Lessons learned from successes and failures associated with geosynthetics

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ABSTRACT: Based on a review of approximately 100 case histories, this paper analyzes systematically the modes of failure of structures incorporating geosynthetics and reviews the design and field situations that lead to failures. Numerous examples are presented, and lessons learned from the failures are summarized. The various modes of failure observed are classified in different categories and relationships between modes of failures and characteristics of geosynthetics are discussed. Finally, successes of geosynthetics are reviewed in order to put failures in perspective. Note: This paper is an expansion by approximately 50% of the paper titled "*Lessons learned from failures associated with geosynthetics*" published by the author in 1999.

1 INTRODUCTION

Geotechnical engineers who do not learn from successes achieved by others will miss opportunities. Geotechnical engineers who do not learn from mistakes made by others will learn from their own mistakes. This should encourage geotechnical engineers to read this paper.

1.1 *A science, not an art*

Geotechnical engineering is an art as much as a science, as many like to say. This statement is incorrect and it may mislead those who are learning about geotechnical engineering. Geotechnical engineering is a science, it is not an art. It is a science because all phenomena of geotechnical engineering can be explained rationally. It is not an art because, in geotechnical engineering, there is no room for personal emotions and abstract imagination. One may object that the word "art", being used in expressions such as "the art of building", does apply to geotechnical engineering. In these expressions, the word "art" designates *methods and skills*, generally *derived from practice*. Geotechnical engineering, being an applied science, certainly includes activities that require "methods and skills derived from practice" (e.g. the art of conducting field investigations or, even, the art of writing papers). However, geotechnical engineering itself is a science, an applied science, not an art.

1.2 *Rational analyses, not common sense*

As a science, geotechnical engineering requires reliable tools. Common sense, which is often invoked by geotechnical engineers, is not a reliable tool, because it is a random collection of beliefs, many of them being bad habits, only 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. Therefore, common sense cannot be used as a basis for rational decisions in a scientific discipline.

1.3 *Learning from experience*

The fact that, in a scientific discipline, all phenomena can be explained rationally on the basis of first principles does not mean that all knowledge must result from logical deduction. In fact, a large fraction of the present scientific knowledge — and this applies to all disciplines — was generated from experience, often by chance. Rational explanations of the phenomena were developed eventually. This is particularly true for geotechnical engineering, a discipline where the complexity of materials, mechanisms and boundary conditions makes it difficult to predict phenomena only by pure logical deduction. This is also true for geosynthetics, because, in addition to the constraints inherent to geotechnical engineering, there is the fact that the use of geosynthetics is relatively new. As a result, the body of rational knowledge is still under development while the variety of uses and users creates a wealth of experience from which additional knowledge can be tapped.

It is clear from the above discussion that no opportunity should be missed to learn from experience. However, there is a great difference between experience and learning from experience. The only way to learn from experience is to analyze available data and incorporate the results of the analyses into an organized body of knowledge. This is particularly true for learning from failures, which constitute the ultimate level of experience. In this paper, numerous case histories are used to show how lessons can be learned from a rational analysis of failures.

Based on the above discussion, it is important to know what a failure is.

1.4 *Definition of failure*

Asking the question, “What is a failure?”, regarding geotechnical structures, often attracts a confusing answer based on “common sense”, the magic phrase used every time it appears difficult to develop a rational approach. Indeed, it is not easy to rationally define what a failure is, as seen below.

A failure in a geotechnical structure can affect the entire structure (e.g. a road embankment), a system (e.g. a cover system on a landfill), or a component (e.g. a geosynthetic). Several definitions can be considered for a failure.

A first tentative definition, which is often mentioned, would be:

> *A structure, system, or component fails if it does not perform its intended function.*

Certainly, a structure, system, or component must perform its intended function, but a definition that only contains this requirement is not complete. This definition may be too lax or may be excessive depending on the interpretation of the word “function”. For example, according to the above definition, a retaining structure that exhibits a very large deformation, but still retains the soil, is not considered a failure regardless of the consequences of the large deformation if the function of the retaining structure is only understood to be “to retain the soil”. Also, according to the above definition, a geomembrane liner with a very small defect causing an inconsequential leak would be considered a failure if it is understood that the intended function of a liner is to act as an absolute fluid barrier. At this point, it is important to note that there is a difference between the function of a structure and the function of the geosynthetic in the structure. Thus, while the function of the geomembrane liner in a pond is to act as a fluid barrier, the function of the pond is to contain a liquid. This distinction is illustrated by the case of a small pond where the geomembrane liner is entirely uplifted by gas (a real case); in this case, the pond fails to perform its function of containing liquid while the geomembrane liner does perform its function of acting as a fluid barrier. The function of the structure should not only be clearly defined, it should also be quantified; for example, in the case of a geomembrane-lined pond, the volume of liquid to be contained should be specified. However, this may still not be sufficient, because a single geomembrane bubble in the case of a large pond may not significantly affect the volume of liquid contained, but may affect the long-term performance of the geomembrane (by exposing the geomembrane to sunlight, wind, etc.) and may hamper the operation of the pond. Clearly a definition of failure based on the function of the structure is too vague to be adequate. Based on a comment made above, the definition of failure should include a number of quantified requirements, i.e. performance criteria. This leads to the second tentative definition:

> *A structure, system, or component fails if it does not meet its performance criteria.*

This definition is better than the first definition because it includes performance criteria, but it is flawed because it implies that performance criteria were set for the considered structure, system, or component, which is not always the case. (In other words, this definition opens the door to the absurd situation where there cannot be a failure because no criteria were set.) Also, this definition implies that the performance criteria, if any, are complete and adequate. For example, simplistic performance criteria such as "no settlement" or "zero leakage" are not adequate because they cannot be met and, therefore, any behavior is a failure with respect to such criteria.

Clearly, a better definition is needed. Combining the two above tentative definitions in a phrase such as "*if it does not perform its intended function and/or does not meet its performance criteria*" does not solve the problems illustrated by the examples presented above.

Finally, the proposed definition could be:

> *A structure, system, or component fails if it does not meet complete and adequate performance criteria.*

This definition is technically correct because "*complete and adequate performance criteria*" can be expected to define and quantify, completely and adequately, the intended function of the structure, system or component. A potential drawback of the above definition is that the adjectives "*complete and adequate*" may be subject to interpretation and discussions. However, it should be possible to develop guidance regarding what "*complete and adequate performance criteria*" are. Tentatively, the following guidance is proposed.

1.5 *Types of failure*

To be complete, the criteria should address the three following potential types of failure: failure to perform the function of the structure, system, or component; disruption of, or nuisance to, operation or use of the structure, system, or component; and threat to the future performance of the structure, system, or component. These three potential types of failure are discussed below.

1.5.1 *Failure to perform the function of the structure, system, or component*

As stated after the first tentative definition, it is clear that a structure, system, or component must perform its intended function. Therefore, to be *complete and adequate*, performance criteria should include qualitative and quantitative requirements describing the ability of the structure, system, or component to perform its intended function. In the case of a pond, examples of such requirements are: the volume of liquid that the pond must contain and the maximum allowable leakage rate. Examples of failures to meet these requirements would be: a geomembrane liner uplifted by gas to the extent that the required volume of liquid cannot be contained; a leak that exceeds the maximum allowable leakage rate; and a very large leak that both exceeds the maximum allowable leakage rate and prevents the pond from containing the the required volume of liquid.

1.5.2 *Disruption of, or nuisance to, operation or use of the structure, system, or component*

Every structure, system, or component is operated or used. Therefore, there are disruptions of, or nuisances to, the operation or use of the structure, system, or component that cannot be tolerated by the operator or user. This kind of failure is often referred to as "serviceability failure". Therefore, to be *complete and adequate*, performance criteria should include qualitative and quantitative requirements describing the disruptions of, or nuisances to, the operation or use of the structure, system, or component that cannot be tolerated. In the case of a pond, an example of such requirements is that boats can navigate in all parts of the pond, which means that the localized uplift of the geomembrane liner by gas cannot be tolerated even if it does not affect the ability of the pond to perform its function, which is to contain a certain volume of liquid.

1.5.3 *Threat to the future peformance of the structure, system, or component*

A structure, system, or component must perform its function and be operated or used for a certain period of time. Therefore, to be *complete and adequate,* performance criteria should include qualitative and quantitative requirements describing the ability of the structure, system, or component to perform its function and be operated or used during a certain period of time usually referred to as the design life. Criteria can even include trends (such as change in some geomembrane characteristic that indicates degradation, or monitoring of the inclination of a reinforced-soil wall facing) or symptoms (such as water seeping through the downstream face of a dam) that may help predict future failure, or even imminent failure (if the trends and/or symptoms indicate rapid or even accelerating material and/or structure degradation). Failures that result from not meeting the requirements related to the future performance of the structure, system, or component can be referred to as "durability failures". In the case of a pond, a localized uplift of the geomembrane liner forming a "bubble" may not prevent the pond from performing its function (which is to contain a certain volume of liquid) and may not hamper the operation and use of the pond. Therefore, the first two types of criteria are met. However, the bubble exposes the geomembrane to sunlight and vandals, which may decrease the ability of the geomembrane liner to perform its function during the entire design life of the pond. Therefore, the performance criteria should include some language treating the development of a geomembrane bubble as a symptom that is not acceptable and requires immediate action because it indicates the beginning of a mechanism leading to failure.

1.6 *Discussion of the types of failure*

The boundaries between the three types of failures are not totally rigid and some criteria may be at the limit between two types. For example, the deformation of a reinforced soil wall may be only a nuisance to the user if it affects the appearance of the wall face or it is a failure to perform the function if, due to the deformation of the wall, a foundation that was to be built on the retained soil cannot be built. (The limit may even evolve with time: a wall with a face tilting forward may only be a "nuisance to the use of the structure", however, as the tilting continues to increase, it may become a warning of imminent collapse.) However, the above guidance makes it possible to establish a list of criteria that is *complete,* which is essential. In addition to be *complete,* the criteria should be *adequate*. Adequate criteria are criteria that are rationally quantified in a way that reflects the performance of the structure and the needs of its operators and users.

It should be noted that the three types of failure mentioned above are different from the two types often mentioned, structural failure and serviceability failure. The terminology "*structural failure and serviceability failure*" comes from the designers of structures that may collapse when poorly designed and/or constructed (e.g. reinforced-soil structures with a vertical face). This terminology is not applicable to the many types of structures that do not collapse. Clearly, instead of referring to "*structural failure and serviceability failure*", it is more general and more correct to refer to "*functional failure, serviceability failure, and durability failure*", as explained in Sections 1.5.1, 1.5.2 and 1.5.3, respectively. An advantage of the proposed definition of failure (see the end of Section 1.4) is that it makes it possible to evaluate rationally designs and specifications and to identify those that are based on incomplete or inadequate performance criteria.

1.7 *Defects and failures*

According to the proposed definition, a defect is not necessarily a failure. Whether a defect is a failure depends on its acceptability. A relatively large hole in a geomembrane is clearly a defect but it may not cause a failure if the resulting leakage is acceptable and is properly handled by an adequate drainage system. In contrast, a relatively small hole in a geomembrane is a failure if it causes unacceptable pollution of the soil or ground water. However, it may not be appropriate to attribute this failure to the geomembrane. It is likely that, in such a case, the unacceptable pollution is due to a design mistake because small defects are known to happen in geomembranes and a different design should have been considered (e.g. a double liner instead of a single liner).

1.8 *Terminology*

The following terms will be used in the analyses and discussions: *mechanisms, modes, categories, types, causes*, and *reasons*. The following definitions are proposed:

- *Mechanism*: description of the case-specific steps leading to failure.
- *Mode*: similar to mechanism, but not case-specific.
- *Category*: each class in a classification, such as the categories mentioned in Section 1.13 and used as the headings of Sections 2 to 6.
- *Type*: description of failure based on performance criteria, as indicated in Sections 1.5 and 1.6.
- *Cause*: set of events leading to failure.
- *Reason*: action or set of actions that explain why the set of events leading to failure took place.

To better understand the terminology, an example is necessary:

- *Mechanism*: particles migrating from an unstable soil and passing through the geotextile filter that has been installed by the contractor instead of the geotextile filter specified by the design engineer, thereby accumulating in the gravel drain.
- *Mode*: clogging of drain by particles migrating through a filter.
- *Category*: malfunctioning of filters and drains.
- *Type*: functional failure.
- *Cause*: inadequate specifications and construction mistake.
- *Reason*: lack of knowledge about construction practice on the part of the design engineer, and lack of knowledge on geosynthetics on the part of the contractor.

It is not always easy to strictly follow the above terminology, and there may be some inconsistencies in this paper.

1.9 *Failures during construction*

The types of failures that are covered by the proposed definition generally occur when the structure is in service. However, certain types of failures may also occur during construction. For example, the rotational instability of a road embankment during construction is a failure because it seriously compromises the construction of the road. In contrast, construction problems which are solved during construction (e.g. a geomembrane torn during construction and repaired) are not failures because they do not prevent the structure, system, or component from meeting performance criteria and from being constructed.

1.10 *Consequences of failures*

The consequences of a failure depend on the function of the structure, system, or component and may vary widely. Thus, after a failure, a structure, system or component is repaired, reconstructed or abandoned. Regardless of the magnitude of the consequences, all failures result in an interruption of the operation or use of the structure; from this viewpoint, an imminent failure (i.e. a failure defined above as being characterized by trends and/or symptoms indicating rapid or even accelerating material and/or structure degradation) is equivalent to an actual failure.

1.11 *Functions of structures and functions of geosynthetics*

Based on the above discussion on the definition of failure, it is necessary to have a good understanding of the functions performed by structures, systems, or components to understand and avoid failures. It is important to note that functions performed by structures are different from functions performed by geosynthetics. For example: the function of a geosynthetic-reinforced retaining structure is to retain the soil, whereas the function of the geosynthetic is to reinforce the soil; and the function of a drainage system is to drain the soil whereas the function of the geotextile filter is to act as a filter for the drainage system. The function of the structure is defined in relation to the soil mass or the environment, whereas the function of the geosynthetic is defined in relation to the structure.

In any case, it is important to understand the functions of geosynthetics to avoid and investigate failures. It is also necessary to properly identify the properties required for a geosynthetic to perform a given function. Furthermore, it is necessary to understand the requirements for performing each function, such as the geosynthetic and soil movements associated with the performance of each function. Indeed, it will be seen in this paper that these geosynthetic and soil movements may have a significant impact on the performance of structures incorporating geosynthetics. Information on functions of geosynthetics can be found in several publications on geosynthetics (Giroud 1980; Giroud et al. 1985; Holtz et al. 1997; Koerner 1998).

1.12 *Failures and successes*

It is important to put failures in perspective. To prepare this paper, approximately 100 documented case histories were reviewed. Certainly the author did not collect all of the case histories of failures of structures incorporating geosynthetics. However, the author performed a thorough survey of failures, published and unpublished, and, as a result, collected many of the case histories related to significant failures. Assuming that the author collected only 10% of the case histories related to significant failures that occurred since the late 1960s, it may be inferred that 1000 significant failures occurred. During the same three decades of geosynthetic use, 15 billion m^2 of geosynthetics have been used in several million projects. Therefore, the rate of significant failures is less than 0.1%. Clearly, the geosynthetic discipline has been characterized by success far more than by failure. However, as in everyday life, there is more to learn from failures than from successes. Therefore, as discussed below, a greater part of this paper will be devoted to analyzing failures than to presenting successes.

1.13 *Scope and organization of this paper*

The introduction of this paper is in great part inspired from a preceding paper by the same author (Giroud 1999). However, the rest of this paper is quite different. In the present paper, the case histories of failures are discussed in five sections that correspond to five typical categories of problems encountered in geotechnical engineering: leakage, clogging, instability, deformation, and degradation. In contrast, in the preceding paper (Giroud 1999), the failures were discussed in only two sections: “modes of failures” and “situations leading to failures”.

Throughout the paper, special emphasis is placed on lessons learned from case histories. To that end, many of the 100 documented case histories that were reviewed will be described, either as short “examples” or as rather detailed “case histories”. A complete presentation of these case histories will appear in a book that is presently being written and edited by the author of this paper. The book will comprise papers describing the case histories contributed by various authors. These authors are referred to herein in italics and without a date, contrary to the regular publications that are referred to the usual way, i.e. with the names of authors (not italicized) and a date.

A major difference between this paper and the preceding paper is that this paper includes two parts in order to provide a thorough analysis of failures that is consistent, to the extent possible, with the terminology presented in Section 1.8. Failure *mechanisms* and *modes* will essentially be discussed in the first part (Sections 2 to 6) whereas *causes* and *reasons* will be mostly discussed in the second part (Sections 8 and 9).

Another difference between this paper and the preceding paper is that successes are discussed in this paper, whereas only failures were discussed in the preceding paper. Successes are discussed in Section 10.

PART I — MECHANISMS AND MODES OF FAILURE ASSOCIATED WITH GEOSYNTHETICS

2 LEAKAGE

2.1 *Overview of leakage*

Most structures incorporating geosynthetics whose function is to contain liquids are using geomembranes to perform the containment function. Therefore most leakage problems are associated with geomembranes. These leakage problems result from lack of continuity of the geomembrane, such as geomembrane defects (Section 2.2) and geomembrane rupture (Sections 2.3, 2.4 and 2.5). In addition, there are leakage problems that result from the presence of preferential paths for water due to improperly installed geomembrane or transmissive geosynthetic (Section 2.6).

2.2 *Geomembrane defects*

2.2.1 *Overview*

The terminology "geomembrane defects" designate lack of continuity of geomembrane resulting from manufacturing, construction activities, or operations. Modern geomembranes have virtually no manufacturing defects, Therefore, geomembrane defects generally result from construction activities, and sometimes from operation of the geomembrane-lined structure.

2.2.2 *Examples*

Examples — Defects resulting from seams and connections. Failures due to lack of continuity of geomembrane liners occur when geomembrane seams are inadequate (numerous examples are provided by *Laine and Darilek*, *Rollin and Jacquelin*, and *Nosko and Ganier*), or when connections between geomembrane liners and appurtenances are not waterproof (see the case history of a geomembrane liner on a karstic soil in Section 2.4.3).

Examples — Defects resulting from mechanical damage. The following types of mechanical damage have been reported: (i) puncture, tear, abrasion and other mechanical damage of geomembranes (*Well, Datye and Gore, Laine and Darilek, Rollin and Jacquelin, Nosko and Ganier*), in particular during placement of soil on top of a liner system (*Nosko and Ganier*) and due to steel wire mesh used for the reinforcement of concrete slabs (*Datye and Gore*); (ii) puncture of the entire liner system of a landfill by a well driven through the waste (*Gross et al.*); (iii) geomembrane liner cut by vandals and by construction workers shooting nails intentionally (both cases observed by the author of this paper); (iv) damage to geomembranes by small animals (*Datye and Gore*), which is extremely rare, whereas damage by large animals (e.g. deer, bears) is not infrequent, especially during construction, as pointed out by Thiel (1999); and (v) puncture of geosynthetic clay liner and decrease of geosynthetic clay liner thickness due to squeezing of bentonite (*Peggs and Olsta*).

Statistics regarding damage to geomembrane liners. Based, in particular, on results of electric leak detection and location surveys presented by *Nosko and Ganier*, the author of this paper has established the following approximate statistics for geomembrane defects in geomembrane liners that do not exhibit any failure mode other than localized defects:

- 25% of the detected leaks are due to installation problems (including 20% inadequate seams and 5% mechanical damage);
- 70% of the detected leaks are due to mechanical damage caused during placement of the overlying soil; and
- 5% of the detected leaks are due to problems that occurred during operations.

