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ARTICLE DE RECHERCHE / RESEARCH ARTICLE

Lessons learned from case histories of reservoirs lined with geomembranes

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Abstract – Three case histories (in Europe, the Middle East and North America) are used to address some important aspects of the design and performance of geomembrane-lined reservoirs constructed on, or in, soil and rock. After a brief introduction to geomembranes and related geosynthetics, a first case history presents the failure of the liner of a reservoir located on karstic ground. The following lesson was learned: a defective construction detail, combined with an inadequate design (due in part to ignorance of the geological and geotechnical conditions), can cause a catastrophic failure. This case history led to the development of the double liner concept. The second case history is about a double liner. It illustrates the important role played by the mechanical properties of the geomembrane. Geotechnical engineers, who are accustomed to deal with complex materials such as soils and rocks, are well prepared to understand the properties of geomembranes. A third case history shows that a "zero-leakage guarantee" offered by irresponsible suppliers of geomembranes, and believed by uninformed owners and engineers, can lead to a catastrophic failure. This case history illustrates the importance of a design that addresses the potential consequences of leakage through liners. The conclusion of this paper is that only a rigorous engineering approach, including both geotechnical and geosynthetics aspects, can ensure the successful performance of geomembrane-lined reservoirs and other liquid containment structures such as dams and canals. Examples presented at the end of the paper show that large reservoirs, canals and dams have been successfully constructed with a geomembrane liner as the sole waterproof component.

Keywords: geomembrane / geosynthetics / reservoir / liner / leakage / performance / case history

Résumé – Leçons tirées d'exemples de réservoirs revêtus de géomembranes. Trois exemples de projets (en Europe, au Moyen-Orient et en Amérique du Nord) permettent d'aborder d'importants aspects de la conception et de la performance des réservoirs revêtus de géomembranes construits sur, ou dans, des massifs de sol ou de roche. Après une brève introduction aux géomembranes et aux géosynthétiques associés aux géomembranes, un premier exemple est celui de la défaillance de l'étanchéité d'un réservoir situé sur un terrain karstique. La leçon suivante a été tirée de cet exemple : un détail de construction défectueux, combiné à une conception inadéquate (due en partie à l'ignorance des conditions géologiques et géotechniques), peut causer une défaillance catastrophique. Cet exemple a conduit au développement du concept de double étanchéité. Le deuxième exemple est justement à propos d'une double étanchéité. Il illustre le rôle important joué par les propriétés mécaniques de la géomembrane. Les géotechniciens, qui sont habitués aux matériaux complexes tels que les sols et les roches, sont bien préparés pour comprendre les propriétés des géomembranes. Un troisième exemple montre qu'une "étanchéité garantie sans fuite" offerte par des fournisseurs irresponsables, et acceptée par des maîtres d'ouvrages crédules et des ingénieurs mal informés, peut entraîner une défaillance catastrophique. Cet exemple illustre l'importance d'une conception d'ouvrage qui tienne compte des conséquences potentielles des fuites à travers les étanchéités. La conclusion de cet article est que seule une approche rigoureuse, comprenant les aspects géotechniques et géosynthétiques, peut assurer la bonne performance des étanchéités par géomembranes pour les réservoirs ainsi que pour d'autres ouvrages contenant des liquides comme les barrages et les canaux. Des exemples présentés à la fin de l'article montrent que de grands réservoirs, canaux et barrages ont été construits avec succès en utilisant une géomembrane comme seule étanchéité.

Mots clés : géomembrane / géosynthétiques / réservoir / étanchéité / fuite / comportement / exemples

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1 Introduction

1.1 Geomembranes

Over the past 50 years, geomembranes have changed the way geotechnical structures are waterproofed. In fact, since the 1970s, geomembranes have progressively replaced traditional liner materials in many applications. Below is a brief overview of geomembranes.

The term "geomembrane" proposed by the author of this paper (Giroud and Perfetti, 1977) has been adopted worldwide. Geomembranes are quasi-impermeable membranes ("membrane" implying continuity and flexibility) used in geotechnical engineering applications as barriers to the migration of fluids (*i.e.* both liquids and gases). Geomembranes are mostly used as barriers to contain liquids, redirect their flow or prevent their migration, in a multitude of structures including reservoirs, canals, dams, hydro-tunnels, shafts, tailings dams, leach pads, waste storage landfills, and underground structures (*e.g.* transportation tunnels and below-ground buildings). The quasi-impermeable component of geomembranes is either a polymer or bitumen. Polymers used in geomembranes include polyethylene, polyvinyl chloride (PVC) and several others. A variety of chemical and mineral additives are incorporated in the polymer or the bitumen to improve some of their properties.

Geomembranes are either un-reinforced or reinforced. Reinforced geomembranes are typically reinforced using woven or nonwoven fabrics:

- A woven fabric is used to reinforce some polymeric geomembranes. It is then encapsulated within the geomembrane.
- A nonwoven fabric bonded to an un-reinforced geomembrane forms a type of reinforced geomembrane called "composite geomembrane". In this case, the nonwoven fabric (which is, in fact, a nonwoven geotextile) is outside the geomembrane, *i.e.* it is bonded to one face of the geomembrane; alternatively, two geotextiles may be bonded to an un-reinforced geomembrane, one on each face of 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.

The fabrics used to reinforce geomembranes are typically made of polymers, such as polypropylene and polyester.

The thickness of geomembranes typically ranges from 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 as high-performance barriers for leakage control.

More details on geomembranes can be found in a series of six articles in French (Giroud, 2015a, b, c, d, e, f).

1.2 Geosynthetics associated with geomembranes

A variety of geosynthetics can be associated with geomembranes to form multilayer liner systems. Among them, geotextiles and geonets are involved in the case histories presented in this paper and are briefly described below.

Geotextiles are fabrics (woven or nonwoven) used in geotechnical engineering applications. Geotextiles are typically made of polypropylene or polyester fibers. Thick nonwoven geotextiles are often used as cushioning layers to protect geomembranes from mechanical damage, such as puncturing by stones.

Geonets are thick polymeric structures with sufficient hydraulic transmissivity to be able to convey liquid in their planar directions. They are used to construct drainage layers associated with geomembrane liners. They replace granular drainage layers in many applications, in particular on slopes, where granular materials may be unstable and/or difficult to place.

1.3 Lessons learned from practice

While a sample of geomembrane is impermeable, a geomembrane liner installed in the field is likely to have defects, including holes through which leakage of liquid can take place. In the modern practice of geomembrane installation, most holes in installed geomembrane liners can be found and repaired thanks to construction quality assurance and electrical leak location surveys. However, even with modern practice, the presence of a few holes in an installed geomembrane liner is possible and, in the case of defective design or unforeseen events, holes in a geomembrane liner may develop while the geomembrane-lined containment structure is in service. Engineers designing geomembrane-lined reservoirs should be aware of the possibility of leakage and should design accordingly.

