Behaviour of Lining Systems on Waste Landfills Slopes: An Experimental Approach

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ABSTRACT: Lining systems are more and more used to provide an environmental protection to the industrial and domestic waste disposals. The behaviour of such lining systems can be critical during their installation and the placement of waste. First measurements from an experimental site are described. Two lining systems, HDPE geomembrane and bentonite membrane were installed in experimental cells with slope of 1/2 and 1/1 (vertical/horizontal). As the experimental program is still in work only information on displacements and behaviour of a bentonite membrane with its protective layer is available and discussed.

1 INTRODUCTION

Recently the French regulation for industrial waste disposals has been reviewed. The use of geosynthetics as an active security to facilitate the drainage is now enforced by law. The regulation for domestic waste disposal will probably be reviewed with a similar approach. Lining systems will be installed more and more in the next years. The behaviour of these lining systems on slope is of a great importance to be well known in order they remain as an active security. Design must involve the installation which can be a critical phase and the service conditions. Design deals with mechanical behaviour, stability on slope and interaction with waste. This paper describes an experimental site on which different lining systems were instrumented to monitor their displacements on slope and by calculation strain as well as the tensile anchorage forces on top. The results will be used as far as possible to improve the French design methods of the lining systems on slope.

2 EXPERIMENTATION

The experimentation described in this paper is a part of a more complete research program performed by a French waste management company CGEA-ONYX with public laboratories CEMAGREF (Antony), Ponts et Chaussées (LRPC Nancy) and University of Grenoble (IRIGM) at the experimental site Montreuil s/ Barse. Several publications are available on this project (Le Tellier et al., 1993).

2.1 The lining systems

Four lining systems are tested in four waste cells of identical geometry. Two of them were instrumented to study their behaviour on slope in the experimental cells. Two slopes were constructed in each cell : 1/1 and 1/2 (vertical/horizontal).

In the cell using an HDPE geomembrane the protective layer will be a layer of used tyres filled with a silty sand of the site placed as the cell is filled with waste (Fig.1)

In the cell using a bentonite membrane the protective layer was installed in the same time as the membrane in order to confine the bentonite. On the 1/2 slope a 0.30 m thick layer of calcareous gravel was used while on the 1/1 slope ; the silty sand was used with a geosynthetic alveolar structure to confine it on the slope (Fig.1).

2.2 Instrumentation to monitor the displacements

Lining systems (Fig.1) were instrumented to assess their behaviour during their placement and the filling with

2 LEAKAGE RATE EVALUATION

2.1 Equations for leakage rate evaluation

Geomembrane liner. As shown by Giroud and Bonaparte (1989a), the rate of leakage through a geomembrane liner due to geomembrane permeability is negligible compared to the rate of leakage through defects in the geomembrane. Consequently, only leakage through defects is considered herein. As proposed by Giroud (1984), Bernoulli's equation for free flow through an orifice can be used to evaluate the rate of leakage through a defect in a geomembrane overlain and underlain by a very permeable medium:

$$Q = 0.6\ a\ \sqrt{2gh} \tag{1}$$

where: Q = leakage rate; a = defect area; g = acceleration of gravity; and h = hydraulic head on top of the geomembrane.

Equation 1 can only be used if the flow through the geomembrane defect is free, i.e., is not impeded by the materials in contact with the geomembrane. This condition is met if the average opening size, O_{avg}, of the material in contact with the geomembrane is greater than the diameter, d_d, of the geomembrane defect:

$$O_{avg} > d_d \tag{2}$$

In the case of soils, the following relationship exists:

$$k \approx 10^3 \text{ to } 10^4\ d_{avg}^2 \tag{3}$$

where: k = hydraulic conductivity of the soil; and d_{avg} = average diameter of soil particles. In Equation 3, often referred to as Hazen's equation, k is in m/s and d_{avg} in m.

In typical soils, the average opening size is approximately one third of the average particle size:

$$O_{avg} \approx d_{avg}/3 \tag{4}$$

Combining Equations 2, 3 and 4 gives:

$$k > 10^4 \text{ to } 10^5\ d_d^2 \approx 10^4 \text{ to } 10^5\ a \tag{5}$$

where: a = defect area in m^2.

Although it was demonstrated for soils, Equation 5 is considered to be applicable to any permeable medium with a hydraulic conductivity k. Therefore, free flow conditions are ensured and Equation 1 is valid if the hydraulic conductivity of the media (e.g., soil, geonet) in contact with the geomembrane is greater than 10^{-1} to 1 m/s if a = 0.1 cm^2 (10^{-5} m^2) and greater than 1 to 10 m/s if a = 1 cm^2 (10^{-4} m^2).