Since problems that occurred during operations probably result from mechanical damage, it appears that 80% of geomembrane defects are due to mechanical damage and that most defects result from damage that occurs during placement of soil overlying the geomembrane.

2.2.3 *Lessons learned from the above examples*

Several of the above examples show that great precautions should be taken during placement of geomembranes and geosynthetic clay liners. Construction quality assurance of geomembrane and geosynthetic clay liner installation is essential. It should include monitoring the placement of materials overlying the geomembranes and geosynthetic clay liners. It may also include an electric leak detection and location survey after placement of the materials overlying the geomembranes. Since the placement of overlying materials is a major cause of damage to geomembranes, design engineers should, whenever possible, select overlying materials that are least likely to damage the geomembrane: (i) when granular soil is used, the particles should be as small as possible; (ii) if necessary, a thick needle-punched nonwoven geotextile acting as a cushion should be used between the geomembrane and the granular soil; and (iii) when reinforced concrete is used to protect a geomembrane (as on the upstream face of dams), fiber-reinforced concrete should be preferred to the traditional concrete reinforced with steel bars (Tisserand et al. 1997).

Precautions must also be taken during the placement of geosynthetics other than geomembranes because construction damage may reduce the ability of a geotextile to perform its function. For example, holes may cause a geotextile filter to fail, and construction damage may reduce the ability of a geogrid to reinforce a soil.

2.3 *Geomembrane rupture due to stress concentration*

2.3.1 *Overview*

Due to their two-dimensional nature, geosynthetics are often subjected to tensile stresses. Therefore, the most typical mode of geosynthetic failure is tensile rupture, which occurs when the tensile stresses are excessive. Tensile rupture may happen when the excessive tensile stresses are applied or at a later time due to creep (since all polymeric materials exhibit creep), or due to slow crack growth resulting from stress cracking. Tensile rupture typically occurs as the result of a failure mechanism that leads to an increase in tensile stress. Many examples of such mechanisms are given in this paper (e.g. uplift, subsidence, waste or ore slide, collapse of a structure). Since tensile rupture is the most typical mode of failure of geosynthetics, design engineers should make every effort to avoid situations likely to lead to excessive tensile stresses in geosynthetics. In particular, they should try to avoid concentrated tensile stresses as discussed below.

Because geosynthetics are thin, any abrupt change in their thickness may cause concentration of tensile stresses likely to result in geosynthetic rupture. (Indeed, any change in thickness is a departure from the ideal two-dimensional conditions.) This is particularly the case for geomembrane seams. Examples are given below.

2.3.2 *Examples of tensile rupture due to thermal contraction*

Thermal contraction results in geomembrane tension, which may cause tensile failure (in the case of geomembranes that become stiffer at low temperature) or rupture of geomembranes that are exhibiting slow crack growth due to stress cracking (Giroud 1994a; *Giroud, Thomas and Kolbasuk*).

2.3.3 *Examples of seam failures*

A number of geomembrane failures have been observed next to seams (Giroud 1994a, 1994b; *Thomas and Kolbasuk*). Many of these failures result from stress concentration as shown and quantified by Giroud (1994b) and Giroud et al. (1995b). In many cases, the tensile stress that initiated the geomembrane rupture was due to thermal contraction resulting from a decrease in temperature. The geomembrane failure was either tensile rupture or rupture due to stress cracking in the form of rapid crack growth following a long period of slow crack growth under a smaller tensile stress (Giroud 1994a).

2.3.4 *Tear initiated by seam*

An interesting example is provided by *Sharma and Settepani*. They reported the case of a long tear in a geomembrane liner in a landfill that occurred near the top of a slope during an earthquake and started at the seam of a patch covering a hole in the geomembrane resulting from the removal of a geomembrane sample for destructive testing.

2.3.5 *Lessons learned from the above examples*

The above examples show that stresses that lead to failures are often associated with seams. Therefore, the number of seams in a geomembrane liner should be minimized. In particular, the number of samples removed from an installed geomembrane liner for destructive testing should be limited.

Also, these samples should not be taken in areas where tensile stresses are likely to be large, such as the tops of slopes. Finally it is suggested that research be conducted to develop seams that cause minimum stress concentration.

Regarding the recommendation for minimizing the number of seams, an interesting case has been discussed by Giroud et al. (1993). The specifications for the construction of a geomembrane liner for a landfill included criteria for destructive testing with extremely high values for the shear and peel strengths of the tested seams. These values were so high that many samples failed the tests. Therefore, more tests were needed and additional samples had to be taken, which resulted in additional holes in the geomembrane. The intent of the stringent criteria was to improve liner quality; the result was a liner weakened by an excessive number of patched holes.

2.4 *Subsidence of the supporting soil causing geomembrane rupture and leakage*

2.4.1 *Overview*

In case of localized subsidence of the soil supporting a geomembrane, which results in a cavity, if the geomembrane is subjected to a normal stress, it tends to deflect toward the bottom of the cavity. The resulting tensile stresses in the geomembrane may cause the geomembrane to rupture. The challenge for the design engineer is to predict the size of the cavity, which is an essential parameter in the calculation of the tensile stress. Several examples are presented below.

2.4.2 *Case history — Geomembrane liner on a soil with a high carbonate content*

A single geomembrane liner was installed in a large (206 × 98 m), 3-m deep pond to contain phosphoric acid. The pond was located in a desert. Eleven months after the first filling, the liner burst over a 1-m diameter solution cavity (Giroud and Fluet 1986; Giroud et al. 1990a; Giroud 1993). Acid leaking through a defect in the geomembrane had attacked the high carbonate content subgrade soil. The owner insisted that the soil cavities be repaired (there were several cavities, each caused by a different leak in the geomembrane) and the geomembrane replaced by an identical geomembrane, so the pond would be reconstructed as initially designed. The owner's insistence resulted from his belief that the only problem was a deficiency in the geomembrane liner, based on the project specifications which indicated that the "pond will be lined with a flexible, impermeable membrane to prevent seepage".

The consulting engineer hired to investigate the problem (the author of this paper) had to convince the owner that the same accident would occur again because it is not possible to install a geomembrane over a large area without any defect. The consulting engineer indicated that the problem resulted essentially from a conceptual mistake: acid should not be impounded over a soil with a high carbonate content using a single liner. Finally, the owner agreed that the conceptual design be revised. Answering questions from the consulting engineer, the owner indicated that the pond had two functions: storage and evaporation. The consulting engineer then recommended that the two functions be separated. Accordingly, the large pond was replaced by three smaller ponds that occupied the same total footprint:

- one storage pond, with a small surface area, but rather deep (6 m), with a double geomembrane liner and a leakage detection/collection layer between the two liners; and
- two twin evaporation ponds, large and very shallow (0.5 m of liquid), with a single geomembrane liner.

The concept of the adopted solution is a follows:

- large, shallow ponds promote evaporation;
- considering that the rate of leakage through a geomembrane defect under a liquid depth of only 0.5 m is expected to be small and that leakage would not cause water contamination because there was no ground water under the ponds, the use of a double liner for the evaporation ponds was not justified;
- comparing liquid levels in the twin evaporation ponds provides a means to rapidly detect if one of the two ponds is leaking; this pond would then be repaired while the other is still used;

- a double liner was justified in the storage pond because a large rate of leakage through a geomembrane defect could be expected under a depth of liquid of 6 m, which would cause the development of a cavity in the soil; and
- the soil excavated to construct the storage pond was used as backfill under the evaporation ponds, which made it possible to repair the subgrade soil which had been damaged in many areas by solution cavities.

It is noteworthy that calculations performed during the investigation using the method developed by Giroud (1981, 1982a) showed an excellent correlation between the depth of liquid at the time of failure, the density of liquid, the diameter of the solution cavity, and the tensile strength of the geomembrane. This showed that the failure could be explained rationally.

SUMMARY OF CASE HISTORY — Mechanism: leakage through the geomembrane, which caused the development of solution cavities under the geomembrane; *Mode*: lack of support of the geomembrane from the material underlying the geomembrane, hence bursting of the geomembrane; *Cause*: the design engineer and the owner failed to recognize the potential failure mechanism; *Reason*: it is possible that the site investigation did not appear necessary due to unrealistic expectations regarding the performance of the geomembrane ("impermeable").

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- Geosynthetics do not make miracles and should not be expected to make miracles. A design that relies on unrealistic expectations about geosynthetic performance is flawed and could lead to failures.
- The geosynthetic should not be automatically considered as the main culprit if a failure occurs. Furthermore, the geosynthetic should not be used as a scapegoat when the design is flawed.
- A failure may provide an opportunity to improve a flawed design. Even if entitled to do so under the contract, the owner should not demand that the facility be reconstructed as initially designed until the design is evaluated to determine if it is flawed. Also, it is inappropriate, when a structure incorporating geosynthetics fails, to reject geosynthetics systematically and to demand that the problem be solved using a traditional design solution. It is worth noting that failures involving geosynthetics are usually successfully repaired using geosynthetics.
- Observed failures can always be rationally explained if appropriate data have been collected during the investigation. Failures provide an opportunity to calibrate design methods. When such calibration is done, it appears generally that available methods for designing geosynthetics applications are satisfactory. Design engineers are encouraged, therefore, to believe the results of their analyses, especially when these results lead to predicting a failure.
- The worst situation for a design engineer, if a failure occurs, is finding that any expert could explain the failure rationally using a method that was available at the time the project was designed.

2.4.3 *Case history — Geomembrane liner on karstic soil.*

The geomembrane used as a single liner for a reservoir burst as a result of the opening of a karstic cavity in the supporting soil (Giroud and Goldstein 1982; Giroud 1993). The investigation showed that the opening of the karstic cavity had been provoked by intrusion of water into the ground resulting from leakage at a defective connection between the geomembrane and a concrete water intake tower. The owner hastily concluded that a geomembrane liner could not provide a reliable solution and decided to reline the reservoir with bituminous concrete reinforced with steel strips. This solution seemed to be based on common sense, but the consulting engineer hired to investigate the failure realized that the problem was due to a defective conceptual design: a simple geologic exploration at the design stage would have shown that the reservoir was founded on a karstic terrain (which the original designer had not realized) and that intrusion of water into the ground would cause erosion of the clay bridging the top of karstic cavities. The consulting engineer then convinced the owner that, because bituminous concrete is not absolutely impermeable, there would be some intrusion of water into the ground and a new karstic collapse could occur. Therefore, the consulting engineer recommended that a double liner be used. This was achieved by using the bituminous concrete with steel reinforcement as the secondary liner and a geomembrane as the primary liner, with an intermediate leakage detection/collection layer made of gravel stabilized with bitumen and numerous collector pipes. It is interesting to note that the owner was comfortable with the use of steel-reinforced bituminous concrete (i.e. a "reinforced traditional solution") because of the prevailing belief that "stronger is better". In contrast, the consulting engineer designing the repair was comfortable with the solution that addressed the problem, i.e. the double liner.

SUMMARY OF CASE HISTORY — Mechanism: leakage at a geomembrane-appurtenance connection, which caused the opening of a karstic cavity; *Mode*: lack of support from the material underlying the geomembrane, hence bursting of the geomembrane; *Cause*: the design engineer and the owner failed to recognize the potential failure mechanism due to lack of soil investigation; *Reason*: it is possible that a soil investigation did not appear necessary because of unrealistic expectation regarding the performance of the geomembrane (i.e. the geomembrane was believed to be "impermeable" and would, therefore, protect the soil).

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- Proper soil investigation is as important in the case of a structure incorporating geosynthetics than in the case of conventional geotechnical structures.
- Unrealistic expectations regarding geosynthetic performance may lead to negligence.
- Common sense often leads one to believe that traditional solutions are safer than solutions involving new materials such as geosynthetics. Those who think so fail to recognize that there is no general answer to the comparison between traditional and innovative solutions. Only a rational analysis on a case by case basis may provide a valid answer. There are cases where it is possible to show that a geosynthetic solution is safer than a traditional solution, and vice versa. Once more, common sense can be wrong, and it is often wrong. Common sense is not a substitute for good design.

2.4.4 *Case history — Geomembrane liner in a dam reservoir*

A large reservoir lined with a geomembrane was used for the water supply of a winter resort (Giroud 1993). In the winter, the reservoir emptied and water had to be transported by trucks to the resort at great expense. Due to snow, field investigation was not possible until June. By that time, most people involved were convinced that failure of the geomembrane was responsible for the observed problem. Indeed, common sense indicated that, if water was leaking, the cause had to be a defective liner. Accordingly, the general feeling was that the geomembrane supplier/installer was liable.

At the insistence of the geomembrane supplier/installer, a thorough investigation was conducted. The investigation showed that the geomembrane had defects, but also showed that the breach in the geomembrane that emptied the reservoir had been caused by a depression of the soil supporting the geomembrane due to the collapse of a drainage pipe. The investigation also showed that the design of the dam had been done under strict time constraints.

SUMMARY OF CASE HISTORY — Mechanism: subsidence of the soil underlying the geomembrane due to the crushing of a pipe, hence bursting of the geomembrane; *Mode*: lack of support from the material underlying the geomembrane; *Cause*: the design engineer and the owner failed to recognize the potential failure mechanism; *Reason*: negligence at the design stage, in part due to lack of time.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- Usual design steps (e.g. checking the strength of drainage pipes) should not be omitted.
- Geosynthetics should not automatically be blamed for all problems in a project, even if they caused some of them.
- Common sense is afraid of novelty and, therefore, leads to using geosynthetics as scapegoats when there are problems.
- Failure investigations must be thorough in order to have a chance of finding all the causes.

2.5 *Lack of contact between the liner and the supporting soil causing geomembrane rupture and leakage*

Case history — Geomembrane liner in an underground reservoir. It is hard to believe that a mode of failure that never happened in the past could happen, even if this mode of failure is predicted using a rational analysis. Indeed, geotechnical engineers are accustomed to learn from precedents. However, it should be noted that, while such an attitude may be justified in a relatively old discipline such as geotechnical engineering, it is not appropriate in a relatively new discipline such as geosynthetics engineering. This is illustrated by the following case history.

In 1980, the design engineer for a deep (20 m) rectangular reservoir (Giroud 1993, *Giroud and Stone*) concluded, from an analysis of the stress-strain curve of the selected geomembrane (a high density polyethylene geomembrane), that this geomembrane would fail if it were installed as planned. Due to the relative stiffness of the geomembrane, the design engineer realized that it would be difficult to place the geomembrane in intimate contact with the corners of the rectangular reservoir. The rationale presented by the design engineer, orally and in writing, can be summarized as follows:

- The geomembrane stress-strain curve obtained in a tensile test has a yield peak at a rather small strain (of the order of 10%) compared to the strain at break, which is of the order of 1000%.
- As the reservoir is filled, tensile stresses in the geomembrane will increase in the vicinity of the reservoir corners, where the geomembrane is not supported.
- It can be predicted that the distribution of tensile stresses in the geomembrane will not be perfectly uniform, in particular because some irregularities of geomembrane thickness cannot be avoided and because of the curved shape of the geomembrane in the corners of the rectangular reservoir.
- As a result of the non-uniform stress distribution, the tensile stress will reach the peak value, at a certain Cross Section A of the geomembrane, while, in the rest of the geomembrane, the tensile stress will have a smaller value.
- As soon as the tensile stress at Cross Section A reaches the peak value, the strain at Cross Section A increases suddenly.
- It appears that a small difference between the tensile stresses at Cross Section A and at other cross sections in the geomembrane (which can be close to Cross Section A) causes a significant difference in strain: the strain at Cross Section A is of the order of 100 to 1000% while the strain in the rest of the geomembrane is less than 10%.
- As a result of its very large strain at Cross Section A, the geomembrane becomes very thin at that location and bursts under the liquid pressure in areas where it is not supported, i.e. in the corners of the reservoir. The geomembrane bursts only in a small area (because the geomembrane strain is small at cross sections other than Cross Section A), but this is sufficient to cause significant leakage.

The design engineer thus described a mode of failure he had never observed before. This mode of failure had not been observed either by the geomembrane manufacturer/installer, in spite of his experience. Furthermore, the geomembrane manufacturer/installer insisted that common sense dictated that, since the geomembrane breaks at a 1000% strain in a tensile test, it would not break in the reservoir where the strain had no chance to reach such a high value. Everyone in the project team, including the owner, disagreed with the design engineer. The geomembrane manufacturer/installer convinced the owner that the prediction by the design engineer was just an academic exercise that had nothing to do with reality. The design engineer insisted his analysis was rational, but he had to acknowledge that there were no facts to prove that the failure prediction derived from the analysis was correct since the predicted mode of failure had never been observed before. As a result, the design engineer could not convince the other members of the team (in part because he, too, respected experience based on precedents and, therefore, was not fully convinced himself by the prediction he had made).

The design engineer finally concluded that he was overly pessimistic, and the measures he had recommended were not taken. The recommended measures consisted essentially of changing the shape of the reservoir corners by constructing concrete chamfers. The geomembrane liner was installed in 1981 and failed during the first filling in one of the reservoir corners, as predicted. The geomembrane was repaired, the reservoir was filled again, and the geomembrane liner failed again, with the same mode of failure. Finally, the concrete chamfers were built, which was done without removing the geomembrane, using the geomembrane as a form. The reservoir was then successfully filled. The same mode of failure has occurred since then in other rectangular reservoirs.

A quantitative analysis of the mode of failure described above has been published in a paper (Giroud 1984d, 1984e) which established and disseminated the concept that geomembranes with a yield peak on their stress-strain curve can only be used in situations where their strain is less than the yield strain, which is approximately 50 to 100 times less than the strain at break measured in a uniaxial tensile test.

SUMMARY OF CASE HISTORY — Mechanism: the geomembrane had to deform under the water pressure to come in contact with the cavity wall; the resulting geomembrane elongation was excessive; *Mode*: lack of support from the material underlying the geomembrane; *Cause*: the design engineer and the owner recognized the potential failure mechanism, but failed to recognize that it would be critical; *Reason*: lack of experience.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- In a relatively new discipline such as geosynthetics, the fact that a certain mode of failure did not occur before is of limited value. Those who claim to have experience in a new discipline often do not; those who have experience often did not have the time or the means to analyze it and, therefore, did not learn. To be valuable, experience must be complemented by rational analyses.
- If a rational analysis based on adequate data shows that a failure can occur, then it is likely to occur. (The only reason that would prevent such a failure from occurring would be the presence of hidden factors of safety.) The engineer who predicts a failure through a rational analysis should believe the results of the analysis, regardless of past experience and common sense. The engineer should, therefore, take the risk of failure seriously and should convince the owner that the failure is likely to occur even if the predicted mode of failure has not been observed before.
- Common sense can be wrong, as well as it can be right. Since the basis for common sense is not known, it is not possible to distinguish between the good and bad aspects of common sense. As a result, common sense is not reliable.
- A rational analysis is the only reliable way to make sound decisions.

2.6 *Preferential path*

2.6.1 *Case history — Leakage through a dam due to liner bypassed by transmissive geotextile*

The geomembrane liner for the upstream face of a small earth dam was underlain by a needle-punched nonwoven geotextile acting as a cushion protecting the geomembrane (*Levillain*). Both the geomembrane and the geotextile were anchored in the same anchor trench at the toe of the dam, with the geotextile slightly longer than the geomembrane. As a result, water from the dam reservoir could infiltrate into the geotextile. Needle-punched nonwoven geotextiles have hydraulic transmissivity. Therefore, the water that infiltrated into the geotextile was conveyed by the geotextile through the dam, resulting in a considerable amount of leakage. This failure would not have occurred if the extremity of the geotextile had been properly sealed in the anchor trench.

