XXIII. Széchy Károly Emlékkonferencia

2017 február

Készült a
Magyar Geotechnikai Egyesület
és a
Magyar Mérnöki Kamara Geotechnikai Tagozata
együttműködésével.

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ISBN 978-963-12-7847-7

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J. P. Giroud

Dr. Giroud a Grenoblei egyetem professzora volt 1965-1978 között, majd 2001-ig a GeoSyntec tervezője, technikai igazgatója volt. Ma önálló mérnökként, saját tervezőirodáját vezeti. A Nemzetközi Geoműanyag Szövetség (IGS) korábbi elnöke és a Geosynthetics International szerkesztőbizottságának elnöke. Sok évtizedes kutatómunkája és aktív tervezői tevékenyése során több mint 400 publikációja jelent meg a témában. Ő alkotta meg a „geotextília” és a „geomembrán” szavakat is 1977-ben. A geoműanyagok tervezésében használatos szabványok közül is sok megalkotásában részt vett és bővítette a geoműanyagok felhasználási körét, különös tekintettel hulladéklerakókra, víztározókra és gátakra. 1994-ben az IGS a legrangosabb előadását „Giroud Előadásnak” nevezte a geoműanyagok fejlesztése terén végzett munkája elismeréseképp 2002-ben az IGS tiszteletbeli tagja lett, mint „A Nemzetközi Geoműanyag Szövetség (IGS) és a geoműanyag tudományág atyja”. 2005-ben az Amerikai Építőmérnökök Szövetsége (ASCE) Geo-Intézete a „hős” címet adományozta számára. 2005-2006-ban az IGS és az ISSMGE által közösen támogatott, igen tekintélyes Mercer Előadásokat is ő tarthatta meg. 2007-ben a Bukaresti Műszaki Egyetem a Doctor Honoris Causa címet adományozta számára. 2008-ban az ASCE igen tekintélyes Terzaghi Előadását tarthatta meg. 2009-ben az amerikai Nemzeti Mérnöki Akadémia tagjává választották. 2010-ben a Légion d’Honneur kitüntette a Chevalier címmel. 2016-ban az ISSMGE Victor de Mello Előadását is megtarthatta.

Design and Performance of Reservoirs Lined with Geomembranes

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Abstract

Four 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 excavated in soil and rock. After a brief introduction to geomembranes and related geosynthetics, a first case history presents the failure of the geomembrane liner of a reservoir located in karstic terrain. The following lessons were 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 case history of the first double liner with two geomembranes is then presented. This case shows that adequate design is essential to control leakage, which makes it possible to construct a safe reservoir on a potentially unstable soil. A third case history shows that a "zero-leakage guarantee" offered by irresponsible suppliers, and believed by uninformed owners, can lead to catastrophic failure. This case history illustrates the importance of a design that addresses the potential consequences of leakage. A fourth case history, and related theoretical analyses, illustrate the important role played by the mechanical properties of the geomembrane. Geotechnical engineers who are accustomed to deal with complex materials, soils and rocks, are well prepared to understand the properties of geomembranes. The conclusion of this paper is that only a rigorous engineering approach 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.

Introduction

Geomembranes

In 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 & 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 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.

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.

Geosynthetics related to geomembranes.

Geotextiles are fabrics (woven or nonwoven) used in geotechnical engineering applications. Geotextiles are often used to protect geomembranes from mechanical damage, such as puncturing by stones.

Geonets are thick polymeric structures 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.

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. Engineers designing geomembrane-lined reservoirs should be aware of this possibility. 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 four case histories presented herein show that, when there is a problem, there is always a solution. Furthermore, lessons learned from these case histories should enable engineers to avoid problems by adopting adequate solutions at the design stage.

Case history 1: Reservoir built on karstic ground

Introduction of the case

The first case history will show 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 close to an abandoned quarry, which provided an opportunity to see the karstic formation (Figure 1). Numerous cavities could thus be observed. The soil layer on top of the limestone was thin. Unfortunately, at the design stage, no geological study was performed and the quarry was not observed. The quarry was observed only when the failure of the reservoir was investigated. As a result, the designer of the reservoir ignored the presence of the karstic formation hidden by a thin layer of soil.