This paper is intended to raise the level of awareness of engineers regarding both the many possibilities offered by geomembranes and some of the potential problems associated with the use of geomembranes. The three case histories presented herein show that, when there is a problem associated with a geomembrane, there is always a solution involving a geomembrane. Furthermore, lessons learned from these case histories should enable engineers to avoid problems by adopting adequate solutions at the design stage.

The three case histories presented in this paper are extreme cases where significant failures occurred. These cases should not be considered as representative of usual applications of geomembranes in reservoirs. However, it is useful to present extreme cases, because they teach bold lessons.

2 Case history 1: reservoir built on karstic ground

2.1 Introduction of the case

This first case history shows that both design details and conceptual design are important. This case history describes the failure of a geomembrane-lined reservoir built on karstic ground.

A reservoir for water storage was constructed on a layer of natural soil, only a few meters thick, overlying a karstic formation. A karstic formation is a mass of limestone that includes cavities. These cavities are either empty or partly filled with soil. The reservoir was near an abandoned quarry,

Fig. 1. Side view of the karstic formation seen from an abandoned quarry located near the reservoir, which is behind the trees (photo J.P. Giroud).
Fig. 1. *Formation karstique vue d'une carrière abandonnée située près du réservoir, lequel se trouve derrière les arbres (photo J.P. Giroud).*

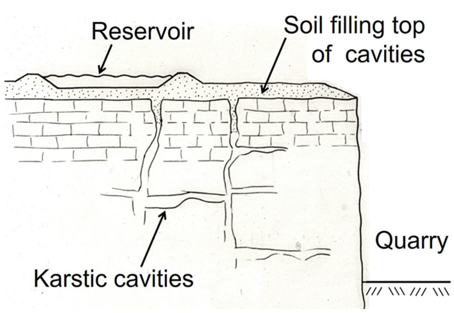

Fig. 2. Schematic cross section (not to scale) of the site on top of which the reservoir was constructed.
Fig. 2. *Coupe schématique (non à l'échelle) du site sur lequel le réservoir a été construit.*

which provided an opportunity to observe the karstic formation (Fig. 1). Numerous cavities could thus be observed, and it could be seen that the soil layer on top of the karstic formation was relatively thin. A schematic cross section of the site is shown in Figure 2.

Unfortunately, at the design stage, no geological or geotechnical study was performed, and the quarry was not observed by the designer of the reservoir. The quarry was observed only when the failure of the reservoir was investigated. As a result, the designer of the reservoir was not aware of the presence of the karstic formation hidden by a thin layer of soil.

2.2 Liner system

The reservoir was lined with a single geomembrane underlain by a gravel leakage collection and detection layer placed directly on the soil (Fig. 3). This was not an adequate design because a leakage collection and detection layer, placed directly on the soil, cannot prevent leakage into the ground,

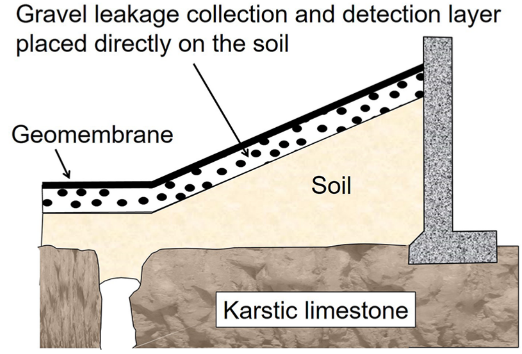

Fig. 3. Liner system of the reservoir located on karstic ground.
Fig. 3. *Système d'étanchéité du réservoir situé sur un terrain karstique.*

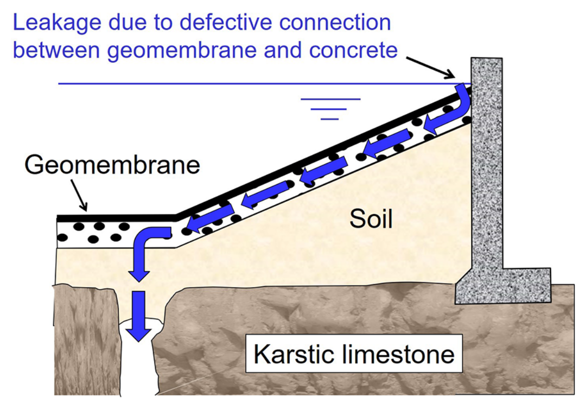

Fig. 4. Leakage at a defective connection between the geomembrane and a concrete structure; then, flow of water in the leakage collection and detection layer; and, finally, flow of water into a cavity.
Fig. 4. *Fuite à une connexion défectueuse entre la géomembrane et une structure en béton ; puis, écoulement de l'eau dans la couche de collecte et de détection des fuites ; et, enfin, écoulement de l'eau dans une cavité.*

with two possible consequences: (1) the leaking liquid may have a detrimental impact on the ground (*e.g.* erosion, dissolution, pollution); and (2) leakage detection may not be reliable (*i.e.* depending on the relative permeabilities of the leakage collection and detection layer material and the underlying soil, the rate of leakage may not be correctly evaluated or leakage may not be detected).

2.3 Failure

During the first filling of the reservoir, leakage occurred at a defective connection between the geomembrane and a concrete structure (Fig. 4). The leaking water flowed downslope in the leakage collection and detection layer and, at the toe of the slope, reached an area where soil covered and partly filled a cavity, which happened to be near the toe of the slope.

Erosion progressively removed the soil from the top of the cavity. As a result, the geomembrane liner was no longer supported, and it burst over the cavity under pressure from the reservoir water (Fig. 5).

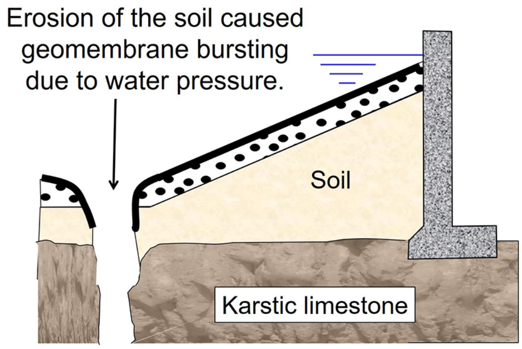

Fig. 5. Bursting of the geomembrane over a karstic cavity after erosion of the soil covering the cavity.
Fig. 5. *Éclatement de la géomembrane au-dessus d'une cavité karstique après érosion du sol recouvrant la cavité.*

Fig. 6. View of the failure area and the concrete structure (photo J.P. Giroud). (Note: The photo was taken several days after the failure. A large piece of geomembrane had been removed by workers. Also, a significant part of the embankment [that was missing around the concrete structure when the photo was taken] had been removed using a crane. Only a fraction of the missing embankment had disappeared into the cavity.)
Fig. 6. *Vue de la zone de défaillance et de la structure en béton (photo J.P. Giroud). (Remarque : La photo a été prise plusieurs jours après la défaillance. Une partie de la géomembrane avait été enlevée par des ouvriers. En outre, une partie importante du remblai [qui manquait autour de la structure en béton lorsque la photo a été prise] avait été enlevée à l'aide d'une grue. Seule une fraction du remblai manquant avait disparu dans la cavité.)*

The geomembrane liner failure caused massive leakage. As a result, the reservoir emptied rapidly through the cavity and several cubic meters of embankment also disappeared into the cavity. A photo taken a few days after the failure is presented in Figure 6.