SUMMARY OF CASE HISTORY — Mechanism: preferential path due to geotextile hydraulic transmissivity; *Mode*: detrimental effect of a geosynthetic that otherwise performs a useful function (geomembrane protection); *Cause*: the design engineer failed to recognize the potential failure mechanism or failed to properly specify for installation, or the installer did not follow the specifications; *Reason*: unknown.

Lessons learned from the above case history. The above case history shows that a needle-punched nonwoven geotextile can convey enough water to cause a failure. Such cases should be identified by the design engineer and appropriate measures should be taken; in particular, strict specifications for installation should be prepared by the design engineer to avoid mistakes during construction.

2.6.2 *Case history — Dam failure due to lack of continuity of geomembrane liner*

A geomembrane liner was placed over the entire area of the reservoir of a dam. The dam was a 18 m high embankment dam with an upstream clay zone. The geomembrane liner did not extend on the upstream face of the dam; rather, the geomembrane lining the reservoir floor was stopped at the upstream toe of the dam and buried in the clay with a flat end. There were no seams between adjacent geomembrane sheets; rather, all geomembrane connections were made by folding the ends of adjacent sheets over twice. After five years of operation, breaching of the dam occurred within a few hours. First, seepage was noticed in the immediate vicinity of the dam; then the rate of seepage increased rapidly and the seeping water started carrying solids, until the dam was breached. The breach was 40 m wide and the 1,500,000 m^3 of water stored in the reservoir escaped through the breach. The forensic analysis (*Sembenelli*) showed that the failure could be explained by piping due to the combination of high hydraulic gradient and lack of continuity of the geomembrane liner: (i) the folded connections between adjacent geomembrane sheets were not sufficiently watertight; and (ii) the connection between the geomembrane and clay at the toe of the dam created preferential paths for the water.

SUMMARY OF CASE HISTORY — Mechanism: preferential path due to geomembrane lack of continuity resulting from incorrect method of geomembrane installation; *Mode*: detrimental effect of a geosynthetic that otherwise performs a useful function (geomembrane liner); *Cause*: the design engineer failed to recognize the potential failure mechanism or failed to properly specify for installation, or the installer did not follow the specifications; *Reason*: unknown.

Lessons learned from the above case history. The above case history shows that lack of continuity of a geomembrane can cause failures, in particular when high hydraulic gradients are involved. Therefore, strict specifications for installation should be prepared by the design engineer to avoid mistakes during construction. Also, great precautions should be taken during placement of geomembrane liners at locations where high hydraulic gradients are likely to exist; these precautions should include the implementation of a strict construction quality assurance program.

2.6.3 *False leakage detection*

Example. In two landfills, water that had penetrated into the anchor trench at the top of the slope reached the geonet leakage collection and detection system, thereby causing false leakage detection (*Gross et al*.). The geonet should have been sealed in the anchor trench.

Lessons learned from the above example. The above example confirms that geotechnical engineers designing structures incorporating geosynthetics should remember to consider all possible preferential paths for liquids.

3 MALFUNCTIONING OF FILTERS AND DRAINS

3.1 *Overview*

The two most typical modes of malfunctioning of a filter are clogging of the filter and excessive migration of particles through the filter, which may result in clogging of the drain that the filter is intended to protect.

Clogging of filter or drain results in various degrees of damage: from the formation of a wet area (which can be a serious problem in roads, sports fields, etc.) to the development of pore water pressure and instability. In the case of instability, failures can be spectacular.

Such spectacular failures — some of which occurred a long time ago — have led some engineers to reject geotextile filters. In reality, geotextile filters that are properly used function satisfactorily. For example, the first geotextile filter installed in a dam (1970) has been working with no problem for 30 years (Delmas et al. 1992, 1993; Giroud 1984e; Giroud et al. 1977a, 1977b, 1984; Giroud and Gross 1993).

The following six cases will be presented below: Clogging of filter by migrating particles (Section 3.2); Clogging of filter due to lack of intimate contact between filter and soil (Section 3.3); Biological clogging (Section 3.4); Clogging of drain due to particle migration through geotextile filter (Section 3.5); Clogging of drain due to lack of filter continuity (Section 3.6); Intrusion of geotextile in geonet (Section 3.7); and Drainage system with insufficient flow capacity (Section 3.8).

3.2 *Clogging of filter by migrating particles*

3.2.1 *Overview — Soil particle migration*

With the exception of silt fences and similar applications, the goal of a filter in geotechnical engineering is not to stop particles that are moving but to prevent particles from moving. Any filter (sand, geotextile, or other) gets clogged if it is placed at a location where it has to stop particles (which is how an air filter works, but an air filter is periodically replaced, which is not possible for a filter buried in the soil). Therefore, filters in geotechnical structures should never be put in a location where they are exposed to moving particles. In the case of silt fences and similar applications, the geotextile becomes clogged after some time; such applications are temporary.

There are internally unstable soils in which fine particles migrate when water flows through the soil. This is in particular the case for gap-graded soils. As indicated by Giroud (1982b, 1996) and Giroud et al. (1998), a gap-graded soil where the fine fraction is less than approximately 20% by weight can be internally unstable (i.e. fine particles can migrate) if it is subjected to a flow of water. If a filter is used in such a soil and if this filter has the appropriate opening size to retain the particles, clogging is likely to occur. This is true whether the filter is a sand or a geotextile. This is illustrated by the following case history and examples.

3.2.2 *Case history and examples — Clogging by migrating particles*

Case history — Road edge drain. An edge drain along a road was placed 5 to 8 cm away from the edge of the pavement structure, instead of being next to the pavement structure (*Bieth and Faure*). The 5 to 8 cm space located between the pavement structure and the geotextile filter of the drain consisted of a soil that was internally unstable, as demonstrated by Bieth and Faure using laboratory tests. As a result, fine particles of this soil migrated when water flowed from the pavement structure to the drain, thereby causing accumulation of particles in front of the filter. The resulting clogging caused the failure of the road drainage system and the formation of wet areas on the pavement surface.

SUMMARY OF CASE HISTORY — Mechanism: clogging of geotextile filter by particles migrating from an internally unstable soil; *Mode*: filter in presence of internally unstable soil; *Cause*: either the design engineer failed to recognize the potential failure mechanism or construction problem; *Reason*: unknown.

Examples — Erosion control systems. Several failures of geotextile filters used with gap-graded silty sands have been analyzed by Fluet and Luettich (1993). In all those cases, the geotextile function — filtration — was properly identified, but the way the geosynthetic performs the function was not clearly understood by the designers of the projects. The soils were gap-graded; they contained fine particles that migrated, accumulated on the filter, and clogged it. These failures could have been avoided by using a geotextile filter with large openings so the migrating particles could pass. As shown by Fluet and Luettich (1993) and Gourc and Faure (1990), clogging of geotextile filters can result in spectacular uplifts because of the geotextile tensile strength, a property that sand filters do not have.

Examples — Geotextile separators in road ad railroad structures. In road and railroad applications, there have been observations of geotextile separators that became clogged by soil particles migrating upward. In the case of road and railroad applications, particle migration is facilitated by the mechanism of “pumping” due to repeated loads. Water retained beneath the clogged geotextile causes pore pressure buildup, which may lead to the failure of the road or railroad structure.

Clearly, geotextile separators must be designed for performing the function of filtration, in addition to being able to withstand the concentrated mechanical that are part of the separation function.

Lessons learned from the above case history and examples. The above case history and examples show that the phenomenon of migration of fine particles in some soils cannot be ignored, and can result in the clogging of a geotextile filter (as it would clog a granular filter). In the presence of such soils, a solution consists of using a filter with large openings. This is possible only if the loss of a significant amount of soil particles is acceptable. If the loss of some soil particles is not acceptable, it may be impossible to find an adequate filter.

3.2.3 *Case history — Potential clogging due to additional geotextile*

The following case of a potential (and quasi certain) failure has been reported by Giroud (1993). A perforated drainage pipe was to be placed in a drainage trench filled with gravel. An engineer (the author of this paper) had been invited to visit the site during construction. The engineer realized that a drainage pipe wrapped with a geotextile had been placed in the trench. The contractor told the engineer that the perforated pipe had been delivered with the geotextile and that the presence of a geotextile "filter" could only enhance the functioning of the drain. Indeed, common sense dictates that a drain with a filter is better than a drain without a filter. The engineer explained that, in contrast, the geotextile was useless and even detrimental: (i) useless, because the gravel size was greater than the size of the pipe perforations and, therefore, it was not necessary to use a filter to prevent the gravel from entering the pipe; and (ii) detrimental, because the gravel was dirty (i.e. covered with fine particles) and the geotextile would get clogged rapidly when it stops fine particles washed from the gravel and carried by the water being drained. Indeed, the gravel plus the fine particles was a gap-graded soil, i.e. it was an internally unstable soil. The engineer explained that the goal of a filter in geotechnical engineering is not to stop particles that are moving, but to prevent particles from moving. He explained that any filter (sand, geotextile, or other) gets clogged if it is placed at a location where it has to stop particles (which is how an air filter works, but an air filter is periodically replaced, which is not possible for a filter buried in the soil). The engineer recommended that the drain be dismantled, the geotextile removed from the pipes, the gravel washed and placed again, and the pipe placed again, but without the geotextile. The owner agreed that this recommendation had to be implemented, which was done. The engineer was not invited by the contractor to visit the site again.

SUMMARY OF CASE HISTORY — Mechanism: clogging of geotextile filter by particles migrating from an internally unstable soil; *Mode*: addition of a geosynthetic that was detrimental; *Cause*: construction problem; *Reason*: lack of knowledge from the part of the contractor and lack of construction quality assurance.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- Common sense, which indicates that adding a geosynthetic can only improve the performance of a structure, is wrong. An additional geosynthetic can be detrimental.
- Common sense, which indicates that adding a filter can only improve a drain is wrong. There are cases where a filter can be detrimental.
- Specifications must be as precise as possible. Ideally, engineers who prepare specifications should address problems that would result from potential misinterpretation of the specifications during construction. In some cases, it is recommended to include in the specifications a warning against certain specific uses of a geosynthetic if experience dictates that, in the considered applications, contractors are tempted to use an extra geosynthetic, not knowing that it can be detrimental.
- Installers should be instructed not to place extra geosynthetics as they may cause problems such as clogging of drainage systems and development of slip surfaces. Installers should be instructed not to add a geosynthetic during construction without being authorized by the design engineer.
- Design engineers should visit construction sites to learn about typical mistakes made during construction. This helps them write better specifications.

- The presence of the design engineer at the construction site may help prevent mistakes that could lead to failures.
- Construction quality assurance provided by a qualified team helps prevent mistakes during construction.

3.3 *Clogging of filter due to lack of intimate contact between filter and soil*

3.3.1 *Overview*

Ever since the first observations of the performance of Valcros dam, the first dam with a geotextile filter (Giroud et al. 1977a), the importance of intimate contact between a geotextile filter and the adjacent soil has been recognized. The concept has been discussed in detail by Giroud (1989, 1996).

As indicated in Section 3.2.1, a filter (geotextile or sand) that stops moving particles will clog. Therefore, filters in geotechnical structures should never be put in a location where they are exposed to moving particles. If a filter is not placed in intimate contact with the soil, soil particles can move in the space between the soil and the filter; the water current generally conveys these particles toward the filter and, as a result, the filter progressively stops the particles and becomes clogged. Lack of intimate contact is one of the main causes of failure of geotextile filters. This problem does no exist with granular filters, because they naturally conform to the shape of the soil surface.

3.3.2 *Examples — Clogging of geotextile filters placed next to rigid drains*

Dikes (including geotextile filters and traditional gabions) were constructed across rivers (*Vertematti*). Due to the rigidity of the gabions, against which the geotextile filter was placed, and the fact that the excavation surface was not smooth, the geotextile and the soil were not in intimate contact. As a result, water flowed between the geotextile and soil, causing soil erosion. Fine soil particles carried by water caused clogging of the geotextile.

Examples of failures due to lack of intimate contact between a geotextile filter for prefabricated edge drains and the adjacent soil have been reported by *Koerner and Koerner* In these cases, the lack of intimate contact between the geotextile and soil was due to the fact that the geotextile filter was attached to a relatively rigid element, the prefabricated edge drains, that were not sufficiently flexible to follow the shape of the trench (*Koerner and Koerner*).

3.3.3 *Examples —Bank protection failures due to lack of intimate contact*

Traditional bank protection systems include several layers, from large blocks to small granular material, each layer acting as a filter for the underlying layer, while the uppermost layer composed of large blocks absorbs wave energy. When geotextiles are used in bank protection systems, it is tempting to take advantage of the geotextile continuity to use only two layers: the geotextile and the blocks (assuming that the geotextile is sufficiently strong to withstand mechanical damage). The drawback of this situation is that the portions of geotextile located between the blocks are not pressed against the soil and move away from the soil under wave action. As a result of this lack of intimate contact between the geotextile and soil, soil particles move under wave action and some of them accumulate on the geotextile, which may become clogged at locations between the blocks. This problem was observed by the author on the first dam where a geotextile filter was used in the upstream protection, Valcros Dam (Giroud et al. 1977). A similar problem has been described by *Gustin* .

Intimate contact between the geotextile filter and soil is also important in the case of bank protection systems that consist of articulated concrete slabs associated with a geotextile filter. Examples of failures have been presented by *Heerten* who recommends the use of thick needle-punched geotextiles in this application to ensure intimate contact with the soil.

3.3.4 *Case history — Bank protection*

The following case has been reported by Giroud (1993) and *Giroud*. Two identical ponds, surrounded by earth embankments, had their banks protected with a layer of rounded blocks placed on a geotextile filter. Rapid drawdown of the water in one of the ponds caused the bank protection system (i.e. blocks and geotextile) to slide. Investigation of the other pond showed that the geotextile had many wrinkles, all filled with fine soil particles, hence the following explanation. During the drawdown of the pond, the quasi-impermeable layer formed by these fine particles did not allow dissipation of the pore water pressure resulting from the presence of water in the embankment. This pressure uplifted the entire bank protection system (fine soil particles, geotextile, and blocks), just enough to decrease the shear strength at the interface between the fine particles and the rest of the embankment, hence the slide.

The investigation showed that the geotextile had been installed without wrinkles and that the wrinkles resulted from the placement of the rounded blocks that tended to move along the slope as they were placed. Because of the wrinkles, the geotextile was not in close contact with the soil; consequently it could not prevent the fine soil particles from being eroded by wave action and rain. The particles thus eroded, accumulated naturally in the space between the geotextile and the bank. It should be noted that nothing in the specifications indicated the importance of an intimate contact between the geotextile and the soil.

SUMMARY OF CASE HISTORY — Mechanism: clogging of geotextile filter by particles; *Mode*: lack of intimate contact between geotextile and soil; *Cause*: construction problem; *Reason*: lack of knowledge from the part of the contractor and lack of construction quality assurance.

3.3.5 *Lessons learned from the above examples and case history*

The following lessons can be learned from the above examples and case history:

- Geosynthetics are construction materials like soil, and failure mechanisms (such as uplift of materials in case of rapid drawdown) which are known in geotechnical engineering can occur with geosynthetics.
- Some construction methods can have a detrimental effect on the performance of geosynthetics. For example, any construction method that does not ensure intimate contact between a geotextile filter and soil leads almost automatically to clogging of the filter (Giroud 1989, 1996).
- The following recommendations can be made to ensure intimate contact between a geotextile filter and the adjacent soil. In the case of drainage trenches, this can be achieved by using a flexible geotextile and filling the trench with relatively small stones (Giroud 1996). In the case of a relatively rigid prefabricated edge drain, sand should be poured in the space between the edge drain filter and the walls of the trench (Giroud 1996; *Koerner and Koerner*). In the case of bank protection, this can be achieved by using a geotextile that is thick, flexible and compliant (*Heerten*) with a layer of relatively small stones between the geotextile and the rocks (Giroud 1996).
- Specifications must be sufficiently complete to prevent the contractor from using construction methods that may have a detrimental effect on geosynthetic performance.
- Users of geosynthetics (i.e. designers and contractors) must be educated to prevent the use of construction methods that may have a detrimental effect on geosynthetics.

3.4 *Biological clogging*

3.4.1 *Overview*

As indicated by Giroud (1996), the development of biological clogging involves two mechanisms: (i) the growth of bacteria which form a biofilm that adheres to granular particles and geotextile fibers; and (ii) the precipitation of inorganic compounds on the biofilm (a phenomenon referred to as “encrustation”). The biofilm rarely grows to a point where it occupies the entire pore volume of the filter. In contrast, the precipitation of inorganic compounds on the biofilm can develop to the point where it occupies entire pore volume of the filter.

3.4.2 *Case history — River bank protection instability*

The failure of a portion of riverbank protection system incorporating a geotextile filter was due to the biological clogging of the geotextile (*Davis et al.*). The clogging of the geotextile caused pore water pressure buildup under the geotextile, which resulted in localized instability of the bank protection system. The investigation showed that, in the portion of the bank protection system where the failure occurred, water with a high organic content was seeping out of the bank. This water originated in a wastewater pond that was located on top of the bank. The potential for the wastewater to infiltrate into the ground and to daylight along the riverbank had not been recognized due to an insufficient site investigation. In this case, basic geotechnical engineering was neglected, and it is likely that a traditional sand filter would have failed as the geotextile filter did. Furthermore, the specified geotextile filter had been replaced by an “equivalent” geotextile that was significantly more susceptible to biological clogging than the specified geotextile. Although a major mistake in that project was the insufficient site investigation, as pointed out above, the replacement of the specified geotextile by another geotextile contributed to the failure.

SUMMARY OF CASE HISTORY — Mechanism: instability of bank protection system due to biological clogging of geotextile filter exposed to wastewater; *Mode*: biological clogging of geotextile filter; *Cause*: potential failure mechanism was not recognized by design engineer due to lack of field investigation; *Reason*: unknown.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- A good site investigation decreases the risk of failures.
- A specified geosynthetic should not be replaced by another geosynthetic unless the equivalency between the two geosynthetics has been demonstrated using a rigorous analysis.
- Too often it is assumed that biological clogging of geotextile filters can only take place in municipal solid waste landfills. In reality, biological clogging can occur anytime a geotextile (or granular) filter or a geosynthetic (or granular) drainage layer is in contact with a liquid carrying organic matter.

3.5 *Clogging of drain due to particle migration through geotextile filter*

3.5.1 *Case history — Dewatering system where the specified nonwoven geotextile was replaced by a woven geotextile*

Two different drains were needed in the dewatering system for the foundation of a building (*Christopher*). The design engineer had rightfully specified two different geotextile filters because the soils in contact with each drain were different. The specified geotextile filters were: a filter with relatively large openings (a monofilament woven geotextile) for the first drain (a drainage trench) that was in contact with a sand; and a filter with relatively small openings (a needle-punched nonwoven geotextile) for the second drain (a horizontal drainage layer) that was in contact with a sandy silt. The contractor had ordered too much woven geotextile for the first drain. When construction of the first drain was completed, the contractor decided to use the remaining woven geotextile for the second drain, although a nonwoven geotextile filter had been specified for that drain. The dewatering system progressively failed because the woven geotextile allowed fine soil particles to pass due to its excessively large opening size for this type of soil. Also, the contractor used one pump instead of the three specified. As a result of insufficient dewatering, the sandy silt became soft and deformed under the weight of construction equipment, which tended to separate some of the geotextile overlaps. Furthermore, some of the overlaps were separated by construction equipment pushing aggregate on top of the geotextile in the wrong direction. Due to the separation of some geotextile overlaps, more silt particles passed through the geotextile. The aggregate contaminated with silt particles and the woven geotextile were removed, and were replaced by the specified nonwoven geotextile and clean aggregate. After that (and adding the two missing pumps), the dewatering system performed satisfactorily.