Soil liner. The rate of leakage through a soil liner can be evaluated using Darcy's equation (Darcy, 1856):

$$Q/A = ki = k(1 + h/D) \tag{6}$$

where: A = surface area of the soil liner; k = hydraulic conductivity of the soil; i = hydraulic gradient; h = hydraulic head on top of the liner; and D = thickness of the soil liner. (Note: Hydraulic conductivity is also called "coefficient of permeability" and soils with a small hydraulic conductivity are generally referred to as "low-permeability soils".)

Composite liner. A composite liner is composed of two components: a geomembrane and a layer of low-permeability soil. Herein, the geomembrane is assumed to be on top of the low-permeability soil component, which can be a compacted soil layer or a geoclay.

Based on studies presented by Giroud and Bonaparte (1989b), the following equations were established by Giroud et al. (1989) for the evaluation of the rate of leakage through a defect in the geomembrane component of a composite liner. These equations depend on the quality of contact between the geomembrane and the underlying soil:

$$Q = 0.21\ a^{0.1}\ h^{0.9}\ k^{0.74} \text{ (for good contact)} \tag{7}$$

$$Q = 1.15\ a^{0.1}\ h^{0.9}\ k^{0.74} \text{ (for poor contact)} \tag{8}$$

Equations 7 and 8 must be used with the following units: Q (m^3/s), a (m^2), h (m), and k (m/s). These equations are valid if the hydraulic head above the geomembrane is less than the thickness of the soil component of the composite liner (i.e., $h < D$); therefore, these equations are not applicable to composite liners where the low-permeability soil component is a geoclay (since D, in this case, is very small: typically 6 mm). Also, Equations 7 and 8 are valid only if the hydraulic conductivity, k, of the soil component of the composite liner is less than 10^{-6} m/s, according to Giroud et al. (1989).

In the case where the lower component of the composite liner is a compacted soil layer, good and poor contact conditions were defined by Giroud and Bonaparte (1989b), and described as follows by Bonaparte et al. (1989) and Giroud et al. (1992):

- Good contact conditions correspond to a geomembrane installed, with as few wrinkles as possible, on top of a low-permeability soil layer that has been adequately compacted and has a smooth surface.
- Poor contact conditions correspond to a geomembrane that has been installed with a certain number of wrinkles, and/or placed on a low-permeability soil that has not been well compacted and does not appear smooth.

Good contact conditions are assumed in all the parametric studies presented herein because it is believed that such conditions can be achieved with proper construction and strict quality assurance.

If the head of liquid above the geomembrane is greater than the thickness of the soil component of the composite liner, the following equations established by Giroud et al. (1992) can be used to evaluate the rate of leakage through a geomembrane defect:

$$Q = 0.21\ i_{avg}\ a^{0.1}\ h^{0.9}\ k^{0.74}\ \text{(for good contact)} \quad (9)$$

$$Q = 1.15\ i_{avg}\ a^{0.1}\ h^{0.9}\ k^{0.74}\ \text{(for poor contact)} \quad (10)$$

where i_{avg} is a dimensionless factor given in Fig. 1. Equations 9 and 10 must be used with the following units: Q (m^3/s), a (m^2), h (m), and k (m/s). Fig. 1 shows that $i_{avg} = 1$ if $h < D$; therefore, increasing the soil component thickness beyond D = h (hydraulic head) does not decrease the calculated rate of leakage through a composite liner.

Equations 9 and 10 are used in the case of liquid impoundments, canals, and dams, where the hydraulic head is large. In the case of landfills, Equation 9 is used if the low-permeability soil component of the composite liner is a geoclay, because the thickness of this material (typically 6 mm) is generally less than the hydraulic head on top of the liner. In this case, good contact conditions can be considered because: (i) geoclay panels have a smooth surface; and (ii) when bentonite hydrates, it swells which presses the geoclay against the geomembrane.

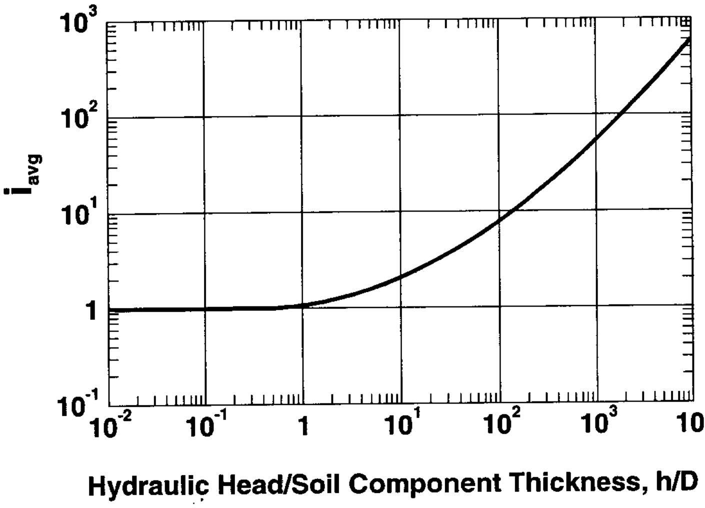

Fig. 1 Value of i_{avg} .