Figure 1. Side view of the karstic formation from an abandoned quarry located near the reservoir.

The liner system

The reservoir was lined with a single geomembrane, which was underlain by a gravel leakage collection and detection layer placed directly on the soil (Figure 2). This was not an adequate design because a leakage collection and detection layer, placed directly on the soil, cannot prevent leakage into the ground.

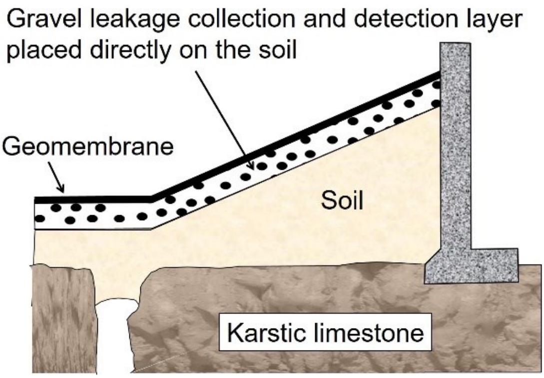


Figure 2. Liner system of the reservoir located on karstic ground.

The failure

During the first filling of the reservoir, extensive leakage occurred at a defective connection between the geomembrane and a concrete structure (Figure 3). 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.

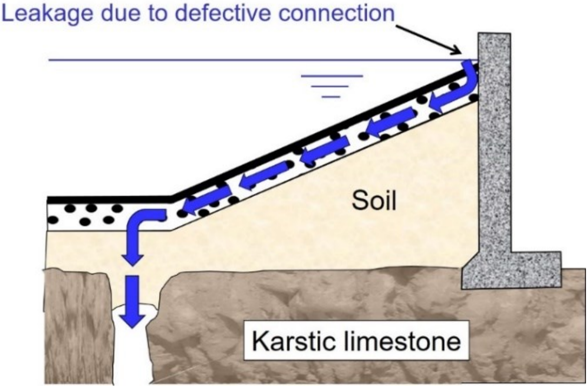


Figure 3. Leakage at a defective connection between the geomembrane and a concrete structure and flow of water in the leakage collection and detection layer.

Erosion progressively removed the soil from the top of the cavity. As a result, the geomembrane was no longer supported and it burst over the cavity under pressure from the reservoir water (Figure 4).

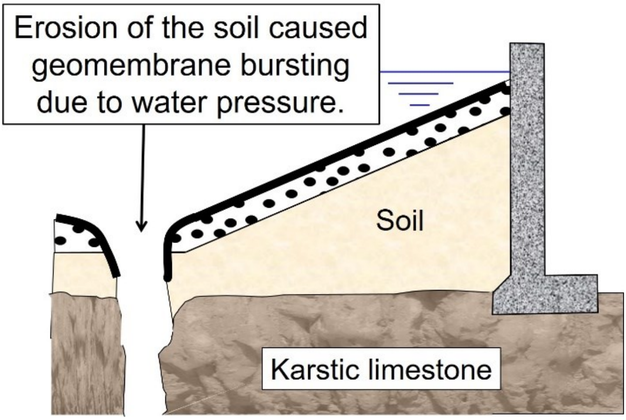


Figure 4. Bursting of the geomembrane over a karstic cavity.

This resulted in massive leakage. The reservoir emptied rapidly after the failure. Several cubic meters of embankment disappeared into the deep cavity (Figure 5).

Figure 5. View of the failure area and the concrete structure.

The remediation

The remediation consisted in replacing the single geomembrane by a double liner with a geomembrane as the primary liner and bituminous concrete as the secondary liner (Figure 6). The function of the secondary liner (i.e. the liner located under the leakage collection and detection layer) was to prevent water collected by the leakage collection and detection layer from infiltrating into the ground.