SUMMARY OF CASE HISTORY — Mechanism: migration of soil (i) through geotextile filter with openings that were too large and (ii) through open overlaps; *Mode*: clogging of drain; *Cause*: (i) the contractor replaced the selected geotextile filter by another geotextile and (ii) soil deformation caused the geotextile overlaps to open; *Reason*: lack of knowledge from the part of the contractor and lack of construction quality assurance.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- Properly selected geotextile filters are required for satisfactory performance of drainage systems.
- Contractors should not replace a specified geotextile by another geotextile and should not ignore instructions regarding geosynthetic installation.
- The design engineer should educate contractors on geosynthetic construction requirements which are most likely unfamiliar to them.
- When two different geosynthetics of the same type (e.g. two geotextiles) are used on the same project, the design engineer must realize that there is a non-negligible probability that the contractor will use one geosynthetic for the other, either intentionally or accidentally. This even occurred in a large dam. Therefore, the design engineer must take great precautions to prevent this construction problem.

3.5.2 *Example — Migration of bentonite particles*

Another example of particle migration is that of bentonite particles which may extrude from geosynthetic clay liners and, then, intrude into the adjacent material or interface. The influence on bentonite on interface shear strength is discussed in Section 4.2.3. As part of the design of of a landfill liner system, Giroud and Soderman (2000) have considered and evaluated the possibility for bentonite from a geosynthetic clay liner to intrude into the adjacent geonet, thereby reducing the hydraulic transmissivity of the geonet or even clogging it. However, no failure of this type has been reported.

3.6 *Clogging of drain due to lack of filter continuity*

3.6.1 *Overview*

Since a basic characteristic of a two-dimensional material is continuity, a basic failure mode of a geosynthetic is lack of continuity. In the case of geotextile filters, this failure mode may result from mechanical damage of the geotextile, as discussed in Section 5.9, or because of open overlaps, as discussed in Section 3.6.2.

The lack of continuity of a geosynthetic may result in a failure that is particularly severe if the hydraulic gradient is large, as illustrated by dike failures (*Vertematti*) due to lack of continuity of geotextile filters (with the geotextile discontinuity resulting from overlaps that were insufficient or should have been sewn, and from tears and punctures).

3.6.2 *Examples — Lack of continuity of geotextile filters due to insufficient overlaps.*

Overlaps of geotextile filters should be sufficiently wide to remain closed even if the soil adjacent to the geotextile deforms. In a case of dike failures reported by *Vertematti*, the geotextile overlaps separated as a result of differential settlement. In a case history of a dewatering system reported by *Christopher* (Section 3.5.1), the geotextile overlaps separated as a result of settlement of the soft soil. Ironically, in that case, the soil was soft because of ineffective drainage. In the same dewatering system, some geotextile overlaps separated due to improper placement of soil on top of the geotextile (*Christopher*, Section 3.5.1). This failure mode may also occur because a geotextile filter was not continuous when it was installed, which may have occurred in the case of a sewer pipe excavation reported by *Rowe and Seychuk*.

3.6.3 *Lessons learned from the above examples*

The above examples and case history show that lack of continuity of geotextile filters can cause failures. Therefore, great precautions should be taken during placement of geotextile filters, and during placement of overlying materials, to ensure the continuity of the filter. Also, if deformation of the soil adjacent to the geotextile can be expected, the overlaps should be wide or should be sewn.

3.7 *Intrusion of geotextile into geonet*

3.7.1 *Overview*

When two geosynthetics are in contact, one of them may intrude (i.e. partly penetrate) into the other. This is the case in particular for geotextiles penetrating into geonets, thereby reducing their hydraulic transmissivity, a problem that was reported first by Williams et al. (1984). No failure due to geotextile intrusion into geonet has been reported, but a potential failure was prevented at the last minute, as indicated below.

3.7.2 *Case history — Flow capacity reduction due to additional geotextile*

The leachate collection system in a waste disposal landfill consisted of a gravel layer on the floor of the landfill and a geonet on the side slope. A needle-punched nonwoven geotextile cushion was specified between the gravel and the geomembrane liner, but was not needed between the geonet and the geomembrane liner. The geotextile was shown on construction drawings to extent “0.3 m minimum” beyond the gravel-geonet junction. In the area where the geotextile was to be in contact with the geonet (i.e. approximately 0.5 m beyond the gravel-geonet junction), a double layer of geonet was rightfully shown in the construction drawings. This double geonet layer was intended to maintain sufficient hydraulic transmissivity in spite of the fact that the geotextile would intrude into the geonet. The contractor had too much geotextile on the site and decided to use a geotextile that extended more than 1 m beyond the gravel-geonet junction. Certainly, this met the letter of the “0.3 m minimum” specification. Furthermore, the contractor, using common sense, deemed he had improved the leachate collection system by installing a geotextile larger than required. As a result, however, a portion of the geotextile was in contact with the geonet in an area where only a single layer of geonet was used. Intrusion of the geotextile into the geonet channels would have decreased the geonet’s hydraulic transmissivity, hence decreasing the flow capacity of the leachate collection system. The problem was discovered, and solved, at the last minute by the design engineer as he visited the site (Giroud 1993). The solution consisted of adding another layer of geonet in the area where the geonet would be in contact with the extra length of geotextile.

SUMMARY OF CASE HISTORY — Mechanism: reduction of flow in geonet due to intrusion by adjacent geotextile; *Mode*: contact problem; *Cause*: construction problem; *Reason*: lack of knowledge from the part of the contractor and lack of construction quality assurance.

Lessons learned from the above case history. The following lessons can be learned from the above case histories:

- Common sense, which indicates that adding a geosynthetic can only improve the performance of a structure, is wrong. An additional geosynthetic can be detrimental. Similarly, extending a geosynthetic beyond the area intended by the design engineer may cause a serious problem, because a geosynthetic may be beneficial in one area (where it is needed and specified) and detrimental in another area.
- Specifications must be as precise as possible. Ideally, engineers who prepare specifications should address problems that would result from potential misinterpretation of the specifications during construction. For example, there are cases where a minimum and a maximum geosynthetic length, width, or overlap should be specified, not only a minimum.
- Installers should be instructed not to place extra geosynthetics as they may cause problems such as clogging of drainage systems and development of slip surfaces. Installers should be instructed not to add a geosynthetic or extend the area covered with a geosynthetic during construction without being authorized by the design engineer.
- Design engineers should visit construction sites to learn about typical mistakes made during construction. This helps them write better specifications.
- The presence of the design engineer at the construction site may help prevent mistakes that could lead to failures.

- Construction quality assurance provided by a competent team should be used to reduce the risk of failures.

3.8 *Drainage system with insufficient flow capacity*

Case History — Use of a geocomposite drain in a drainage system that was undersized. A drainage system using geocomposite drains for a sports ground did not work, as evidence by ponding water. It was first considered that the geocomposite was the cause of the failure. However, the investigation showed that the design of the entire system was inadequate. Clearly, a geocomposite drain cannot work when used instead of a conventional granular drain in a drainage system that was destined to fail, regardless of the type of drain (conventional or geosynthetic), due to its inadequate overall design (*Sprague et al.*).

SUMMARY OF CASE HISTORY — Mechanism: insufficient flow rate; *Mode*: drainage failure; *Cause*: inadequate design; *Reason*: unknown.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- The use of a geosynthetic does not replace adequate design.
- The geosynthetic should not be automatically used as a scapegoat when a failure occurs.

4 INSTABILITY

4.1 *Overview*

The forces (e.g. gravity — possibly increased by seismic forces — and water pressure) that cause instability of soil, ore or waste slopes and masses that do not incorporate geosynthetics also cause instability of soil, ore or waste slopes and masses that do incorporate geosynthetics.

The examples and case histories presented below are organized as follows: slip surface along the interface between a geosynthetic and an adjacent material (Section 4.2), slip surface passing through the mass of soil or waste (“internal failure”) (Section 4.3), and slip surface located between geosynthetic layers in a reinforced-soil structure (“surficial failure”) (Section 4.4). In addition, three sections deal with the effects of water on stability: excessive water supply (Section 4.5), rapid drawdown (Section 4.6), and soil erosion (Section 4.7).

4.2 *Interface failure*

4.2.1 *Overview*

Geosynthetics are more or less smooth. At best, the shear strength at a geosynthetic-soil interface (interface shear strength) is equal to the shear strength of the soil (internal shear strength). This can be achieved in some cases. However, in general, the presence of geosynthetics creates one or several planes of low interface shear strength. These planes increase the risk of instability. Instability of a soil, waste or ore slope or mass is one of the main causes of failures associated with geosynthetics. Examples follow. (It should be noted that asphalt overlays may also fail by sliding due to insufficient interface shear strength. Failures of asphalt overlays will be discussed in Section 5.8.)

It is very important to properly select the values of interface shear strength to be used in design. As illustrated in some of the following examples and case histories, it may be dangerous to use values of interface shear strength published in the literature. This is because interface shear strength depends on many parameters. In particular, it is important to realize that the presence of water (sometimes ice) at the interface has a significant influence on the interface shear strength, as shown in some of the examples and case histories.

4.2.2 *Waste Slides*

Overview. Waste slides affect large masses of waste in landfills and can be very catastrophic. Examples and case histories are presented below. Additional cases, where water plays a significant role, are presented in Section 4.5.4.

Examples. Several examples of waste slides in landfills equipped with a geosynthetic liner system have been reported (*Chang et al., Ouvry et al., Stark et al.)*. The forces involved in these slides (gravity, hence waste density, and pore water pressure) are the forces typically involved in landslides studied in geotechnical engineering. Therefore, landfill designers who do not have an in-depth knowledge of geotechnical engineering run a high risk; and geotechnical engineers should realize that the presence of geosynthetics in a slope, soil mass or waste mass often increases the risk of instability.

Indeed, in all these slides, a key role was played by low interface shear strength associated with the presence of geosynthetics. Geosynthetics are indispensable in landfills because they are needed to construct liner systems where they play a key role, but their presence in a waste mass increases the risk of instability.

An important parameter that played a role in some of the reported failures was the water content at the geosynthetic-soil interface (*Chang et al., Ouvry et al.*). In the latter case, the high water content was due to rainfalls prior to geomembrane placement. Another case where rainfalls prior to geomembrane placement played a role is discussed in Section 4.2.3 (see the example on frost action).

Proper selection of the interface shear strength value at the design stage is essential. A large waste slide occurred in a landfill where the interface shear strength was overestimated based on published values (*Ouvry et al.*). The analysis of a landfill failure (*Stark et al.*) showed that the waste mobilized its peak shear strength at a displacement 10 to 15 times larger than the displacement at which the critical interface (between the geosynthetic clay liner and the compacted soil liner) mobilized its peak shear strength.

Case History — Incorrect assumption regarding slip surface. In a hazardous waste disposal landfill, a waste slide occurred, with the slip surface along the geomembrane. The investigation (Giroud 1993) showed that waste stability calculations had been conducted using circular slip surfaces entirely contained within the waste mass and that no slip surface along the geomembrane had been considered by the design engineer. The design engineer had learned from a waste slide which had occurred in another landfill (where no waste stability analyses had been conducted) that the possibility of a slide should be considered. However, this engineer had not learned how to select the critical slip surface, i.e. the engineer had not learned that the presence of a geosynthetic can create one or several planes of low shear strength along which a slide can occur.
SUMMARY OF CASE HISTORY — Mechanism: slip surface along geomembrane; *Mode*: interface instability; *Cause*: potential failure mechanism was not recognized by design engineer; *Reason*: lack of knowledge.

Lessons learned from the above examples and case history . The following lessons can be learned from the above examples and case history:

The above examples and case history show that an engineer using geosynthetics should not forget the forces, well known in geotechnical engineering, that impact the stability of slopes and masses. These forces should be considered at all times (i.e. the design engineer must check that the structure is stable at all stages of construction) and all locations (i.e. the design engineer must check that all parts of the considered structure have an appropriate factor of safety).

- In the design of a landfill, slip surfaces that run along geosynthetics should always be considered. However, deep-seated slip surfaces that intersect the liner system and slip surfaces contained in the waste should also be considered.
- Geosynthetic properties should not be estimated, they should be measured. This is particularly true in the case of interface friction angles, because this property, which often plays a critical role in the performance of structures, is difficult to estimate. Furthermore, a slight error on the interface friction angle may lead to the belief that a slope is stable when it is not.
- As more and more geosynthetics are available on the market, the probability increases that there are significant differences in properties between geosynthetics that may appear to be identical. This is one more reason to measure (and not to estimate) interface shear strength.

- The influence of water at the interface on interface shear strength should be taken into account at the design and construction stages. Geomembranes should not be placed on clay shortly after a rainfall.
- The peak internal shear strength of waste and the peak interface shear strength along a geosynthetic are not mobilized for the same displacement. This important fact must be taken into account at the design stage.

4.2.3 *Liner systems and cover systems on slopes*

Overview. As a liner or cover system is relatively thin compared to the length of the slope, the stability of these systems is often referred to as "veneer stability". Numerous examples of failures show that liner systems incorporating geosynthetics can be unstable on slopes (*Richardson et al., Stark et al., Bonaparte et al., Vander Linde et al., Frobel and Comer)*. In all these slides, a key role was played by low interface shear strength.

Examples — Influence of pore pressure. The pore pressure was a parameter that played an important role in the reported failures: water pore pressure (*Richardson et al*., *Vander Linde et al*., *discussion by Giroud et al. of Vander Linde et al.'s paper*); and gas pore pressure (*Richardson et al.*). Geomembranes and geosynthetic clay liners are used as liners because they have a low permeability. However, due to this low permeability, they may block natural drainage paths. As a result, pore pressure may develop under the liner, causing the liner to be uplifted (*Datye and Gore*) or the slope to become globally unstable (*Bonaparte et al.*).

Examples — Influence of bentonite from geosynthetic clay liner (GCL) on interface shear strength. In the case of liner systems incorporating GCLs, hydrated bentonite extruded from, or otherwise migrating from, the GCL decreases the interface shear strength (*Bonaparte et al.*).

Examples — Influence of construction activities. The placement of the soil layer on a liner system on a slope may have an influence on stability; the slide of a soil layer on a geomembrane on the 1V:2.5H upstream slope of a dam has been reported (Girard et al. 1990) where the slide was attributed in part to the braking of construction equipment working on the soil layer and to the vibration by the vibratory compactor used on the soil layer.

Examples — Evaluation of interface shear strength. During the design of several waste disposal landfills, the interface friction angle between adjacent geosynthetics was estimated on the basis of published test data or results of tests on similar geosynthetics conducted for earlier projects. In one of these landfills, a major slide of the liner system occurred near the end of construction (Giroud 1993).

Examples — Frost action. Liner systems are rather thin, and geosynthetics, which are thin (with the exception of geofoam panels), are unable to prevent frost from penetrating into the underlying soil. Therefore, failure mechanisms involving frozen soil are to be considered. For example, a canal liner system incorporating a geomembrane failed by sliding on ice lenses, when the canal was empty during the winter (*Frobel and Comer*). A similar failure occurred on a landfill cover (*discussion by Luettich et al. of Frobel and Comer's paper*); in a case mentioned by *Luettich et al.*, the formation of ice was due to high water content of the soil resulting from heavy rainfalls prior to the placement of the geomembrane. A major waste slide where rainfalls prior to geomembrane placement played a role is discussed in Section 4.2.2.

Lessons learned from the above examples. The following lessons can be learned from the above examples:

- The presence of a geosynthetic can create one or several planes of low shear strength along which a slide can occur.

- Interface shear strength should be measured, not guessed or estimated on the basis of published data.
- The water content of the soil adjacent to a geomembrane can have a significant influence on the interface shear strength, especially if the interface can be exposed to below-freezing temperatures.
- The presence of a low-permeability geosynthetic (geomembrane or geosynthetic clay liner) promotes the buildup of water and gas pore pressure, which can have a detrimental impact on stability.
- The presence of hydrated bentonite at an interface can result in low interface shear strength.

Case History — Liner system slide caused by additional geosynthetic. During the design of a waste disposal landfill, a simple, but correct, analysis had convinced the design engineer that a layer of sand, which was to be placed on the smooth geomembrane liner on the landfill side slope, would be unstable. To improve stability, the design engineer decided to place a needle-punched nonwoven geotextile between the geomembrane and the sand. Common sense indicated that, since high friction angles are generally obtained with needle-punched nonwoven geotextiles, the incorporation of such a geotextile in the system could only improve the stability of the slope.

In reality, the geomembrane-sand interface friction angle was less than the geotextile-sand interface friction angle (which seemed to support the above approach based on common sense), but was greater than the geotextile-geomembrane interface friction angle (which caused the failure). The design engineer had failed to recognize that the critical slip surface would be located between the geomembrane and the additional geotextile. The slope was constructed and failed, shortly after a rainfall, with a slip surface at the geotextile-geomembrane interface. Clearly the addition of the geotextile should have been followed by a new design effort where the new conditions created by the addition of the geotextile would have been reviewed.

SUMMARY OF CASE HISTORY — Mechanism: veneer instability; *Mode*: interface slip surface; *Cause*: use of inadequate geosynthetic; *Reason*: lack of experience and lack of peer review.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- The friction angle (and, more generally, the shear strength) at the interface between two materials depends on both materials. It is not an intrinsic property of one material. The fact that high interface friction angles are obtained between a certain geosynthetic and some soils or other geosynthetics does not mean that high interface friction angles will be obtained between this geosynthetic and all soils and other geosynthetics.
- Adding a geosynthetic may be detrimental. In the design of all structures incorporating geosynthetics, potential detrimental effects of geosynthetics must be considered. If such effects appear likely, they must be quantified.
- Simple failure mechanisms can be predicted easily by a geotechnical engineer using rational analyses, not common sense.
- Water flowing on a slope (e.g. after a rainfall) has an impact on slope stability, in particular on veneer stability. However, it is important to note that, as shown by Giroud et al. (1995c), while water flowing on a slope above the geomembrane liner has a marked impact on the stability of the liner system if the slip surface is above the geomembrane, it has virtually no impact on the stability of the liner system if the slip surface is below the geomembrane.

4.2.4 *Ore heap slides*

Examples — Several slides have been observed in the case of ore heaps constructed on pads equipped with geosynthetic liner systems, during or at the end of construction of the first lift of ore (typically 5 to 10 m high) (*Smith, Breitenbach*). This common type of failure of ore heaps is due to the fact that the most critical phase of the construction of an ore heap is often the first lift. The reason is the following. The ore is typically placed at the angle of repose. Then a horizontal bench is used between each lift to decrease the average slope to a value determined at the design stage in order to ensure an acceptable factor of safety. As a result, the factor of safety at the end of the construction of the first lift may be less than the factor of safety of the entire heap (and it is definitely less if the ore is a cohesionless material, which is generally the case, at least approximately). The design engineer who calculates the factor of safety for the entire heap may neglect to calculate the factor of safety for the first lift based on the belief that the factor of safety of a slope generally decreases as the height of the slope increases, forgetting that, in this case, the two slopes (i.e. the slope of the first lift and the average slope of the entire heap) do not have the same slope angle.