2.4 Remediation

The owner of the reservoir concluded that a geomembrane liner was not appropriate because it was too weak and decided to use a "strong liner" constructed with traditional materials: a

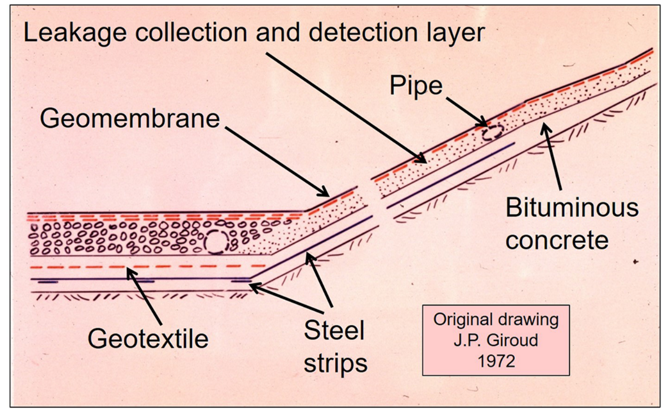

Fig. 7. Cross section of the double liner system used to repair the reservoir. (Note: The pipe on the slope is running downslope in an oblique direction, as seen in Fig. 8.)
Fig. 7. *Coupe du système de double étanchéité utilisé pour réparer le réservoir. (Remarque : Le tuyau situé dans la pente a une direction oblique, comme on le voit à la Fig. 8.)*

layer of bituminous concrete reinforced with steel strips. This solution seemed to be based on common sense. However, the consulting engineer hired to investigate the failure (the author of this paper) indicated that the failure had not been caused by lack of strength of the geomembrane but by a design mistake: the extreme sensitivity to erosion by leaking water of the soil underlying the reservoir had not been recognized. The consulting engineer convinced the owner that, because bituminous concrete is not absolutely impermeable, there would be some intrusion of water into the ground and there was a risk of a new karstic collapse. Therefore, the consulting engineer recommended a double liner system.

The selected double liner system comprised a geomembrane as the primary liner, a layer of bituminous concrete reinforced with steel strips as the secondary liner, and a leakage collection and detection layer between the two liners (Fig. 7). The function of the secondary liner (*i.e.* the liner located under the leakage collection and detection layer) was to prevent water (possibly leaking through holes in the geomembrane) collected by the leakage collection and detection layer from infiltrating into the ground. For the owner, it was important to use, in the double liner system, a "reinforced traditional solution", the layer of bituminous concrete reinforced with steel strips, because of the belief that "stronger is better".

2.5 Construction of the remediation

A new butyl rubber geomembrane (identical to the original one) was used as the primary liner. The leakage collection and detection layer consisted of gravel (which, on the side slopes, was stabilized with bitumen, while remaining very permeable). To increase the flow capacity of the leakage collection and detection layer, pipes were included in the gravel layer (Figs. 7 and 8). As indicated above, the bituminous concrete secondary liner was reinforced to prevent eventual collapse of the liner system into a cavity. Reinforcement was achieved by using,

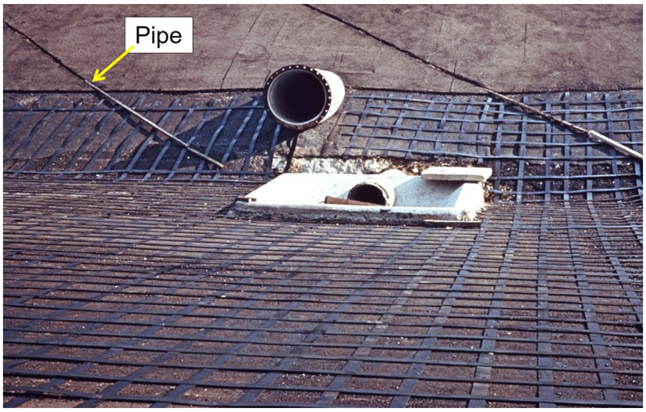

Fig. 8. Steel reinforcement used in the secondary liner made of bituminous concrete (photo J.P. Giroud).

Fig. 8. *Armatures en acier utilisées dans l'étanchéité secondaire en béton bitumeux (photo J.P. Giroud).*

between two layers of bituminous concrete: (1) a layer of nonwoven geotextile; and (2) two layers of steel strips at right angle (Fig. 8). While the effectiveness of a nonwoven geotextile reinforcement in bituminous concrete is negligible, the use of two layers of steel strips (of the type used in reinforced earth walls) was probably overconservative. Clearly, the most important feature of the remediation was the prevention of leakage into the ground by a double liner system. In fact, this remediation was the beginning of the development of the double liner concept, which is one of the lessons learned from this case history, as discussed hereafter.

2.6 Conclusion of this case history

A defective detail (the leaking connection between geomembrane and concrete structure) triggered the failure. But the main cause of the failure was the lack of geological and geotechnical understanding of the site, which led to a conceptual design flaw: the absence of a liner under the leakage collection and detection layer. With an appropriate conceptual design (*i.e.* a double liner system), a defective detail, the leaking connection between the geomembrane and the concrete structure, should have triggered only a loss of water, not a major failure. It is possible that the negligence at the design stage (*i.e.* the absence of geological and geotechnical study) was caused by excessive reliance on geomembrane "impermeability".

2.7 Lessons learned from this case history

With a geomembrane liner (as with any type of liner), leakage is always possible (for example, due to a geomembrane hole or a defective connection). Therefore, the potential consequences of leakage should always be analyzed. This implies that a soil investigation should be undertaken. Considering that a soil investigation is not necessary because a geomembrane liner is used may lead to a catastrophic failure. In fact, a soil investigation should be a required element of the design of any containment system, as it is for the design of any civil engineering structure.

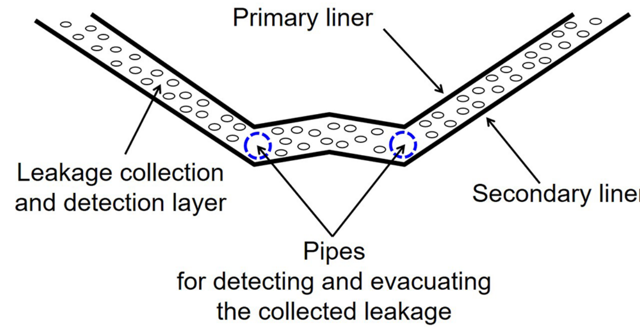

Fig. 9. Schematic cross section of a double liner system, which includes not only two liners but also a leakage collection and detection layer. (Note: The leakage collection and detection layer is symbolically represented as made of gravel, but it can also be made of a geosynthetic drainage material such as a geonet, as shown in the next case history.)

