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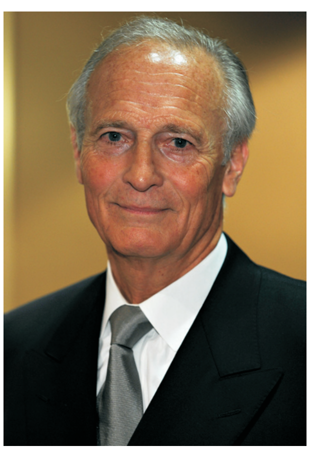
# *Victor de Mello Lecture*

**The Victor de Mello Lecture** was established in 2008 by the Brazilian Association for Soil Mechanics and Geotechnical Engineering (ABMS), the Brazilian Association for Engineering Geology and the Environment (ABGE) and the Portuguese Geotechnical Society (SPG) to celebrate the life and professional contributions of Prof. Victor de Mello. Prof. de Mello was a consultant and academic for over 5 decades and made important contributions to the advance of geotechnical engineering. Every second year a worldwide acknowledged geotechnical expert is invited to deliver this special lecture, on occasion of the main conferences of ABMS and SPG.

The fifth Victor de Mello Lecture is delivered by Prof. J.P. Giroud, an internationally renowned professor, author, consultant, practitioner and researcher. Prof. de Mello established, during his term as president of the ISSMGE, the Technical Committee that started to study the behaviour and the contributions of geosynthetics to the diverse fields of geotechnical engineering. The challenges of introducing a synthetic material for the crucial task of filtering or waterproofing an interface of soils of different grain size distributions needed sound concepts and a focused research effort. Prof. Giroud shares with us, in his lecture, the rationale behind reliable engineering solutions using geomembrane liners.



**Prof. J.P. GIROUD**, a consulting engineer, is a former professor of geotechnical engineering. He is chairman of the editorial board of *Geosynthetics International* and past president of the International Geosynthetics Society (the IGS). Dr. Giroud is a member of the US National Academy of Engineering and Chevalier in the Order of the Légion d'Honneur. He has authored over 400 publications and he coined the terms "geotextile" and "geomembrane" in 1977. Dr. Giroud has 54 years of experience in geotechnical engineering and he has developed many of the design methods used in geosynthetics engineering. The IGS has named its highest award "The Giroud Lecture", "in recognition of the invaluable contributions of Dr. J.P. Giroud to the technical advancement of the geosynthetics discipline". A Giroud Lecture is presented at the opening of each International Conference on Geosynthetics by a lecturer selected by the IGS. Dr. Giroud has delivered prestigious lectures, such as the Vienna Terzaghi Lecture, the Mercer Lecture and the Terzaghi Lecture of the American Society of Civil Engineers.

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# Leakage Control using Geomembrane Liners

J.P. Giroud

**Abstract**. Geomembrane liners are used in all types of containment structures. Evaluating the performance of a geomembrane liner is a challenge. While zero leakage into the ground is a legitimate goal if the leaking liquid may pollute the ground and the ground water, or if the soil integrity can be impaired, zero is unrealistic and impossible to measure. Furthermore, zero leakage is not an appropriate goal in some applications such as geomembrane-lined dams. In this paper, it is shown that the difference between acceptable and unacceptable leakage should result from a rational analysis of the potentially detrimental consequences of leakage. Also, it is shown that the specified leakage must be achievable and measurable. Therefore, emphasis is placed on the quantitative evaluation of leakage. Practical guidance is provided for leakage reduction at construction stage and design stage; and typical leakage rates are mentioned. Potential failures associated with leakage control measures are described. Case histories illustrate both failures in case of misuse of geomembranes and the durability of geomembranes. This paper is intended to contribute to the appropriate design and the safety of geomembrane-lined structures.

**Keywords:** geosynthetics, geomembranes, drainage, liners, leakage, reservoirs, dams.

## 1. Introduction

### 1.1. The Fifth Victor de Mello Lecture

Victor de Mello was a visionary. In the 1980s, he encouraged the use of geotextiles and geomembranes and created the first Technical Committee on Geotextiles of the International Society for Soil Mechanics and Geotechnical Engineering and he appointed the author of this paper as chairman of this committee. The author of this paper is both indebted to Victor de Mello and very honored to present the Fifth Victor de Mello Lecture. The information presented in this paper is consistent with the interest of Victor de Mello for innovative materials as evidenced by the following words, "Engineering creativity is vital and of the essence in geotextiles and geomembranes technology", from the foreword Victor de Mello wrote for the paper summarizing the work of the Technical Committee on Geotextiles (Giroud *et al.*, 1985).

### 1.2. This paper

This paper is devoted to leakage control using geomembranes. To that end, this paper will address various topics pertaining to leakage such as liner materials, terminology, influence of parameters on leakage, measures taken at design and construction stages to reduce leakage, leakage detection and measurement, and leakage prediction. The discussions presented in this paper are relevant to containment structures lined with geomembranes, such as landfills, reservoirs and dams.

## 2. General Introduction to Leakage

### 2.1. Leakage happens and must be addressed

"All liners leak": this was stated by Giroud & Bonaparte (1989a) at the beginning of their paper. This should not be construed as meaning that there is no way to safely store liquids. In fact, recognizing that all liners may leak is the first step to the safe design of liquid containment systems. The design of a containment structure cannot be safe if the possibility of leakage is not recognized in the first design step. Depending on the desired degree of leakage control, there is a choice of adequate solutions using geomembrane liners, including single geomembrane liner, composite liner (*i.e.* geomembrane associated with clay), and double liner. This paper will show that, with a realistic goal regarding acceptable leakage rate, it is possible to achieve the desired level of leakage control using appropriate design and construction methods.

### 2.2. Terminology related to leaks, leakage and leakage rate

Adapting from several dictionaries, and restricting the discussion to liquids, it can be said that the word "leak" has two meanings: (i) a passageway through which liquid can unintentionally escape; and (ii) the liquid that escapes through a passageway, such as liquid flowing unintentionally out of a reservoir. To avoid possible confusion due to this dual meaning of the word "leak", the word "hole" is used herein to mean a passageway through the liner such as a puncture, tear or crack, or a passageway at the periphery

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Intited Lecture, no discussions.

of the liner such as a gap between the liner and an appurtenance.

The word "defect" is often used to designate a hole that makes a leak possible. In fact, the use of "defect" to designate a hole should be avoided, because many types of defects do not constitute a passageway for liquid. All holes associated with a liner are defects (either defects in the liner or inadequate connections between the liner and adjacent structures), but not all defects are holes.

The word "leakage" designates the amount of liquid that escapes from a containment structure. The term "leakage rate" designates the amount of leakage per unit of time. Sometimes, the term "leakage rate" is also used to designate what is more accurately called "leakage rate per unit area", which implies "per unit area of liner", a concept applicable to some, but not all, containment structures. The distinction between "leakage rate" and "leakage rate per unit area" appears in the units.

### 2.3. Units use for leakage rate

The following units are used for leakage rate:

1 $m^3/s$ = 1000 liters per second = 60,000 liters per minute

The following units are used for leakage rate per unit area:

1 liter per hectare per day (lphd) = $1.157 \times 10^{-12}$ m/s = $1.157 \times 10^{-10}$ cm/s.

A liquid level drop of 1 mm per day is equal to 10,000 lphd.

A rate of leakage of 1 $m^3/s$ in one hole per ha is equivalent to $8.64 \times 10^7$ lphd $\approx 1 \times 10^8$ lphd.

### 2.4. Zero leakage, a desirable goal but an inappropriate specification

Zero leakage is a desirable target. However, "zero" is impossible to measure in engineering. Since zero leakage cannot be measured, it is inappropriate to specify zero leakage. Therefore, a small, but rationally established, maximum leakage rate should be specified. One of the goals of this paper is to provide guidance for the selection of a rational maximum leakage rate.

If zero leakage is detected in the monitoring of a containment structure, it is recommended to draw careful conclusions:

- The zero-leakage detection may, indeed, result from excellent performance, but it is only representative of the current situation and there is no guarantee that the performance will continue to be excellent. Monitoring should continue.
- The zero-leakage detection may result from incorrect or inaccurate measurement. The method used for leakage detection and measurement should be scrutinized using as a guide the review of potential errors in leakage rate measurement, which is presented hereafter in Section 8.3.

Another reason for selecting a rational value for the specified maximum leakage rate is the following: when zero or excessively small values of maximum leakage rates are specified, extensive investigations to find holes in the geomembrane and extensive geomembrane repairs may be required to try to meet the specified leakage rate. The investigation and repair activities may cause collateral damage to the liner, which has resulted in higher leakage rates in several instances (see Sections 8.3.1 and 8.3.3).

From the foregoing discussion, it is clear that, rather than pursing the unrealistic goal of zero leakage, it is preferable to follow the rational approach that consists in discussing the limit between acceptable and unacceptable leakage, which requires an understanding of the potentially detrimental consequences of leakage.

### 2.5. Potentially detrimental consequences of leakage

#### *2.5.1. Review of the potentially detrimental consequences of leakage*

Leakage can be potentially detrimental for several reasons, including economic loss, environmental damage, perceived damage, geotechnical damage, and liner damage or disturbance, as described below:

- Economic loss including: (i) loss of water (an increasingly valuable liquid), or loss of other valuable liquids (*e.g.* chemical liquids in industrial reservoirs, and pregnant solutions in mining ponds); (ii) loss of generated power in the case of massive leakage in reservoirs for pump-storage stations; (iii) difficulty in maintaining an acceptable liquid level (*e.g.* in decorative ponds, reservoirs for recreation or sport activities); and (iv) cost associated with the following four items.
- Environmental damage due to: (i) contamination of soils, water streams and ground water by chemical components of the leaking liquids; and (ii) flooding due to massive leakage.
- Perceived damage, such as visible leakage through the downstream face of a concrete dam, which may be technically safe and, therefore, technically acceptable, but is detrimental regarding public perception
- Geotechnical damage by: (i) deterioration of the material supporting the liner by intrusion of leakage in the soil supporting the liner (*e.g.* erosion of the ground under the geomembrane, formation of solution cavities, internal erosion of an embankment (dam or dike), softening of the soil supporting the geomembrane causing soil deformation thereby inducing strains in the geomembrane, erosion and/or softening of the soil supporting the geomembrane bringing stones in contact with the geomembrane, physical and/or chemical deterioration of concrete in the case of concrete dams); and (ii) instability of the soil or structure supporting the liner (*e.g.* due to phreatic surface buildup and pore water pressure increase in the ground supporting the liner, due to excessive pore water

pressure in embankment dam or dike, due to water pressure in cracks or joints of concrete dams).

- Liner damage or disturbance, such as: (i) damage to the liner (and consequently increase in leakage rate) caused by the liquid flow pressure (*e.g.* erosion of a clay liner or increase of geomembrane hole size); and (ii) uplifting of liner (which, in the case of a geomembrane, reduces the reservoir capacity, induces tensile stresses in the geomembrane, exposes the geomembrane to mechanical damage and weather-generated deterioration).

Examples of consequences of leakage are summarized in Table 1. It appears in Table 1 that the risk of geotechnical damage may be more frequent than other risks. Therefore, engineers designing liner systems should pay special attention to the potential deterioration of geotechnical conditions due to leakage, rather than focusing exclusively on economic loss and contamination of ground, as they often do.

#### *2.5.2. Acceptable leakage based on the detrimental consequences of leakage*

As often mentioned by the author of this paper, it must be recognized that "all liners leak, or may leak" and that "a leak should only be a leak", *i.e.* a loss of liquid without unacceptable consequences. In other words, a leak should not trigger an unacceptable problem, *i.e.* one of the detrimental consequences mentioned above in Section 2.5.1.

As discussed above in Section 2.4, zero leakage is an inappropriate requirement. Therefore, the only relevant approach is, for each specific case, to determine the limit between acceptable and unacceptable leakage based on an evaluation of the detrimental consequences of leakage listed above in Section 2.5.1. As adapted from Giroud (1984a) and Peggs & Giroud (2014), leakage from a geomembrane-lined reservoir can be acceptable if the following five requirements are met: (i) the loss of liquid remains small enough to be economically acceptable; (ii) the leaking liquid does not cause unacceptable pollution of the ground or the ground water; (iii) the leakage is not perceived by the public as unacceptable; (iv) the leaking 1liquid does not cause a degradation of the soil or the structure supporting the geomembrane; and (v) the leaking liquid does not uplift the geomembrane liner or otherwise damage the liner.