Such a basic cause of failure exists regardless of the presence of geosynthetics. However, the analysis shows that, in all these slides, a key role was played by low interface shear strength associated with the geomembrane liner. An important construction recommendation has been made by *Smith* and discussed in detail by *Smith and Giroud*: when ore is placed on a pad with a slope (e.g. 5%), the ore should be placed in the up-slope direction, because if there is any departure from the designed slope (e.g. 6% slope) the factor of safety increases in case of up-slope placement and decreases in case of down-slope placement. This recommendation results from failures observed in the field (*Smith*) and has been theoretically demonstrated (*Smith and Giroud*) based on slip surfaces that run along the geomembrane lining the pad. Clearly, this recommendation stems from the influence of interface shear strength on stability.

Lessons learned from the above examples. The following lessons can be learned from the above examples:

- As a general rule, design engineers should evaluate the stability of any structure at all stages of construction.
- In the case of ore heaps with geomembrane liner, the stability of the first lift of ore is often the most critical. Indeed, most slides of ore heaps occur during construction of the first lift of ore.
- If the geomembrane-lined pad has a slope, which is generally the case (e.g. 5%), and the stability of the first lift of ore depends on the direction of placement. The first lift of ore is more stable if it is placed in the up-slope direction than in the down-slope direction.

4.3 *Internal failure*

4.3.1 *Overview*

Even though the low interface shear strength due to the presence of geosynthetics results in slip surfaces that often run along a geosynthetic-geosynthetic or geosynthetic-soil interface, this is not always the case. There are many cases where the most critical slip surface in a structure incorporating geosynthetics intersects the geosynthetics. Examples are given below.

4.3.2 *Case history — Deep-seated failure of a landfill*

The author of this paper knows of the deep-seated failure of a landfill for the disposal of contaminated soil. This landfill was constructed on a very soft soil. The failure surface intersected the liner system, which included geomembrane, geonet and geotextile. Slope stability analyses involving deep-seated slip surfaces had been performed at the design stage, but the mechanical properties of the soil located beneath the landfill had been overestimated by some members of the design team.

SUMMARY OF CASE HISTORY — Mechanism: deep-seated slip surface; *Mode*: instability; *Cause*: improper evaluation of soil properties; *Reason*: lack of consensus within the design team, lack of peer review.

4.3.3 *Case history — Deep-seated failure of an ore heap*

In an ore heap leach pad, a deep-seated slide occurred, involving movements of the ore and the foundation soil (Van Zyl 1993). In that case, the design engineer had considered only slip surfaces within the ore, or along the geomembrane, or in the foundation soil at shallow depth. Because of inadequate sub-soil investigation, the design engineer had not realized that the critical slip surface could be deep-seated.

SUMMARY OF CASE HISTORY — Mechanism: deep-seated instability; *Mode*: internal failure; *Cause*: potential failure mechanism was not recognized by design engineer due to lack of field investigation; *Reason*: unknown.

4.3.4 *Examples — Instability of geosynthetic-reinforced soil walls*

A geosynthetic-reinforced soil wall can collapse as a result of several mechanisms: (i) internal instability of the reinforced soil mass; (ii) external instability of the soil mass acting as a block (which includes sliding, overturning, and bearing capacity failure); (iii) global (also called overall) instability which corresponds to an instability of the entire mass of (generally) natural soil where the geosynthetic-reinforced soil wall is located, i.e. instability along a failure surface (sometimes referred to as "deep-seated) that passes behind and beneath the reinforced soil mass; and (iv) compound instability which corresponds to an instability that involves partly the reinforced soil mass and partly the soil surrounding the reinforced soil mass, i.e. instability along a failure surface that passes partly through the soil and partly through the reinforced soil mass. Factors of safety for all of these mechanisms must be calculated. Several cases of failures of geosynthetic-reinforced soil walls have been reported where the failure was due to global or compound instability, aspects of the design that had been omitted by the designer who focused on the internal and external stability of the reinforced soil wall (*Berg and Meyers*, *Valentine and Damm*, *Giroud and Beech*). In other words, the designer focused on the geosynthetic aspect of the design (i.e. the design aspects involving only the geosynthetic-reinforced soil) and not on the design aspects involving the soil (i.e. the geotechnical aspect of the design). As pointed out by *Berg and Meyers*, this may happen in particular if there are two designers for the same project, one in charge of the reinforced soil structure, the other in charge of geotechnical engineering, without good communication between the two designers and, especially, without a clear understanding of who is in charge of the compound stability, which is a hybrid case.

4.3.5 *Example — Insufficient reinforcement in a reinforced-soil wall*

Failures of reinforced-soil walls have occurred due to insufficient amount and/or length of reinforcement (*Watn*, *Al Hussaini*). In a case history reported by *Frost et al*. (Section 4.5.3), a geogrid was missing.

4.3.6 *Lessons learned from the above case history and examples*

The following lessons can be learned from the above case history and examples:

- Usual design steps should not be omitted from the design of a structures incorporating geosynthetics. These usual design steps include, for example: site investigation for all types of structures, in particular to identify sources of water and soil profile; deep-seated failure analysis for embankments and ore heaps; and global stability and bearing capacity for a reinforced-soil structure.
- Communication between team members and peer review are essential.
- All potential failure mechanisms should be considered.
- Properties of the soil surrounding the considered structure should be carefully evaluated.
- One of the tasks of the construction quality assurance team is to ensure that all the specified geosynthetics are installed.

4.4 *Surficial failure*

4.4.1 *Examples — Surficial instability of reinforced soil slopes*

The surficial instability of a reinforced soil slope, i.e. the localized instability that occurs at the face of the reinforced soil slope between geosynthetic reinforcement layers (*Collin*), is a reminder that layers of reinforcement act discretely. As a result, there may be locations in a reinforced soil structure where the geosynthetics do not have an impact on the soil behavior. In those locations, the behavior of the soil will be that of a soil without geosynthetic reinforcement. Therefore, in those locations, the modes of failure of a non-reinforced soil apply.

4.4.2 *Lesson learned from the above examples*

The presence of a structure incorporating geosynthetics should not lead the design engineer to disregard traditional modes of failures.

4.5 *Excessive water supply*

4.5.1 *Overview*

It is known in geotechnical engineering that water often plays a key role in instability of geotechnical structures. As can be expected, this is also true in the case of structures incorporating geosynthetics. Examples are given below.

4.5.2 *Examples — Failures of canal and river banks due to excessive water supply*

In a case reported by *Well*, the instability of a canal liner protective soil layer was caused in part by water infiltrating under the liner due to inadequate surface drainage and the lack of anchor trench on top of the geomembrane liner. In another case, the instability of a river bank protection system incorporating a geotextile was caused by wastewater seeping from a wastewater pond (*Davis et al.*) (Section 3.4.2).

4.5.3 *Case histories of reinforced soil walls*

Case history — Instability of reinforced-soil retaining wall linked to insufficient site investigation. The failure of a modular-faced reinforced-soil wall illustrates the detrimental impact of insufficient site investigation (*Bernardi*). The only section of the wall that collapsed was located next to a street with inadequate surface drainage. Furthermore, at that location, the soil profile was different from expected and, as a result, the earth pressure on the lowest portion of the wall was greater than expected. These two important features of the site, the surface drainage and the soil profile, would have been identified if a thorough site investigation had been performed.

SUMMARY OF CASE HISTORY — Mechanism: collapse of reinforced-soil structure due in part to water supply: *Mode*: instability; *Cause*: insufficient soil investigation, inadequate design due to the fact that the potential failure mechanism was not recognized; *Reason*: negligence.

Case history — Global stability of reinforced-soil quay wall. A quay wall constructed with geogrid-reinforced clay and faced with prefabricated full-height concrete panels exhibited excessive bulging after intensive rainfalls (*Giroud and Beech*). The investigation showed that the bulging had two causes, which were not directly related to the geogrid reinforcement: (i) global stability of the reinforced soil mass was decreased by pore water pressure resulting from water intrusion in deep desiccation cracks located behind the reinforced mass, a mechanism that was not properly accounted for in the stability analysis; and (ii) hydrostatic pressure was applied directly on the concrete panels by water that accumulated in a sand drain located behind the panels because the sand was not permeable enough and because the drain (which was only intended to collect water seeping from the clay fill) was saturated by runoff water due to inadequate surface drainage. The investigation showed that most of the design effort was devoted to the design of the reinforced-soil mass, while paying less attention to the traditional aspects of design such as surface water drainage and global stability.

SUMMARY OF CASE HISTORY — Mechanism: excessive bulging due to global instability of reinforced soil structure linked to water supply; *Mode*: instability; *Cause*: inadequate design because the design did nor recognize the potential mode of failure; *Reason*: negligence resulting from excessive focus on the design of the geosynthetic application.

Case histories — Geogrid-reinforced soil walls. The collapse or near-collapse (one of the walls was demolished before it collapsed) of two geogrid-reinforced soil walls (9 and 6 m high) constructed with cohesive fill has been reported by *Frost et al*. The investigation shows that the failures were caused by the decrease in strength of the cohesive fill due to: (i) poor surface drainage that resulted in a large amount of water infiltrating into the fill; and (ii) the fact that the fill had been placed 4 percentage points dry of the optimum water content, which made it very sensitive to an increase in water content (resulting in settlement and loss of strength). Also, the lateral deformation of the facing had not been properly evaluated and the wrap-around facing came in contact with the protective non-structural facing during construction (see Section 5.9.1). Furthermore, at one of the two walls:

(i) the fill was poorly compacted, which further decreased the fill strength; (ii) the top geogrid was missing; (iii) the sloping bedrock at the bottom of the excavation was not as planned due to insufficient soil investigation and, as a result, the placement of the bottom layers of geogrid was inconsistent with the construction drawings; and (iv) a major slide of the excavated slope occurred during construction, which led to an accumulation of non-compacted debris at the bottom of the excavation contributed to the large deformation of the structure once water infiltrated the backfill. Clearly, what was constructed did not reflect what was designed and an engineer should have been present during construction.

SUMMARY OF CASE HISTORY — Mechanism: excessive deformation of reinforced soil structure due in part to water supply: *Mode*: instability; *Cause*: insufficient soil investigation, inadequate design due to the fact that the potential failure mechanism was not recognized, and construction problems; *Reason*: incomplete design and lack of construction quality assurance.

Lessons learned from the above examples and case histories. The following lessons can be learned from the above examples and case histories:

- At the design stage, all possible mechanisms of failure must be considered. The presence of a geosynthetic generally does not eliminate the need for evaluating traditional mechanisms of failure, such as global stability.
- Water is often a cause of instability in geotechnical engineering, and structures incorporating geosynthetics are affected by water like traditional geotechnical structures.
- Insufficient site investigation leads to construction problems. As pointed out by *Frost et al*., a geosynthetic-reinforced soil structure should not be regarded as a pre-fabricated system that is simply inserted in the field without consideration of the site conditions.
- As in traditional geotechnical structures, the use of cohesive fill requires certain precautions during placement.
- The use of cohesive fill in a geosynthetic-reinforced soil structure requires careful consideration of the potentially detrimental effects of water and pore water pressure within the fill. Also, potential sources of water likely to reach the reinforced-soil mass should be identified.
- An evaluation of the constructibility of a structure is an important part of design, and measures must be taken at the design stage to ensure that construction will proceed smoothly. Also, at the design stage, an effort should be made to foresee potential construction problems and propose tentative solutions.
- Construction quality control and quality assurance are important in the case of critical structures, in particular to ensure that all the specified geosynthetics are installed.

4.5.4 *Leachate recirculation in landfills*

Examples. Leachate recirculation has been promoted by environmental scientists to accelerate leachate decomposition, which has merits from the viewpoint of waste management. However, many of those who have promoted leachate recirculation did not consider the geotechnical consequences of this technique. These consequences can be very serious because leachate recirculation significantly increases the moisture content of the waste, thereby promoting pore pressure buildup in the waste, which decreases the stability of the waste mass. Indeed, waste slides have been attributed to leachate recirculation (*Gross et al*., Hendron et al. 1999). If the leachate collection layer at the base of the landfill has been adequately designed to accommodate the high leachate flow rate due to leachate recirculation, and if it performs adequately, the pore water pressure at the base of the landfill is zero and the maximum pore water pressure occurs a few meters above the base of the landfill. As a result, in case of instability, the slip surface may not involve the liner system. In contrast, if the leachate collection layer at the base of the landfill does not perform adequately, the maximum pore water pressure occurs at the base of the landfill and, in case of instability, the slip surface is likely to involve the liner system.

Lessons learned from the above examples. The above examples confirm that water is a major cause of failures of geotechnical structures, whether they incorporate geosynthetics or not. When a new technology is developed, such as leachate recirculation, its potentially detrimental effects should be considered, especially if this new technology involves water.

4.6 *Water drawdown*

4.6.1 *Examples — Rapid drawdown*

Two case histories illustrate failures of ponds with geosynthetics in case of rapid drawdown. The first case is that of a bank protection system incorporating a geotextile (Section 3.3.4), and the second case is that of a geomembrane liner placed on top of an existing liner (Section 5.5.4). Rapid drawdown is a situation typically considered by geotechnical engineers for dams and water reservoirs.

4.6.2 *Lessons learned from the above examples*

The above examples show that an engineer using geosynthetics should not forget the mechanisms, well known in geotechnical engineering, that impact the stability of slopes and masses, such as rapid drawdown.

4.7 *Erosion*

4.7.1 *Examples*

Soil erosion may affect structures incorporating geosynthetics as it affects traditional geotechnical structures (i.e. structures that do not incorporate geosynthetics). Erosion contributed to the failure of a canal liner protective soil layer reported by *Well*; several failures of landfill cover systems to which soil erosion contributed have been reported (*Gross et al.*). Also, geotextile filter clogging due to soil erosion has been reported by *Vertematti* (Section 3.3.2). Erosion was also a factor in the bridge abutment problems reported by *Palmeira and Fahel* (Section 5.2.2), and the case discussed below.

4.7.2 *Case history — Foundation failure of the modular facing of a reinforced-soil wall*

The collapse of a section of the modular facing of a reinforced-soil wall located on a slope was caused by erosion of the soil at the toe of the facing (*Gourc et al.*). Clearly, the failure was a foundation failure affecting only the facing of the reinforced-soil structure. Indeed, the reinforced-soil mass remained stable after the collapse of the facing.

4.7.3 *Lessons learned from the above examples and case history*

The facing of reinforced-soil structures requires a good foundation. Sometimes, design engineers tend to focus on the design of the reinforced-soil mass and neglect the design of the foundation of the facing. The fact that a structure incorporating geosynthetics is used should not prevent design engineers from considering traditional modes of failures, such as the failure of a foundation due to erosion or lack of bearing capacity of the supporting soil.

5 DEFORMATIONS

5.1 *Overview*

While instability is never acceptable, deformations can be acceptable. However, depending on the function performed by the geosynthetic, the type of structure, and the performance criteria, some deformations are acceptable, and some are not. This was discussed in Sections 1.5 and 1.6.

There is a wide variety of failure modes that fall into the “deformation” category. The examples presented below can be put in the following sub-categories:

- Two cases where the geosynthetic follows soil deformations: (i) differential settlements (Section 5.2), and lack of support (Section 5.3).
- Two cases of deformations affecting only the geosynthetic: wrinkles (Section 5.4) and uplift (Section 5.5).

- Two cases of damage, caused by static forces (Section 5.6) and dynamic forces (Section 5.7).
- Three cases of interaction between the geosynthetic and the adjacent material: road and pavement deformation (Section 5.8), deformation required to perform the function (Section 5.9, and displacement compatibility (Section 5.10).

5.2 *Differential settlements*

5.2.1 *Overview*

One of the main causes of problems and failures in geotechnical engineering, differential settlement, also exists in the case of structures incorporating geosynthetics. Several examples are given below.

5.2.2 *Case history — Geotextile-reinforced soil*

The failures of the facings of two geotextile reinforced retaining wall bridge abutments built on soft soil have been reported by *Palmeira and Fahel*. The pavements of the highways supported by the bridge abutments were also damaged: they exhibited excessive deformation. The observed problems were mainly caused by differential settlements between the reinforced and unreinforced portions of the structure, and by erosion due to a river flood (Section 4.7.1). The investigation showed that, in spite of rather large differential settlements, the geosynthetic-reinforced structure had been sufficiently flexible to accommodate the differential settlements, requiring rather light repairs to the wall faces and pavement of the highway. Geotechnical engineers must design transition zones between geosynthetic-reinforced soil masses and adjacent non-reinforced fills to alleviate the effects of differential settlement.

SUMMARY OF CASE HISTORY — Mechanism: distress of reinforced soil structure due to differential settlement; *Mode*: structure deformation; *Cause*: the potential failure mechanism was not recognized; *Reason*: unknown.

5.2.3 *Case History — Geotextile-reinforced slope*

In the summer of 1982, an existing road, built partly on an embankment, was widened using a 3.2 m high geotextile-reinforced slope with a face batter of 1.5V:1H (*Ingold*). Construction was completed successfully, but by the spring of 1984 the pavement of the road extension supported by the slope was showing severe longitudinal cracking. The slope had suffered a serviceability failure with total collapse being imminent. The investigation revealed that an outlet pipe for surface water drainage, buried in the fill, had fractured, leading to development of a high internal water table in both the original fill and the reinforced fill, which in turn caused the failure. The pipe fracture was attributed to differential movement between the original embankment fill and the reinforced slope extension. An adequate degree of stability was restored by the use of remedial drainage.

SUMMARY OF CASE HISTORY— Mechanism: differential settlement between reinforced and unreinforced portions of a soil structure; *Mode*: serviceability failure and imminent collapse; *Cause*: the potential failure mechanism was not recognized; *Reason*: unknown.

5.2.4 *Examples — Connections between geosynthetics and structures*

Differential settlement affects connections of geosynthetics to structures (such as connections of geomembrane liners to appurtenances, e.g. concrete structures), or elements of structure (such as connections of geosynthetic reinforcement to wall facing) (*Richardson*). In a number of cases, geomembrane liners have failed because of differential settlements between the soil supporting the geomembrane and the concrete structure to which the geomembrane was connected (Giroud 1977a, 1977b, 1983a, 1983b, 1984a) and Giroud and Soderman (1995a). Geotechnical engineers must review connections very carefully because they are sometimes designed by individuals who have an insufficient knowledge of geotechnical engineering and who, therefore, do not realize that even a small amount of differential settlement may cause the connection to fail. The proper selection of a geomembrane to withstand differential settlement at the connection with a rigid structure involves the concept of co-energy (Giroud and Soderman 1995b), which is somewhat different from what common sense would dictate.

5.2.5 *Examples — Damage to geotextile filter*

Differential settlement of dikes (including geotextile filters and traditional gabions) constructed across rivers have caused: (i) tension of the geotextile filter, resulting in tearing and puncturing of the geotextile at the contacts between the geotextile and gabions; and (ii) separation of overlaps between adjacent sheets of geotextile (*Vertematti*). Due to the high hydraulic gradient, these discontinuities in the geotextile filter resulted in significant piping and partial destruction of several dikes.