Fig. 9. *Coupe schématique d'un système de double étanchéité, qui comprend non seulement deux étanchéités, mais aussi une couche de collecte et de détection des fuites. (Remarque : La couche de collecte et de détection des fuites est représentée symboliquement comme étant faite de gravier, mais elle peut aussi être faite d'un matériau de drainage géosynthétique tel qu'un géoespaceur ou un géofilet, comme le montre l'exemple suivant.)*

If the soil investigation shows that the consequences of leakage are unacceptable, the design should be adapted accordingly (or a different site should be considered, if that is a possible option). The use of a double liner system is usually the best solution to minimize the risk of leakage into the ground. Increasing the strength of the liner is generally not the right option, even though it is supported by common sense.

Shortly after the above-described remediation, a paper in French (Giroud, 1973) presented the double liner concept. A double liner system consists of two liners (primary liner and secondary liner) separated by a drainage layer acting as leakage collection and detection layer (Fig. 9).

Assuming that the drainage capacity of the leakage collection and detection layer is adequate, the essential feature of a double liner system is the very low hydraulic head on the secondary liner, which ensures that there is very little leakage into the ground, even if there is significant leakage through the primary liner and there are holes in the secondary liner. In addition to this fundamental advantage, double liner systems have practical advantages:

- leakage through the primary liner is completely monitored, *i.e.* it is detected, it can be measured, and its composition can be analyzed;
- the leaking liquid is collected: (1) if this liquid is a contaminant, it can be treated; and (2) if this liquid is valuable, it can be used or pumped back into the reservoir;
- air from the leakage collection and detection layer may create bubbles in the reservoir liquid if there is a hole in the primary liner, which makes it possible to locate a leak.

For the above reasons, double liners are routinely used when strict leakage control is essential, in particular in waste storage landfills.

3 Case history 2: reservoir excavated in a salt formation

3.1 Introduction of the case

The extraordinary case history presented herein illustrates the importance of mechanical properties of geomembranes and teaches a good lesson to engineers. This case history shows that a predicted failure can nevertheless occur if the design engineer fails to convince the owner that the recommended preventive measures are necessary.

In 1980, a large volume of water (about 8500 m^3) was needed for "The Proton Decay Experiment", a fundamental physics project implemented by a team led by a Nobel prize winner to evaluate the life span of protons. As the proton life span was predicted to be 10^{32} years, ten protons were expected to decay every year in this volume of water. The water was the purest water ever produced in order to detect the faint light given off by decaying protons. The water was to be contained in a geomembrane-lined reservoir (Fig. 10).

The reservoir was 20 m deep with a horizontal cross section approximately rectangular, 24×18 m. The reservoir was located 600 m underground (because, at that depth, cosmic radiation is 20 000 times less than on the earth's surface) and it was excavated in a salt formation (because salt has a low level of natural radioactivity compared to other rock formations). Both cosmic radiation and radioactivity would have disturbed the experiment.

3.2 Design of the liner system

A high-density polyethylene (HDPE) geomembrane was selected for its chemical inertia. Geomembranes of several other types could have contaminated the extremely pure water by releasing small amounts of chemicals. It is important to note that HDPE geomembranes are stiff compared to most other geomembranes, which had a significant impact on performance, as discussed below.

The author of this paper was asked to be the design engineer of the liner for this extraordinary cavity-reservoir. Due to the solubility of the salt, the design engineer recommended a double liner system (*i.e.* two liners and a leakage collection and detection layer in between). As explained at the end of the preceding case history, there is almost no leakage into the ground with a well-designed and well-operated double liner system (see Fig. 9). At the bottom of the reservoir, an additional drainage layer was located between the secondary geomembrane liner and the salt. More details on the design of the Proton Decay Experiment reservoir can be found in Giroud and Stone (1984).

For the leakage collection and detection layer and the drainage layer located between the secondary geomembrane and the salt, the design engineer selected a geonet, because (contrary to gravel) a geonet is not radioactive and can be installed vertically. Geonets are briefly described at the beginning of this paper. This was the first use of a geonet for a leakage collection and detection layer, and the first entirely geosynthetic double liner system ever designed and constructed. Since then, entirely geosynthetic double liner systems (with two geomembranes and a geonet between the two

Fig. 10. The 20-m deep Proton Decay Experiment reservoir during geomembrane liner installation (Courtesy J.L. Stone).
Fig. 10. *Vue de l'installation de l'étanchéité par géomembrane dans le réservoir de 20 m de profondeur utilisé pour le Proton Decay Experiment (photo fournie par J.L. Stone).*

geomembranes) have been routinely used in reservoirs and waste storage landfills.

The salt walls had a very irregular surface. Furthermore, a chain-link mesh was rock-bolted to the walls to prevent spalling of salt. To prevent puncturing of the geomembrane under the pressure of 20 m of water, the following precautions were taken: (1) the selected geomembrane for both liners was 2.5 mm thick, which was the thickest HDPE geomembrane available; and (2) heavy-duty protection, comprising polyethylene plates and reclaimed conveyor belts, was placed between the chain-link mesh and the secondary geomembrane. This protection system was subjected to laboratory testing, as described in Giroud and Stone (1984), and it was effective because the geomembranes were not punctured during the entire service life of the reservoir. However, due to the geomembrane thickness, the liner system was very stiff, which caused significant problems as discussed hereafter.

The cavity had been excavated with an approximately rectangular shape before the liner system was designed. The corners of the cavity were not exactly at right angles, but their

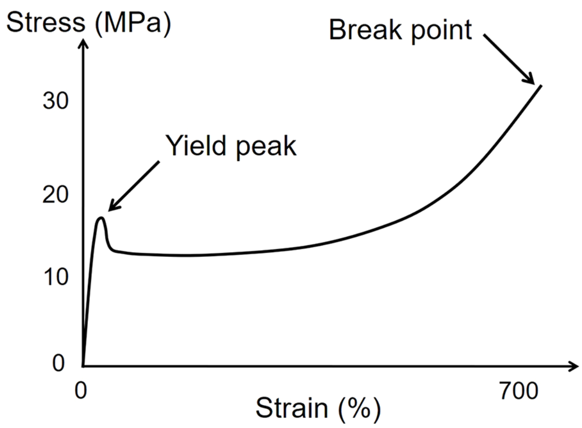

Fig. 11. Typical stress-strain curve of HDPE geomembrane obtained from a tensile test.
Fig. 11. *Courbe contrainte-déformation typique obtenue par essai de traction sur une géomembrane PEHD.*

radius of curvature (imposed by the excavating machine) was small (0.6 to 0.9 m). Due to the stiffness of the liner system (composed of two thick HDPE geomembranes and a geonet), the design engineer predicted that it would be impossible to install the liner system in close contact with the corners of the cavity. As a result, the liner system would not be supported by the walls of the cavity in the vicinity of the corners, and water pressure would induce high tensile stresses in the two geomembranes. To analyze the behavior of the liner system, the design engineer requested the tensile stress-strain curve of the geomembrane from its manufacturer. This was an unusual request at that time (1980).