#### *2.5.3. Acceptable leakage based on achievability and measurability*

The specified leakage rate must be achievable and measurable. Specifying a leakage rate that cannot be achieved is counterproductive because it will trigger endless investigations and repairs that often result in causing damage to the liner, hence more leakage (see Sections 2.4, 8.3.1 and 8.3.3).

In order to adequately specify, it is necessary to be able to predict, and to predict it is necessary to be able to quantify. Accordingly, guidance will be provided to evaluate leakage (see Section 8). This is essential, because engineering is essentially done with numbers.

## 3. Liners and Liquid Migration

### 3.1. Geomembranes and other liner materials

#### *3.1.1. Presentation of geomembranes*

The term "geomembrane" proposed by the author of this paper (Giroud & Perfetti, 1977) has been adopted worldwide. Geomembranes are quasi-impermeable membranes ("membrane" implying continuity and flexibility) used in geotechnical engineering applications as a barrier to the migration of fluids. Geomembranes are mostly used as barriers to contain liquids, redirect their flow or prevent their migration, in particular in reservoirs, canals, dams, hydro tunnels, tailings dams, leach pads, waste storage landfills, and underground structures (tunnels, below-ground buildings, etc.). The quasi-impermeable component of geomembranes is either a polymer or bitumen. A variety of chemical and mineral additives are incorporated in the polymer or the bitumen to improve some of their properties.

Geomembranes are un-reinforced or reinforced. Reinforced geomembranes are reinforced using a woven fabric or a nonwoven fabric:

- A woven fabric is used to reinforce some polymeric geomembranes. It is then placed inside the geomembrane.
- A nonwoven fabric impregnated and coated with bitumen is used to manufacture bituminous geomembranes. Some bituminous geomembranes are reinforced with glass fibers, in addition to the nonwoven fabric.
- A nonwoven fabric bonded to a geomembrane (Fig. 1) forms a type of reinforced geomembrane called "composite geomembrane"; in this case the nonwoven fabric

**Table 1** - Examples of detrimental consequences of leakage.

| Detrimental consequence | Containment of water | Containment of mining pregnant solution | Containment of wasted liquid |
|---|---|---|---|
| Loss of valuable liquid | Yes | Yes | No |
| Contamination of ground | No | Yes | Yes |
| Geotechnical damage | Yes | Yes | Yes |

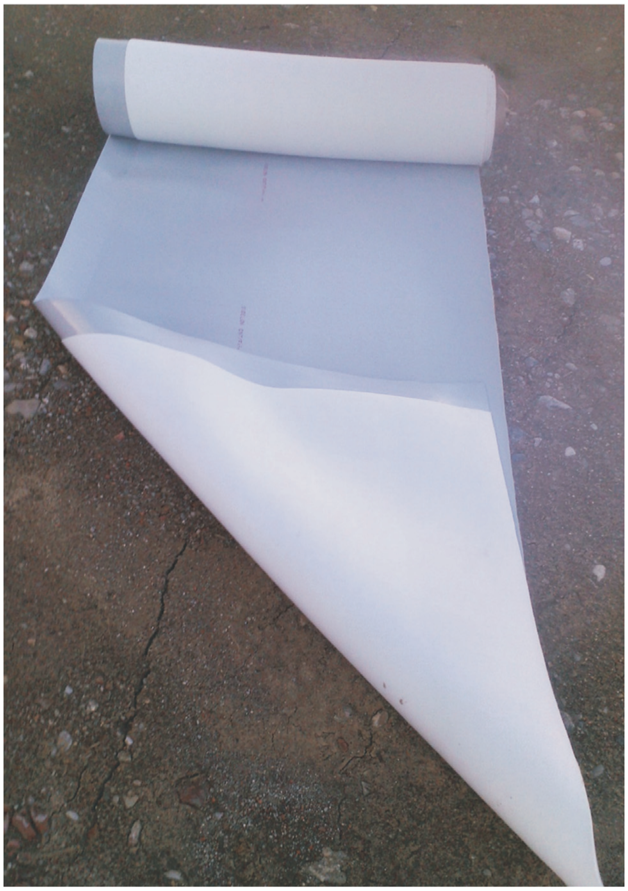

**Figure 1** - Composite geomembrane composed of a geomembrane (grey color) bonded to a nonwoven geotextile (white color). The selvage with no geotextile is reserved for seaming the geomembrane to the adjacent panel [Courtesy Carpi].

(which is, in fact, a nonwoven geotextile) is outside the geomembrane.

The thickness of geomembranes is typically from approximately 1 to 5 mm. Geomembranes are available in rolls (typically 2 to 10 m wide), which are assembled by seaming to form large liners.

All the geomembranes considered herein are made in a manufacturing plant. It is generally considered that geomembranes made in situ by spraying a low-permeability compound onto a geotextile or directly on the ground are not sufficiently reliable to be used for high-performance leakage control.

Since the 1970s, geomembranes have progressively replaced traditional liner materials in many applications.

#### *3.1.2. Presentation of liner materials other than geomembranes*

Traditional liner materials include cement concrete, bituminous concrete, and compacted clay. Typical thicknesses for liners made using these traditional materials are 0.1-0.2 m for cement concrete and bituminous concrete, and 0.3-1.0 m for compacted clay.

There is a category of geosynthetic liner material whose low-permeability component is bentonite, a variety of clay with very low permeability: the bentonite geocomposites, also called geosynthetic clay liners. Typically, a bentonite geocomposite consists of a layer of bentonite between two layers of fabric. The thickness of bentonite geocomposites is typically 5-7 mm when the bentonite is dry and of the order of 10 mm when the bentonite is hydrated.

All of the above materials can be associated with geomembranes to form composite liners (see Section 6). This is typically done with compacted clay and bentonite geocomposites.

### 3.2. Liquid migration through liners

#### *3.2.1. Modes of liquid migration*

Leakage associated with any type of liner include:

- Liquid migration through the liner via the following mechanisms:
    - diffusion (which takes place at the molecular scale),
    - advective flow, which includes laminar flow (through a porous medium, and through thin cracks and very small holes) and non-laminar flow through cracks and holes.
- Liner bypass (*i.e.* flow at and around the periphery of the liner).

These mechanisms are discussed in the following sections, with particular emphasis on the case of geomembranes.

#### *3.2.2. Diffusion*

Diffusion through geomembranes occurs essentially in the case of some volatile organic compounds, such as benzene, toluene, trichloroethylene, and xylene. Diffusion through geomembranes is negligible in the case of water and non-organic compounds such as chlorides. In the case of compounds that could migrate through geomembranes by diffusion, the migration can be reduced by proper selection of the type of geomembrane, and the effect on the ground of compounds that migrate by diffusion can be alleviated by placing a thick layer of fine-grained soil under the geomembrane. This layer, called “attenuation layer”, is typically made of clay or silt and it is typically more than 1 m thick.

Diffusion will not be discussed further in this paper. Leakage through holes in the geomembrane is the only mode of leakage through the geomembrane that will be discussed in this paper. In addition, leakage due to flow at and around the periphery of the geomembrane will be addressed later in this paper (see Section 5.2).

*3.2.3. Laminar advective flow*

All liner materials except geomembranes are porous media. Furthermore, when these materials are intact, the pores are so small that the flow is generally laminar. Therefore, Darcy's equation, which is strictly applicable to laminar flow through porous media, can be used for these liners. As a result, a hydraulic conductivity (*i.e.* coefficient of permeability) can be defined and measured for these liners.

Strictly speaking, the coefficient of permeability cannot be used for liquid migration through geomembranes because geomembranes are not porous media. However, some standard tests conducted to evaluate geomembrane acceptance can be interpreted by deriving an "equivalent coefficient of permeability". In the case of good-quality modern geomembranes the equivalent coefficient of permeability is typically less than $10^{-14}$ m/s.

The equivalent coefficient of permeability is a convenient way to compare geomembranes to other liner materials. Typical orders of magnitude of the coefficient of permeability (for liners others than geomembranes) and the equivalent coefficient of permeability (for geomembranes) are as follows:

- Cement concrete: $10^{-12}$ m/s in ideal laboratory conditions.
- Cement concrete: $10^{-10}$ m/s to $10^{-8}$ m/s in the field.
- Roller compacted concrete: $10^{-8}$ m/s to $10^{-6}$ m/s.
- Bituminous concrete: $10^{-9}$ m/s in ideal laboratory conditions.
- Bituminous concrete: $10^{-8}$ m/s in the field.
- Compacted clay layer: $10^{-9}$ m/s with excellent construction and quality control.
- Compacted clay layer: $10^{-8}$ m/s with ordinary construction and quality control.
- Bentonite geocomposite $10^{-11}$ m/s (when hydrated and not exposed to calcium cations).
- Geomembranes: < $10^{-14}$ m/s (when intact).

These orders of magnitude show that geomembranes can be considered quasi-impermeable materials while other liner materials are low-permeability materials. However, it is not because geomembranes are quasi impermeable that geomembrane-lined containment structures do not leak. Impermeability of an intact geomembrane on a small scale does not guarantee impermeability on a large scale under field conditions.

*3.2.4. Non-laminar advective flow through holes*

When a geomembrane with holes rests on a highly permeable material such as coarse gravel (possibly stabilized with a small amount of cement or bitumen), the flow of liquid through the holes is non-laminar and the equation for free flow through an orifice is applicable (see Section 8.2.2) The leakage rate is then high.

The rate of leakage through a hole in a geomembrane can be drastically reduced by placing the geomembrane on another liner material such as a compacted clay layer or a bentonite geocomposite. A "composite liner" is thus formed. An entire section will be devoted to this important way of using geomembranes, which has significant advantages but requires precautions for a safe use (see Section 6).

In modern geomembranes, there are no holes in the geomembranes made in a manufacturing plant. The development of holes during construction (geomembrane installation and, more importantly, subsequent construction activities such as placement of materials on top of the geomembrane) and in service depend in great part on the mechanical properties of the geomembrane. Thus, tensile characteristics, puncture resistance and tear resistance of a geomembrane are essential properties (see Section 5.2.2).

*3.2.5. Conclusion on liquid migration*

In conclusion, it is not appropriate to characterize a geomembrane using a coefficient of permeability (except for a simplistic comparison with other types of liners). As leakage through geomembranes occurs essentially through holes, it is more important to characterize a geomembrane by the size and frequency of holes. This will be discussed in Section 8.1.

Leakage through geomembrane liners can be reduced by actions taken during construction (such as construction quality assurance and electric leak location survey) and decisions made at the design stage (such as geomembrane damage control, use of composite liner, use of double liner). These important aspects will be addressed in subsequent sections: leakage reduction by measures taken during construction (Section 4), leakage reduction by controlling geomembrane damage (Section 5), leakage reduction by using composite liners (Section 6), and leakage reduction by using double liners (Section 7).

## 4. Leakage Reduction by Measures Taken During Construction

### 4.1. Detection of holes during construction

The usual way to improve liner quality and, in particular, to find holes is by implementing a construction quality assurance plan. In the case of geomembrane liners, construction quality assurance consists of inspections and measures taken by a team independent from the geomembrane installer during installation of the geomembrane and associated materials, including overlying materials. Indeed, damage to geomembrane liners is often caused by the placement of materials (in particular soil layers) on top of the geomembrane.

Typical construction quality assurance activities aimed at finding holes in the geomembrane include:

- Nondestructive tests on seams to find gaps in seams.
- Visual inspection of the entire geomembrane liner to find: (i) punctures and tears in the geomembrane, and (ii) gaps in attachments of geomembrane to appurtenant structures.

These typical construction quality assurance activities (seam testing and visual inspection) may be sufficient in the case of first-class projects, characterized by: excellent workmanship; and excellent working conditions. This is the case for sophisticated applications, such as geomembrane-lined dams. But, experience shows that these typical construction quality assurance activities (seam testing and visual inspection) are not sufficient in the case of usual projects, such as landfills and many reservoirs where they miss a number of holes. In such projects, it is recommended to perform electric leak location surveys in addition to the implementation of construction quality assurance.

