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# Provisional Equations for Determining Leachate Leakage Rate through Composite Barriers from Compromised Geomembrane

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**Abstract**

From years ago to present date the equations available for determining the rate of leachate leakage through composite barriers from geomembrane (GM) failures necessitated the use of graphs to attain the value of one of the terms of the equations for the case where the leachate head is larger than the thickness of the low-permeability soil medium of the composite barrier. This work reveals that the terms requiring graphs can be expressed analytically, which shows a new set of equations that leads to an entirely analytical approach of determining the rate of leachate leakage through composite barriers. The provisional set of equations is principally beneficial when the leachate level is large as against the thickness of the low-permeability soil medium of the composite barrier. This is usually the case when the low-permeability soil medium allied with the GM to form a composite barrier is a geosynthetic clay liner (GCL). Whether the failure in the GM is small or large or where the leachate level on top of the barrier is large as against the thickness of the low-permeability soil layer of the composite system, a provisional equation can be used to determine the leakage rate through the system. Although in such a scenario, graphs are essential in attaining the value of one of the terms of the equations. Therefore, this paper shows that the graphs can be replaced by equations, which proceeds to the generation and utilization of an entirely analytical method of determining the rate of leachate leakage through a failed composite waste containment barrier, irrespective of the leachate level overlying the system.


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*Keywords:* Leahate; Leakage rate; Composite barrier; Geomembrane (GM); Geosynthetic clay liner (GCL)

## 1. Introduction

There are a number of equations available for computing the rate of leachate leakage through a composite barrier from geomembrane (GM) failures. As reported by [1] this could be in conditions where the leachate head over the liner is small compared to the thickness of the low-permeability soil medium of the composite barrier or whether the failure is small or large [2, 3]. Furthermore, equations are also available for cases where the leachate head over the barrier is large as against the thickness of the low-permeability soil medium of the composite barrier [4, 5]. Although as recorded by [1] such a case would require the use of graphs in attaining the value of one of the terms of the equations which makes the entire process weighty and lengthy. For this reason, this paper opted to show that the

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graphs can be substituted by equations leading to a completely analytical approach for the assessment of the leachate leakage rate through a failed composite barrier, irrespective of the leachate level overlying the barrier.

**Nomenclature**

| | |
|---|---|
| Composite barrier | a barrier or liner consisting of two or more components or media |
| Geomembrane | very low permeability synthetic barrier used to control fluid or gas leakage in earth works |
| Leachate | liquid that drains from a landfill containing both dissolved and suspended solids |

## 2. Composite Barrier System

A system composite barrier refers to a liner consisting of two or more media used to control the leakage of either gas or fluid from a man-made engineered containment facility. For the purpose of this work however, the term composite barrier indicate liners comprising of two media or components; (i) a geomembrane and (ii) a low-permeability soil overlain by the GM. The low-permeability soil medium of a composite barrier is mostly either a compacted clay liner (CCL) or a geosynthetic clay liner (GCL). A CCL has thickness typically in the range of 0.3-1.5 m while the thickness of a hydrated GCL depends on the applied pressure during hydration and is normally in ranges of 5-10 mm i.e., on the order of 100 times less than the thickness of a CCL [1]. The hydraulic conductivity of both CCLs and GCLs rely on the nature of the material, the nature of the liquid and the pressure applied to the system. In a case where the restrained fluid is water or a normal leachate, that does not react or affect the hydraulic conductivity of clay/clayey materials, including bentonite. A standard CCL has hydraulic conductivity typically in the range of $1 \times 10^{-10}$ to $1 \times 10^{-9}$ m/s while a standard GCL has hydraulic conductivity normally in the range of $5 \times 10^{-12}$ to $5 \times 10^{-11}$ m/s, in the order of 10-100 times lower than the hydraulic conductivity of a CCL.