3.3 Analysis and failure prediction

Upon inspection of the stress-strain curve of the HDPE geomembrane, the design engineer realized that there was a yield peak on the curve (Fig. 11), which was a surprise since no other geomembrane known at that time had a yield peak on its stress-strain curve. The yield peak occurred at a tensile strain of approximately 12%, whereas the strain at break of the HDPE geomembrane (*i.e.* the end of the stress-strain curve) was approximately 700%.

The design engineer understood that any irregularity of the surface of the geomembrane (*e.g.* a scratch at the geomembrane surface or a seam between two geomembrane panels) would create a strain concentration, thereby causing the yield strain to be reached in a small part of the geomembrane while the strain in the rest of the geomembrane is still smaller than the yield strain. In other words, the geomembrane would be in a plastic state in a small area and remain in the elastic state everywhere else. As a result, the strain in a small area of the geomembrane would increase to several hundred percent. This would cause localized thinning of the geomembrane until it burst under water pressure. It is important to note that, while the strain is several hundred percent in a small area, the average strain over the entire geomembrane area subjected to tensile stress is of the order of the yield strain. In other words, the design engineer predicted that geomembrane failure would occur for an average strain of the order of the yield strain, *i.e.* 12%, not for a 700% average strain. This is illustrated in Figure 12.

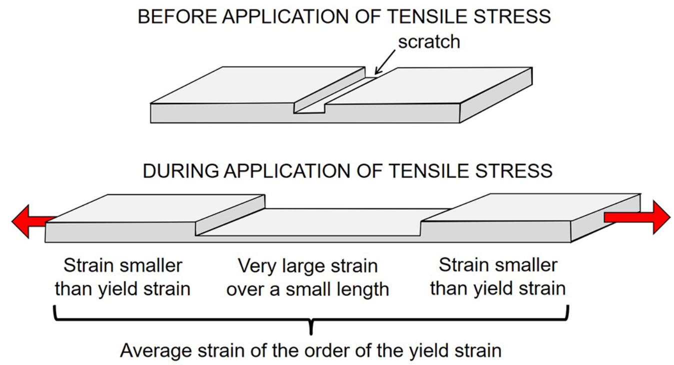

Fig. 12. Illustration of localized large strain and thinning of a geomembrane with a yield peak (see Fig. 11) at the location of a scratch at the surface of the geomembrane when it is subjected to tensile forces. (Note: For the sake of clarity of the top part of the figure, the scratch size has been exaggerated; in fact, a very small scratch can initiate the mechanism described above.)
Fig. 12. *Illustration de la grande déformation localisée et de l'amincissement d'une géomembrane ayant un pic d'écoulement (voir Fig. 11), qui se produisent à l'emplacement d'une égratignure de la surface de cette géomembrane lorsqu'elle est soumise à un effort de traction. (Remarque : Pour la clarté de la partie supérieure de la figure, la dimension de l'égratignure a été exagérée ; en fait, une très petite égratignure peut initier le mécanisme illustré ci-dessus.)*

Figure 12 shows that a slight irregularity at the geomembrane surface is sufficient to cause premature rupture of the geomembrane. A stress-strain curve such as the one shown in Figure 11, where rupture occurs at 700% strain, can only be obtained because laboratory tensile tests are conducted in ideal conditions with intact geomembrane specimens having a smooth surface. Such conditions do not exist in the field where the surface of geomembranes always contains a number of small scratches as a result of transportation, handling and installation of the geomembrane rolls.

3.4 Recommended preventive measure

As a preventive measure against the risk of excessive strain in the two geomembrane liners, the design engineer recommended that the quasi right-angle corners be eliminated by constructing a chamfer (with concrete or wood) in each corner of the reservoir (Fig. 13).

The design engineer wrote a report describing the analysis and stating that the geomembranes would fail unless chamfers were constructed. The design engineer explained, in writing and in a meeting, that chamfers were indispensable because the geomembranes would otherwise fail under an average strain of the order of 12%, a strain value which was going to be reached in the vicinity of the corners of the reservoir under water pressure. However, the geomembrane supplier convinced the client (the physics experiment team) that the recommended chamfers were overly conservative because tensile tests show that HDPE geomembranes can elongate up to 700% before rupture (see Fig. 11). In other words, common sense dictated

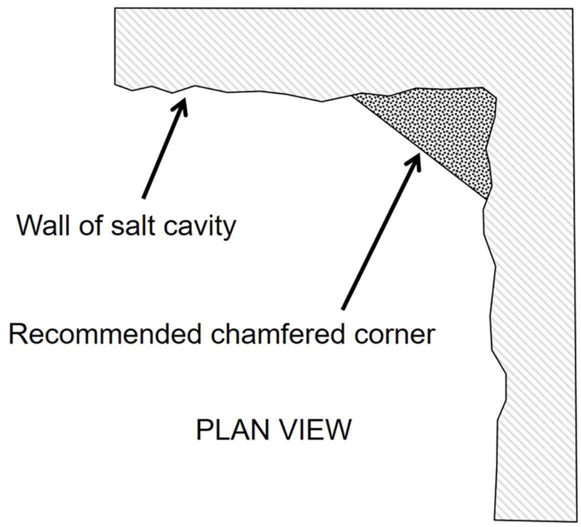

Fig. 13. Recommended chamfers in the corners of the reservoir.
Fig. 13. *Chanfreins recommandés dans les angles du réservoir.*

that geomembrane rupture in the field could only occur at a 700% strain, like in the laboratory. The most compelling argument used by the geomembrane supplier was that the type of failure predicted by the design engineer had never been observed in the field. The client and the geomembrane supplier agreed that experience and common sense should prevail over the “purely academic exercise” done by the design engineer.

The design engineer could not convincingly promote his recommendation for a preventive measure because owners prefer to hear reassuring statements rather than predictions of potential failures. Furthermore, the design engineer was a geotechnical engineer and, in geotechnical engineering, there is a tendency to rely on what has been seen before in the field. This makes it difficult, for a geotechnical engineer, to believe predictions of new failure mechanisms and promote the related preventive measures. However, what is predicted rationally should be believed, in particular by the engineer who made the prediction.

3.5 Liner system installation

Based on the decision made as indicated above, the liner system (two geomembranes and a geonet in between) was installed in the reservoir without chamfered corners. The consequences of this decision appeared during the filling of the reservoir.

It was even more difficult than expected to install the liner system close to the walls of the cavity due to the stiffness of the HDPE geomembranes. Measurements showed that the perimeter of the installed primary geomembrane was approximately 4 to 5% smaller than the perimeter of the cavity. Based on this measurement, it appeared that, when the reservoir is filled with water, the average strain of the primary geomembrane in the horizontal direction would be 4 to 5%. This is about one third of the yield strain of the geomembrane; and the geomembrane strain in the corners could be expected to be greater than the average value.