5.2.6 *Lessons learned from the above examples and case histories*

The above examples and case histories confirm that differential settlements are a major cause of problems in geotechnical structures, whether they incorporate geosynthetics or not. Furthermore, structures incorporating geosynthetics provide new opportunities for differential settlements to cause problems, for example: effects on adjacent materials of differential settlement between reinforced and non-reinforced fill; effects of differential settlements on geosynthetic-structure connections; and effects of differential settlements on geotextile filter overlaps.

5.3 *Lack of support*

5.3.1 *Overview*

A geosynthetic may be damaged by excessive tension resulting from out-of-plane deformation, which may result from lack of support of the underlying soil. Lack of support may be due to deformation of the soil underlying the geosynthetic (Section 5.3.2), localized subsidence of the soil underlying the geosynthetic (Sections 5.3.3 and 5.3.4), or because the geosynthetic was not placed in contact with the soil (Section 5.3.5).

Clearly, engineers designing with geosynthetics should consider all soil deformations that are possible (assuming that, in many cases, the geosynthetic will not have any significant influence on these deformations) and should evaluate the impact of soil deformation on the geosynthetics. Also, at the construction stage, all efforts should be made to place the geosynthetic in intimate contact with the soil.

5.3.2 *Examples of bank deformation*

There are many examples of geomembrane liners that have been affected by deformations of the supporting soil due to wave action, even though the geomembrane separates the soil from the liquid (*Fourie, Giroud*).

5.3.3 *Case histories of localized subsidence*

Geosynthetics are often placed horizontally and normal stresses develop on top of them. As a result, in case of localized subsidence of the underlying medium, geosynthetics sag, stretch and may rupture. It should be noted that both uplift and localized subsidence result from out of plane stress, i.e. the geosynthetic, a two-dimensional material, is subjected to three-dimensional stresses. In the two case histories presented in Section 2.4, the geomembrane failure was caused by localized subsidence. An additional case is presented below.

5.3.4 *Case history— Localized subsidence due to bearing capacity failure of a sludge pond cover system*

Badu-Tweneboah et al. give the example of a sludge pond cover system that exhibited localized subsidence during construction under the weight of equipment due to lack of bearing capacity of the sludge. The cover system of the sludge pond included a PVC geomembrane and a geosynthetic clay liner. The PVC geomembrane was able to elongate sufficiently to follow the deformed shape of the supporting material without rupturing, whereas the geosynthetic clay liner separated at a seam.

5.3.5 *Example of lack of support due to geomembrane placement*

In the case history presented in Section 2.5 (Giroud and Stone 1984; Stone 1984; *Giroud and Stone*), failure of the geomembrane liner occurred because of lack of support. The HDPE geomembrane was stiff and could not follow the rectangular shape of the reservoir to be lined. As a result, the geomembrane was installed too far from the corners of the reservoir. During the first filling of the reservoir, the geomembrane underwent excessive strain as it was forced to move toward the reservoir corners by water pressure. This caused the geomembrane to rupture.

5.3.6 *Lessons learned from the above example and case histories*

Excessive out-of-plane deformation followed by tensile rupture is a typical mode of failure of geosynthetics. Engineers designing a geosynthetic application should be knowledgeable in geotechnical engineering to be able to identify all possibilities of soil deformation and localized subsidence, and to make a reasonable assumption of the extent and depth of the area affected by deformation or subsidence. Then, quantification of the geosynthetic strain and tension is relatively easy thanks to available analytical methods (Giroud 1982a; Giroud et al. 1990a; Giroud 1995b). Also, at the construction stage, all efforts should be made to place the geosynthetic in intimate contact with the soil. If the geomembrane is too stiff to follow the shape of the supporting material, then the shape should be changed, or a more flexible geomembrane should be used. Alternatively, in the case of a rectangular reservoir with smooth walls (e.g. concrete reservoir) each wall may be lined separately, and a geomembrane cap strip may be used in corners.

5.4 *Wrinkles*

5.4.1 *Overview*

All polymers have a large coefficient of thermal expansion-contraction (i.e. about ten times as large as that of usual construction materials such as concrete and steel). However, polymers that are drawn (i.e. stretched in a controlled manner to make fibers and geogrid ribs) do not significantly expand and contract (and may even shrink, but in an irreversible manner, when heated excessively). As a result, geonets and non-reinforced geomembranes significantly expand or contract when temperature increases or decreases, respectively; in contrast, geotextiles, geogrids and reinforced geomembranes do not exhibit significant thermal expansion and contraction.

Thermal expansion of geomembranes results in wrinkles. The drawbacks of geomembrane wrinkles are as follows: (i) they can be damaged by placement of soils over them; (ii) in landfills, they impede the flow of leachate in leachate collection layers; (iii) in the case of composite liners, they prevent geomembranes from being in intimate contact with the underlying low-permeability soil (compacted clay or geosynthetic clay liner), thereby preventing the formation of an effective composite liner; and (iv) wrinkles can promote the mechanism of desiccation that deteriorates the clay component of a composite liner, which is illustrated by the case history presented in Section 6.1.1.

The mechanism of geomembrane wrinkle formation, which has been demonstrated by Giroud and Morel (1992) and further discussed by Giroud (1994b, 1995a), can be summarized as follows: (i) a geomembrane that has expanded due to temperature increase is longer than original geomembrane, hence the formation of wrinkles; (ii) a wrinkle develops a bending moment that is a function of the bending modulus of the geomembrane; (iii) this bending moment must be balanced by resisting forces in the plane of the geomembrane on each side of the wrinkle; (iv) the resisting forces are generated by interface shear strength (essentially friction) between the geomembrane and the underlying medium; (v) therefore, the resisting forces are proportional to the distance between consecutive wrinkles; (vi) as a result, the distance between wrinkles is small — and, consequently, *the wrinkles are small* for a given thermal expansion — when the resisting forces per unit length of geomembrane are large; and (vii) the resisting forces per unit length of geomembrane are large if the friction between the geomembrane and the underlying medium is high and the mass per unit area of the geomembrane is high. In conclusion, a smooth HDPE geomembrane will have high wrinkles, but will not have many, because: (i) it has a large coefficient of thermal expansion-contraction; (ii) it has a high bending modulus; (iii) it has a low interface shear strength with most soils; and (iv) it is light. It is important to note that, contrary to what common sense dictates, HDPE geomembranes do not exhibit many wrinkles, but few wrinkles; and, because there are not many wrinkles, they are high. This is precisely why these wrinkles are undesirable. In contrast, PVC geomembranes, which also have a large coefficient of thermal expansion-contraction, have a low bending modulus (i.e. they are flexible) and, as a result, they have many (not few) wrinkles; since they have many wrinkles, these wrinkles are small and pose no problem.

5.4.2 *Lessons learned*

The above discussion clearly shows that there is no hope to understand wrinkle formation on the basis of common sense. Only a rational analysis can explain the mechanism of wrinkle formation.

Based on the above discussion, geomembranes that are less likely than others to exhibit large wrinkles are: (i) geomembranes with a white upper surface, which reduces thermal expansion by limiting the geomembrane temperature; (ii) geomembranes with a small coefficient of thermal expansion, such as reinforced geomembranes; (iii) geomembranes with a low bending modulus, i.e. flexible geomembranes; (iv) geomembranes with a textured lower surface, which generally results in a high interface shear strength between the geomembrane and the underlying medium; and/or (v) heavy geomembranes, since weight results in an increased normal stress, therefore in increased interface shear strength.

5.5 *Uplift*

5.5.1 *Overview*

Low-permeability geosynthetics, such as geomembranes, geosynthetic clay liners, and some geotextiles (especially if clogged), allow pressures to develop under them and are sensitive to negative pressure (suction) applied by the wind on their upper face; and, because they are light, geosynthetics are relatively easily uplifted when the resulting pressure is in the outward direction. Therefore, low-permeability geosynthetics can be uplifted by the pressure from liquids or gas that accumulate beneath the geosynthetic and by the suction applied by wind above the geosynthetic. Also, all kinds of geosynthetics can be uplifted by dynamic forces, such as wind gusts and water current. However, dynamic forces are more difficult to quantify than static or quasi-static forces.

Regarding uplift by the wind, it should be noted that, when a geomembrane starts being uplifted, a suction develops under the geomembrane. This suction is negligible if the material underlying the geomembrane is permeable, but can be significant if the material underlying the geomembrane has a low permeability. As a result, geomembranes are less likely to be uplifted by the wind if the material underlying the geomembrane has a low permeability (assuming that the geomembrane is sealed at its periphery and is not torn or punctured).

Uplift may result in two types of failures: disruption in the operation of the structure or geosynthetic damage. For example, an uplifted geomembrane may be damaged, in the short term, by excessive tensile stresses (especially in case of duynamic forces, such as wind gusts and water current) or, in the long term, by creep, by exposure to wind and sunlight, and by being a tempting target for vandals and hunters.

5.5.2 *Typical examples of geosynthetic uplift*

Examples of uplift include: (i) uplift of geomembrane or geotextile by wind (Giroud et al. 1995a; Zornberg and Giroud 1997; *Fairborn and McKelvey, Fayoux*); (ii) uplift of geomembrane liner by liquid in a pond (*Giroud*); (iii) uplift of geomembrane liner or geosynthetic clay liner by liquid, which may occur when the liner blocks the natural drainage of ground water (*Datye and Gore*); (iv) uplift by gas of geomembrane liner in a pond (*Fayoux*, *Frobel*, *Giroud*) or geomembrane and geosynthetic clay liner in a landfill cover (*Richardson et al.*); (v) uplift of geomembrane liner by air entrapped between the geomembrane and liquid that is present under the liner (*Fayoux*, *Giroud*) (the air generally accumulates under the geomembrane liner over high spots of a rather flat pond bottom during the first filling of the pond, and the liquid present under the geomembrane pond liner results either from leakage through the geomembrane or from an external source, such as a rising ground water); (vi) uplift of clogged geotextile filter, as mentioned in the examples of erosion control systems presented in Section 3.2.2 (Gourc and Faure 1990; Fluet and Luettich 1993); and (vii) uplift of a geosynthetic used for erosion control (*Jacotot et al.*) (Section 5.7.1).

5.5.3 *Example of geomembrane uplift by wind on landfill cover*

Exposed geomembranes (i.e. geomembranes that are not covered by a layer of soil) are increasingly considered as landfill covers. Such landfill covers must be designed against uplift by wind (Gleason et al. 1998, 1999). The geomembrane must be secured at many locations in anchor trenches or beneath anchor benches. In one instance, a failure occurred because the geomembrane was connected to a gas vent located between two anchor trenches, i.e. at a location where the geomembrane should have been free to be uplifted by the wind. During construction, the geomembrane was uplifted by wind and was torn at the connection with the gas vent. The problem was solved by relocating the gas vent at an anchor trench. It should be noted that, in landfill covers with gas extraction, the geomembrane is unlikely to be uplifted during normal operation because the suction exerted on the lower face of the geomembrane by the landfill gas being extracted is generally greater than the suction exerted by the wind on the upper face of the geomembrane, thereby stabilizing the geomembrane (unless the wind that tends to uplift the geomembrane is part of a major storm that interrupts electric power supply to the landfill, thereby stopping the pumps that extract the landfill gas).

5.5.4 *Case history of geomembrane uplift by liquid due to detrimental impact of geosynthetic redundancy*

Those who are overly enthusiastic about geosynthetics may believe that adding a geosynthetic to an existing structure may only improve the structure. This is not always the case as illustrated by the following case history. This case history shows that two liners are not necessarily better than one, contrary to what common sense would dictate.

A reservoir waterproofed with a bituminous roofing membrane had contained brine for years (Giroud 1993; *Giroud*). A limited amount of leakage occurred, causing ground water pollution. Instead of repairing the bituminous roofing membrane, it was proposed to reline the pond with a geomembrane placed directly over the existing bituminous roofing membrane. A consulting engineer (the author of this paper), working on another part of the project, warned the geomembrane installer in writing that the geomembrane could be uplifted in case of rapid drawdown of the reservoir, a mechanism that geotechnical engineers are accustomed to consider. The consulting engineer indicated that, to prevent geomembrane uplift, it was necessary either to place a drainage system between the two liners or to place a load on the geomembrane (e.g. soil layer, concrete). The installer considered that the consulting engineer was too pessimistic and preferred to listen to common sense, which dictated that two liners were certainly better than one. Therefore, the installer placed the geomembrane directly on top of the bituminous roofing membrane, and did not place a load on the geomembrane or a drainage layer between the geomembrane and the bituminous roofing membrane.

The reservoir was part of a pumping station and its level fluctuated every day. However, it was never completely empty and, as a result of the lack of transparency of the brine, it was not possible to observe the condition of the immersed portion of the geomembrane. A few months after the geomembrane installation, a geomembrane bubble appeared at the brine surface. The consulting engineer was called to investigate the problem. He requested that the reservoir be emptied. When the reservoir was empty, it appeared that a considerable amount of brine had accumulated between the bituminous roofing membrane and the geomembrane. There was some gas on top of the entrapped brine, which explained the geomembrane bubble. The investigation showed that the geomembrane had defects, which had caused the brine to leak and accumulate between the geomembrane and the bituminous roofing membrane (which was impervious enough to retain most of the brine leaking through the geomembrane).

The presence of brine between the geomembrane and the bituminous roofing membrane was unacceptable for two reasons: (i) the entrapped brine was bound to progressively leak through the bituminous roofing membrane and pollute the ground water; and (ii) each time the level of brine in the reservoir fluctuated, the entrapped brine moved, thereby inducing tensile stresses and fatigue in the geomembrane. Repair was done as follows: (i) the geomembrane was removed; (ii) a thick needle-punched nonwoven geotextile was placed on the bituminous roofing membrane to be used as a drain and was connected to an outlet; and (iii) a new geomembrane was placed on the geotextile. *SUMMARY OF CASE HISTORY — Mechanism*: geomembrane uplift by liquid; *Mode*: structure deformation; *Cause*: the potential failure mechanism was not recognized; *Reason*: negligence due to lack of knowledge.

5.5.5 *Lessons learned from the above examples and case history*

The following lessons can be learned from the above case history:

- Adding a geosynthetic to an existing structure without reviewing the design may cause problems.
- Common sense, which indicates that two are always better than one, is wrong. Two liners may be better than one only if precautions have been taken to prevent uplift of the upper liner.
- Two geomembrane liners must never be placed directly on top of each other. If two liners (geomembrane or other) are used, they must be part of a properly designed and constructed double liner system (i.e. a system that includes two liners and an intermediate drainage layer connected to an outlet).
- Geosynthetics are construction materials like soil, and failure mechanisms (such as uplift of materials in case of rapid drawdown) which are known in geotechnical engineering can occur with geosynthetics.
- Geotechnical engineers who use rational analyses, not common sense, can relatively easily predict simple failure mechanisms, i.e. those that stem directly from principles of physics such as pressure balance.
- Engineers designing a geosynthetic application where the geosynthetic is not covered by a layer of soil, or is covered by only a very thin layer of soil or a layer of soil that could be eroded or otherwise removed, should identify all possible sources of fluids capable of uplifting the geosynthetic.
- If a geomembrane is designed to be uplifted, it should be properly anchored (Giroud et al. 1999), and it should not be attached to fixed structures such as gas vents.

5.6 *Damage to geosynthetic by static forces*

5.6.1 *Mechanical damage caused by compressive stresses*

Some geosynthetics are compressible and their performance can be affected by compressive stresses such as overburden stresses. This is the case for geonets (Giroud 1985) and needle-punched nonwoven geotextiles (Giroud 1981, 1996). Although no failures have been reported that can be attributed to compressive stresses, some of the characteristics of certain geosynthetics are affected by compressive stresses. For example: (i) the opening size of needle-punched nonwoven geotextile filters is reduced, which can be quantified, as shown by Giroud (1996); and (ii) the hydraulic transmissivity of geonets and needle-punched nonwoven geotextiles is reduced, which can also be quantified using a method developed by Giroud et al. (2000c). It should be noted that there is a difference in behavior between needle-punched nonwoven geotextiles and geonets: while the thickness of needle-punched nonwoven geotextiles decreases significantly under small loads and, then, reaches an equilibrium under high loads, geonets (and some other geosynthetics used as geocomposite cores) are not very compressible until a certain load (“crushing load”) is reached and, then, collapse. Design engineers should address the issue of damage by compressive stresses in their designs.

5.6.2 *Intrusion*

A problem that is related to the effect of compressive stresses is the intrusion of a geosynthetic into the adjacent geosynthetic (Section 3.7). The effect of compressive stresses on the hydraulic transmissivity of geocomposites may in fact result mostly from the intrusion of the geotextile component of the geocomposite into the geonet component of the geocomposite. Design engineers should make every effort to avoid the detrimental effects of compressive stresses, in particular the concentrated stresses discussed below.

5.6.3 *Effect of concentrated stresses*

Because they are thin, geosynthetics may be damaged by concentrated stresses. The typical modes of rupture due to concentrated stresses are: (i) puncture and burst, which are two types of concentrated normal stresses; and (ii) tear and grab, which are two types of concentrated tensile stresses, but are initiated by puncture. Damage by concentrated stresses was discussed for geomembranes in Section 2.2.2. Examples for geotextiles used in railroad tracks are given by *Raymond*. An example of puncture of geosynthetic clay liner and decrease of geosynthetic clay liner thickness due to squeezing of bentonite is provided by *Peggs and Olsta* (Section 2.2.2).

Survivability tests, which are intended to evaluate the ability of a geotextile to “survive” concentrated stresses in the field, include tear, grab, puncture and burst tests. This type of damage occurs during construction (“construction damage”) or after if adequate precautions are not taken, and may result in a major failure if the geosynthetic performs a function for which continuity is critical (e.g. geotextile used for filtration and/or separation; and geomembrane or geosynthetic clay liner used as fluid barrier). Another type of failure linked to the thinness of geosynthetics is abrasion, as reported by *Raymond* for the case of railroad tracks.

Another example of damage is the case of geonet strands indenting into geomembranes, thereby locally reducing the geomembrane thickness. However, this case is rare (*Laine and Darilek*, and *discussion by Giroud et al. of Laine and Darilek’s paper*.).

5.7 *Damage to geosynthetics or structures incorporating geosynthetics by dynamic forces*

5.7.1 *Case history — Insufficiently strong geosynthetics used for erosion control in a torrent bed*

As part of a full-scale experiment, various erosion control systems including several types of geosynthetics (geotextiles, geotextile-geonet geocomposites, geotextile-geomat geocomposites, geocells) were used, instead of the traditional solution which consists of using large rocks or concrete blocks, to control erosion in several reaches of a mountain torrent bed. The erosion control systems and the geosynthetics were severely damaged by the flow of water. This type of failure is not surprising considering the magnitude of the drag forces developed by water flow during the short periods of time when the torrent is full (i.e. forces that can displace large rocks). Therefore, it was predictable that erosion control systems, which did not include heavy elements such as rocks or blocks, would not resist (*Jacotot et al.*).

5.7.2 *Case history — Use of geomembrane tubes for coastal protection*

A case has been reported where large sand-filled geotextile tubes were used for coastal protection and failed (*Richardson*). In this case again, the expectations regarding the geosynthetic were too high considering the magnitude of subgrade erosion resulting from the forces associated with ocean waves.

5.7.3 *Lessons learned from the above case histories*

The following lessons can be learned from the above case histories:

- In erosion control applications where a geosynthetic is in contact with moving water (i.e. flowing water or wave action), large dynamic forces are involved and materials that are strong and/or heavy are required. Caution should be exerted when geosynthetics are used in these applications. Furthermore, there is a lack of design methods for these applications because the forces by their nature and magnitude make analyses difficult.