## 4.2. Electric leak location survey of geomembranes

### *4.2.1. Definition*

The modern technology for finding holes in geomembrane liners is the electric method designated by "electric leak location survey" or "electric liner integrity survey" or similar terms (such as "electric hole-detection survey", which indicates that the method detects holes, not leaks, according to the terminology presented in Section 2.2). When it is applicable, this technology makes it possible to detect a significant number of holes that are not typically detected by visual inspection. After repair of the detected holes, the geomembrane liner has been significantly improved, because the number and size of holes has been significantly reduced.

The principle of electric leak location surveys is simple. Most geomembranes are electrical insulators. Therefore, electric current will pass if there is a hole in the geomembrane or a gap in an attachment of the geomembrane to an appurtenant structure. The electric liner integrity survey requires a conductive layer immediately beneath the geomembrane. Therefore, the electric liner integrity survey is not effective if the geomembrane is not in contact with the underlying soil unless a conductive-backed geomembrane is used (*i.e.* a geomembrane with a thin conductive layer along its lower face). In particular, with ordinary geomembranes (*i.e.* geomembranes with no conductive layer), the electric leak location technique is not effective at locations where the geomembrane exhibits wrinkles.

### *4.2.2. Performance and sensitivity*

In the past two decades, the electric leak location technology has made significant progress. Today, electric leak location can be performed on a bare geomembrane, on a geomembrane under water, or on a layer of soil overlying a geomembrane.

When a geomembrane is to be covered by a layer of soil, it is important to perform electric leak location survey, not only after geomembrane installation, but also after placement of the soil layer because holes in the geomembrane are often caused by soil placement.

The sensitivity of electric leak location survey (*i.e.* the size of holes that can be found by electric leak location survey) depends on the amount of material covering the geomembrane when the survey is performed. With current technology (2016), the sensitivity limit of the electric leak location technique (*i.e.* the minimum size of holes that can be found) is approximately: (i) 1 mm for a bare geomembrane; and (ii) 6 mm under 0.6 m of soil. Clearly, electric leak location can find small holes, but not all. This leads to the following discussion on the limitation of this technology.

### *4.2.3. Limitation of the technology*

The same leakage rate may result from one hole (easy to find by electric survey) or several small holes that are difficult to find. Therefore, if the specified maximum leakage rate can be generated by small holes, much time could be wasted and much expenses could be incurred using the electric liner survey technique to try unsuccessfully to find holes that are too small to be detected. A similar concern has been expressed by Darilek & Laine (2013). Furthermore, excessive activity on a geomembrane liner to try to find holes may result in additional damage to the geomembrane liner, as illustrated in the case history presented in the Section 8.3.3.

This situation shows the limit of the electric survey technology and is a reminder that electric survey does not replace geomembrane installation by a skilled crew with strict construction quality assurance, which is the best way to minimize the risk of holes before performing an electric liner integrity survey. This situation is also a reminder that the specified maximum leakage rate must be selected rationally (see Section 2.5.3).

### *4.2.4. Use of the electric leak location survey technology*

An inquiry based on data collected by two suppliers of electric leak location surveys (Beck & Darilek, 2016) and summarized by the author of this paper has shown that 2% of the geomembrane liner surface area installed in the United States in 2014 was subjected to electric leak location survey, which is very small, compared to 21% in the province of Quebec in 2014 (Charpentier *et al.*, 2016).

## 4.3. Conclusion on leakage reduction by measures taken during construction

The measures taken during construction to reduce the number and size of holes (and therefore, reduce leakage) are useful but not sufficient. These measures do not replace good workmanship in geomembrane liner installation, and they do not replace adequate design.

Measures at the design stage are often necessary in addition to the measures taken at the construction stage. A general characteristic of these measures is that they generally associate complementary materials:

- Association geomembrane/geotextile, the geotextile protecting the geomembrane from adjacent materials (see Section 5).
- Association geomembrane/clay to form a composite liner (see Section 6).
- Association geomembrane/drainage layer/geomembrane thereby forming a double liner (see Section 7).

## 5. Leakage Reduction by Controlling Geomembrane Damage

### 5.1. Geomembrane protection using a geotextile

Holes in geomembranes car result from geomembrane puncture by sharp objects (generally stones) during construction and in service. The state of practice is to use nonwoven geotextiles for geomembrane protection, a technique initiated by the author of this paper in 1971 (Giroud, 1973).

Nonwoven geotextiles are available with different masses per unit area. There is currently wide discrepancy between practices in different countries: for example, nonwoven geotextiles with a mass per unit area of the order of 500 g/m$^2$ are typically used in North America to protect geomembranes compared to 1000 g/m$^2$ frequently used in Europe. In technically advanced cases, a mass per unit area of the order of 2000 g/m$^2$ is not uncommon. This was done, for example, for the rehabilitation of several masonry dams with a very rough upstream face. An example is illustrated in Figs. 2 and 3.

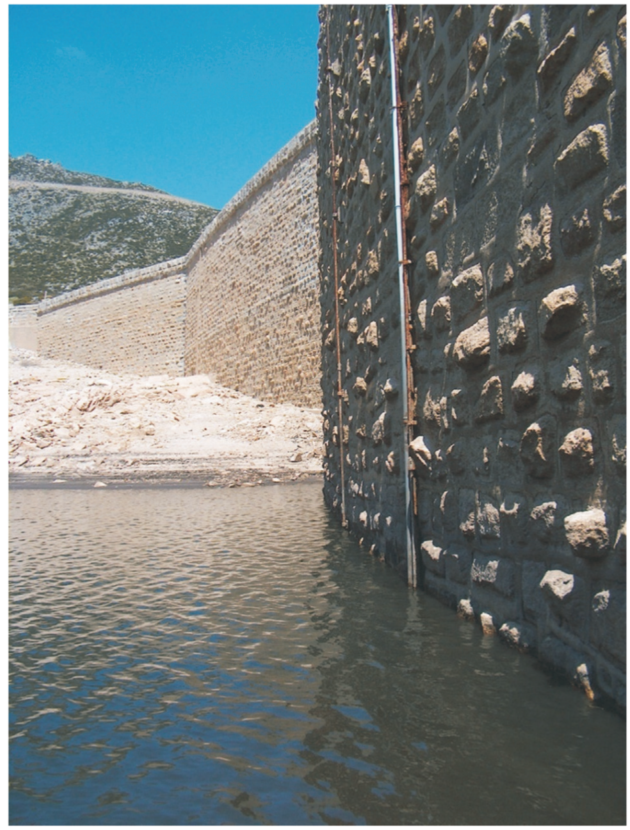

**Figure 2** - Face of a masonry dam on which a nonwoven geotextile with a mass per unit area of 2000 g/m$^2$ was placed prior to installing a geomembrane, Covão do Ferro Dam, Portugal [Courtesy Carpi].

### 5.2. Attachment to appurtenant structures

*5.2.1. Statement of the problem*

Good installers know how to make attachments to appurtenant structures that are leak-proof provided the structure has a simple geometry. However, geomembrane liners can rupture while in service next to their attachment to a rigid structure. In fact, a significant fraction of observed leakage of geomembrane-lined facilities occurs at or near the attachments between the geomembrane and rigid appurtenant structures.

Causes of geomembrane failure next to attachment to a rigid structure include:

- Geomembrane failure due to stresses induced by large differential settlement between the embankment that supports the geomembrane and the rigid structure.
- Geomembrane failure due to stresses induced by repeated displacement of geomembrane by wind action, by wave action, or by cycles of filling-emptying of the reservoir.

Two failure modes are observed: (i) tensile rupture of the geomembrane; and (ii) failure of the geomembrane seam that is closest to the attachment. Indeed, seams are generally weaker that the geomembrane and the seam geometry causes stress concentration by a factor of the order of 2 (Giroud *et al.*, 1995). This is particularly true in the case of polyethylene geomembranes when the seam closest to the attachment is an extrusion seam, which is weaker that the fusion seam.

The first of the above mentioned two causes (differential settlement) is well known. In contrast, the second cause (repeated displacement of the geomembrane) has not received sufficient attention. Repeated displacement of the geomembrane is, in fact, a major cause of geomembrane seam failure located next to an attachment. The geomembrane being restrained on one side of the seam and free to move on the other side, the seam is subjected to repeated tension and bending, which progressively causes fatigue of the seam and, eventually, cracking, especially in the case of extrusion seams of HDPE geomembranes. The author of this paper works on a large reservoir where several tens of extrusion seams have thus failed as a result of repeated wind action.

The two aspects to be considered when dealing with attachments are: (i) geomembrane selection, and (ii) geometric considerations, *i.e.* shape of the rigid structure and configuration of the geomembrane in the vicinity of the attachment.

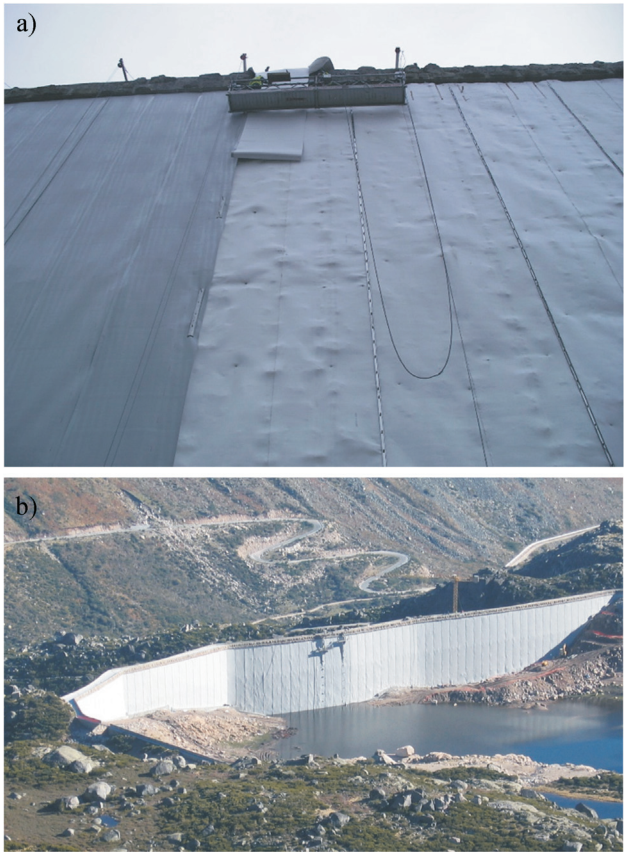


**Figure 3** - Rehabilitation of a masonry dam: (a) placement of the geomembrane on the geotextile on the upstream face of Covão do Ferro Dam, Portugal, and (b) view of the completely rehabilitated dam [Courtesy Carpi].

### *5.2.2. Selection of the geomembrane for withstanding differential settlement at attachment*

A theoretical analysis of the case of differential settlement between an embankment and the rigid structure to which a geomembrane is attached has been conducted (Giroud & Soderman, 1995, Giroud, 2005). The analysis demonstrates that the factor of safety against geomembrane rupture in this case is the square root of the ratio of the ultimate co-energy of the geomembrane and the required co-energy:

- The ultimate co-energy is the area between the tension-strain curve of the geomembrane and the tension axis (*i.e.* the vertical axis). This is the area hatched in red in Fig. 4, *i.e.* area ADE, with E being the end of the tension-strain curve (or, more strictly, the end of the useful portion of the tension-strain curve considered in design).
- The required co-energy depends on the magnitude of the settlement, the pressure of the contained liquid, and the interface friction angle between the geomembrane and the embankment soil. The required co-energy can be calculated for each specific case. The required co-energy is represented by the shaded area in Fig. 4 (*i.e.* area ABC). It is limited by the calculated tension in the geomembrane, Tc.