In the case of Equations 7, 8, 9 and 10, the liquid first passes through the defect in the geomembrane, then flows laterally some distance between the geomembrane and the underlying low-permeability soil, and, finally, migrates into and eventually through the low-permeability soil. The quality of contact between the geomembrane and the soil governs the amount of lateral flow, hence the difference between Equations 7 and 8, and 9 and 10. Lateral flow would be eliminated in the case of perfect contact between the geomembrane and the soil. Perfect contact does not exist in the case of usual landfill composite liners, as indicated by Giroud and Bonaparte (1989b), but may exist if a low-permeability soil is deposited as a slurry on top of a geomembrane and consolidates with time under a large compressive stress. In this case, the rate of leakage through a geomembrane defect can be evaluated using an equation established by Forchheimer (1930):

$$Q = 4\ r\ h\ k = 4\ h\ k\ \sqrt{a/\pi} \quad (11)$$

where: r = radius of the geomembrane defect.

Equation 11 may be used as a basis to evaluate the typical composite liners used in landfills. Fig. 2 shows that the rate of leakage through a typical composite liner consisting of a geomembrane on a layer of compacted soil with a hydraulic conductivity of 10^{-9} m/s is approximately 1000 to 3000 times greater than the rate of leakage through the same geomembrane defect if the geomembrane were in perfect contact with the soil. It should not be concluded that composite liners are not effective. In fact, although they are not as effective as they could be if the geomembrane/soil contact were perfect, composite liners used in landfills are far more effective than other liners, as shown in Section 3.

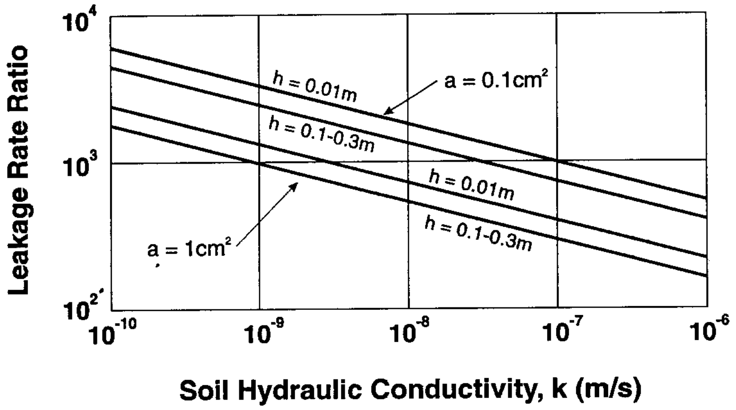

Fig. 2 Ratio between rates of leakage through a composite liner and a geomembrane in perfect contact with soil. (In both cases, the geomembrane has the same defect and is underlain by the same soil.)

2.2 Geomembrane defect size and frequency

Studies presented by Giroud and Bonaparte (1989a) have shown that geomembrane liners installed with strict construction quality assurance could be considered having a frequency of one to two defects per 4000 m^2

with a diameter of 2 mm (i.e., a defect area of 3.14 x 10^{-6} m^2). For the sake of simplicity, a frequency of one defect per 4000 m^2 is considered with a defect area of 0.1 cm^2 (10^{-5} m^2) for liner performance evaluation and a defect area of 1 cm^2 for conservative design.

Electric leak detection surveys (Laine, 1991) have shown that geomembrane liners installed with strict construction quality assurance have five or more defects per 4000 m^2 with a defect diameter less than 0.5 mm. For such defects where the diameter is less than the thickness of the geomembrane, Equations 1, 7, 8, 9 and 10 may not be valid. However, using Equations 1 and 7 for the sake of comparison shows that, in the case of 5 defects having a diameter of 0.5 mm, the rate of leakage is approximately 10 times less with a geomembrane alone and 3 times more with a composite liner than in the case of one defect having an area of 0.1 cm^2. These factors of 1/10 and 3 may be used to modify the rates of leakage presented in Section 3 which were established for one 0.1 cm^2 defect per 4000 m^2.

2.3 Graph for leakage rate evaluation

Equations 7, 8, 9 and 10 for composite liners are complex and a graph is useful for rapid leakage rate evaluation and to visualize the influence of parameters. Fig. 3 gives the leakage rate in m^3/s for one defect and the leakage rate per unit area in liters/hectare per day (lphd) assuming one defect per 4000 m^2. The linear portions of the curves were obtained using Equation 7, which is valid for $k < 10^{-6}$ m/s, according to Giroud et al. (1989). The non-linear portion of each curve was graphically interpolated between the end of the linear portion, which occurs for $k = 10^{-6}$ m/s, and the maximum value obtained using Equation 1, which is valid for large values of the hydraulic conductivity of the underlying medium. The non-linear portion of the curves reach the maximum value for $k = 10^{-1}$ m/s if $a = 0.1$ cm^2 and $k = 1$ m/s if $a = 1$ cm^2, as indicated in Section 2.1 after Equation 5.