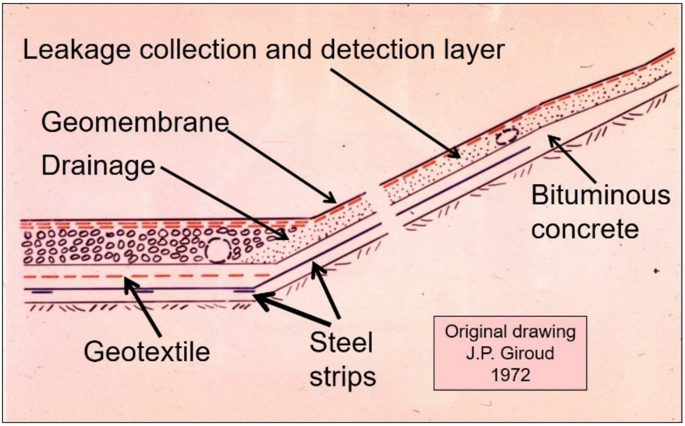


Figure 6. Cross section of the double liner system used to repair the reservoir.

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). As a precaution, the bituminous concrete secondary liner was reinforced to prevent eventual collapsing of the liner system into a cavity. Reinforcement was achieved by using between two layers of bituminous concrete: (1) a layer of nonwoven geotextile; and (2) two layers of steel strips at right angle (Figure 7). While the effectiveness of a nonwoven geotextile reinforcement in bituminous concrete is questionable, the use of two layers of steel strips (of the type used in mechanically stabilized 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. In fact, this remediation lead to the development of the double liner concept, which is discussed in the next case history.

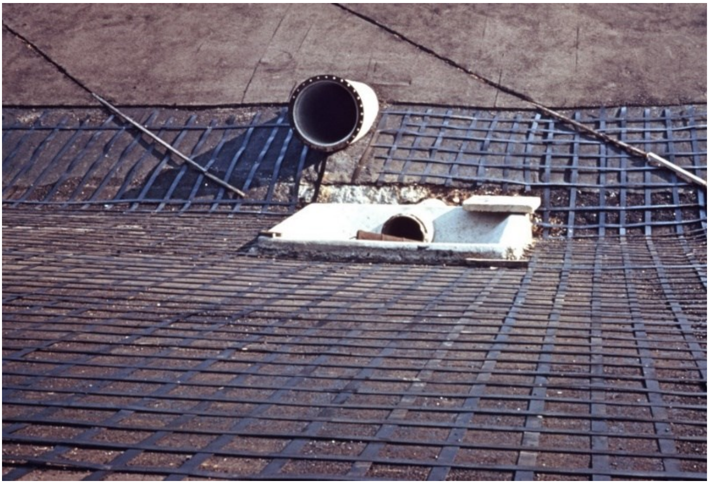


Figure 7. Steel reinforcement used in the secondary liner made of bituminous concrete.

Conclusion of this case history

A detail (leaking connection between geomembrane and concrete structure) triggered the failure. But the main cause was a conceptual design flaw: the absence of a liner under the leakage collection and detection layer. With an appropriate conceptual design, a detail, the leaking connection between the geomembrane and the concrete structure, should have triggered only a loss of water, not a major failure. Also there was negligence at the design stage because there was no geological study and soil investigation.

Lessons learned from this case history

With a geomembrane liner, a leak is always possible (for example, due to a geomembrane hole, or a defective connection). Therefore, the potential consequences of a leak should always be analyzed. If the consequences are unacceptable, the design should be improved.

Case history 2: Reservoir built on steep slope

Introduction of the case

While the first case history was about a failure, the second case history is not about failure. The second case history is about a successful performance thanks to adequate design. This is the case history of the first double liner constructed with two geomembranes.

The double liner concept

After the design of the remediation, of the preceding case history, a paper (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. The essential feature of a double liner is the very low hydraulic head on the secondary liner, which ensures that there is very little leakage into the ground.

In addition to this fundamental advantage, double liners have practical advantages:

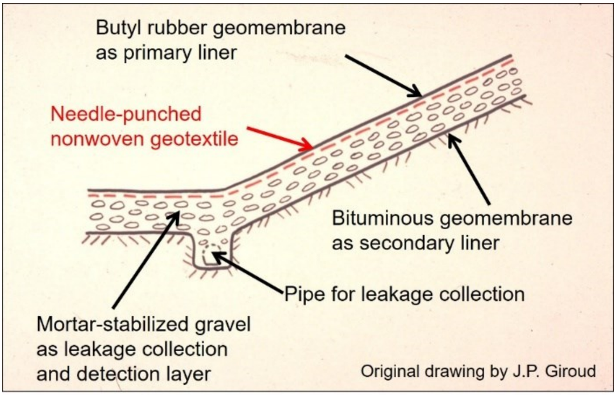
- Leakage through the primary liner is detected and can be measured.
- The leaking liquid is collected: (1) if this liquid is a contaminant, it can be treated; and (2) if this liquid is valuable, it can be pumped back into the reservoir.
- Air from the leakage collection and detection layer may create bubbles in the reservoir liquid if there is a hole in the primary liner, which makes it possible to locate a leak.