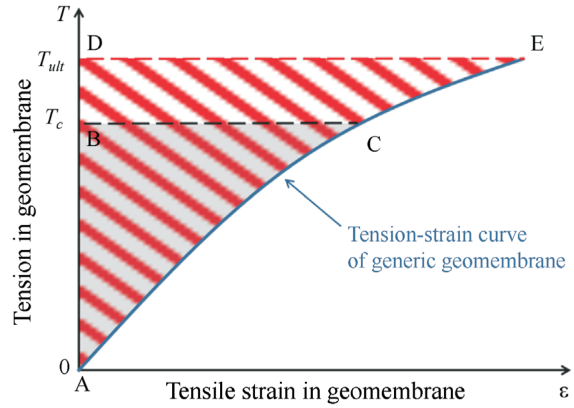


**Figure 4** - Required co-energy (grey area, ABC) *vs.* maximum co-energy (area with red stripes).

The factor of safety (which is the square root of the ratio of the hatched area and the shaded area, as indicated above) can be determined graphically. It can also be determined analytically if the equation of the geomembrane tension-strain curve is known. This has been done for HDPE geomembranes (4$^{th}$ degree parabola) and composite geomembranes that consist of a PVC geomembrane bonded to a nonwoven geotextile (straight line).

While the various available geomembranes are all quasi-impermeable and, therefore, quasi-equivalent from the viewpoint of impermeability, their tension-strain curves are very different as illustrated in Fig. 5. Based on the analysis, the geomembranes that have tension-strain curves close to the vertical axis (*i.e.* the geomembranes that have a small co-energy) are the most likely to rupture next to their attachments to rigid structures in case of differential settlement.

### *5.2.3. Shape of the structure and configuration of the connection*

Two geometric measures can be taken to prevent geomembrane rupture in the vicinity of a rigid structure to

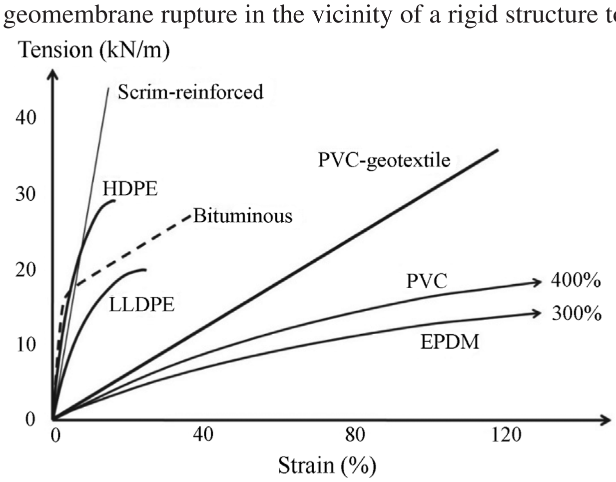


**Figure 5** - Tension-strain curves of various geomembranes.

which the geomembrane is attached: (i) eliminating the abrupt differential settlement by an appropriate shape of the structure (Fig. 6); and (ii) providing an extra length ("slack") to the geomembrane such that the geomembrane is not under tension after settlement of the embankment has taken place (Fig. 7). This solution has been used, in particular, in the Water Saving Basins of the Panama Canal Locks in 2016 (Fig. 8).

## 6. Leakage Reduction by Using Composite Liners

### 6.1. The concept of composite liner

#### *6.1.1. Definition of composite liner*

The term "composite liner" could have several meanings. It is generally used to designate a liner composed of two complementary materials: a synthetic component and a mineral component. The most frequent type of composite liner consists of a geomembrane and a layer of low-permeability soil, with the geomembrane overlying the low-permeability soil (Fig. 9). The low-permeability soil component of a composite liner is generally either a compacted clay layer or a bentonite geocomposite. The thickness of a compacted clay layer is typically between 0.3 and 1.5 m whereas the thickness of a hydrated bentonite geocomposite depends on the compressive stress applied during hydration and is typically approximately 10 mm after hydration under load. Whereas a compacted clay layer is two orders of magnitude greater than the thickness of a bentonite geocomposite, the permeability of bentonite is two orders of magnitude lower than the permeability of compacted clay.

#### *6.1.2. Effectiveness of composite liners*

A composite liner is effective, because, if there is a hole in the geomembrane (which should always be assumed at the design stage), the leakage rate is low because of the presence of the low-permeability soil next to the hole.

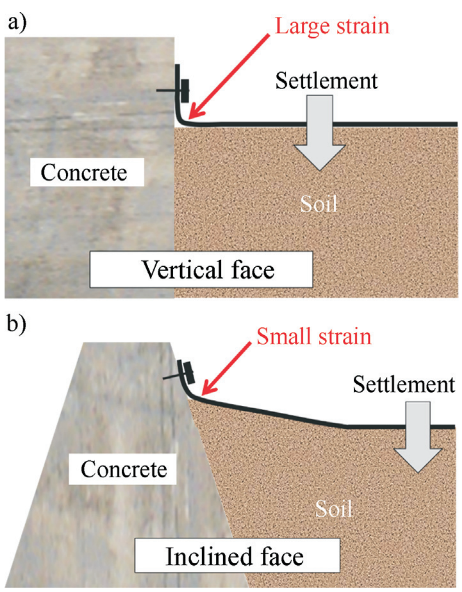


**Figure 6** - Impact of the shape of a rigid structure on the tensile stress and strain in the geomembrane next to the attachment, in case of differential settlement between concrete and soil: the stress and strain in the geomembrane are (a) large if the face of the structure is vertical, and (b) small if the face is inclined.

**Figure 8** - Slack in the geomembrane next to a rigid structure in the Water Saving Basins of the Panama Canal Locks, 2016 [Courtesy Carpi].

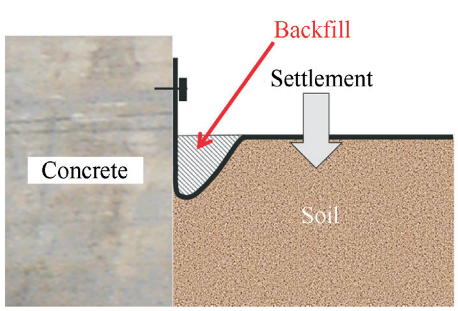


**Figure 7** - Slack in the geomembrane to reduce the tensile stress next to a rigid structure in case of differential settlement between concrete and soil [Courtesy Carpi].

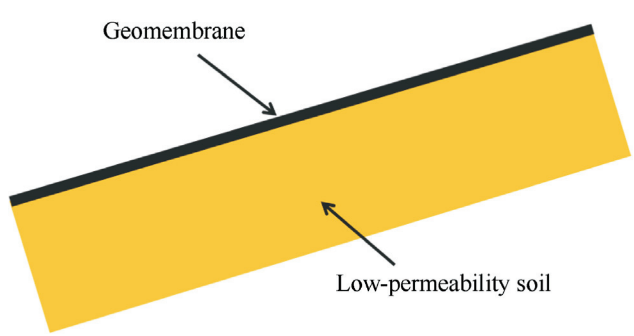


**Figure 9** - Composite liner.

This assumes that there is intimate contact between the geomembrane and the low-permeability soil. This intimate contact concept (Giroud & Bonaparte, 1989b) is the cornerstone of the effectiveness of composite liners. There is no intimate contact at locations where geomembrane exhibits wrinkles, which happens with geomembranes that have both high stiffness and high coefficient of thermal expansion. Therefore, when a composite liner is used, it is important to minimize wrinkles by good installation practice.

Composite liners are very effective in reducing leakage. As shown by Giroud & Bonaparte, (1989b) and others (*e.g.* Rowe, 1998, Touze-Foltz *et al.*, 2008), the rate of leakage through a composite liner is typically two to four orders of magnitude less than the rate of leakage through a geomembrane alone with the same hole size and frequency.

#### *6.1.3. A special type of composite liner*

In some technically advanced cases, a manufactured liner that consists of a layer of bentonite encapsulated between two geomembranes has been used. This is a special type of composite liner where the intimate contact between the two components exists even in case of wrinkles.

### 6.2. Precautions with the association of two liners

#### *6.2.1. Risk of uplift of the geomembrane component of a composite liner*

Composite liners are used extensively in landfills. However, composite liners should be used with caution in reservoirs and dams. A composite liner should not be directly exposed to the impounded liquid. As pointed out by Giroud & Bonaparte (1989a, p. 37): "Composite liners must be used with caution in liquid containment facilities. If the geomembrane component of the composite liner is directly in contact with the contained liquid (in other words, if the geomembrane is not covered with a heavy material such as a layer of earth or concrete slabs), and if there is leakage through the geomembrane, liquids will tend to accumulate between the low-permeability soil (which is the lower component of the composite liner) and the geomembrane, since the submerged portion of the geomembrane is easily uplifted. Then, if the impoundment is rapidly emptied, the geomembrane will be subjected to severe tensile stresses because the pressure of the entrapped liquids is no longer balanced by the pressure of the impounded liquid. Therefore, a composite liner should always be loaded, which is automatically the case in a landfill or in a waste pile, and which must be taken into account in the design of a liquid containment facility."

According to Thiel & Giroud (2011), "there would be a significant potential that a hole in the primary geomembrane could allow some liquid to get between the geomembrane and the underlying mineral component, and cause uplifting of the geomembrane due to gas formation, liner buoyancy, or unbalanced liquid pressure in case of fluctuation of the liquid level or turbulence in the pond. In general, unballasted (exposed) composite primary liners in ponds cannot be expected to perform as true composite liners. While the mineral component of such a primary composite liner system would serve to impede the leakage rate into the leakage collection layer, it may tend to act alone as a single mineral liner as the geomembrane uplifts, and equations for predicting leakage through holes in composite liners cannot be used with these systems. If an exposed primary composite liner is proposed, the owner should strongly consider minimizing the risk of holes in the geomembrane by having a first-rate construction quality assurance program and an electric hole-detection survey performed, and be committed to emptying the pond and repairing the geomembrane at the first sign of any leakage or geomembrane displacement. Considering these constraints, the authors do not generally recommend this configuration. Furthermore, the authors would recommend against using this configuration in cases where the geomembrane could be exposed to expected mechanical damage, and cases where there are conditions of quickly-fluctuating water levels and turbulence (*e.g.* pumped-storage projects, and ponds with aerators)."

The above comments make it clear that the problem is not the potential uplift of the composite liner as a whole, but the potential uplift of the geomembrane, resulting in separation of the geomembrane component of the composite liner from the low-permeability soil component. The above comments are so important that they are repeated below for the case of dams.

A composite liner should not be used on the upstream slope of an embankment dam. This is because during normal operation, in case of a leak, even small, through the geomembrane, water may accumulate in the space between the geomembrane and the soil component of the composite liner. In case of rapid drawdown of the reservoir, the pressure of the water entrapped between the two components of the composite liner is no longer balanced by the pressure of the water in the reservoir. Depending on the amount of water entrapped between the two components of the composite liner, and the weight of material (if any) above the composite liner, instability of the upstream slope may occur at the interface between the two components of the composite liner. Even if instability does not occur, the geomembrane and the materials (if any) above the geomembrane may be uplifted, which may have detrimental consequences such as permanent deformations or cracking.

Therefore, if a composite liner is used in a dam, the weight of materials on top of the geomembrane should be sufficient to exceed the pressure of the water likely to be entrapped between the two components of a composite liner. From a practical standpoint, this means that, if a composite liner is used in a dam, it should be inside the dam rather than being at the upstream face. As an additional benefit, the normal stress applied by the materials located on top of the geomembrane, reduces the amount of water likely to be entrapped between the two components of the composite liner. However, it should be pointed out that the use of composite liners is very rare in dams; the usual design consists of a geomembrane liner associated with a drainage layer (see Section 9.1.2).

The conclusion of this discussion is that a composite liner (or any two superposed liners) can be used in reservoirs and dams only if sufficient load is placed on the upper liner. This conclusion applies to all cases where a liner is placed on top of another liner (which should not be done, as a general rule).

As a consequence of the fact that two low-permeability layers should not be placed on each other (unless they are sufficiently ballasted), in dams, the layers underlying the geomembrane liner should be sufficiently permeable to avoid accumulation of water. Indeed, drainage layers are generally associated with geomembranes in dams (see Sections 9.1.2 and 9.3.4).