Fig. 3 shows that when Equation 7 is valid (i.e., for $k < 10^{-6}$ m/s), the size of the geomembrane defect is not a significant parameter. The same would be true for Equations 8, 9 and 10.

3 COMPARISON OF LINERS

3.1 Leakage rate values

Leakage rates per unit area calculated using the equations presented in Section 2.1 are presented in Table 1, which shows that composite liners are significantly more effective than liners made with only one material.

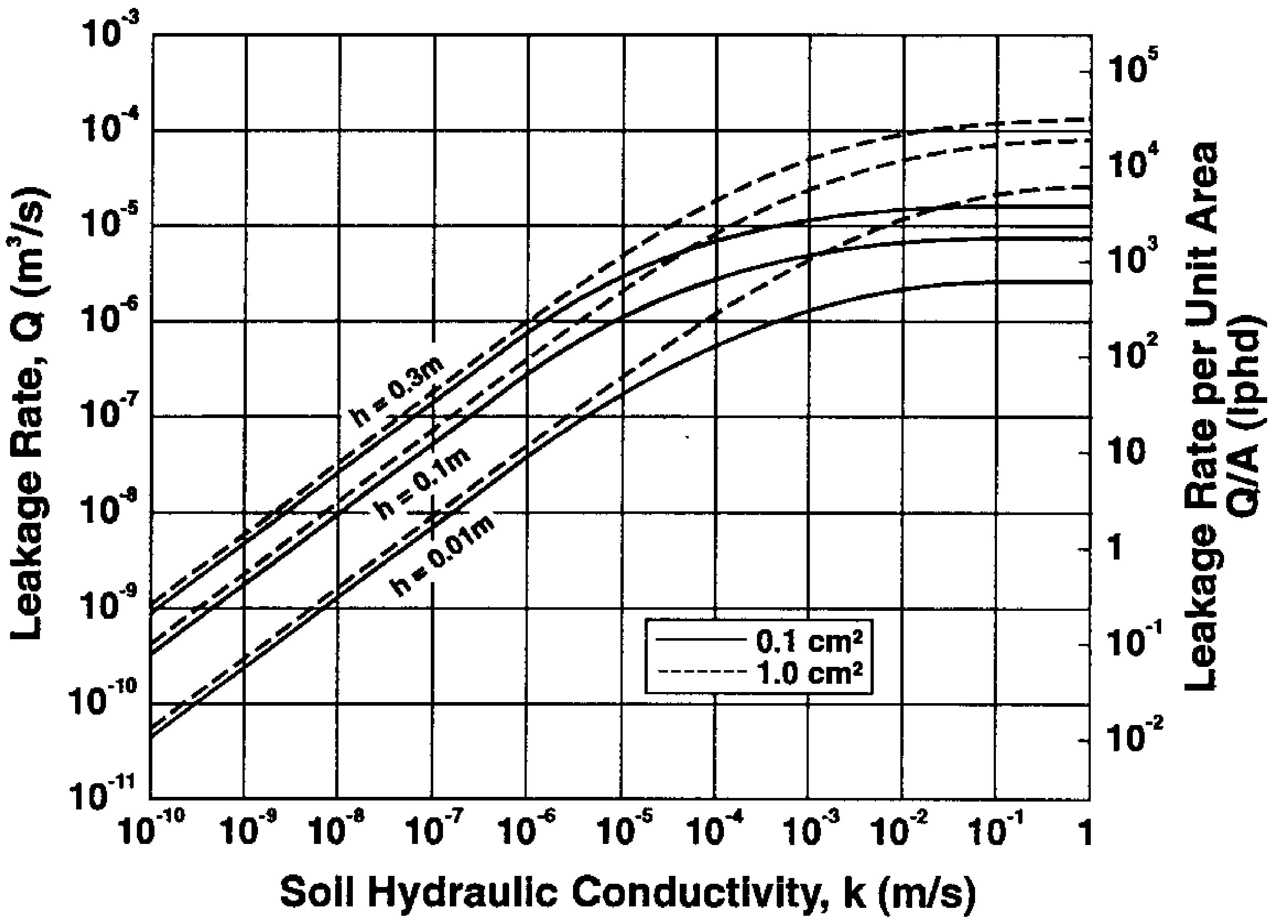

Fig. 3 Rate of leakage through a composite liner for good contact conditions. Values should be multiplied by 5.5 for poor contact conditions, as shown by dividing Equation 8 by Equation 7. If h > D, the above values should be multiplied by i_{avg} given in Fig. 1.