- When huge forces are involved, geosynthetics should not be expected to make miracles.

5.8 *Unacceptable deformation of pavements and road structures*

5.8.1 *Overview*

Deformations of pavements and road structures are different from deformations of other structures incorporating geosynthetics and, therefore, deserve a specific section. The examples presented below are related to asphalt overlays (Sections 5.8.2 to 5.8.5) and to an unpaved road (Section 5.8.6).

5.8.2 *Examples of failures of asphalt overlays incorporating geotextiles*

When a geotextile is used between an existing pavement and an asphalt overlay, it is essential to have intimate contact, between the geotextile and the underlying pavement and between the geotextile and the overlay, to ensure that the overlay will be entirely supported by the existing pavement, thereby preventing localized cracking of the overlay. A failure due to lack of contact between a geotextile and the underlying pavement has been reported by *Guram*. The overlay underwent excessive deformation and cracking. The failure was due to the fact that the geotextile, after impregnation with asphalt, was rolled with a steel roller. This roller, being rigid, could not force the geotextile to follow the shape of the existing pavement surface which was irregular. Instead, a pneumatic roller should be used. Also, the deepest depressions of the existing pavement could have been filled.

When a geotextile is used between an existing pavement and an asphalt overlay, it is essential to have high interface shear strength, between the geotextile and the underlying pavement and between the geotextile and the overlay, to ensure that the overlay will not fail by sliding along one of the two geotextile interfaces. In the case of asphalt overlays, the interface shear strength is essentially of the adhesive type. It is ensured by using the appropriate amount of asphalt to impregnate the geotextile and coat its two surfaces (“asphalt tack coat”). *Baker and Marienfield* have shown that the main cause of asphalt overlay failure is lack of geotextile-asphalt pavement or overlay-geotextile adhesion due to an insufficient amount of asphalt tack coat.

5.8.3 *Examples of failures of asphalt overlays incorporating geogrids*

Failures of asphalt overlays have been reported by *Wilmers* in cases where geogrids were used between an existing pavement and an asphalt overlay. These failures were due to the fact that the presence of the geogrid prevented proper bonding between the overlay and the existing pavement, thereby decreasing the interface shear strength between the overlay and the existing pavement.

5.8.4 *Lessons learned from the above examples*

The following lessons can be learned from the above examples:

- Interface shear strength between geotextile and pavement layers is essential to ensure proper performance of the asphalt overlay. This can be achieved by intimate contact between the geotextile and the pavement to be repaired and proper bonding of the geotextile to the adjacent pavement layers.
- Cracking of overlay due to lack of support can occur if the geotextile is not placed in intimate contact with the existing pavement.
- Intimate contact appears to be a major consideration in a variety of applications of geosynthetics.
- Clear instructions must be given to contractors regarding the importance of proper placement of geosynthetics and adjacent materials to ensure intimate contact and proper bonding.

5.8.5 *Case History — Blisters in an asphalt pavement reinforced using woven geogrids*

One of the most intriguing cases reviewed by the author of this paper has been reported by *Wilmers*. Blisters up to 0.6 m in diameter and 4 cm in height appeared in an asphalt overlay less than a year after construction of the overlay. Prior to construction of the asphalt overlay, a woven geogrid layer had been placed on the existing pavement to prevent cracking of the overlay. It took several night-day cycles for the blisters to grow to their final size, during a period where the days were warm and the nights were cool. The unique development of these blisters was explained by a pumping mechanism and quantified through extensive calculations (*discussion by Giroud of the paper by Wilmers*): during the day, as a result of high temperature, the blister grows by vaporization of humidity contained in the entrapped air; and, during the night, as a result of low temperature, the blister does not decrease because the asphalt stiffens and the pressure in the blister decreases, thereby sucking into the blister some additional humid air. The air was able to flow toward the blister because it was conveyed in the ribs of the woven geogrids, which were not impregnated with asphalt during construction. The reported failure would not have occurred if the geogrid had been impregnated or coated with asphalt.

SUMMARY OF CASE HISTORY — Mechanism: pavement overlay uplift; *Mode*: structure deformation; *Cause*: construction problem; *Reason*: lack of knowledge due to experimental nature.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- In asphalt overlay applications, it is important to impregnate geogrids (and geotextiles) with asphalt. This is important not only to ensure adequate bonding of the geosynthetic and the adjacent pavement layers, but also it prevents the geosynthetic from being transmissive, thereby preventing water and humid air from being conveyed to locations where they could cause blisters in the overlay.
- Even when a failure mechanism is unusual and seems complex, it can be explained rationally. However, this does not mean that the failure would have been predicted. At least, it means that lessons can be learned, because better lessons are learned if the failures are rationally explained.
- Clear instructions must be given to contractors regarding the importance of proper impregnation of geotextiles and woven geogrids used in asphalt overlays applications.

5.8.6 *Case history — Haul road where the specified geogrid was replaced by a geotextile*

The failure by excessive deformation (excessive rutting) of a haul road where the specified geogrid was replaced by a geotextile has been reported (*Bostian et al.*). The haul road had been designed to be used for two types of traffic loads: (i) first, trucks; and (ii) then, cranes moving on wide timber mats. To save time, the contractor used the haul road for the cranes without the timber mats. The haul road performed satisfactorily for truck traffic, but exhibited excessive rutting with the cranes (serviceability failure). The analysis showed that the replacement of the geogrid by a geotextile was not to be blamed for the failure, because the haul road would have failed with any geosynthetic approximately equivalent to the specified geogrid.

SUMMARY OF CASE — Mechanism: excessive rutting of unpaved road; *Mode*: excessive deformation; *Cause*: use of the haul road for loads that were not considered in design; *Reason*: lack of knowledge on the part of the contractor.

Lessons learned from the above case history. Although replacement of a specified geosynthetic by another geosynthetic is often a cause of poor performance and failures, the fact that the specified geosynthetic was replaced by another geosynthetic should not be automatically blamed for a failure. If the structure has not been designed for the actual loads, it will fail whether or not the specified geosynthetic is replaced by an equivalent geosynthetic or not.

5.9 *Deformation needed to perform the function*

5.9.1 *Overview*

When geosynthetics are used for soil reinforcement, a certain geosynthetic strain is required to mobilize the geosynthetic tension. This strain requires a displacement of the soil, which may cause a deformation of the geosynthetic-reinforced soil structure. The deformation of the structure may affect its serviceability to the point that it may be considered that the structure failed (see the case history reported by *Bathurst et al.* in Section 5.9.2 and the case history reported by the author of this paper in Section 5.9.3). Sometimes, the wrap-around facing of a geosynthetic-reinforced soil wall is hidden behind a non-structural vertical facing to protect the geosynthetic from exposure to sunlight and for aesthetic reasons. It is important to leave sufficient space between the wrap-around facing and the non-structural vertical facing to allow for lateral displacement of the wrap-around facing as the geosynthetic tension progressively increases. The failure of a geogrid-reinforced soil wall involving this mechanism has been reported by *Frost et al.* (see the case history in Section 4.5.3). Finally, if the reinforcing geosynthetic is installed with wrinkles, its tension may never be mobilized, and the structure collapses (Section 5.9.4).

5.9.2 *Case history — Reinforced-soil wall*

In a case reported by *Bathurst et al.*, a 14 m high modular faced vertical geogrid-reinforced soil wall was constructed to retain the soil on one side of an excavation for the construction of a multi-story building. The wall facing moved laterally by up to 150 mm. As a result, it was impossible to construct the building on the foundations that had been constructed at the bottom of the excavation, near the wall facing. It was, therefore, necessary to construct new foundations away from the wall facing, which caused significant additional expenses. While the geogrid-reinforced soil wall performed the function of retaining the soil, it was considered to have failed, i.e. it was not a structural failure but it was a serviceability failure.

SUMMARY OF CASE — Mechanism: excessive deformation of reinforced soil structure; *Mode*: deformation needed to perform the function; *Cause*: the potential failure mechanism was not recognized; *Reason*: unknown.

Lessons learned from the above case history. The following lessons can be learned from the above case history: a geosynthetic-reinforced soil wall always exhibits lateral deformation due to the progressive tensioning of the layers of geosynthetic reinforcement. This deformation can be evaluated (*Bathurst et al.*) and must be accounted for in designing structures to be constructed next to a geosynthetic-reinforced soil wall.

In the above case history, as the geosynthetic tension increases, the soil deformation is in the direction of the geosynthetic, i.e. perpendicular to the wall face. In contrast, in the case of a geosynthetic reinforcing an unpaved road, the required soil deformation is perpendicular to the geosynthetic. An interesting example of such deformation is provided by the following case history.

5.9.3 *Case history — Geotextile in the construction of an airport taxiway*

New taxiways were being constructed in an airport (Giroud 1993). According to the design, a geotextile had been placed between the soft subgrade and the aggregate base. A thick concrete slab would then be built on top of the aggregate base. Prior to placing the concrete slab, a certain area of the aggregate base was used as an access road for the construction trucks. Some rutting developed and aggregate was added several times to fill the ruts.

Prior to constructing the concrete slab, a grader was used to level the aggregate surface at the design grade. In the area that had been used as an access road, the grader had to remove excess aggregate. In doing so, the grader’s blade cut the geotextile in places where it had moved up between the ruts. (The upward movement of the geotextile had remained unnoticed by the contractor, because the geotextile had remained covered with the added aggregate.) The contractor did not understand what was happening because the geotextile supplier had stated that the geotextile would “reinforce” the aggregate base.

The contractor was dissatisfied with the performance of the geotextile, but the consulting engineer in charge of the investigation (the author of this paper) told him he was lucky, because if the problem had not been discovered (thanks to the grader’s blade) the aggregate base under the concrete slab would have had a non-uniform thickness, which could have caused cracking of the slab. Repair was simple: in all areas where the aggregate base had been used as an access road, the aggregate base and the geotextile were removed, the foundation soil was graded, and, finally, a new geotextile and a new aggregate base were placed.

SUMMARY OF CASE — Mechanism: excessive deformation of unpaved road; *Mode*: deformation required to perform the function, leading to serviceability failure; *Cause*: the potential failure mechanism was not recognized; *Reason*: unrealistic expectations due to lack of knowledge.

Lessons learned from the above case history. The following lessons can be learned from the above case history:

- Unsupported claims on geosynthetic performance can lead to wrong expectations.
- It is important to identify the function of the geosynthetic, and to understand the mechanisms involved when the geosynthetic performs its function. If a geosynthetic must perform two functions, one during construction (e.g. reinforcement), the other in service (e.g. separation), this may cause problems that the designer engineer must foresee and solve at the design stage.
- This shows that the design engineer must not only consider the functions performed by the geosynthetic in the designed structure, but also the functions that the geosynthetic may temporarily perform during construction.

5.9.4 *Example — Geosynthetic installed with wrinkles*

Pre-tensioning of the geosynthetic reinforcement may be a way to minimize the required soil and structure deformation. On the other hand, installing a reinforcing geotextile with wrinkles may result in the collapse of the reinforced-soil structure, because the soil may not be able to deform sufficiently to mobilize the geotextile strength that would be required to ensure the stability of the structure. An example of such a failure has been reported by *Gale* for an embankment.

5.10 *Displacement compatibility*

Another aspect of soil-geosynthetic mechanical interaction is the necessary compatibility between the displacements of all of the materials (such as geosynthetics, soil or waste) and interfaces involved in a deformation mechanism. In particular, two adjacent materials must have the same displacement, unless they slide with respect to each other (which generally, but not always, is undesirable). If two materials have displacements that are compatible (i.e. related through a certain mechanism) or equal, it is unlikely that they will both mobilize their maximum shear strength, because the strains that correspond to these displacements are unlikely to be precisely the strains that are required for the two materials to mobilize their maximum strength. Indeed, each material requires a certain strain to mobilize its own strength, and the strain required to mobilize the geosynthetic strength is generally different from the strain required to mobilize the strength of the adjacent material (such as soil or waste). This important point is illustrated by the following example.

As indicated in Section 4.2.2, the analysis of a landfill failure (*Stark et al.*) showed that the waste mobilized its peak shear strength at a displacement 10 to 15 times larger than the displacement at which the critical interface (between the geosynthetic clay liner and the compacted soil liner) mobilized its peak shear strength.

6 PHYSICO-CHEMICAL MODES OF FAILURE

6.1 *Overview*

6.1.1 *Effect of temperature*

Examples — Thermal expansion-contraction. All polymers have a large coefficient of thermal expansion-contraction. Geosynthetics that expand due to temperature increase may exhibit wrinkles under certain conditions, as discussed in Section 5.4. When temperature decreases, thermal contraction results in geosynthetic tension, which may cause tensile failure (for example, in the case of geomembranes that become stiffer at low temperature) or stress cracking, as discussed in Section 2.3.2.

Case histories — Desiccation of clay component of composite liner. Observations made on several slopes lined with geomembranes that are not overlain with a protective cover (*Basnett and Bruner*) have shown that clay, placed immediately under the geomembrane, could undergo significant desiccation and cracking, whereas common sense indicates that the sheer presence of the geomembrane should prevent evaporation and help the clay keep its moisture content constant. According to *Basnett and Bruner*, the explanation is as follows:

- during the day, the geomembrane heated by the sun expands and becomes wrinkled;
- air entrapped in the wrinkles becomes saturated with water vapor that evaporates from the clay;
- during the night, the geomembrane cools and water vapor condenses against the lower face of the geomembrane;
- condensation water migrates along the slope toward the toe of the slope; and
- at each cycle, clay desiccates a little more along the slope, and the toe of the slope becomes more humid.

Case History — Differential icing. Geofoam panels are thick and have a low coefficient of thermal conductivity. As a result, they are used to delay, minimize or prevent frost penetration (*Horvath*), especially under pavements. However, the phenomenon of differential icing reported by *Horvath* results from an unexpected disadvantage of the low coefficient of thermal conductivity of geofoam: under special and rare weather conditions, a thin sheet of ice has developed on a pavement section underlain by geofoam, while ice did not develop on the adjacent pavement section that did not incorporate geofoam, thereby creating dangerous driving conditions. This may be considered as one of the most subtle cases of serviceability failure.

6.1.2 *Lessons learned from the above case histories*

The following lessons can be learned from the above case histories:

- Engineers must learn that the behavior of geosynthetics is affected by temperature.
- Under certain circumstances, a geosynthetic may have a detrimental effect on the behavior of another material.
- Some detrimental effects of geosynthetics result from mechanisms that are not easy to predict, even if they can be explained after observations are made. Engineers must therefore keep themselves informed of field observations.
- Common sense, as often, can be misleading.

6.2 *Failure modes due to geosynthetic degradation*

6.2.1 *Overview of geosynthetic degradation*

The failure modes discussed in Sections 2 to 5 resulted from the application of stresses to the geosynthetics or the structures incorporating geosynthetics. These failure modes can be characterized as macro-failures. Section 6 is devoted to micro-failures, i.e. failures that result from material degradation. Virtually all of these failure modes result from the polymeric nature of most geosynthetics. Indeed, polymers are physically and chemically affected by fire, heat, ultraviolet radiation, radioactivity, and chemicals; also, some polymers may exhibit cracking; finally, some geosynthetics may exhibit delamination and blistering. These failure modes are discussed below.

6.2.2 *Fire*

Polymers burn more or less easily, but all can be easily damaged by the heat generated by a fire. A case of geomembrane liner, geonet and geotextile damaged by landfill fire has been reported (*Adams et al.*). Two cases of geofoam fire have been reported (*Horvath*); these fires were caused by welding steel members (unrelated to the geofoam blocks) too close to uncovered geofoam blocks (which were not made of flame-retardant geofoam). The author of this paper knows of a fire that occurred during the installation of a liner system; several rolls of drainage geocomposite (polyethylene geonet core with polyester geotextile filter) caught fire after being struck by lightning, and the fire damaged the installed high density polyethylene (HDPE) geomembrane liner on which the geocomposite rolls were resting prior to being installed.

6.2.3 *Heat*

Thermoplastic polymers (e.g. polyethylene, polypropylene, polyvinyl chloride) soften when heated and, as a result, deform. This may happen during seaming when “overheating” results in large geomembrane deformations next to seams, which promotes the development of stress concentration. Heat may also affect the degree of crystallinity of polyethylene. As a result, the behavior of polyethylene geomembranes in the vicinity of seams may be affected, which (in conjunction with stress concentration, Section 2.3.3) may lead to geomembrane failures next to seams (Giroud 1994a, 1994b). Geomembranes made of polyvinyl chloride (PVC) tend to lose plasticizers when heated. As a result, they shrink and may crack. A failure of this type has been reported (Giroud 1984c, 1984e; *Giroud*). Also, heat promotes thermo-oxidation of some polymers such as polyolefins (polyethylene and polypropylene).

6.2.4 *Ultraviolet radiation*

Overview. All polymers tend to deteriorate when they are exposed to ultraviolet radiation, i.e. to sunlight. Geosynthetics can be protected against ultraviolet radiation using chemical additives ("antioxidants") and carbon black. The additives, which are included in the polymeric compounds used to manufacture geosynthetics, tend to block the degradation process triggered by the presence of oxygen and the energy supplied by ultraviolet radiation. These additives are progressively consumed, whereas carbon black is inert and remains in the polymeric compound. However, carbon black alone is not sufficient to effectively protect a geosynthetic from ultraviolet radiation. Carbon black used in polymeric compounds is in the form of aggregates of small particles that are mixed with the polymer; these particles stop the ultraviolet radiation, but they have no chemical action. A small percentage of carbon black (e.g. 2 or 3%), used in addition to antioxidants, is sufficient to effectively protect polyethylene and polypropylene geomembranes, geonets and geogrids for many years. In contrast, fibers, because of their small diameter (typically from 20 to 50 μm), cannot be effectively protected by carbon black for the following reasons: (i) the depth of penetration of ultraviolet radiation before it is stopped by carbon black particles is not negligible compared to the fiber diameter (whereas, in the case of geomembranes, geonets and geogrids, the depth of penetration of ultraviolet radiation is small compared to the thickness of the geosynthetic); and (ii) the amount of carbon black in fibers must be limited because the presence of too many aggregates of carbon black particles creates discontinuities that may weaken the fiber. Furthermore, fibers are more exposed to radiation of all kinds than geomembranes, geonets and geogrids, because they have a larger specific surface area (i.e. surface/volume ratio); therefore, the amount of radiation per unit mass of material is greater in the case of geotextiles than in the case of other geosynthetics. As a result, geotextiles cannot be effectively protected against long-term exposure to ultraviolet radiation. Their durability when exposed outdoors depends of the "additive package", which varies from one geotextile to another.

Examples — Holes in geotextiles exposed on landfill slopes. Geotextiles exposed on landfill slopes have undergone severe degradation to the point that large holes (10 cm in diameter or more) developed (*Artières et al*., *Giroud et al*.) after being exposed for periods of the order of one month to one year. The extent of the degradation depended significantly on the type of geotextile.

Example — Degradation of "wrap-around" geotextile facing of a reinforced soil slope. As reported by *Cazzuffi et al*., a geotextile-reinforced soil slope had to be dismantled because of the degradation of the geotextile at the face of the structure due to exposure to sunlight. The reinforced soil slope was eventually reconstructed using a geogrid.

Example — Degradation of geomembrane liner. As reported by *Hsuan et al*., an exposed flexible polypropylene geomembrane in a pond degraded because the antioxidant package used in this particular flexible polypropylene geomembrane was unable to provide the required protection at the geographical location of the pond, even though the carbon black content was appropriate.