*6.2.2. Risk of desiccation of the low-permeability soil component of a composite liner*

When a composite liner is not covered with a protective soil layer, it is exposed to cycles of high and low temperatures, such as day-night cycles. As a result, the geomembrane temperature fluctuates. When the ambient temperature is high, the geomembrane temperature may reach 80 °C if the geomembrane is black. As a result, moisture from the low-permeability soil component evaporates. At the same time, wrinkles may be formed and vapor accumulates in the wrinkles and in the small space, if any, between the relatively flat portions of the geomembrane and the underlying material. At night, when the geomembrane cools down, the entrapped vapor condenses on the lower face of the geomembrane in the form of drops of water. If the geomembrane is on a slope, the drops of water flow downslope along the lower face of the geomembrane. After a number of day-night cycles, water is transferred from the upper part of a slope to the lower part of the slope. As a result, the low-permeability soil is desiccated in the upper part of the slope. The consequences of this desiccation are:

- If the low-permeability soil is compacted clay, the clay cracks and no longer performs its function of liner component.
- If the low-permeability soil is a bentonite geocomposite, the tendency of the bentonite to crack is counteracted by the geotextile components of the bentonite geocomposite. As a result, the bentonite geocomposite shrinks and adjacent panels get separated unless they were installed with generous overlaps.

Both mechanisms hamper the composite liner effect. The cracking and related shrinkage mechanisms can be prevented by covering the composite liner by a protective soil layer within a few weeks after installation of the geomembrane, in particular on slopes. This recommendation is particularly important in the case of the side slopes of landfills. Indeed, several instances of clay desiccation and bentonite geocomposite shrinkage have been observed on the side slopes of landfills where a composite liner had been left uncovered for months because the placement of waste was delayed.

*6.2.3. Conclusion on composite liners*

Composite liners are very effective because they reduce the leakage rate by orders of magnitude compared to a geomembrane used alone. However, the foregoing discussions show that there are two important risks with exposed composite liners: geomembrane uplift and low-permeability soil desiccation.

The case of a double liner discussed below is different from a composite liner. In a double liner the two liners are not in contact because there is a leakage detection layer in between. In other words, a double liner associates two liners that are not in contact, whereas a composite liner associates two liners that are in contact.

## 7. Leakage Reduction Using Double Liners

### 7.1. Definition and concept of double liner

*7.1.1. Definition and terminology*

Recognizing that individual liners may leak has led to the development of the concept of the double liner system, which is a very safe way to contain liquids with negligible leakage into the ground, even though individual liners may leak. The concept was presented by Giroud (1973) and used for the first time with two geomembranes in 1974, as described by Giroud & Gourc, (2014) (see Section 7.3).

In the terminology of geosynthetics engineering, a double liner consists of two liners separated by a drainage layer (Fig. 10). The upper liner is called the "primary liner" and the lower liner is called the "secondary liner". The purpose of the drainage layer is to collect, convey, detect and remove leakage that may occur through the primary liner, hence the terminology "leakage collection, detection and removal layer" or, more simply, "leakage collection layer" or "leakage detection layer".

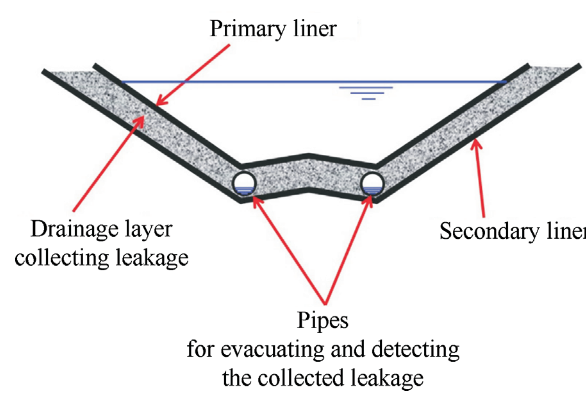


**Figure 10** - Double liner concept.

*7.1.2. The double liner concept*

The essential aspect of the double liner concept is that the thickness of liquid flow in the leakage detection layer must be as small as possible and less than the thickness of the leakage detection layer. As a result, there is no pressure buildup in the leakage detection layer and the hydraulic head on the secondary liner is small. Consequently, there is little leakage into the ground, even if there are some holes in the secondary liner.

Another aspect of the double liner concept is that leakage through the primary liner can be detected at the outlet of the leakage detection layer. It should be noted that the leakage detection layer is not a leak detection layer: it detects leakage, it does not find the leaks.

## 7.2. Functioning of a double liner

*7.2.1. Primary liner*

Theoretically, any type of liner can be used as the primary liner of a double liner. However, since the goal of a double liner is to minimize leakage, the rate of leakage through the primary liner should be as small as possible. To that end, a geomembrane or a composite liner should be used. The leakage rate through the primary liner is much lower if the primary liner is a composite liner than if the primary liner is a geomembrane.

Here, it is important to remember that composite liners should only be used if they are sufficiently ballasted to prevent the geomembrane component of the composite liner from being uplifted (see Section 6.2). As a result, the use of composite liners as primary liners is practically limited to landfills (since the weight of the waste ensures ballasting). In landfills, it should be remembered that the composite liner should be promptly covered by a protective soil layer, in particular on the side slopes, to prevent desiccation and related shrinkage of the low-permeability soil component of the composite liner (see Section 6.2.2).

Rough orders of magnitude of typical leakage rates through the primary liners of landfills are: 100 to 1000 lphd ($10^{-10}$ to $10^{-9}$ m/s) for geomembrane alone; 0.1 to 1 lphd ($10^{-13}$ to $10^{-12}$ m/s) for composite liner with compacted clay layer as the low-permeability soil component; and 0.01 to 0.1 lphd ($10^{-14}$ to $10^{-13}$ m/s) for composite liner with bentonite geocomposite as the low-permeability soil component.

As indicated in Section 6.1, a composite liner consists of a geomembrane underlain by a low-permeability soil layer. In general, the low-permeability soil layer component of a composite liner can be a layer of compacted clay or a bentonite geocomposite. However, if a composite liner is used as the primary liner of a double liner system, it is not recommended to use a layer of compacted clay as the low-permeability soil component of the primary liner, because the discharge of water expelled from the clay (when the clay compresses under load) can be of the same order of magnitude as, and even greater than, leakage through the primary liner. As a result, the liquid detected by the leakage detection layer can be incorrectly considered to be due to leakage only.

The rate at which water is expelled from a clay layer subjected to a load applied progressively (such as waste disposal in a landfill, or filling of a reservoir) can be calculated using equations for the consolidation of soil subjected to a load applied linearly with time (Giroud, 1983). Calculations done using these equations by Gross *et al.* (1990) gave the following rough orders of magnitude for typical landfill cases: 10 to 1000 lphd. These values are significantly higher than the typical leakage rate of 0.01 to 1 lphd for composite liners mentioned above. Clearly, leakage monitoring cannot be done using a leakage detection layer overlain by a primary liner where the low-permeability soil component is a compacted clay layer. Therefore, when the primary liner of a double liner is a composite liner (which is a good design to reduce leakage), the low-permeability component of the composite liner should be a bentonite geocomposite (or the special composite liner described in Section 6.1.3).

*7.2.2. Functioning of the leakage collection and detection layer*

The flow capacity of the leakage collection and detection layer is essential. This layer must have an appropriate slope and the material of this layer must have high hydraulic conductivity to rapidly convey the flow with a hydraulic head as small as possible. Indeed, rapid flow ensures rapid leakage detection and small hydraulic head is required to ensure small leakage rate through the secondary liner, *i.e.* small rate of leakage into the ground. The leakage collection and detection layer must be designed with a high factor of safety, for example with a flow capacity at least ten times the expected leakage rate through the primary liner, to ensure that there will be no pressure buildup in the leakage collection and detection layer unless there is a catastrophic failure of the primary liner. In that case, warning will be provided by the abnormally high detected leakage rate, the double-lined containment facility should then be put out of service, and the liner should be repaired.

Adequate leakage detection layer materials are gravel and geosynthetic drainage layers with low compressibility, such as geonets and drainage geocomposites with a geonet core. Sand is not adequate because it is not sufficiently permeable to ensure rapid flow and it retains water by capillarity.

The risk of clogging is a legitimate concern regarding all drainage layers. Because of the very small flow rate, clogging by migrating particles is not typically expected in leakage collection and detection layers, unless sand is used as the drainage material and geotextile filters are misused. Another possibility is clogging by precipitation of calcium carbonate, which may happen in the presence of concrete (for example for drainage associated with concrete dams or concrete-faced dams). In these dams, the drainage system can be washed periodically in case of evidence of flow capacity reduction.

The above discussion is related to the requirements to ensure there is a low hydraulic head on the secondary liner. Requirements for accurate leakage detection are presented in Section 8.3.2.

#### *7.2.3. Important requirement for the secondary liner*

The secondary liner of a double liner system plays an essential role. The only suitable material for a secondary liner is a geomembrane because the leakage rate through the primary liner is generally so small that, if the secondary liner is a soil, even a low-permeability soil such as clay, much of the leakage collected will flow through the soil rather than being conveyed, detected and removed.

The secondary liner is not simply a back-up to the primary liner. It has an essential role for proper leakage collection and measurement. As indicated in Section 7.2.1, typical leakage rate per unit area through a geomembrane-only primary liner is of the order of $10^{-10}$ to $10^{-9}$ m/s in a landfill and $10^{-9}$ to $10^{-8}$ m/s in a reservoir. As also indicated in Section 7.2.1, smaller leakage rates can be expected with a composite liner primary liner. These leakage rates per unit area are of the same order as the vertical flow rate through compacted clay with a hydraulic gradient of 1. Clearly, if the secondary liner is made of clay only (rather than geomembrane or clay overlain by a geomembrane), at least a large fraction of the collected leakage will infiltrate into the clay and, therefore, will not be detected. If the secondary liner is made of only a bentonite geocomposite, most of the liquid leaking through the primary liner will be used to hydrate the bentonite. In other words, if the leakage detection layer does not rest on a geomembrane, the rate of leakage through the primary liner will not be measured.

### 7.3. Case history: the first double liner

The first double liner with two geomembranes was constructed in 1974 and has been in continuous service since then (Giroud & Gourc, 2014). The lined structure is a 10 m deep, 195 m long and 55 m wide water reservoir, located on top of a 50 m high 33° slope. The geotechnical study concluded that the slope was stable, but could become unstable in case of major leakage of water from the reservoir. Any risk of instability was unacceptable because a large chemical plant was, and still is, located at the toe of the slope. Because safety was essential, a double liner was recommended by the author of this paper. It is interesting to note that the need for strict leakage control resulted from the risk of geotechnical deterioration, which was emphasized in Section 2.5.1.

The primary liner is a 1.5 mm thick butyl rubber geomembrane. It is exposed (in other words, it is not covered with a protective layer). The secondary liner is a bituminous geomembrane. The leakage detection layer between the two liners is made of gravel stabilized with mortar. The reservoir has been monitored since the end of construction. No leakage was detected until 2004, *i.e.* 30 years after construction, when a trickle of water appeared at the outlet of the leakage detection layer. This indicates that the leakage collection and detection system performed its function.

The leak was repaired under water. It is interesting to note that the leak took place at the seam closest to the concrete intake structure. This confirms the fact that high stresses can develop next to rigid structures and that failure is likely to take place at seams due to stress concentration (see Section 5.2.1). It should be noted that the reservoir was not subjected to filling-emptying cycles, which could have caused greater stresses and more seam failures (see Section 8.3.3).

This case history shows that a butyl rubber geomembrane can last more than 40 years when it is exposed (*i.e.* with no protection) in a temperate climate with hot summers, which is remarkable. Ironically, the use of butyl rubber geomembranes has been practically discontinued in the 1990s, in part because they were thought to have insufficient durability. Indeed, several types of modern geomembranes would last longer than butyl rubber, *i.e.* longer than 40 years under the same conditions, which confirms the durability of modern geomembranes.

## 8. Quantitative Evaluation of Leakage

### 8.1. Data on holes in geomembranes

#### *8.1.1. Data on frequency of holes in geomembranes*

The frequency of holes is the number of holes per unit area (usually per hectare). Since the first publication presenting data on frequency and size of holes in installed geomembrane liners (Giroud & Bonaparte, 1989a), a number a studies have been published. It would be beyond the scope of this paper to review these studies. A summary was published by Giroud & Touze-Foltz, (2003) who stated "(i) The number of holes at the end of geomembrane installation with construction quality assurance is typically believed to be from 1 to 5 holes per hectare; these holes are generally small, and their number is smaller for large liners (*e.g.* greater than 2 ha) than for small liners. (ii) The number of holes caused by the placement of soil on top of the geomembrane varies in a wide range, from very few to 20 per hectare, depending on the amount of care taken during placement of soil on top of the geomembrane and the type of geomembrane protection used; these holes can be large (and often are)."