Table 1. Leakage rate per unit area in liters per hectare per day (lphd)[(a)] through various types of liners.

Liner Type	Soil Hydraulic Conductivity k (m/s)	Hydraulic Head, h (m)			
		0.01	0.03	0.1	0.3
Soil (b)	10^{-7} 10^{-8} 10^{-9}	90000 9000 900	90000 9000 900	100000 10000 1000	150000 15000 1500
Geomembrane (c)	$>10^{-2}$	600	1000	2000	3000
Geomembrane on Semi-Permeable Medium (d)	10^{-3} 10^{-4} 10^{-5} 10^{-6}	300 100 40 10	500 250 100 20	1100 600 200 60	2000 1400 600 150
Geoclay (e)	10^{-11}	25	50	150	450
Composite Liner with Compacted Soil Layer (f)	10^{-7} 10^{-8} 10^{-9}	1.5 0.3 0.05	4 0.7 0.15	12 2 0.4	30 6 1
Composite Liner with Geoclay (g)	10^{-11}	0.002	0.008	0.04	0.2

(a) 1 lphd ≈ 10^{-12} m/s ≈ 0.1 gpad (gallons/acre/day).
(b) Equation 6 with $0.3 < D < 0.9$ m.
(c) Equation 1 with 1 defect/4000 m^2 having an area $a = 0.1$ cm^2.
(d) Interpolated between Equations 1 and 7 using Fig. 3 for $a = 0.1$ cm^2.
(e) Equation 6 with D = 6 mm.
(f) Equation 7 (for good contact) with 1 defect/4000 m^2 having an area $a = 0.1$ cm^2. In the case of poor contact conditions, leakage rates have to be multiplied by 5.5, as shown by dividing Equation 8 by Equation 7.
(g) Equation 9 with 1 defect/4000 m^2 with an area $a = 0.1$ cm^2.

3.2 Comparison between geomembrane and soil liners

Fig. 4, established using Equations 1 and 6, gives the ratio between the rates of leakage through a compacted soil liner (CSL) and a geomembrane (GM). The soil liner has a thickness, D, ranging from 0.3 to 0.9 m. The geomembrane has one defect per 4000 m². Two defect sizes are considered: $a = 0.1$ cm² and $a = 1$ cm². The geomembrane is assumed to be on a very permeable material; therefore, free flow conditions are ensured and Equation 1 is applicable (see Section 2.1 after Equation 5).

Fig. 4 shows that a geomembrane with one 0.1 cm² defect per 4000 m² is equivalent to a compacted soil liner with a hydraulic conductivity of 10^{-9} m/s. However, the comparison presented in Fig. 4 is only valid if the entire liner (whether it is geomembrane or compacted soil) is exposed to the liquid. This condition is approximately met by the primary liner in a landfill, but is not met by the secondary liner in a double-lined landfill. The secondary liner is exposed in only limited areas to the very small amount of liquid that leaks through the primary liner. All or most of this liquid would percolate into and through a secondary liner made of compacted soil, whereas most or all of the liquid would not encounter the defects of a geomembrane secondary liner and, therefore, would not leak through a geomembrane secondary liner. Clearly a geomembrane secondary liner is far superior to a compacted soil secondary liner.