Description of the case

The case history presented herein has been described in detail in other publications (Giroud & Gourc 2014, 2015a, 2015b). This case is remarkable, because the double geomembrane liner installed in 1974 is still in service more than 42 years later. A brief description follows.

A reservoir of industrial water is located on a steep slope. The geotechnical study (by the author of this paper) showed that leakage from the reservoir could impair the stability of the slope. Slope stability was essential because there was a large chemical plant at the toe of the steep slope, 50 meters lower than the reservoir (Figure 8). To minimize leakage into the ground, a double liner system was selected. The primary liner is a butyl rubber geomembrane and the secondary liner is a bituminous geomembrane. The leakage collection and detection layer is a layer of rounded gravel stabilized with a small amount of mortar and placed directly on the bituminous geomembrane (Figure 9). A nonwoven geotextile was used as a protection between the primary liner geomembrane and the gravel.

Figure 8. Reservoir on a 50 m high steep slope.



Original drawing by J.P. Giroud

Figure 9. Cross section of the double liner system.

Performance

Only one incident happened: very small leakage was detected by the leakage collection and detection system in 2004, i.e. 30 years after construction. The exact location of the leak was found thanks to air bubbles moving up to the reservoir water surface. The hole in the geomembrane was small, as reported by divers. The leak was near the water intake structure. It is not surprising to have a geomembrane failure next to a concrete structure, because the geomembrane may exhibit very large strain at this location due to differential movements between the earth embankment and the concrete structure. The hole in the geomembrane was successfully patched under water.

An important aspect of the performance of the geomembrane liner is its durability considering that, above water level, the geomembrane was exposed (i.e. it was not covered by a protective layer). The geomembrane supplier had indicated to the design engineer (i.e. the author of this paper) that butyl rubber ages more rapidly when it undergoes tensile strain. To that end, the portion of the geomembrane that was expected to be permanently above water level was reinforced with a scrim (a lightweight fabric) that makes the geomembrane very stiff in tension while remaining flexible. The strain restraint provided by the scrim has been an important factor in the remarkable durability of the geomembrane. The durability of the butyl rubber geomembrane in this project is all the more remarkable that this type of geomembrane is now superseded by more durable geomembranes.

Conclusion of this case history

No leakage was detected for 30 years. The leak, observed 30 years after construction, was presumably small since the hole was small, as reported by divers. The fact that a small leak was detected makes it possible to evaluate the functioning of the double liner system in this project. Indeed, there may be a potential uncertainty with double liners. When zero leakage is detected, there are three possibilities:

- the primary liner does not leak;
- the secondary liner is leaking so much that all leakage from the primary liner infiltrates into the ground and is not detected; and

- leakage through the primary liner is retained in the leakage collection and detection layer by capillarity or clogging.

In this particular case, capillarity is not possible in gravel and clogging is unlikely since the liquid is industrial water. Therefore, the fact that a small leak was detected shows that the secondary liner is in good condition. In conclusion, it is clear that double liner system worked in this particular project.

The durability of the geomembrane, still in service 42 years after installation, is remarkable for a type of geomembrane that is no longer supplied today because it has been superseded by more durable geomembranes. As noted above, a good understanding of the aging mechanism of the geomembrane played a key role in this success. This was the result of good communication between the geomembrane supplier and the design engineer.

It is important to note that that the reason for using a double liner for this reservoir was neither economical (prevention of loss of liquid) nor environmental (prevention of ground contamination), which are the usual reasons for leakage control. Rather, the reason for using a double liner was geotechnical (prevention of slope instability). This is a lesson that should be remembered by geotechnical engineers.

