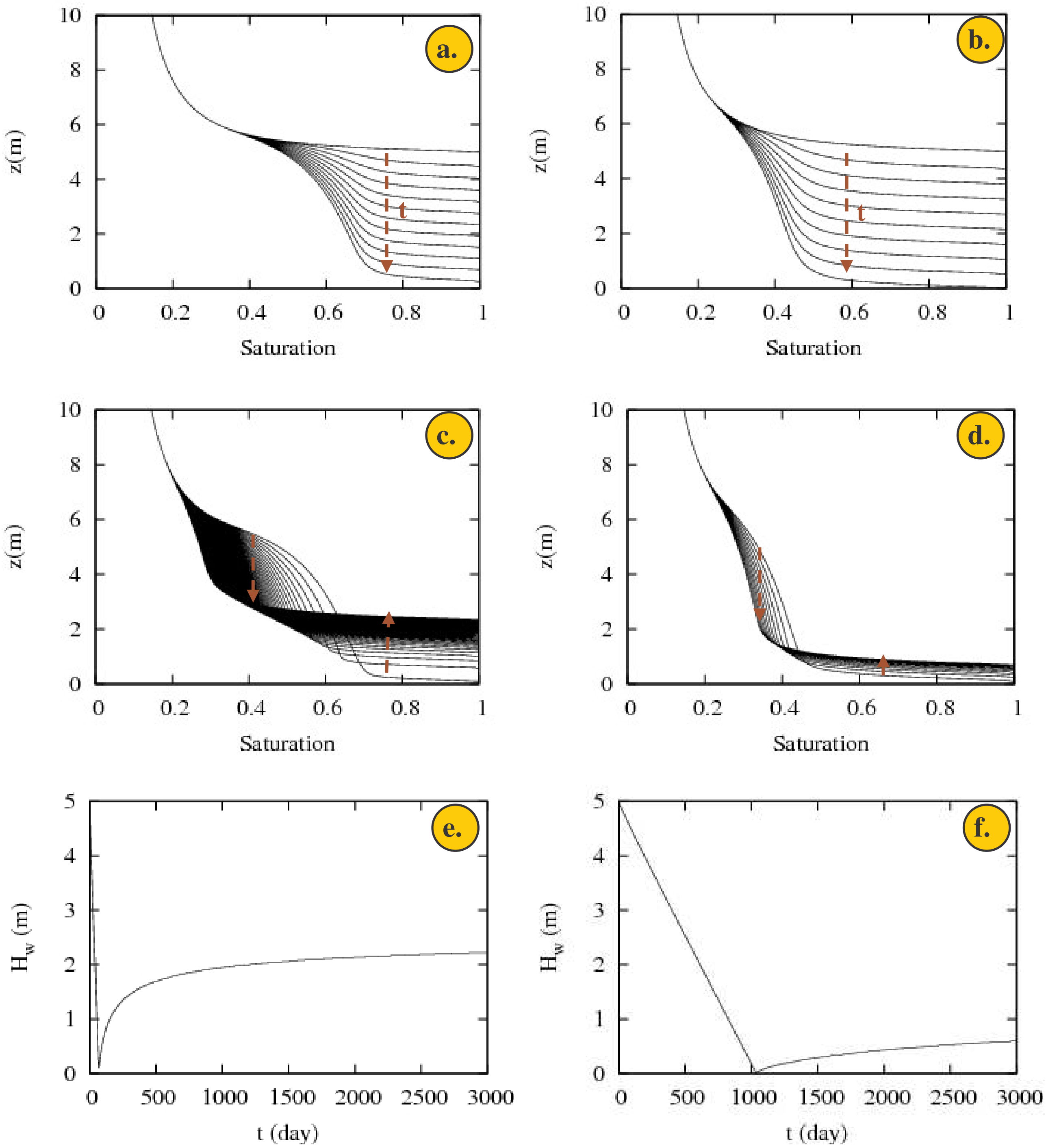

Figure 5. Influence of the pumping flux on the moisture distribution [High pumping flux (a, c, e) - Low pumping flux (b, d, f)] [Pumping phase (a, b) - Relaxation phase (c, d) - Water table level versus time (e, f)].

7. CONCLUSIONS

In this paper, the issue of leachate accumulation has been addressed from the point of view of its drainage, by means of immerged pumps. The implementation of pumping tests monitored with piezometers seems to provide useful information regarding the hydraulic parameters of saturated waste materials. The analysis based on the Theis and Cooper Jacob models is used to evaluate the drainage porosity and the hydraulic conductivity of the medium. In order to define a pumping strategy at the scale of a landfill cell, these parameters may be used through 3D flow models such as Modflow-Surfact. This leads to a straightforward evaluation of the duration of drawdown and the volume of leachate pumped with respect to the pumping rate for instance. This tool can be used to take into account complex cell configurations and to optimize the set up of pumping wells. It was also used to develop pumping abacuses providing a simple engineering tool to evaluate the efficiency of a pumping strategy before its implementation. The entrapment of leachate in the waste associated with capillary effects should however be considered with great care. Since the relative permeability of waste material is highly non linear, the drainage porosity exhibits a significant dependency on the pumping flow rate. This phenomenon can lead to a dramatic over-estimation of the effective drawdown. A complementary study of pumping tests taking into account the capillary effects is proposed in order to improve the evaluation of the drainage porosity.

Finally, it is possible to develop a rigorous strategy in order to drain saturated landfill cells, thus making possible the modulation of the number of pumps and the leachate pumping discharge according to the operating constraints. As such, the sooner one sets up a pumping strategy, the better it will be.

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