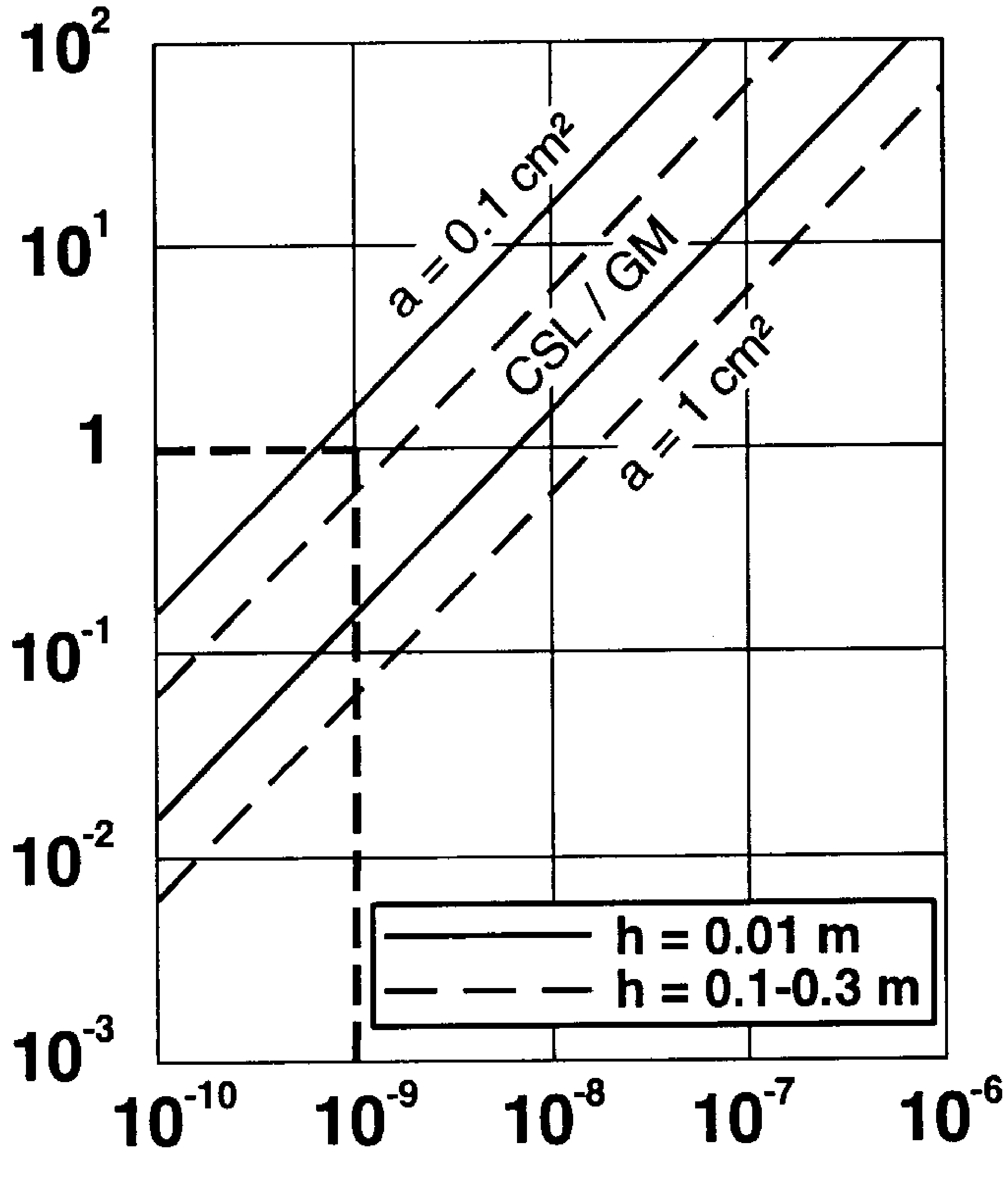

Fig. 4 Comparison between a geomembrane liner and compacted soil liners.

3.3 Evaluation of composite liners

In Fig. 5, established using Equations 1, 6 and 7, two types of curves provide comparisons involving composite liners:

- Curves (1) give the ratio between the rates of leakage through two liners: (i) the first liner is either a compacted clay liner (CCL) with $k = 10^{-9}$ m/s or a geomembrane (GM) placed on a permeable soil (these two liners being equivalent as shown in Section 3.2); and (ii) the second liner is a composite liner with a soil component having a hydraulic conductivity k (GM + CSL). The geomembrane, whether it is used alone or as a component of a composite liner, has one 0.1 cm² defect per 4000 m².
- Curves (2) give the ratio between the rates of leakage through a compacted soil liner with a hydraulic conductivity k (CSL) and a composite liner made with a geomembrane placed on the same compacted soil liner (GM + CSL).