Lessons learned from this case history

Leakage control is achieved by careful design and not by just relying on “geomembrane impermeability”. Therefore, careful design is rewarded by good performance.

Engineers designing geomembrane-lined reservoirs or other geomembrane-lined structures should learn chemical properties of geomembranes from the suppliers. These properties govern the durability of geomembranes.

Geotechnical engineers play a key role in the design of geomembrane-lined structures, because many of the problems affecting the success of a geomembrane-lined structure are of geotechnical nature, such as slope stability, differential movements between concrete structures and embankments, sensitivity of the soil to leaking liquid. This comment is important, because a number of geomembrane-lined structures are constructed without geotechnical design and many of them result in inadequate performance.

Case history 3: Reservoir built on soil sensitive to acid

Introduction of the case

A large pond containing phosphoric acid was constructed on a soil with a high calcium carbonate content. The size of the pond was about 2 ha and the depth of liquid was 6 m. The pond was lined with a geomembrane installed without construction quality control.

The failure

Acid leaked through holes in the geomembrane liner and attacked the calcium carbonate, thereby creating cavities. The pond emptied after bursting of the geomembrane over several large cavities.

The investigation

Inspection after the failure showed that the geomembrane had many holes (open seams, punctures, tears) due to careless construction. 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 (Figure 10).

Figure 10. Cavities caused by several leaks of acid.

These cavities resulted from dissolution by phosphoric acid of calcium carbonate contained in the soil. 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 1 m in diameter (Figure 11).

Figure 11. A large cavity over which the geomembrane burst.

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 6 m of water, over a cavity having a diameter of approximately 1 m. This result is in agreement with the observed failure.

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 pond demanded that the contractor install a new geomembrane “with zero leakage”. However, 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 author of this paper understood that the large pond had two functions, evaporation and storage, and concluded that the solution would consist in separating the two functions. After earthwork to eliminate the soil contaminated and/or attacked by acid, three smaller ponds were constructed to replace the large pond. The large and deep pond with two functions (evaporation and storage) was replaced by three ponds: a deep storage pond and two shallow evaporation ponds (Figure 12).

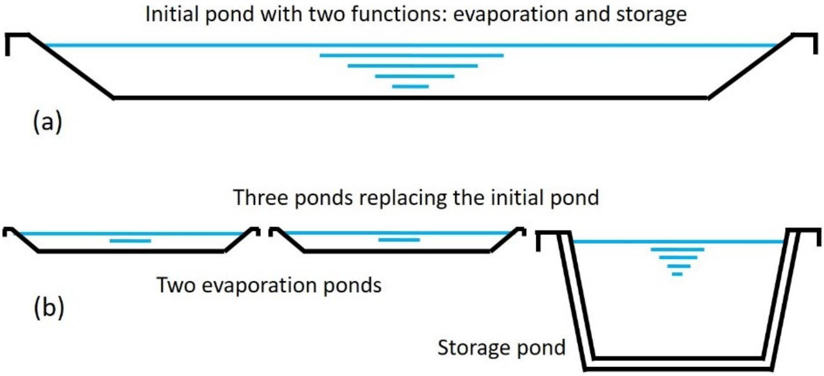


Figure 12. Schematic representation of the replacement of the large pond (a) with three ponds (b).

The storage pond had a double liner to prevent leakage of acid into the ground. The reason for having two evaporation ponds rather than one was the following:

- To promote evaporation, the two evaporation ponds were very shallow (0.5 m of acid).

- As a result of the low liquid pressure on the geomembrane liner, the risk of leakage was limited and the evaporation ponds only needed a single liner.
- However, leakage causing soil dissolution could still happen.
- But leakage is unlikely to happen in the two evaporation ponds at the same time.
- If leakage were to happen in one evaporation pond, repair could be done without interrupting the operation of the facility.

Conclusion of this case history

The observed failure occurred because no geotechnical engineer was involved in 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 geotechnical 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.

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 may be required. Examples of harmful liquids include:

- acid dissolving calcium carbonate contained in soil;
- water dissolving gypsum contained in soil;
- water causing soil instability by excess pore pressure; and
- 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 the reservoir should be adapted in accordance with the results of the analysis.