Also, the design engineer predicted that, because of the irregular shape of the walls, the geomembrane would move down by approximately 0.5 m during filling of the reservoir. To accommodate this displacement, the 22 m high geomembrane panels were hung from 55 adjustable chains at the top of the cavity. This original design, described in Giroud and Stone (1984) and Stone (1984), was essential to the success of the installation.

3.6 Observations during filling of the reservoir and liner failure

Thanks to the leakage collection and detection layer, leakage was continuously monitored. Furthermore, numerous observations of the primary liner were made under water by divers using special equipment, which had been selected to minimize water contamination and was kept at the site.

Leakage was detected during a first filling of the reservoir up to a water depth of 2 m. The reservoir was emptied and inspection showed that several defective seams were the cause of the detected leakage. Also, it was noticed that the primary geomembrane was far from the secondary geomembrane at several locations. At each of these locations, the primary geomembrane was cut and pushed toward the secondary geomembrane; then an additional piece of geomembrane was seamed.

The reservoir was filled again. Leakage was detected when the water depth was 4 m and it increased when the water depth was 6.5 m. Then, divers found a 2500 mm^2 hole in the geomembrane 1.5 m above the floor near a corner of the reservoir. They measured an average strain of 12.5% in the horizontal direction over a length of 5 m including the hole, using a grid that had been marked on the primary geomembrane at the end of installation. This measurement shows that the average horizontal strain in the vicinity of the hole (*i.e.* in the corner of the reservoir) was close to the yield strain. It is interesting to note that the divers measured a zero strain in the vertical direction, which indicates that the adjustable chains supporting the top of the geomembrane panels were functioning properly.

The hole was patched under water by the divers, the leakage rate decreased significantly, and it was possible to continue filling the reservoir. However, shortly after, when the water depth reached 7 m, massive leakage occurred. Divers found a major breach in the primary liner in the same corner as the above-mentioned hole. The breach was in the lower part of the liner (where water pressure was maximum) and had a vertical height of 1.5 m.

3.7 Inspection and comment

The reservoir was emptied and it was then found that the secondary liner was breached at the same location as the primary liner. Inspection showed that the primary liner had elongated beyond the yield strain in three of the four corners (including the corner where the two geomembranes were breached). Only in one of the four corners, the geomembrane was close to the cavity walls and did not elongate excessively.

It should be noted that the observed breach was inevitable since the divers had measured an average strain close to the yield strain in the corner area, shortly before the major breach occurred. Clearly, the geomembranes had failed as predicted by the design engineer. This is a remarkable case where the failure analysis was done in detail and reported in writing before the failure occurred as predicted. This is all the more remarkable that the mode of failure had never been experienced before.

3.8 Remediation

The preventive measure recommended (but not used) at the design stage (Fig. 13) was only implemented as a remedial measure after the failure described above had occurred. Thus, chamfers were constructed in the three corners where the geomembranes were far from the cavity walls. In the lower ten meters of the reservoir, the chamfers were constructed using reinforced concrete. Construction of the chamfers in the upper ten meters was more original and is discussed hereafter.

Both geomembranes were repaired in the lower few meters of the reservoir, *i.e.* where the breaches had taken place, while the upper part of the liner system was hanging from the adjustable chains. The reservoir could then be filled again.

In the upper ten meters of the reservoir, the chamfers were constructed as follows: aerated lightweight cement was slowly poured in the corners of the reservoir using the lining system as formwork (Fig. 14), while water was progressively added in the reservoir to balance the fresh cement pressure. By carefully adjusting the amount of air-entraining admixture, the specific gravity of the aerated cement was kept as close as possible to 1.0. The water level in the reservoir never exceeded the cement level by more than 0.5 m. Using this original method, cement chamfers were built without removing the liner system. The reservoir was thus successfully filled and the physics experiment could be conducted.

3.9 Observation while the reservoir was in service

After the reservoir was filled, it was used for eight years. During this period, several holes developed in the primary geomembrane. All of these holes were repaired under water by divers using patches specially developed for this project. (The holes that occurred during the first two years of reservoir operation and their repair are described in Stone, 1984.) Therefore, the reservoir was not emptied during the eight years when the experiment was conducted without interruption.

Periodically, the divers took photos of the primary geomembrane, taking advantage of the fact that the extremely pure water was as transparent as air. The photo shown as Figure 15 is particularly interesting. This photo shows a hole (15 mm in the vertical direction and 2 mm in the horizontal direction) in the primary geomembrane, just above the junction between the floor of the cavity and a vertical wall. The hole was patched by the divers after the photo was taken. (It should be noted that this wall/floor junction forms a “horizontal corner”, which, from the viewpoint of geomembrane behavior, is similar to the “vertical corners” formed by wall/wall junctions.)

The hole shown in Figure 15 is in a scratched area near a seam. The scratches seen in Figure 15 were caused by a procedure that consisted in grinding the geomembrane surface, prior to seaming, to remove surface impurities. This procedure has been improved since then.

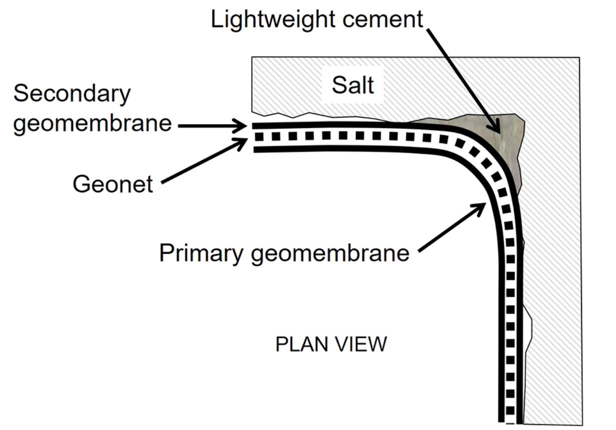

Fig. 14. Lightweight cement poured between the cavity corner and the secondary geomembrane.

Fig. 14. *Ciment à basse densité coulé entre l’angle de la cavité et la géomembrane secondaire.*

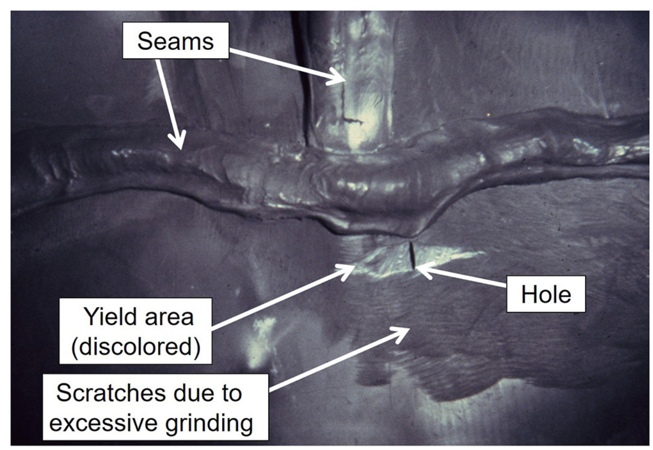

Fig. 15. Underwater photo showing the formation of a hole in the primary geomembrane subjected to excessive strain (Courtesy J.L. Stone).