## 3. Leachate Leakage through Failed Composite Barrier System

It is well known that an intact GM has significantly low permeability and as such, most of the liquid migration through a composite barrier occurs through GM failures/defects [6]. For the purpose of this work, the only mechanism of fluid escape considered herein, is leakage through a compromised/failed GM. The liquid considered in this context is an aqueous solution- leachate, collected from active municipal solid waste (MSW) landfill leachate ponds around the City of Johannesburg (CoJ), South Africa as shown in Fig. 1.

Fig. 1. Permeate collected from different leachate ponds around the CoJ, South Africa

Where the integrity of a GM component of a composite barrier is compromised, the leachate leaks first through the GM failure/defect, then it seeps laterally travelling some distance between the GM and the low-permeability soil, and, finally it percolates into and through the low-permeability soil medium which is the second component of the composite barrier as shown in Fig. 2. The leakage that occurs in the space between the GM and the low-permeability soil is generally known as the interface leakage whereas the area covered by the interface leakage is called the wetted area. As shown in Fig. 3, the quality of the contact/contact condition between the two components of a composite barrier i.e., the GM and the low-permeability soil, is one of the crucial factors governing the rate of leachate leakage through the composite barrier, due to the fact that it governs the radius of the wetted area.

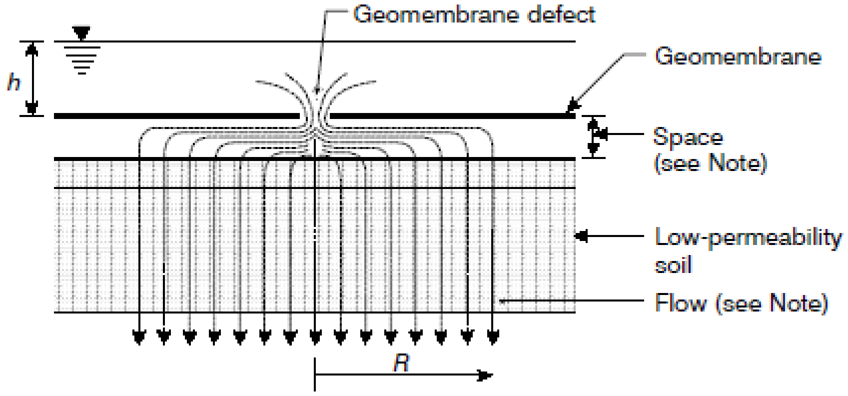
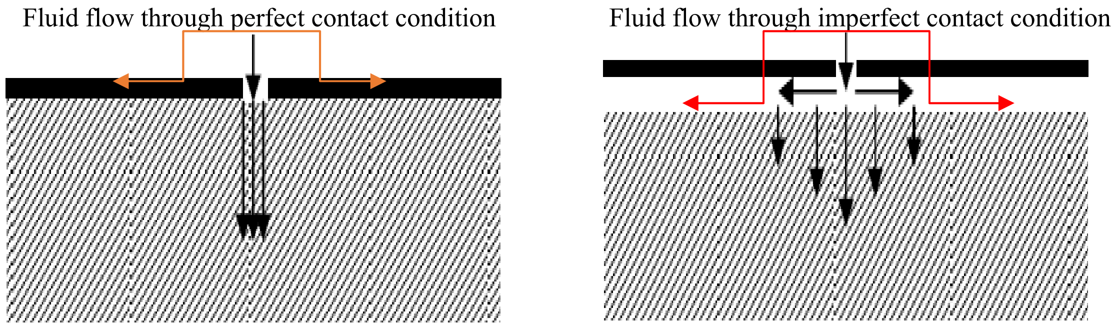



Fig. 2. Leachate leakage through a compromised composite barrier system [1].
Note: The space between the GM and the low-permeability soil is overblown to show the interface leakage. The percolation in the soil is assumed to be vertical and *R* is the radius of the wetted area.