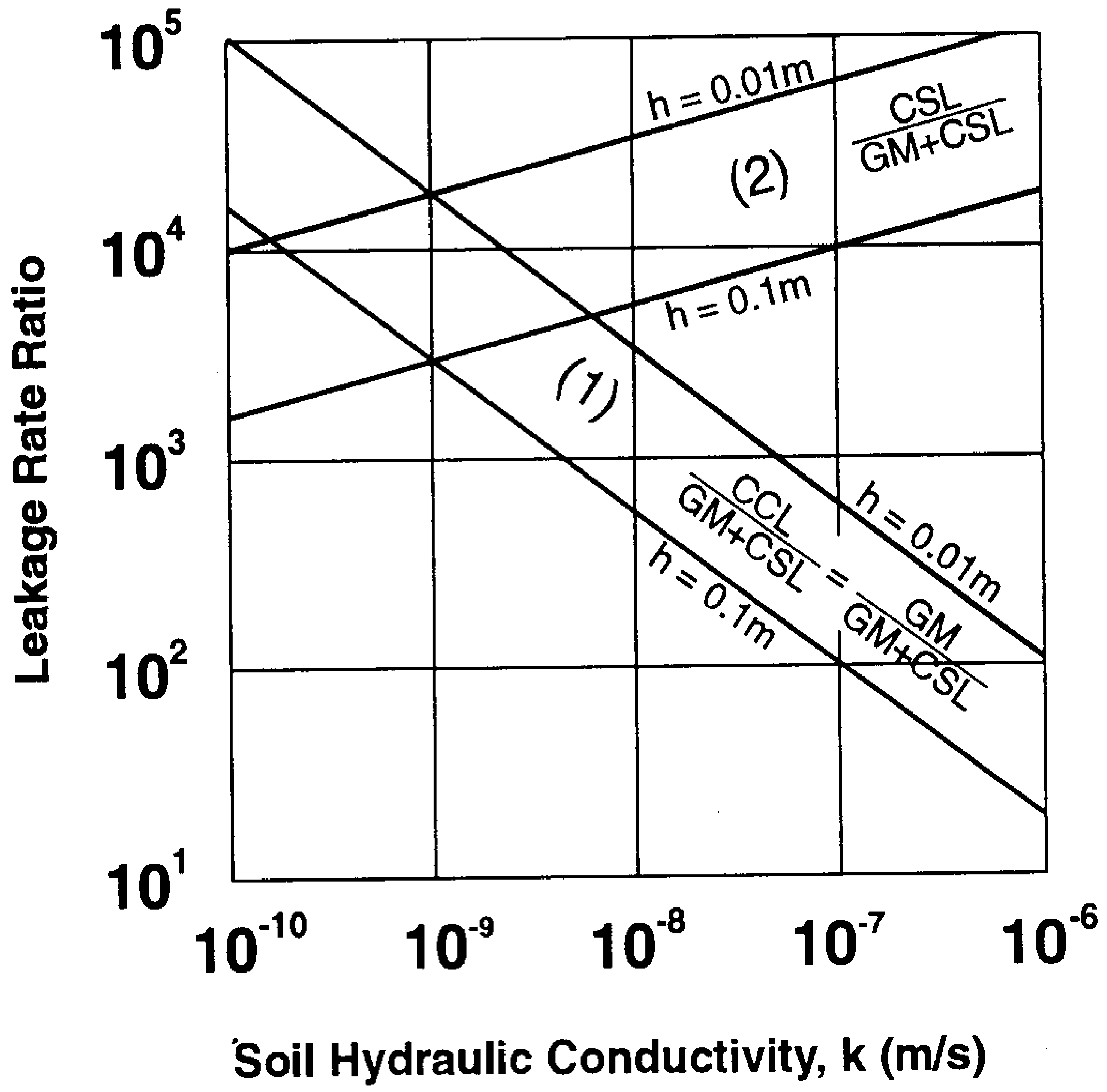

Fig. 5 Evaluation of composite liners.

The following conclusions, drawn from Fig. 5, are valid for $k < 10^{-6}$ m/s, the limit of validity of Equation 7, and for small values of the hydraulic head, h, typical of landfill applications:

- The rate of leakage through a composite liner where the soil component has a hydraulic conductivity $k = 10^{-9}$ m/s is 1000-10000 times less than the rate of leakage through a compacted soil liner with $k = 10^{-9}$ m/s or a geomembrane placed on a permeable soil.
- A composite liner constructed with a soil component having $k = 10^{-6}$ m/s allows 10-100 times less leakage than a compacted soil liner with $k = 10^{-9}$ m/s or a geomembrane placed on a permeable soil.

- The rate of leakage through a composite liner made with a given soil ($k < 10^{-6}$ m/s) is at least 1000 times less than through the soil itself. In other words, placing a geomembrane on the soil decreases the leakage rate by a factor of 1000 or more.

3.4 Evaluation of geoclay liners

Geoclay (GCL) can be used alone as a geoclay liner. Fig. 6 compares such a liner to two other liners:

- The CCL/GCL curve gives the ratio between the rates of leakage through a compacted clay liner and a geoclay liner. This curve was obtained using Equation 6 with $k = 10^{-9}$ m/s and D = 0.3-0.9 m for the compacted clay liner, and $k = 10^{-11}$ m/s and D = 0.006 m (6 mm) for the geoclay liner.
- The GM/GCL curve gives the ratio between the rates of leakage through a geomembrane liner and a geoclay liner. This curve was obtained using: (i) Equation 1 for the geomembrane liner with one 0.1 cm^2 defect per 4000 m^2, assuming that the geomembrane rests on a very permeable soil ($k > 10^{-1}$ m/s); and (ii) Equation 6 for the geoclay liner with $k = 10^{-11}$ m/s and D = 0.006 m (6 mm).

Fig. 6 shows that, under hydraulic heads typical of landfills, the rate of leakage through a geoclay liner is 3 to 40 times less than through a compacted clay liner ($k = 10^{-9}$ m/s) and 7 to 25 times less than through a geomembrane liner located on a permeable soil. Again, the comparison between geomembrane and geoclay is not applicable to secondary liners in double-lined landfills, as discussed in Section 3.2.