Case history 4: Reservoir excavated in a salt formation

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. It will be seen that a predicted failure can nevertheless occur if the engineer fails to convince the owner that the recommended preventive measures are necessary.

A large volume of water (about 8000 m^3) contained in a geomembrane-lined cavity (Figure 13) 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 reservoir was to contain the purest water ever produced in order to detect the faint light given off by decaying protons.

Figure 13. The cavity during geomembrane liner installation.

The 20 m × 20 m × 24 m cavity with vertical walls was excavated in a salt formation (because salt, contrary to rock, is not radioactive) 600 m underground (because cosmic radiation does not penetrate that deep) to contain the water required by the physics experiment. Both radioactivity and cosmic radiation would have disturbed the experiment.

Design of the liner system

A high density polyethylene (HDPE) geomembrane was selected for its chemical inertia. Other geomembranes could have contaminated the water. HDPE geomembranes are stiff compared to 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 reservoir. Due to the solubility of the salt, the design engineer recommended a double liner (i.e. two liners and a leakage collection and detection layer in between). As explained earlier in this paper, there is almost no leakage into the ground with a well-designed and well-operated double liner system. More details on the design can be found in Giroud & Stone (1984).

For the drainage layer between the two HDPE geomembranes, the design engineer selected a geonet, because (contrary to gravel) it is not radioactive and could 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. Since then, double liners with two geomembranes and a geonet have been routinely used in waste storage landfills.

The cavity had been excavated before designing the liner system. The corners of the cavity were at right angles. Due to the stiffness of the liner system (composed of two 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 ot the corners and water pressure would induce high tensile stresses in the two geomembranes. In order to analyze the behavior of the geomembranes, the design engineer requested the stress-strain curve of the geomembrane from its manufacturer. This was an extraordinary request at that time, and it was not easy to obtain the stress-strain curve for a geomembrane.

Analysis and failure prediction

Upon inspection of the stress-strain curve, the design engineer realized that there was a yield peak on the curve, which was a surprise since no other geomembrane known at that time had a yield peak on its stress-strain curve (Figure 14). 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 or a seam between two geomembrane panels) would cause the yield strain to be reached in a small part of the geomembrane while the strain in the rest of the geomembrane is still lower 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 the geomembrane would drastically increase to several hundred percent in a small area. This would cause localized thinning of the geomembrane until it burst under water pressure. It is important to note that, while the strain would be several hundred percent in the failure area, the average strain over the entire geomembrane area subjected to tension is close to the yield strain. In other words, failure occurs for an average strain of the order of 12%, not 700%.

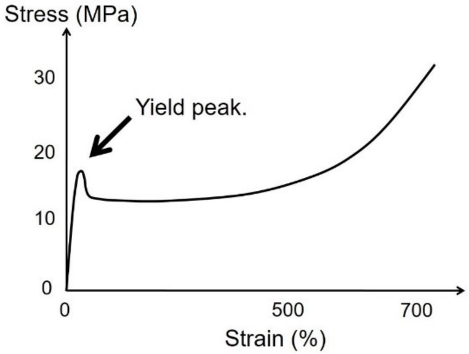


Figure 14. Stress-strain curve of HDPE geomembrane.

Recommended remedial measure

The design engineer recommended that the right-angle corners be eliminated by constructing a chamfer (with concrete or wood) in each corner of the reservoir (Figure 15).

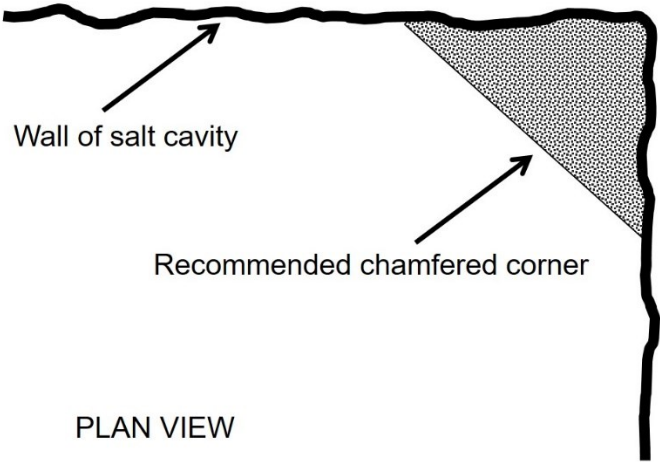


Figure 15. Recommended chamfers in the corners of the reservoir.