More recently, the author of this paper has reviewed data (Beck & Darilek, 2016) from more than 150 cases of electric liner integrity surveys performed on more than 250 hectares of HDPE geomembranes. This review has provided 5.4 holes/ha for HDPE geomembranes installed in the Unites States with typical construction quality assurance.

In conclusion, a number of holes of 5 or 6 per hectare can be considered typical at the end of geomembrane installation with construction quality assurance. In the case where there is no construction quality assurance, a greater hole frequency can be expected, as pointed out by Giroud & Bonaparte (1989a, p. 65), as follows: "A frequency of 25 holes per hectare or more is possible when quality assurance is limited to an engineer spot-checking the work done by the geomembrane installer".

*8.1.2. Data on size of holes in geomembranes*

Typical sizes of holes in geomembranes are summarized below:

- Holes smaller than 1 $mm^2$ cannot be detected by electric leak location survey with the current technology (2016).
- Minimum hole sizes that can be detected by electric leak location survey are of the order of: (i) 1 $mm^2$ under the low depth of water required to perform the electric leak location survey under optimum conditions; (ii) 10 $mm^2$ under a soil layer up to 0.3 m thick; (iii) 30 $mm^2$ under a soil layer up to 0.6 m thick, and (iv) 100 $mm^2$ under a soil layer up to 1.0 m thick.
- A crack due to stress cracking may have an area of the order of 10 $mm^2$. However, it may increase to 100 $mm^2$ or more if the geomembrane remains under tension after the opening of the crack.
- The size of holes due to puncture by stones may be of the order of 10 $mm^2$ or more.
- Holes in the geomembrane due to tears by construction equipment during placement of a layer of soil on top of the geomembrane are generally large, *e.g.* 100 $cm^2$ or even 1000 $cm^2$ (*i.e.* 10,000 or even 100,000 $mm^2$).

*8.1.3. Relationship between frequency and size of holes in geomembranes*

Holes present in a geomembrane at the end of installation of the geomembrane subjected to strict construction quality assurance are less numerous and smaller than assumed in the past and reported in papers published in the 1990s and even in the early 2000s.

After reviewing published data and recent data provided to the author of this paper by suppliers of electric liner integrity surveys (Beck & Darilek, 2016), the hole size distribution presented in Table 2 has been established by the author of this paper for the case of strict construction quality assurance with a 2 mm thick HDPE geomembrane. The following comments can be made on Table 2:

- The hole size ranges have been selected to be such that the spatial frequency is the same for each hole size range: one hole per hectare.
- The hole sizes are expressed as areas ($mm^2$) rather than as diameter (mm) because the area is generally used in leakage calculations.
- This hole size distribution has been established by the author of this paper to be slightly conservative for liner systems subjected to strict construction quality assurance. This level of conservativeness has been confirmed by a provider of electric liner integrity survey with outstanding experience.

The following comments can be made on the data presented in Table 2:

- The frequency of geomembrane holes that corresponds to strict construction quality assurance is 6 per hectare. This is consistent with the 5.4/ha mentioned Section 8.1.1, but it has been rounded.
- Among those 6/ha, 4 holes per hectare can be detected by electric liner integrity survey because they are equal to or larger than 1 $mm^2$. This assumes that the electric liner integrity survey is effective, which depends on either intimate contact between the geomembrane and the underlying soil or the use of a geomembrane with a thin conductive layer at its lower face (see Section 4.2). Therefore, if an effective electric leak location survey is performed at the end of geomembrane installation and the detected holes are repaired, the remaining hole frequency is 2/ha, and these holes are small (*i.e.* smaller than 1 $mm^2$).
- However, if a soil layer is placed on top of a geomembrane that has been subjected to electric leak location survey, new holes will be created depending on the level of care used for soil placement and the level of construction quality assurance associated with this opera-

**Table 2** - Geomembrane hole size distribution for 2 mm thick HDPE geomembrane installed with strict construction quality assurance.

| Possibility of detection by electric liner integrity survey | Hole size range | Hole spatial frequency for the considered hole size range |
|---|---|---|
| Detectable | 5-10 $mm^2$ | 1 hole/hectare |
| | 3-5 $mm^2$ | 1 hole/hectare |
| | 2-3 $mm^2$ | 1 hole/hectare |
| | 1-2 $mm^2$ | 1 hole/hectare |
| Not detectable | 0.1-1 $mm^2$ | 1 hole/hectare |
| | < 0.1 $mm^2$ | 1 hole/hectare |

tion. A second round of electric leak location survey can then be performed. For example, if the soil layer is 0.6 m thick, holes greater than 30 $mm^2$ can then be detected and repaired.

As seen below in Section 8.2, the rate of leakage is proportional to the hole area in the case of a geomembrane resting on a permeable soil, but it is not proportional to the hole area in the case of a composite liner. Therefore, averaging the data presented in Table 2 is delicate.

Tentatively, it can be said that the data presented in Table 2 can be combined in the following statement: A geomembrane liner at end of installation with construction quality assurance can be expected to have 4 holes per hectare with a hole area of 4 $mm^2$. This is not far from the recommendation made in 1989 by Giroud & Bonaparte (1989a, p.64): 2.5 holes per hectare with a hole size of 3.1 $mm^2$ (*i.e.* a diameter of 2 mm).

In 1989, Giroud & Bonaparte (1989a) also made a recommendation for design calculations: 2.5 holes per hectare with a hole size of 100 $mm^2$. This recommendation is still followed with a slight modification: over the years, the practice for engineers as well as researchers has been to consider 5 holes per hectare with a hole size of 100 $mm^2$. This practice may be considered to include some holes caused by the placement of soil on top of the geomembrane. (However, it should be noted that, in 1989, it was not realized that a significant number of additional holes could be caused by placement of a soil layer on top of the geomembrane.) (See Section 8.1.1.)

## 8.2. Theoretical evaluation of leakage rate

*8.2.1. Equations for leakage rate calculation*

A number of equations have been proposed for the calculation of leakage rate through liners. Only typical equations are presented below. The equations make it possible to calculate a leakage rate assuming values for the various parameters, such as the number and size of geomembrane holes, which can be assumed from data presented above in Section 8.1. The equations depend on the type of geomembrane liner: geomembrane alone on permeable soil (Section 8.2.2); composite liner (Section 8.2.3); and geomembrane on a semi-permeable soil (Section 8.2.4). Also, the impact of wrinkles on the leakage rate can be quantified (Section 8.2.5) and the determination of leakage rate calculation in the case of double liners is addressed (Section 8.2.6).

Once leakage rate through a geomembrane hole, $Q$, has been calculated, the leakage rate per unit area, $q$, can be derived as follows (see Section 2.3):

$$q = 8.64 \times 10^{7} NQ \qquad (1)$$

with the leakage per unit area, $q$, in lphd, the frequency of holes, $N$, given as a number of holes per hectare, and the leakage rate in a hole, $Q$, in $m^3/s$.

*8.2.2. Rate of leakage through geomembrane liners*

In the case of a geomembrane liner resting on a permeable medium, such as a permeable ground or a leakage detection layer, the leakage rate can be calculated using Bernoulli's equation as suggested by Giroud (1984b):

$$Q = 0.6a\sqrt{2gh} \qquad (2)$$

where $Q$ = leakage rate, $a$ = hole area, $g$ = acceleration due to gravity, and $h$ = hydraulic head. Eq. 2 can be used with any set of coherent units. The basic SI units are: $Q$ ($m^3/s$), $a$ ($m^2$), $g$ (9.81 $m/s^2$), and $h$ (m).

The leakage rate per unit area is given by the following equation derived from Eqs. 1 and 2:

$$q = 51.84aN\sqrt{2gh} = 230aN\sqrt{h} \qquad (3)$$

with the leakage per unit area, $q$, in lphd, the hole size in $mm^2$, the frequency of holes, $N$, given as a number of holes per hectare, the hydraulic head, $h$, in meters, and $g = 9.81\ m/s^2$.

*8.2.3. Determination of the rate of leakage through composite liners*

The usual equation for calculating the rate of leakage through of holes in the geomembrane component of a composite liner is (Giroud 1997):

$$Q = 0.21\left[1 + 0.1\left(\frac{h}{t}\right)^{0.95}\right] a^{0.1} h^{0.9} k^{0.74} \qquad (4)$$

where $Q$ = leakage rate through one hole, $a$ = hole area, $t$ = thickness of the low-permeability soil component of the composite liner, $h$ = hydraulic head on top of the geomembrane, and $k$ = coefficient of permeability of the low-permeability soil component of the composite liner. This equation is applicable only with the following units: $Q$ ($m^3/s$), $h$ (m), $t$ (m), $a$ ($m^2$), $k$ (m/s).

Several equations derived from the above equation or presented with the same format have been proposed for several specific cases (Touze-Foltz & Giroud, 2003, Touze-Foltz *et al.*, 2008).

*8.2.4. Determination of the rate of leakage in the case of semi-permeable soils*

In the case where a geomembrane rests on a soil that is neither a high-permeability soil nor a low-permeability soil, a methodology has been developed by Giroud *et al.*, 1997b.

*8.2.5. Impact of geomembrane wrinkles on the rate of leakage through a composite liner*

The equations presented above in Section 8.2.3 are based on the assumption that there is intimate contact between the geomembrane and the low-permeability soil component of the composite liner. In the field, geomembranes often exhibit wrinkles.

Wrinkles have no impact on the leakage rate if the considered liner is a geomembrane alone on a permeable material. In contrast, in the case of a composite liner, the leakage rate can be significantly increased if the geomembrane exhibits wrinkles. This effect has been quantified by Rowe (2012), Giroud & Touze-Foltz (2005), and Giroud & Wallace (2016).

*8.2.6. Determination of the rate of leakage in case of double liners*

In the case of a double liner, the rate of leakage through the primary liner (which can be measured thanks to the leakage detection layer) can be calculated using the equations presented in Section 8.2.2 (if the primary liner is a geomembrane alone) or the equation presented in Section 8.2.3 (if the primary liner is a composite liner).

It is important to note that the rate of leakage through the primary liner is not the rate of leakage into the ground. In the case of a double liner, the determination of the rate of leakage into the ground requires three steps: (i) determination of the rate of leakage through the primary liner; (ii) analysis of the flow in the leakage detection layer and determination of the hydraulic head on the secondary liner; and (iii) determination of the rate of leakage through the secondary liner, which is the rate of leakage into the ground.

A methodology for the analysis of the liquid flow in the leakage detection layer and the determination of the resulting hydraulic head on the secondary liner is provided by Giroud *et al.* (1997a).

**8.3. Leakage rate measurement**

*8.3.1. The two situations of leakage rate measurement*

To measure the leakage rate, the containment structure (*e.g.* landfill, reservoir, dam) must be in service or under conditions similar to the conditions in service, such as in a test where a reservoir is filled with water up to the normal service level. Two cases can be considered for the measurement of the resulting leakage: the case where there is a double liner system (which makes it possible to directly measure the rate of leakage through the primary liner); and the case where a liner is used (which requires an indirect evaluation of the leakage rate).

*8.3.2. Measurement of leakage rate in case of double liner*

If there is a double liner system, the leakage rate is obtained by monitoring the outlet of the leakage detection layer. This method is reliable unless the leakage detection layer is not functioning properly. The functioning of leakage detection layers was addressed in Section 7.2.2. Possible errors in the measurement of leakage using the leakage detection layer of a double liner are summarized below. The leakage rate may be overestimated due to the following errors:

- In the first days following the filling of the reservoir, if the water impounded in the reservoir is relatively cold, condensation of water vapor entrapped in the leakage detection layer may result in liquid flow in the leakage detection layer. If this liquid flow is limited in time (*e.g.* a few days), it should not be interpreted as leakage (a case history is presented by Giroud & Gourc, 2014).
- Precipitation water entrapped into the leakage detection layer material during construction may flow toward the outlet after the reservoir is put in service. Such water, if any, should not be interpreted as leakage.
- If the primary liner is a composite liner that consists of geomembrane on clay, water expelled from the clay under compressive stress due to the weight of the impounded liquid (in the case of a reservoir) or the weight of waste (in the case of a landfill) may be falsely interpreted as leakage. As indicated in Section 7.2.2, composite liners where the low-permeability soil component is compacted clay should not be used as the primary liner of a double liner if accurate leakage rate measurement is desired.
- Precipitation and run-off water may percolate in an anchor trench where the primary liner, the leakage detection layer and the secondary liner are anchored. Part of this water may intrude into the leakage detection layer. To prevent such intrusion, it is necessary to seam together the primary and the secondary liners in the anchor trench. Also, the configuration of the anchor trench and surrounding soil should be such that precipitation and runoff waters do not penetrate into anchor trenches.
- In exceptional cases, there may be false leakage detection if high ground water percolates into the leakage detection layer through the secondary liner.