Fig. 15. *Photo prise sous l’eau montrant la formation d’un trou dans la géomembrane primaire soumise à une élongation excessive (photo fournie par J.L. Stone).*

The yield area, *i.e.* the geomembrane area with very large strain in Figure 15, is characterized by a light color, whereas the geomembrane is originally black. The mechanism of geomembrane discoloration is the following. Polyethylene is translucid and the black color of typical geomembranes is obtained by adding carbon black particles to the polymer, as a protection against ultra-violet radiation, which is indispensable in most geomembrane applications. In the Proton Decay Experiment project, an available black geomembrane was used, even though protection against ultra-violet radiation is not needed for an underground application. As the geomembrane strain increases, the number of carbon black particles per unit area decreases, hence the observed discoloration.

The shape of the yield area in Figure 15 indicates that the direction of the tensile stress at this particular location is vertical. This is because the photo was taken just above a "horizontal corner" (as mentioned above) rather than at the vertical corners discussed so far.

From the standpoint of the physics of materials, it is interesting to note in Figure 15 that the hole in the geomembrane is elongated in the direction of the tensile stress. The hole formation mechanism is the following: the development of a very large strain in the geomembrane is associated with the progressive alignment of the polyethylene macromolecules in the direction of the tensile stress. As macromolecules become parallel, they tend to split off, which results in the formation of a hole and in the observed hole shape.

The situation shown in Figure 15 is critical because scratches and seams are the two causes of strain concentration, as mentioned earlier. Furthermore, these two causes of strain concentration are present to a high degree: the seam is prominent and scratching is extensive. However, this situation did not result in a major geomembrane breach because, at that location, the geomembranes were not far from the cavity wall. In contrast, the 1.5 m long vertical breach (which caused the interruption of the reservoir filling, as discussed earlier) was possible because the geomembranes were far from the cavity corner. The 1.5 m vertical breach occurred in an area with no seam and therefore no grinding. But, at that location, with the geomembrane unsupported, a single minor scratch was sufficient to trigger the breach; and, as mentioned earlier, the surface of geomembranes in the field always contains a number of small scratches.

3.10 Conclusion of this case history

Specific lessons learned from the liner failure described above were published shortly after the completion of the reservoir (Giroud, 1984). These lessons have contributed to a significant improvement of the design practice for geomembrane liners: thus, since the mid-1980s, applications of HDPE geomembranes (which are the most frequently used geomembranes) have been designed with an allowable strain of approximately 3 to 6%, which is the yield strain divided by a factor of safety, rather than on the basis of the 700% strain at break. Also:

- Attention has been drawn to the detrimental consequences of strain concentrations in the vicinity of geomembrane seams and research work has been conducted on this subject (*e.g.* Giroud *et al.*, 1995b; Giroud, 2005; Kavazanjian *et al.*, 2017).
- A methodology has been developed for the design of geomembrane liners in reservoirs with angular corners and corners with a small radius of curvature (Giroud *et al.*, 1995a).
- The practice of grinding the geomembrane surface has been eliminated for most types of seams. For the types of seams where grinding is necessary, it has been codified to prevent the presence of harmful scratches at the geomembrane surface after completion of the seam.

3.11 Lessons learned from this case history

The following lessons were learned from this case history:

- understanding the mechanical properties of geomembranes at the design stage is essential to the successful performance of a geomembrane liner system;
- a failure rationally predicted is not certain to happen, but it is likely to happen and, therefore, the design engineer should believe the prediction and should convince others;
- relying on experience and common sense, while ignoring the results of rational analyses, may lead to bad decisions resulting in poor performance.

4 Case history 3: reservoir built on soil sensitive to acid

4.1 Introduction of the case

A reservoir containing phosphoric acid was constructed on a soil with a high calcium carbonate content. The size of the reservoir was about 2 ha and the depth of liquid was 3 m. The reservoir was lined with a geomembrane installed without effective construction quality control or construction quality assurance.

4.2 Failure

In the months following the first filling of the reservoir, acid leaked through holes in the geomembrane liner and attacked the calcium carbonate, thereby creating cavities in the soil underlying the geomembrane liner. Eleven months after the first filling, the reservoir emptied suddenly after bursting of the geomembrane over several large cavities.

4.3 Investigation

Inspection after the failure showed that the geomembrane had many holes (open seams, punctures, tears) due to careless construction and lack of quality control. It was clear that the geomembrane had to be discarded and that a new geomembrane had to be installed. When the geomembrane was removed, many cavities were found (Fig. 16).

Fig. 16. Cavities in the soil caused by several leaks of acid, discovered when the geomembrane was removed for the failure investigation (photo J.P. Giroud).

Fig. 16. *Cavités dans le sol causées par plusieurs fuites d'acide, découvertes lorsque la géomembrane a été retirée pour procéder à l'investigation de la défaillance du réservoir (photo J.P. Giroud).*

Fig. 17. One of the large cavities over which the geomembrane burst (photo J.P. Giroud).
Fig. 17. *Une des grandes cavités sur lesquelles la géomembrane a éclaté (photo J.P. Giroud).*

These cavities resulted from dissolution by phosphoric acid of calcium carbonate contained in the soil underlying the geomembrane. Comparative inspection of the geomembrane and the soil showed that dissolution of calcium carbonate by acid was clearly associated with leaks through the geomembrane. Small leaks were associated with limited dissolution of the soil, whereas large leaks were associated with large cavities, up to one meter in diameter (Fig. 17).

4.4 Analysis

As part of the investigation of the failure, a calculation was done using the methodology presented in Giroud (1982, p. 42). This calculation, using the tensile properties of the geomembrane, showed that this geomembrane would burst, under the pressure exerted by 3 m of phosphoric acid, over a cavity having a diameter of approximately 1 m. This calculation result is in agreement with the observed liner failure.

4.5 Remediation

The supplier of the original geomembrane had guaranteed in writing that the geomembrane was "absolutely impermeable" and that there would be "zero leakage". Accordingly, the owner of the reservoir demanded that the contractor install a new geomembrane "with zero leakage". However, the consulting engineer hired to solve the problem (the author of this paper) convinced the owner that it is impossible to install a geomembrane liner over two hectares without defects, and that the same problem would happen again, unless the project is redesigned.

From a discussion with the owner, the consulting engineer understood that the failed reservoir had two functions, evaporation and storage, and concluded that the solution would consist in separating the two functions. Earthwork was undertaken: (1) to eliminate the soil contaminated and/or attacked by acid, and (2) to reconfigure the site. Thus, the failed initial reservoir with two functions (evaporation and storage) was replaced by three reservoirs: a deep storage reservoir and two shallow evaporation reservoirs (Fig. 18). (Note: Shallow evaporation reservoirs are often referred to as "evaporation ponds", but the term "reservoir" is used herein for consistency throughout this paper.)