*Good* and *poor* contact conditions have been defined by [8] in the following way:

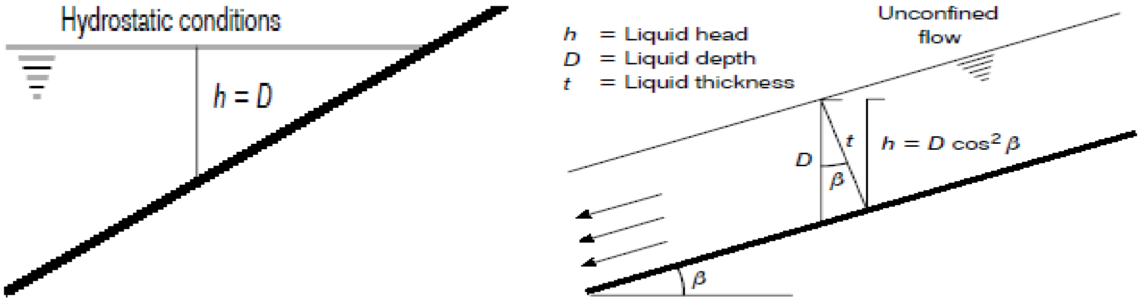
i. *Good* contact conditions relate to a fitted GM with as very few wrinkles as possible, overlying a low-permeability soil medium, sufficiently compacted and smooth at the surface without contours.
ii. *Poor* contact conditions relate to a fitted GM with a certain number of wrinkles overlying a low-permeability soil medium, insufficiently compacted and not smooth at the surface with contours.

For good contact conditions, it is assumed that there is adequate applied pressure to retain the GM in contact with the low-permeability soil medium. For the case of a GCL, good contact conditions may be assumed because GCLs are usually fitted flat, and the bentonite slurry that may emanate from a hydrated GCL adds to establishing a close contact/seal between the GM and the GCL, provided adequate applied pressure is ensured [1].




(a) With perfect interface contact (without gap) (b) With imperfect interface contact (gap)
Fig. 3. Leachate leakage through a compromised GM [7]

Other factors affecting leachate leakage rate through a compromised composite barrier are the size of the failure/defect, the hydraulic conductivity of the low-permeability soil underlying the GM, and the leachate level overlying the GM. In hydrostatic conditions, the leachate level, *h*, overlying the GM equals its depth, *D* and, if the leachate is unconfined and flowing along a slope, the leachate head overlying the GM, *h*, as shown in Fig. 4 is given by the expression in Equation (1).



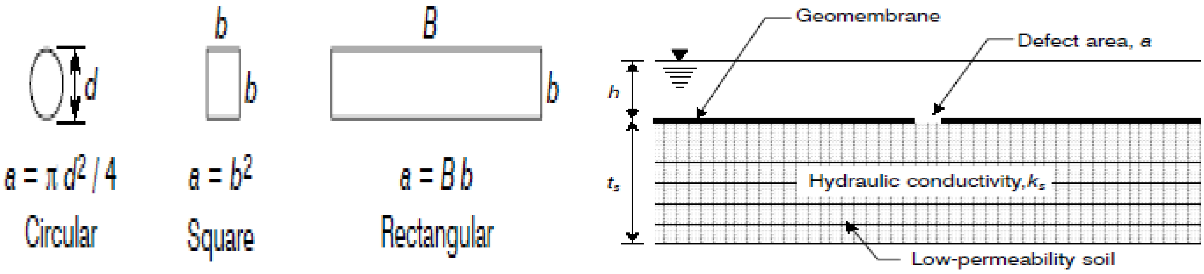
(a) Hydrostatic conditions (b) Unconfined flow along an inclined plane
Fig. 4. Leachate level overlying a barrier for the case of an inclined barrier [1]

$$h = t \cos \beta = D \cos^2 \beta \tag{1}$$

In Equation (1) $t$, $D$ and $\beta$ are; thickness, depth of leachate and angle of inclination/slope respectively.