The above causes of error lead to an overestimation of the leakage rate. In contrast, a fraction, or all, of the leakage through the primary liner may not be detected for the following reasons:

- Some or all of the water collected by the leakage detection layer may leak through the secondary liner.
- Wrinkles in the geomembrane secondary liner may block the flow of water collected by the leakage detection layer.
- Water may be retained by capillarity in the leakage detection layer (for this reason sand should not be used as the leakage detection layer material).

Leakage rate measurement using a double liner is not perfect, but it is much more accurate than leakage rate measurement using a water balance test.

*8.3.3. Water balance tests*

If there is a single liner, the only way to measure leakage rate is a water balance test (also called "ponding test"). The water balance test consists in filling a reservoir with water to the normal service level and measuring the water level drop as a function of time during a certain period of time (*e.g.* 14 days). Corrections for evaporation, rainfall and runoff must be done, but it is difficult to make accurate corrections and errors are frequent. The corrected water level drop (in mm/day) can be converted into leakage rate (in lphd) as indicated in Section 2.3.

The water balance test has the merit of testing at once an entire reservoir. In particular, it detects and measures leakage due to all causes, not only holes in the geomembrane. However, the water balance test has many drawbacks:

- The water balance test is impractical due to large amount of water required,
- The water balance test is time consuming (it typically takes several weeks in a relatively small reservoir, *i.e.* 1 ha, and would take more time in a large reservoir).
- The water balance test is not accurate due to the difficulty in accurately evaluating evaporation.
- The water balance test lacks sensitivity due to the very small impact of leakage on water level. Thus, a level drop of only 1 mm/day, which is hardly measurable, is equivalent to 10,000 lphd, which is a significant rate of leakage.
- According to Darilek & Laine (2013), an error of 2 mm on water level is possible. Over 14 days, this amounts to an error of about 1400 lphd. If the specified maximum leakage rate is 2000 lphd, the error is 70%, and more if there are errors on evaporation and rainfall corrections.
- The water balance test does not find leaks, but only measures leakage. Therefore, it does not find holes in the geomembrane. However, some of the holes can be found by a subsequent visual inspection guided by the results of the water balance test.
- Performing the water balance test may damage the liner if it has not been designed for filling/emptying cycles.
- Activities of the crew involved in conducting the test, inspecting the liner and repairing the detected geomembrane holes may cause additional damage to the geomembrane liner.

The limitations of the water balance test are illustrated by the following case history (Peggs, 2014). A single liner (0.91 mm thick reinforced polypropylene geomembrane placed on a needle-punched nonwoven geotextile on subgrade) was installed in a typical rectangular reservoir with a water depth in service of 4.5 m. The reservoir size was 7,000 $m^2$. There were four penetrations (*e.g.* pipe boots), including a complex one. The specified maximum water level drop was 6 mm in 14 days (which is equivalent to $4.8 \times 10^{-9}$ m/s = 4170 lphd). The sequence of events was as follows:

- The water balance test was performed with the reservoir filled to the service level. The drop in water level over the 14 day test period was more than 10 times higher than the specified 6 mm. (It was about 66 mm /14 days = 47,000 lphd = $5.5 \times 10^{-8}$ m/s.)
- The reservoir was emptied, the liner visually inspected, and repairs made.
- The reservoir was filled, and the water balance test redone. There was insufficient improvement (21 mm/14 days).
- Three more times, the reservoir was emptied, inspection and repairs were made, and the 14-day water balance test was performed, but the measured leakage rate remained high (112 mm/14 days, 23 mm/14 days, and finally more than 130 mm/14 days).
- After several months thus wasted, the geomembrane liner was removed. A second contractor was hired to install a completely new liner identical to the preceding liner. The new liner easily passed its first water balance test (in fact, the leakage rate was so small that it was not measurable).

It should be noted that there were three other similar reservoirs in the same facility with only one or two penetrations each (compared to four penetrations in the considered reservoir). These three reservoirs passed the water balance test the first or second time.

The leakage was increasing in spite of repairs. The leakage increased for at least two reasons:

- Additional damage to the geomembrane liner was caused by the team walking on the geomembrane to perform the visual inspection, and by the crew performing the repairs.
- The cycles of emptying-filling of the reservoir caused repeated displacement of the geomembrane, which resulted in fatigue of the geomembrane at the attachments between the free-to-move geomembrane and the fixed appurtenant structures.

The following additional comments can be made about this case history:

- Visual inspection does not find all holes.
- A number of holes were found at the geomembrane attachments to penetrations (*e.g.* pipe boots).
- Based on observations and comparison with the three other reservoirs, filling/emptying cycles induced stresses in the geomembrane, next to appurtenant structures and pipes.
- It is possible to think that the large fluctuations in the measured water level drops observed on this reservoir are due to the potential errors associated with the interpretation of the water balance test.

The following lessons can be learned from this case history:

- Good workmanship in liner installation is essential to ensure a small rate of leakage.
- Measures taken to find and repair holes in geomembranes are useful, but they do not replace good workmanship.

- The difference between good workmanship and poor workmanship in terms of leakage rate can be very significant. Indeed, in the foregoing case history, the difference was by about two orders of magnitude, between a measured leakage rate much less than the specified value and a measured leakage rate 20 times more than the specified value.
- The number of geomembrane holes caused by excessive activity on a geomembrane liner (by the team performing visual inspection and by the crew repairing the detected holes) may be greater than the number of repaired holes. If inspections and repairs are not properly done, the procedure may, in fact, increase the leakage rate. Therefore, if inspections and repairs are needed, they must be performed with great care.
- The number of appurtenances (*e.g.* pipe boots and various penetrations, ancillary concrete structures) should be minimized.
- Appurtenances must be designed with a geometry that ensures long-term performance of the attached geomembrane.
- If a reservoir is subjected to frequent filling/emptying cycles, the liner should be designed accordingly. In particular, attachments of the geomembrane to appurtenant structures should be such that the geomembrane is not damaged by expected displacements.
- In conclusion, the water balance test is not only prone to errors but also potentially destructive.

Above, there are good lessons for design engineers: they must treat geomembrane liners as seriously as they treat geotechnical issues. Design engineers, who carefully take into account the impact of rapid drawdown on slope stability, should take into account the impact of multiple filling/emptying cycles on geomembrane liners. Also, design engineers should understand that attaching geomembranes to appurtenant structures in a waterproof manner (which geomembrane installers generally do well) is not sufficient. The geometry of the appurtenant structure and the configuration of the geomembrane liner in the vicinity of the appurtenant structure should be designed to ensure long-term performance, as discussed in Section 5.2. This is the responsibility of the design engineer.

### 8.4. Typical leakage rates for geomembrane-lined landfills and reservoirs

#### *8.4.1. Typical leakage rates for geomembrane-lined landfills*

In landfills in the United States a maximum leakage rate of 200 lphd is often specified for the primary liner of double-lined landfills. As indicated in by Peggs & Giroud (2014), the average hydraulic head on the primary liner of landfills during the active leachate production can be considered to be approximately 30 mm. Calculations, performed with Eq. 3 (*i.e.* for a geomembrane-alone primary liner) and a hydraulic head of 30 mm, show that:

- With holes larger than a few $mm^2$, the leakage rate through a geomembrane is significantly higher than 200 lphd even under the small hydraulic head that exists in properly designed landfills.
- If the hole size is 1 $mm^2$, a leakage rate of 200 lphd is obtained with 5 holes per hectare.

The 1 $mm^2$ hole size shows that a maximum leakage rate of 200 lphd for a typical landfill hydraulic head can be achieved only by a very high-quality geomembrane liner installed with strict construction quality assurance and, preferably, subjected to an electric liner integrity survey (see Sections 1.10 and 3.3). This is why, in landfills, a composite primary liner is generally used to meet the 200 lphd maximum leakage rate specification; a leakage rate through the primary liner of the order of 1 lphd can then be achieved.

#### *8.4.2. Typical leakage rates for geomembrane-lined reservoirs*

Typically observed leakage rates for a 5 m deep reservoir range from 5000 to 100,000 lphd and beyond. Calculations done using Eq. 3 (*i.e.* for a geomembrane-alone liner) show that 5000 lphd (*i.e.* a water level drop of 0.5 mm/day) correspond to a geomembrane with 5 holes per hectare having a hole area of 2 $mm^2$. Such a high quality geomembrane can only be achieved under perfect conditions during construction, which can be described as follows:

- Firm and smooth supporting soil;
- Geotextile protection as needed;
- Dry and clean working conditions;
- Moderate temperature and no wind;
- No interference from the general contractor and other contractors;
- No appurtenant structures;
- Cooperation between good geomembrane installer and good quality assurance team; and
- Electric leak location followed by repair of detected holes.

In contrast, a rate of leakage higher than 5000 lphd and as high as 100,000 lphd (10 mm/day water level drop) or even higher may happen in many typical projects where one or more of the above "perfect conditions" are not met.

## 9. Leakage Control in Geomembrane-Lined Dams

### 9.1. Overview of uses of geomembranes in dams

#### *9.1.1. Types of dams where geomembranes are used*

Geomembranes have been used in more than 200 large dams, mostly in the past four decades. Geomembrane-lined dams include tailings dams and a variety of hydraulic dams:

- Embankment dams: (i) rockfill dams; and (ii) earth dams;
- Concrete-related dams: (i) roller compacted concrete dams; (ii) conventional concrete dams; and (iii) masonry dams.
- Cemented-material dams (such as hardfill dams).

Geomembranes have been used in new embankment dams and new roller compacted concrete dams, as well as in the rehabilitation of all types of dams: concrete-faced rockfill dams, bituminous concrete-faced rockfill dams, wood-faced rockfill dams, earth dams, conventional concrete dams, masonry dams, and roller compacted concrete dams.

*9.1.2. Typical configuration*

In most cases, the geomembrane is used at the upstream face of the dam. Fig. 11 illustrates schematically the typical configuration applicable to both embankment dams and concrete dams. It is important to note that a drainage layer is always associated to the geomembrane (see Sections 6.2.1 and 9.3.4). This figure will be useful to follow the subsequent discussions.

## 9.2. Leakage control goals specific to dams

*9.2.1. Differences between dams and other liquid containment structures*

So far in this paper, the emphasis was on landfills and reservoirs, because this is where most work on leakage control has been done in the field of geosynthetic engineering. Hereafter, aspects of leakage control specific to dams are addressed. This is interesting because the approach to leakage control is different in dams than in other liquid containment structures.

The goal and practice of controlling leakage in the case of dams is not exactly the same as the goal and practice of controlling leakage in the case of landfills and reservoirs.

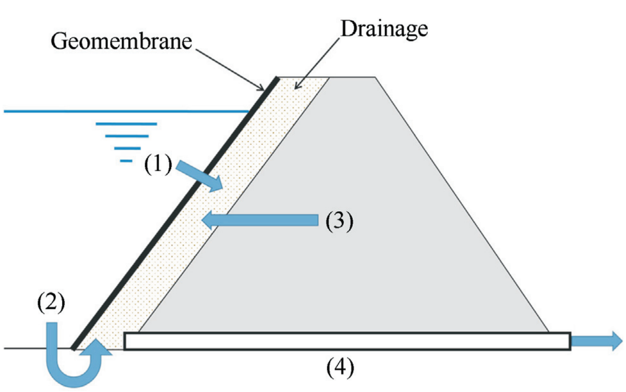


**Figure 11** - Schematic configuration of a geomembrane-lined dam. The drainage system collects (1) water leaking through the geomembrane, (2) water flowing around the geomembrane, and (3) water (if any) drained from the dam, and (4) conveys the collected water to the downstream side of the dam.