The design engineer even wrote a report describing the analysis and stating that the liner system would fail unless chamfers are constructed. However, the geomembrane supplier convinced the client (the physics experiment team) that the recommended measure was overly conservative because tensile tests show that HDPE geomembranes can elongate up to 700% before failure. The most compelling argument used by the geomembrane supplier was that the type of failure predicted by the design engineer had never been observed.

The design engineer could not convincingly champion his recommendation because, in geotechnical engineering, there is a strong tendency to believe only what has been seen before. This makes it difficult to believe predictions of new failure mechanisms. However, what is predicted rationally should be believed.

Failure

The geomembrane was installed without chamfered corners. Significant leakage was detected by the leakage collection and detection layer during the first filling of the reservoir. Inspection by divers showed the geomembrane had failed as predicted. This is a rare case where the failure analysis was done in detail before the failure occurred exactly as predicted.

Photos taken under water (which, being extremely pure, was transparent) showed that the geomembrane had burst in a scratched area near a seam (Figure 16). It should be noted that scratches and seams were the two causes of potential strain concentration identified at the design stage. Scratches had been caused by a seaming procedure that consisted in grinding the geomembrane surface prior to seaming. This procedure has been improved since then.

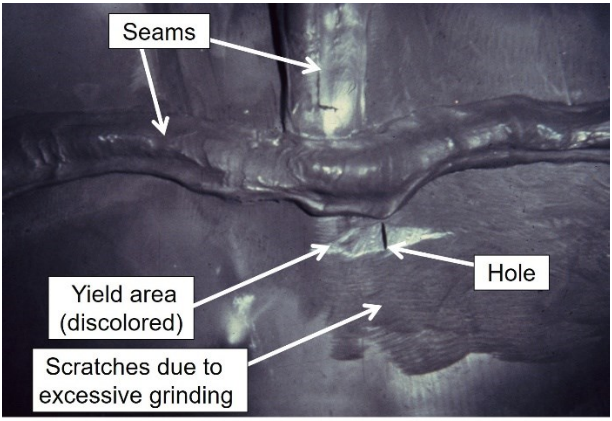


Figure 16. Under water photo showing the failure.

Remediation

The remedial measure recommended at the design stage was implemented as follows. Lightweight concrete was slowly cast in the corners or the reservoir using the lining system as formwork, while water was progressively added in the reservoir to balance the concrete pressure. The reservoir was thus successfully filled and the physics experiment could be conducted.

Conclusion of this case history

Specific lessons learned from this case history 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: today, HDPE geomembranes (which are the most often used geomembranes) are designed with an allowable strain of the order of approximately 3 to 6%, which is the yield strain divided by a factor of safety. Also:

- Attention has been drawn to the importance of strain concentration in the vicinity of geomembrane seams and research work has been conducted on this subject (Giroud et al. 1995, Giroud 2005, Andresen 2016, Kavazanjian et al. 2017).
- Grinding the geomembrane surface next to seams has been eliminated for most 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.

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.

Conclusion

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 require a good understanding of the properties of geomembranes. Geotechnical engineers who are accustomed to deal with complex materials, soils and rocks, are well prepared to understand the properties of geomembranes.

Examples of large reservoirs, canals and dams that have been successfully constructed with a geomembrane liner are illustrated in Figures 17 to 19. It should be noted that in these impressive structures the geomembrane liner is the sole waterproof component,

Figure 17. Water reservoirs for the Panama Canal locks [Courtesy Carpi].

Figure 18. Tekapo canal in New Zealand [Courtesy Carpi].

Figure 19. Pannecière Dam in France [Courtesy Carpi].

The above 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.

Acknowlwegments

The author of this paper is grateful to the Hungarian Geotechnical Society and the Hungarian Chamber of Engineers for the invitation to present the prestigious lecture at the 2017 Széchy Memorial Session.

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