Geoclay can also be used as the low-permeability soil component of a composite liner. In. Fig. 6, the GM + CCL/GM+GCL curve gives the ratio between the rates of leakage through a conventional composite liner, i.e., geomembrane (GM) on a compacted clay layer (CCL) with $k = 10^{-9}$ m/s, and a composite liner consisting of a geomembrane on geoclay (GCL). This curve was established using Equation 7 for the conventional composite liner and Equation 9 for the composite liner with geoclay. It appears that the rate of leakage through a composite liner with geoclay is 6 to 23 times less than through a conventional composite liner.

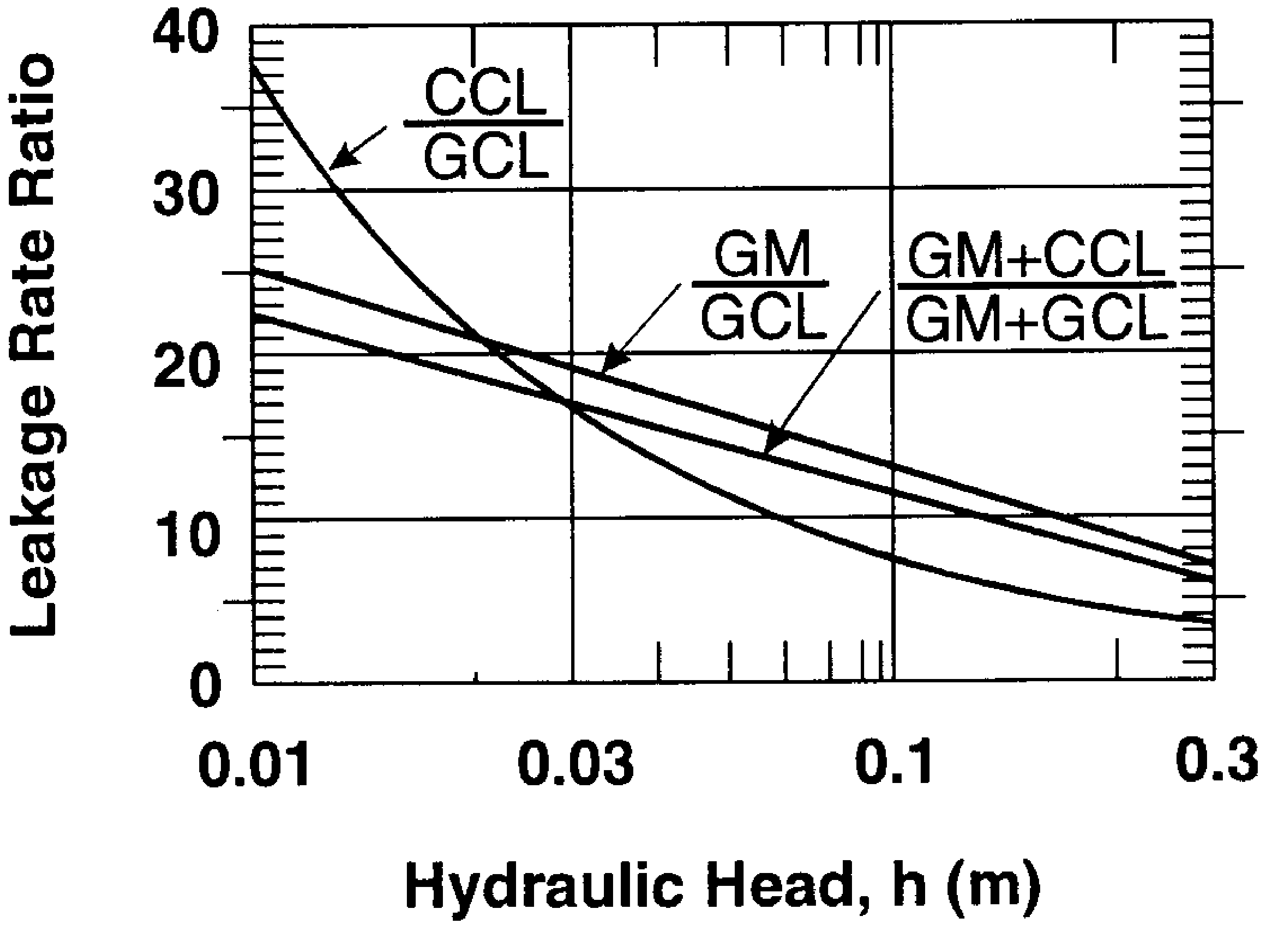

Fig. 6 Leakage rate ratios between liners involving geoclays, which are assumed free from defects.

4 CONCLUSIONS

The equations presented in this paper show that it is possible to evaluate the rate of leakage through all types of liners used in landfills. Comparisons based on these equations show that composite liners are significantly more effective than compacted soil liners or geomembranes used alone on permeable media, and that geoclay is a viable alternative to compacted soil in composite liners.

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