### 3.1. Compromised/Failed Geomembrane

A number of failed or shapes of defects i.e., circular, with a surface area, *a*, and a diameter, *d*; square, with a side length, *b*; rectangular, with a length, *B*, and a width, *b*; and infinitely long ($B = \infty$) with a width, *b*, have been well documented by various authors [1-11]. The parameters for the leachate leakage rates and diagrammatic representations of defects are shown in Fig. 5. For the purpose of this work, only the circular shape failure is considered herein.



(a) Plan schematic of shapes of GM defects (b) Cross sectional schematic of a failed GM
Fig. 5. Leachate level overlying a barrier for the case of an inclined barrier [1]

In the equations that follow below, $Q$ is the rate of leachate leakage through the GM defect. It is important to note that the equations for leachate leakage rate that follow are semi empirical and can only be used with the following basic SI units: $h$ (m), $a$ (m$^2$), $k_s$ (m/s) and $Q$ (m$^3$/s). Where; $k_s$ = hydraulic conductivity of the low permeability soil component of the composite barrier system; $t_s$ = thickness of the low-permeability soil component of the composite liner; and all other symbols are as defined above.

## 4. Existing Equations for Calculating Leachate Leakage Rate through Composite Barriers

### 4.1. Equations for Small Leachate Level/Head

Various equations have been proposed for the case where the leachate level overlying the barrier is less than the thickness of the low-permeability soil component of the composite liner [1-11]. However, only the case of a circular defect is addressed herein expressed in Equation (2) as proposed by [2].

$$Q = C_{qo}\, a^{0.1}\, h^{0.9}\, k_s^{0.74} \tag{2}$$

Hence Equation (2) becomes expressed as shown in (3).

$$Q = 0.976\, C_{qo}\, d^{0.2}\, h^{0.9}\, k_s^{0.74} \tag{3}$$

Where $C_{qo}$ is the dimensionless contact quality factor for a circular hole, with the expression in (4) being:

$$C_{qogood} \leq C_{qo} \leq C_{qopoor} \tag{4}$$

Where; $C_{qogood}$ = value of $C_{qo}$ in the case of good contact conditions; and $C_{qopoor}$ = value of $C_{qo}$ in the case of poor contact conditions as earlier defined for good and poor GM contacts. Thus, the following values were established by [2] as shown in Equations (5) and (6).

$$C_{qogood} = 0.21 \tag{5}$$

$$C_{qopoor} = 1.15 \tag{6}$$

### *4.2. Equations for Large Leachate Level/Head*

When the leachate level overlying the barrier is greater than the thickness of the low-permeability soil component of the composite barrier, Equations (2) and (3) become invalid. However, Equation (7) becomes applicable as proposed by [3].

$$Q = C_{qo}\, i_{avgo}\, a^{0.1}\, h^{0.9}\, k_s^{0.74} \tag{7}$$

Where; $i_{avgo}$ = average hydraulic gradient in the low-permeability soil in the case of a circular failure. The value of $i_{avgo}$ is given in the graph presented in Fig. 6. It appears that, when the leachate level is greater than the thickness of the low-permeability soil component of the composite barrier, the calculation of the rate of leachate leakage is not entirely analytical since the use of graphs must initiated. This is not always convenient, particularly in a scenario involving calculations for a large number of cases.

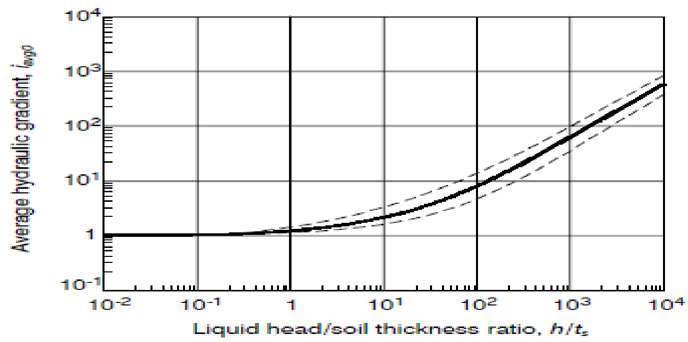



Fig. 6. Values of the average hydraulic gradient to be used in equations for leachate leakage rate calculations for a circular failure [1]