The two differences are: (i) a zero-leakage goal is not relevant to dams; and (ii) controlling the presence and flow of water in the body of the dam is an essential consideration.

It should be noted that the discussions presented hereafter, which are specific to dams, are in part applicable to reservoirs surrounded by dikes or embankments.

*9.2.2. Irrelevance of the zero-leakage goal in dams*

Both geometric and environmental conditions that are specific to dams have an impact on the goal of leakage control goal in dams.

The geometry of geomembrane-lined dams is different from the geometry of geomembrane-lined landfills and reservoirs:

- In the case of landfills and reservoirs, the liquid is completely contained by the liner.
- In the case of dams, the liquid is, in great part, in contact with the natural ground and, therefore, a significant fraction of leakage takes place into the ground.

In addition to the fact that, in the case of geomembrane-lined dams, a significant fraction of the leakage takes place around the liner and not through the liner, a minimum flow rate should be kept in the river downstream of the dam, in particular for environmental considerations. For these two reasons, a zero-leakage goal is not relevant to geomembrane-lined dams. In other words, geomembranes are used in dams for leakage reduction, but the goal is not necessarily zero leakage.

*9.2.3. Essential impact of dam body performance on leakage control goal in dams*

The flow of water through dams, or simply the presence of water in the body of a dam, can be detrimental as a result two mechanisms: (i) progressive deterioration of the dam material, due to erosion and/or chemical reactions; and (ii) instability of the dam due to water pressure. Therefore, the flow and presence of water in a dam should be controlled.

To control the flow and presence of water in a dam, three actions are required: (i) minimizing leakage through the liner; (ii) preventing water that leaks through and flows around the liner from infiltrating into the dam body; and (iii) removing excess water from the dam body. The first action requires a good liner (essentially a geomembrane), while the second and third actions require a drainage system.

*9.2.4. Leakage control approach for dams*

Based on the foregoing discussions, the approach for leakage control in dams includes the association of the liner (for leakage reduction) and a drainage system (to prevent deterioration of the dam body). The drainage system conveys the collected water to the downstream side of the dam, which is consistent with the environmental requirement of keeping minimum flow in the river downstream of the dam.

Furthermore, as pointed out in Section 9.3.4, a drainage layer is also needed behind the geomembrane to prevent the presence of water, which could uplift the geomembrane in case of rapid drawdown of the reservoir water.

## 9.3. Influence of the type of dam on leakage control in dams

The relative importance of the two leakage control goals, leakage reduction and prevention of deterioration of the dam body, depends on the type of dam.

### *9.3.1. Leakage control approach in the case of embankment dams*

In the case of embankment dams, the two potential mechanisms of dam body deterioration by water (material deterioration and instability) are as follows:

- Progressive material deterioration, if it occurs, is by internal erosion (“piping”).
- Instability of the dam, if it occurs, is caused by high pore water pressure in the body of the dam.

It is not safe to rely only on a geomembrane liner to prevent internal erosion and instability in an embankment dam. As a general rule, a dam lined with a geomembrane should be designed in such a way that no catastrophic failure should occur in the case of a major breach in the geomembrane liner, at least during the time necessary to repair the geomembrane (if this can be done under water) or to empty the reservoir if this needs to be done for safety and/or to repair the geomembrane.

To prevent failure of an embankment dam:

- It is important to eliminate leakage through the dam, thanks to the geomembrane, which reduces leakage, and thanks to the drainage system associated with the geomembrane that collects the leakage that flows through holes in the geomembrane and leakage coming from the geomembrane periphery, and conveys it downstream of the dam.
- It is important to design a dam structure (*e.g.* with appropriate materials, filters and drains) that can function safely during a period of time sufficient to perform repairs if there is a major failure of the geomembrane liner and/or the drainage system associated with the geomembrane.
- It is useful to monitor leakage, which is possible thanks to the drainage system associated with the liner. This is possible in the case of concrete dams, because the drainage layer behind the geomembrane is generally vertical or quasi-vertical and the concrete that is backing the drainage layer has a relatively low permeability. As a result, the collected leakage is conveyed to the outlet. In contrast, in the case of embankment dams, part or all of the collected leakage may be lost in permeable zones of the dam.
- It is important to promptly repair the geomembrane if leakage has been detected, which is possible underwater.

In the case of well-designed rockfill dams: (i) the risk of dam body deterioration by water (internal erosion and instability) is low; and (ii) the permeability of the dam materials is high. Therefore, the main goal of the lining system is leakage reduction.

In the case of those earth dams that are sufficiently permeable to justify the use of a geomembrane liner for leakage reduction, the risk of internal erosion and instability (both related to water in the dam body) may be high. Therefore, the two goals of leakage control (leakage reduction and prevention of deterioration of the dam body) are both important in the case of those earth dams.

### *9.3.2. Leakage control approach in the case of conventional concrete dams*

In concrete dams, deterioration of the dam body can result from the following mechanisms:

- Deterioration of the dam material may be due to: (i) leaching of cement by seeping water; (ii) freeze-thaw cycles (obviously linked to water); and (iii) alkali-aggregate reaction in the presence of water.
- Instability of the dam may be caused by water pressure in cracks and lift joints.

Alkali-aggregate reaction deserves a discussion. In modern concrete, aggregate is generally inert. However, some aggregate (especially those containing silica) reacts with alkali hydroxide in concrete, thereby forming a gel that swells when it absorbs water. The swelling pressure progressively deteriorates the concrete.

In conclusion, in the case of concrete dams, for all of the reasons mentioned above (alkali-aggregate reaction, leaching of cement, freeze thaw, instability due to water pressure) the body of the dam must be kept as dry as possible. This is achieved by associating a geomembrane and a drainage system. The drainage system collects leakage water and water drained from the dam body (if any); and it conveys the collected water to the downstream side of the dam.

Based on the preceding discussion, it is important to keep the dam body dry in concrete dams, in particular when there is a risk of alkali-aggregate reaction. This is particularly true in the case of the rehabilitation of old concrete dams where alkali-aggregate reaction has started a long time before rehabilitation is undertaken.

In the case of the rehabilitation of old concrete dams, keeping the dam body dry means: not only, to drain the water leaking through holes in the geomembrane and the water seeping from the periphery of the geomembrane; but, also, to progressively drain water that has accumulated in the dam over the years.

In conclusion, in the case of the rehabilitation of conventional concrete dams, the emphasis is on drainage.

However, it should be noted that drainage can only function behind a waterproof barrier.

*9.3.3. Roller compacted concrete dams*

In roller compacted concrete dams, the potential for leakage through the dam is high, because:

- the permeability of the dam material is high since roller compacted concrete typically has a cement content lower than that of conventional concrete;
- water tightness of the contraction joints is difficult to achieve; and
- the interfaces between lifts of compacted concrete provide preferential paths for water.

Therefore, leakage reduction is an essential goal of the geomembrane facing of roller compacted concrete dams. But, in roller compacted concrete dams, there is a risk of progressive degradation of concrete due to leaching of cement by seeping water and, in some cases, by alkali-aggregate reaction.

Therefore, in roller compacted concrete dams, the two goals of a lining system are both essential: (i) leakage reduction; and (ii) prevention of dam body deterioration.

*9.3.4. Importance and design of the drainage layer in the case of concrete dams*

The foregoing discussions have shown the importance of a drainage system associated with a geomembrane liner in dams.

Based on the foregoing discussions, there is generally a drainage system associated with a geomembrane on the upstream face of dams, including: (i) a drainage layer under the geomembrane; and (ii) collector pipes leading to a gallery or an outlet.

The flow capacity of the drainage system should be sufficient to convey with no excessive pressure buildup:

- water leaking through geomembrane holes;
- water leaking through the attachments of the geomembrane to the peripheral plinth;
- water seeping from the abutments; and
- water that progressively drains from the dam body.

The drainage layer associated with the geomembrane should have a high resistance to compressive stress to ensure the required flow capacity under the high pressure that exists at the toe of the dam.

In fact, a drainage layer behind the geomembrane is also needed for another reason. In all cases where a geomembrane is located at, or near, the upstream face of a dam, a drainage layer is necessary beneath the geomembrane to prevent the presence of water under the geomembrane, which could uplift the geomembrane in case of rapid drawdown of the reservoir water.

One may expect that the drainage system can be used to monitor leakage through the geomembrane liner. However, the situation is complex.

### 9.4. Leakage monitoring in dams

Water collected in the drainage system associated with the geomembrane liner of a dam is not only leakage through the geomembrane or leakage at the geomembrane connections with appurtenant structures, but also (and in great part) seepage from the abutments. In some dams with a drainage system composed of independent sections, careful analyses have shown that up to 90% of the collected water is, in fact, flowing from the abutments (Machado do Vale, 2016). Therefore, the amount of water collected by the drainage system of a dam cannot be interpreted as leakage through the geomembrane, unless there is a sophisticated drainage system where waters from different sources are identified.

An idea of the effectiveness of geomembranes used at the upstream face of dams can be obtained by reviewing data from dam rehabilitation. Data from eight dams rehabilitated using a geomembrane (Wilkes & Schlosser, 2015), analyzed by the author of this paper, show that: (i) the leakage rate ratio before and after rehabilitation ranges between 4 and 1200; and (ii) most typical ratios are between 10 and 100. The wide range is probably due to different conditions at the geomembrane periphery. These data show that there is a significant reduction in leakage when a geomembrane is used at the upstream face of a dam, but it should be remembered that another benefit, which is often the main benefit, is that, in great part thanks to the drainage system, the leakage is not seeping through the dam body and the dam body is drained, so the dam body is dry.

## 10. Summary and Conclusion

### 10.1. Summary of information presented in this paper

The following has been shown in this paper:

- Leakage must be minimized because it is detrimental due to loss of precious liquid and/or damage to ground and ground water.
- Leakage is inevitable, even when a quasi-impermeable liner, such as a geomembrane, is used.
- When a geomembrane liner is used, leakage occurs through holes in the geomembrane and/or defective connections with appurtenant structures.
- Geomembrane holes and defective connections are minimized in number and size by appropriate design and specifications, professional installation, construction quality assurance, and electric hole detection.
- The impact of geomembrane holes on leakage rate can be greatly reduced by associating a geomembrane with a layer of low-permeability material (typically clay) to form a composite liner. However, composite liners must be ballasted to prevent the geomembrane from being uplifted, in particular in case of rapid drawdown. Therefore, composite liners are mostly used in landfills.
- Leakage can be reduced if a double liner is used, which includes a leakage collection and detection layer be-

tween the two liners. As a result, leakage through the primary liner is detected while the hydraulic head is maintained extremely low on the secondary liner, which results in negligible leakage through the secondary liner into the ground.
- Mechanical properties of the geomembrane are essential for minimizing the risk of puncture and the risk of tensile rupture at attachments of the geomembrane to appurtenant structures. The tensile strength of the geomembrane is not the relevant property. An appropriate (and quantifiable) balance of strength and extensibility is required. From this view point, optimum tensile behavior is achieved with a geomembrane reinforced with a nonwoven geotextile.
- Geomembrane liners are often associated with drainage layers.
- The goal and practice of leakage control depends on the type of containment structure. In dams, a geomembrane liner typically reduces leakage while preventing the deterioration of the dam body, functioning in association with a drainage system.
- Leakage monitoring is difficult and sometimes inaccurate. However, available leakage monitoring data confirm the effectiveness of geomembrane liner systems in reducing leakage by a significant factor.

### 10.2. Conclusion

This paper shows that the use of geomembranes, has significantly improved the performance of liquid containment structures. However, using geomembrane liners without appropriate design and adequate workmanship can lead to failures. Too many users think that the mere fact of using a geomembrane will solve all containment problems. Too many engineers have learned about geomembranes while designing landfills, an application where the use of geomembranes is strictly regulated. Then, they design reservoirs and dams without addressing the problems specific to these applications. Geotechnical engineering is not about cutting and pasting; geotechnical engineering is about thinking. This paper should encourage thinking by providing the rationale that supports engineering solutions related to geomembrane liners. The author of this paper believes that this approach is consistent with the spirit of Victor de Mello.

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