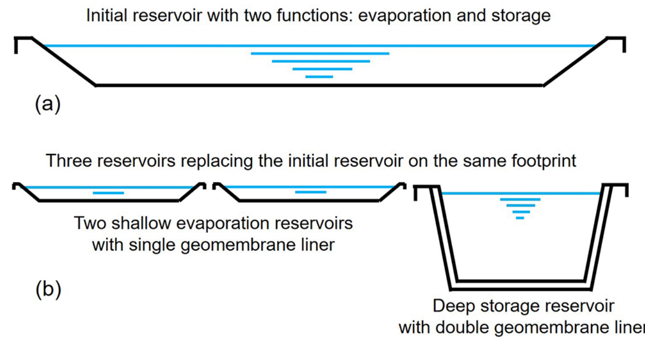

Fig. 18. Schematic representation of the replacement of the initial reservoir (a) with three reservoirs (b).
Fig. 18. *Représentation schématique du remplacement du réservoir initial (a) par trois réservoirs (b).*

The 6 m deep storage reservoir has a double liner system to prevent leakage of acid into the ground. The double liner system concept is schematically described in Figure 9.

The reason for having two identical shallow evaporation reservoirs with a single liner is the following:
- the two evaporation reservoirs are very shallow (with a liquid depth of 0.5 m when full) to promote evaporation;
- as a result of the small liquid pressure on the geomembrane liner, the risk of leakage is limited and, therefore, the evaporation reservoirs only need a single liner;
- however, leakage causing soil dissolution can still happen;
- but leakage is unlikely to happen in the two evaporation reservoirs at the same time;
- comparing the levels of acid in the twin evaporation reservoirs provides a way to detect leakage if it happens in one of the two evaporation reservoirs;
- if leakage happens in one evaporation reservoir, repair of the geomembrane liner can be done without interrupting the operation of the facility.

4.6 Conclusion of this case history

The observed failure occurred because no soil analysis by a geotechnical engineer was performed as part of the design and because the owner was led to believe that geomembrane liners are "absolutely impermeable" and that "zero leakage" was guaranteed. The problem was solved by a consulting engineer who knew that all liners may leak and adapted the design to both the nature of the soil and the needs of the owner.

4.7 Lessons learned from this case history

If the liquid contained in a reservoir can be harmful to the soil, leakage through the liner should be minimized, and a double liner system may be required. Examples of harmful liquids include:
- liquid reacting chemically with the soil, such as acid dissolving calcium carbonate contained in soil;

– water dissolving gypsum contained in soil;
– water causing soil instability by excess pore pressure;
– water causing soil erosion.

Claims such as “zero leakage” or “absolutely impermeable” liner should not be made and should not be believed. In reality, all liners may leak. Therefore, the consequences of leakage should be analyzed and the design of each geomembrane-lined containment structure should be adapted in accordance with the results of the analysis. Furthermore, the probability of leakage should be minimized by minimizing the probability of holes in geomembrane liners through the practice of construction quality control by the geomembrane installer and construction quality assurance by an independent party.

Today, a thorough construction quality assurance program should include an electrical leak location survey at the end of geomembrane installation, which makes it possible to find and repair most holes in an installed geomembrane liner. However, even if an electrical leak location survey is planned, the design engineer should always consider the possibility of leakage, analyze the consequences of leakage, and take preventive measures accordingly.

5 General conclusion

5.1 Role of geotechnical engineers

Only a rigorous engineering approach can ensure the successful performance of geomembrane-lined reservoirs, and other liquid containment structures such as dams and canals. The rational analyses, involved in a rigorous engineering approach of geomembrane liner design, require a good understanding of the properties of geomembranes. Geotechnical engineers, who are accustomed to deal with complex materials such as soils and rocks, are well prepared to understand the properties of geomembranes. Furthermore, geotechnical engineers have an essential role to play in the soil investigations that are necessary to ensure the successful performance of geomembrane-lined reservoirs and other geomembrane-lined containment structures.

5.2 Consequences of unrealistic expectations

Unrealistic expectations about the benefits and performance of geomembranes lead to negligence at the design stage. For example, design engineers who believe that geomembranes are absolutely impermeable may consider that it is not necessary to perform a soil investigation. As a result, they may fail to realize that the liner system they are designing is located on a soil that is excessively sensitive to leakage.

5.3 Importance of rational analyses

An important lesson learned from the case histories presented in this paper is that a design engineer should believe failure predictions made using rational analyses, even if the failure mechanism has never been experienced in the field. The design engineer should then convince others that preventive measures are necessary.

Geotechnical engineers are often told to rely on precedents and to design with common sense. However, examples presented in this paper show that excessive reliance on experience may lead to design mistakes if the predictions made using rational analyses are ignored. More generally, geotechnical engineers should, above all, rely on rational analyses and not on common sense.

5.4 Misleading effects of common sense

This paper shows that common sense may lead to bad decisions. Nevertheless, common sense is often mentioned by some geotechnical engineers. The likely reason is that it is easier to invoke common sense than to perform a rational analysis. In other words, common sense comforts those discouraged by the difficulty inherent to rational analyses.

Geotechnical engineering requires reliable tools. Common sense is not a reliable tool, because it is a random collection of beliefs, which are essentially justified by tradition. As the origin of the beliefs packaged under the label “common sense” is usually unknown, there is no way to distinguish between the good and the bad aspects of common sense. Common sense can be wrong, as well as it can be right. Therefore, common sense cannot be used as a basis for rational decisions in an engineering discipline. Decisions in engineering disciplines, such as geotechnical engineering, should be based on rational analyses conducted with Cartesian rigor.

5.5 Examples of successful applications of geomembranes

Examples of large reservoirs, canals and dams that have been successfully constructed with a geomembrane liner are illustrated in Figures 19–21. It should be noted that, in these impressive structures, the geomembrane liner is the sole waterproof component.

These examples of large geomembrane-lined structures demonstrate that, today, geomembranes are the material of choice for waterproofing geotechnical structures. This is possible because a significant body of knowledge has been established, in part by analyzing the performance of actual structures, as shown in this paper.

Fig. 19. Geomembrane-lined water reservoirs for the new Panama Canal locks (Courtesy Carpi).
Fig. 19. *Réservoirs revêtus de géomembrane pour stocker l’eau des nouvelles écluses du canal de Panama (photo fournie par Carpi).*

Fig. 20. Geomembrane-lined Tekapo Canal in New Zealand (Courtesy Carpi).
Fig. 20. *Canal revêtu de géomembrane, Tekapo Canal en Nouvelle-Zélande (photo fournie par Carpi).*

Fig. 21. Geomembrane-lined Pannecière Dam in France (Courtesy Carpi).
Fig. 21. *Barrage revêtu de géomembrane, Barrage de Pannecière en France (photo fournie par Carpi).*

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