## 5. Provisional Equations for Calculating Leachate Leakage Rate through Composite Barriers

### *5.1. Analytical Expressions of the Average Hydraulic Gradient*

After numerous attempts, it was reached that a good approximation of the values of $i_{avgo}$ presented in Fig. 6 is given by expression given in equation (8).

$$i_{avgo} = 1 + 0.1 \left( h/t_s \right)^{0.95} \tag{8}$$

### *5.2. Provisional Equations for Leachate Leakage Rate*

From Equations (2) and (8) the following equation used to calculate the leachate leakage rate through composite barriers with circular failure is gotten as expressed in Equation (9).

$$Q = C_{qo} \left[ 1 + \left( h/t_s \right)^{0.95} \right] a^{0.1}\, h^{0.9}\, k_s^{0.74} \tag{9}$$

Hence Equation (9) becomes expressed as shown in (10).

$$Q = 0.976\, C_{qo} \left[ 1 + 0.1 \left( \frac{h}{t_s} \right)^{0.95} \right] d^{0.2}\; h^{0.9}\; k_s^{0.74} \tag{10}$$

Values of $C_{qo}$ are given by Equations (4), (5) and (6) while other parameters have earlier been defined. Equation (9) is semi-empirical must be used with the unit as earlier defined. However, it is noted that when the leachate level overlying the barrier is smaller than the thickness of the low-permeability soil component of the composite barrier, the value of $i_{avgo}$ given by Equation (8) is roughly equal to 1, and Equations (8), (9) and (10) become equal to Equations (2), (3) and (7) respectively.

## 6. Demerits of the Provisional Equations

The limits of validity of the above equations have been conversed in detail by [12]. The limits as discussed by [12] are summarized as below:

a. If the failure is circular, the diameter of the defect should be no less than 0.5 mm and not greater than 25 mm. In cases where the failures are not circular, other propositions are made not covered in this paper.
b. The leachate level overlying the GM should be equal to or less than 3 m.
c. The hydraulic conductivity of the low-permeability soil underlying the GM should be equal to or less than a certain value $k_G$, which is less than the value $k_{GB}$ for which the relevant equation for the considered failure type i.e., Equation (9) for a circular defect and Bernoulli's equation for free leakage through an orifice giving the same value of the leachate leakage rate through the GM defect.

To ensure a smooth conversion between leachate leakage rates calculated using Equation (9) and that by Bernoulli's equation, a proposition by [12] of the following value for $k_G$ is given in Equations (11) and (12).

$$k_G = k_{GB}/10 \tag{11}$$

In the case where the GM failure is circular, $k_G$ is given by the Equation (12).

$$k_G = \left\{ \frac{0.3891\, d^{1.8}}{C_{qo} \left[ 1 + 0.1 \left( \frac{h}{t_s} \right)^{0.95} \right] h^{0.4}} \right\}^{1/0.74} \tag{12}$$

Equation (12) must be used with the units as earlier defined. Values of $k_G$ calculated using Equation (12) with $C_{qo}$ = 0.21 i.e., good contact conditions as presented by Equation (5) and $t_s$ = 0.6 m detailed by [1].

## 7. Conclusion

From the equations presented herein, provision was made of a completely analytical approach for calculating the leachate leakage rate through a composite barrier from a circular GM failure having leachate level overlying the barrier to a specification of about 3 m. The provisional equations were concluded to be identical to the existing methods by [3, 5] which required both equations and graphs for leachate level overlying the barrier greater than the thickness of the low-permeability soil component of the composite barrier. Furthermore, the provisional equations are more convenient since values initially obtained from graphs are now combined into the equations as in Equation (9) for circular failures. Moreover, the provisional equations are particularly useful in cases where the low-permeability soil component of the composite barrier is a GCL because the leachate level overlying the barrier is often greater than the thickness of the GCL.

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