Lessons learned from the above examples. The following lessons can be learned from the above examples:

- Geotextiles should not be permanently exposed to sunlight, and temporary exposure should be limited to an extent that depends on the geotextile, but can rarely exceed several months.
- Even though geomembranes are more resistant to outdoor exposure than geotextiles, they are all sensitive to some degree to ultraviolet radiation and to heat.
- For permanent exposure of all types of geosynthetics, the design engineer should review the antioxidant package with the geomembrane manufacturer.

6.2.5 *Radioactivity*

All polymers are sensitive to radioactivity. However, the levels of radioactivity typically encountered, even in the storage of radioactive materials such as low-level radioactive waste, are generally not sufficient to significantly affect geosynthetics (Badu-Tweneboah et al. 1999).

6.2.6 *Chemicals*

Overview. Most synthetic geosynthetics have a high resistance to most chemicals found in geotechnical applications. However, some chemicals found in industrial landfills and ponds may be harmful to some polymers. Also, water and high pH materials such as fresh concrete may cause hydrolysis reactions that can degrade some polymers (e.g. polyester). Also, water causes the bentonite in geosynthetic clay liners to swell and exhibit a marked decrease in shear strength. Examples are given below.

Examples — Degradation of geomembrane due to hydrolysis. An example of degradation of a geomembrane in a pond due to hydrolysis is provided by *Hsuan et al*. Also, the author of this paper knows of a canal liner case where a polyester geotextile degraded as a result of hydrolysis caused by contact with fresh concrete.

Examples — Degradation of geomembrane due to attack by acid. An example of degradation of a polyvinyl chloride (PVC) geomembrane in a pond due to attack by acid is provided by *Giroud*.

Lessons learned from the above examples. The following lessons can be learned from the above examples:

- When chemicals are likely to be in contact with geosynthetics, the design engineer should contact the manufacturer.
- Even geomembranes are not perfectly impermeable, and the design engineer should not forget that leaking liquid may attack the soil (Section 2.4.2).

6.2.7 *Cracking*

High density polyethylene (HDPE) may exhibit stress cracking. A number of geomembrane liner failures occurred in the 1985-1995 period (Giroud 1990, 1994a, 1994b; *Thomas and Kolbasuk*, *Giroud*). In the early 1990s, methods were developed to select the base polyethylene resins used to make HDPE geomembranes, and the frequency of occurrence of failures due to stress cracking has been greatly reduced.

Some geomembranes may exhibit surficial cracking (e.g. geomembranes made with chlorinated polyethylene (CPE) or chlorosulfonated polyethylene (CSPE), and bituminous geomembranes). A failure of this type has been reported by *Kamp and Giroud*.

Lessons learned from the above examples. The following lessons can be learned from the above examples:

- Engineers designing with HDPE geomembranes should be aware that there is a test method to evaluate the resistance to stress cracking of a geomembrane.
- Engineers considering the use of geomembranes that are not frequently used should contact the manufacturer.

6.2.8 *Delamination and blistering*

Some geomembranes are composed of several plies (i.e. layers) and separation of these plies (called "delamination") may occur. This phenomenon occurs mostly with geomembranes that are reinforced with a scrim (a type of lightweight fabric). An example is given by *Giroud*. A geomembrane that starts delaminating must be replaced because, if delamination progresses from one side of a geomembrane sheet to the other, it results in a major leak. Delamination occurs when there is insufficient "ply adhesion", i.e. insufficient adhesion between the layers that constitute the geomembrane.

A mode of geomembrane degradation linked to lack of ply adhesion is blistering, which is the development of blisters between two plies of a geomembrane. An example is given by *Kamp and Giroud.*

Lessons learned from the above examples. Design engineers contemplating the use of scrim-reinforced geomembranes should be aware of the risk of delamination and blistering, and the availability of a ply-adhesion test.

PART II — DISCUSSION OF FAILURES AND SUCCESSES

7 MODES OF FAILURES ASSOCIATED WITH GEOSYNTHETICS

7.1 *Overview of modes of failure*

In Sections 2 to 6, the various types of failures were presented following a classification according to the type of problem: hydraulic problems such as leakage (Section 2) and malfunctioning of filters and drains (Section 3); mechanical problems such as instability (Section 4) and deformations (Section 5); and physico–chemical problems (Section 6). In Section 7, the same types of failures will be put in a different perspective. Some relationships between seemingly unrelated modes of failures will appear. For example, it will be seen that various failure modes are related because they result from the two-dimensional nature of geosynthetics. In Section 7, the failure modes will be put in two categories: the failure modes that are common to soils and geosynthetics (and are already well-known in geotechnical engineering), in Section 7.2; and the failure modes that are specific to geosynthetics, in Section 7.3.

7.2 *Failure modes common to soils and structures incorporating geosynthetics*

7.2.1 *Overview of failure modes common to soils and structures incorporating geosynthetics*

Section 7.2 presents a discussion of modes of failure that are common to soils and structures incorporating geosynthetics. These failure modes are already well-known in geotechnical engineering. This shows that geotechnical engineers are already more familiar than they think with many of the problems affecting geosynthetics. There are similar failure modes between geosynthetic engineering and geotechnical engineering because: (i) some of the functions performed by geosynthetics are identical to functions performed by soil materials; and (ii) even if a geosynthetic does not perform a function that could be performed by a soil, the mode of failure of a structure incorporating geosynthetics may be similar to that of a soil structure. These two points are discussed below.

Some of the functions performed by geosynthetics are identical to functions performed by soil materials. For example, a geotextile filter and a sand filter perform the same function. Geosynthetics and soils that are intended to perform the same function are likely to fail according to similar modes if they do not properly perform the required function. For example, geotextile filters may fail by becoming clogged or by allowing particle migration, as sand filters do.

Even if a geosynthetic performs a function that could not be performed by a soil (e.g. if the geosynthetic performs the reinforcement function), the mode of failure of a structure incorporating geosynthetics may be similar to that of a soil structure. This is the case when the failure mode is mostly governed by soil behavior. Thus, a number of failure modes that are well-known in geotechnical engineering are applicable to geosynthetics engineering.

Examples of modes of failure that are common to soils and structures incorporating geosynthetics are presented in Sections 7.2.2 to 7.2.6.

7.2.2 *Soil erosion and particle migration*

The fact that soil particles can be transported (usually by water) and that soil can be eroded has caused a number of failures associated with geosynthetics. These failures may be of various types, as illustrated by the following examples:

- Clogging of geotextile filters by migrating soil particles (Sections 3.2, 3.3), in particular in the case of internally unstable soils, e.g. gap-graded soils (*Fluet and Luettich*, Section 3.2.2) and soils subjected to "pumping" as a result traffic loads (*Bieth and Faure*, Section 3.2.2).
- Clogging of geotextile filters by soil particles due to erosion of adjacent soil (*Vertematti*, Sections 3.3.2 and 4.7.1), (Giroud 1993, *Giroud*, Section 3.3.4).
- Failure of a canal protective soil layer (*Well*, Section 4.7.1) and of landfill cover systems (*Gross et al*., Section 4.7.1).
- Collapse of the facing of a modular-block geosynthetic-reinforced soil bridge abutment due to erosion of the soil at the toe of the facing (*Gourc et al*., Section 4.7.2). Erosion was also a factor in the bridge abutment problems described in Section 5.2.2 (*Palmeira and Fahel*).

From the above discussion, it may be concluded that an engineer using geosynthetics should consider all potential failure mechanisms caused by soil erosion and particle migration.

7.2.3 *Instability of slopes and masses*

The forces (e.g. gravity — possibly increased by seismic forces — and water pressure) that cause instability of soil, ore or waste slopes and masses that do not incorporate geosynthetics also cause instability of soil, ore or waste slopes and masses that do incorporate geosynthetics. Examples include: waste slides (*Chang et al., Ouvry et al., Stark et al.*, Giroud 1993, Sections 4.2.2 and 4.3.2), ore heap slides (*Smith*, *Breitenbach*, *Smith and Giroud*, Section 4.2.4) and (Van Zyl 1993, Section 4.3.3), and surficial instability of reinforced soil slopes (*Collin*, Section 4.4).

In particular, the influence of water on stability is the same for structures that incorporate geosynthetics and for structures that do not incorporate geosynthetics (see Section 4.5 for excessive water supply, and Section 4.6 for rapid drawdown).

From the above discussion, it may be concluded that an engineer using geosynthetics should not forget the forces, well known in geotechnical engineering, that impact the stability of slopes and masses. These forces should be considered at all times (i.e. the design engineer must check that the structure is stable at all stages of construction) and all locations (i.e. the design engineer must check that all parts of the considered structure have an appropriate factor of safety).

7.2.4 *Deformation of soil*

Section 4 presents a variety of failure modes that belong to the category of excessive deformations. While, some of these failure modes are specific to geosynthetics, in the case of other failure modes the geosynthetic deformation results from a deformation of the soil. Since soil deformations are well known by geotechnical engineers, they may be expected to predict these modes of failures. Examples are given below:

- One of the main causes of problems and failures in geotechnical engineering, differential settlement, also exists in the case of structures incorporating geosynthetics. The examples and case histories presented in Section 5.2 confirm that differential settlements are a major cause of problems in geotechnical structures, whether they incorporate geosynthetics or not. Furthermore, structures incorporating geosynthetics provide new opportunities for differential settlements to cause problems, for example: (i) differential settlement between reinforced and non-reinforced fill, for a wall (*Palmeira and Fahel*, Section 5.2.2) and a geotextile-reinforced slope (*Ingold*, Section 5.2.3); (ii) connections between geosynthetics and structures (Section 5.2.4), such as geosynthetic reinforcement and wall facing, or geomembrane liner and concrete structure; and (iii) damage to geotextile filter (*Vertematti*, Section 5.2.5).

- Unless they perform the reinforcement function, geosynthetics have very little impact on deformations of adjacent soils. A geosynthetic may be damaged by excessive tension due to the deformation of the adjacent soil, especially in the case of localized subsidence of the soil underlying the geosynthetic (*Giroud*, Sections 2.4 and 5.3.3), or in the case of lack of bearing capacity (*Badu-Tweneboah et al*., Section 5.3.4), or in the case of bank deformation by wave action (*Fourie*, *Giroud*, Section 5.3.2), even though the waves are on one side of the geosynthetic and the bank is on the other side.

From the above examples, it may be concluded that engineers designing with geosynthetics should consider all soil deformations that are possible (assuming that, in many cases, the geosynthetic will not have any significant influence on these deformations) and should evaluate the impact of soil deformation on the geosynthetics.

7.2.5 *Inadequate water control*

Improper control of water likely to reach a structure, which is a major cause of failure of traditional geotechnical structures (i.e. structures that do not incorporate geosynthetics), is also a major cause of failure of structures incorporating geosynthetics. Examples are:

- Failures of geosynthetic-reinforced soil structures have been caused, at least partly, by an excessive amount of water reaching the structure (*Bernardi*, *Giroud and Beech*, *Frost et al*., Section 4.5.3).
- Failure of a canal liner protective soil layer was caused in part by water infiltrating under the liner due to inadequate surface drainage and the lack of anchor trench on top of the geomembrane liner (*Well*, Section 4.5.2).
- Failure of a bank protection system incorporating a geotextile was caused by wastewater seeping from a wastewater pond (*Davis et al*., Sections 3.4.2 and 4.5.2).
- Failure of municipal solid waste landfills due to leachate recirculation (*Gross et al*., Hendron et al. 1999, Section 4.5.4).

The above examples confirm that water is a major cause of failures of geotechnical structures, whether they incorporate geosynthetics or not.

7.2.6 *Preferential path*

In geotechnical engineering, it is known that problems can occur when water follows a preferential path. The same mechanism can occur with transmissive geosynthetics such as geonets, geocomposites, and needle-punched nonwoven geotextiles. This mechanism can also occur with geomembranes at the geomembrane–soil interface or along folds (*Sembenelli*, Section 2.6.2) or wrinkles (Section 5.4). Examples include:

- Excessive leakage through a dam, where water was conveyed from the reservoir through the dam by a transmissive geotextile (*Levillain*, Section 2.6.1).
- Collapse of an earth dam due to internal erosion caused by water that was conveyed from the reservoir to the dam due to preferential paths (*Sembenelli*, Section 2.6.2): (i) the folded connections between adjacent geomembrane sheets were not sufficiently watertight and provided preferential paths for water from the reservoir; and (ii) the connection between the geomembrane and clay at the toe of the dam created preferential paths for the water from the reservoir.
- Failure of a pavement due to blisters generated by humid air conveyed by woven geogrids used to reinforce the pavement (*Wilmers*, *Giroud*, Section 5.8.5).
- False leakage detection in two landfills due to water that had penetrated into the anchor trench at the top of the slope and reached the geonet leakage collection and detection system (*Gross et al*., Section 2.6.3)

Based on the above examples, it appears that a geosynthetic while it performs the intended function, may perform another function (fluid transmission) that may be detrimental to the structure. Geotechnical engineers, who are familiar with problems due to preferential paths, need to be aware that such problems may exist with geosynthetics.

7.2.7 *Effect of temperature on soil and asphalt*

It is known in geotechnical engineering that temperature affects the behavior of soil (e.g. action of frost on soils that contain water, and desiccation of clay due to high temperature) and the performance of road pavements. Similar problems can exist with geosynthetics. Geosynthetics, which are thin (with the exception of geofoam panels), are unable to prevent temperature changes from penetrating into the underlying soil; in contrast, geofoam is a thermal insulator. Examples are:

- Instability of liner systems on slopes due to decrease of interface shear strength caused by frost (*Frobel and Comer*, *Luettich et al.*, Section 4.2.3).
- Differential icing, a rare phenomenon, impacting the performance of a road pavement, that results from the low coefficient of thermal conductivity of geofoam panels (*Horvath*, Section 6.1.1).
- Desiccation of clay beneath a geomembrane resulting from high-low temperature cycles (*Horvath*, Section 6.1.1).

It should be noted that the cases illustrated by the above examples are relatively rare. However, design engineers should not ignore them. In fact, geotechnical engineers are well prepared to deal with these failure mechanisms because they are similar to mechanisms that are well-known in traditional geotechnical engineering. It should also be noted that temperature has a direct effect on geosynthetics as discussed in Section 7.3.2.

7.2.8 *Conclusions regarding failure modes common to soils and geosynthetics*

The above examples show that engineers designing with geosynthetics must have a broad knowledge of geotechnical engineering, and, in particular, a comprehensive knowledge of the failure modes of traditional geotechnical engineering structures (i.e. structures that are not incorporating geosynthetics). They should review all the classical failure modes relevant to the considered structure and evaluate if these failure modes are possible in the presence of the geosynthetic considered for a project.

It is interesting to note that, while geotechnical engineering should not be ignored by those designing with geosynthetics, knowledge of geotechnical engineering has been increased thanks to well designed geosynthetic projects or research conducted on geosynthetics. For example, knowledge of granular filters has benefited from research on geotextile filters.

7.3 *Failure modes specific to geosynthetics*

7.3.1 *Overview of failure modes specific to geosynthetics*

In addition to the failure modes that are well known in geotechnical engineering and are applicable to geosynthetic engineering, which were discussed in Section 7.2, there are failure modes that are specific to geosynthetics. Many of these failure modes are related to the fact that most geosynthetics have two characteristics that make them different from soils: they are two-dimensional and they are polymeric. It should be noted that this characterization of geosynthetics does not include geofoam blocks (because they are three-dimensional), but does include geosynthetics made with natural fibers (because these fibers are typically made with natural polymers).

Also, geosynthetics are in contact with adjacent materials (soil, waste, other geosynthetics, etc.); as a result, some of the failure modes that are specific to geosynthetics are linked to interaction mechanisms. In other words, geosynthetics are incorporated in a three-dimensional structure and many of the failure modes of structures incorporating geosynthetics result from the interaction between the (generally) two-dimensional geosynthetic and the three-dimensional structure that surrounds it.

Based on the above discussion, Section 7.3 will include three parts: failure modes associated with the two-dimensional nature of geosynthetics (Section 7.3.2); failure modes associated with geosynthetic degradation (Section 7.3.3); and failure modes associated with interaction between geosynthetics and adjacent materials (Section 7.3.4).

7.3.2 *Failure modes associated with the two-dimensional nature of geosynthetics*

Geosynthetics are the only two-dimensional materials used in geotechnical engineering. A two-dimensional material is thin (hence light) and continuous. As a result of these characteristics, geosynthetics may exhibit the following modes of failure: (i) failure modes due to lack of geosynthetic continuity at the time of construction ; (ii) failure modes due to damage to the geosynthetics caused by tensile and compressive stresses, in particular concentrated stresses; (iii) failure modes due to "out-of-plane" stresses, i.e. stresses applied in a direction approximately normal to the geosynthetic, thereby causing geosynthetic deformation perpendicular to its plane (i.e. uplift and localized subsidence) which results in tensile stresses in the geosynthetic and, if the stresses are excessive, in tensile rupture; and (iv) failure modes resulting from thermal expansion and contraction, which are related to the two-dimensional nature of geosynthetic, as temperature affects differently the two-dimensional geosynthetic and the three-dimensional adjacent soil. Examples and comments follow:

- Since a basic characteristic of a two-dimensional material is continuity, a basic failure mode of a geosynthetic is lack of continuity. This mode of failure affects the geosynthetics applications where continuity is important, such as geomembrane liners and geotextile filters (in particular in case of high hydraulic gradient). Lack of continuity may result from mechanical damage, as discussed in Section 5.6 (and more specifically for geomembranes in Section 2.2.2), or because geotextile filter overlaps separated as a result of settlement (*Christopher*, Sections 3.5.1 and 3.6.2) or differential settlement (*Vertematti*, Section 3.6.2). This failure mode may also occur because a geosynthetic was not continuous when it was installed (see Section 2.2 on geomembrane defects; Giroud 1993, Giroud and Goldstein 1982, Section 2.4.3, on defective connection between geomembrane liner and a concrete structure; and *Christopher*, *Vertematti*, and *Rowe and Seychuk*, Sections 3.5.1 and 3.6.2, on lack of geotextile filter continuity).
- Since geosynthetics are generally light, they can easily be uplifted, which results in tensile stress in the geosynthetic. Examples of geosynthetic uplift include: (i) uplift of geomembrane or geotextile by wind (Giroud et al. 1995a, Gleason et al. 1998, 1999, Sections 5.5.2 and 5.5.3); (ii) uplift by liquid of geomembrane liner (*Fayoux, Frobel, Giroud,* Sections 5.5.2 and 5.5.4); (iii) uplift by gas of geomembrane liner in a pond (*Fayoux, Frobel, Giroud,* Section 5.5.2) or geomembrane and geosynthetic clay liner cover in a landfill (*Richardson et al*., Section 5.5.2); (iv) uplift of geomembrane liner by air entrapped between the geomembrane and liquid that is present under the liner (*Fayoux*, *Giroud*, Section 5.5.2); (v) uplift of clogged geotextile filter (Gourc and Faure 1990, Fluet and Luettich 1993, Sections 3.2.2 and 5.5.2); and (vi) uplift of a geosynthetic used for erosion control by water current (*Jacotot et al*., Sections 5.5.2 and 5.7.1). Uplift may result in two types of failures: disruption in the operation of the structure or geosynthetic damage. For example, an uplifted geomembrane may be damaged, in the short term, by excessive tensile stresses or, in the long term, by creep, by exposure to wind and sunlight, and by being a tempting target for vandals and hunters. Engineers designing a geosynthetic application where the geosynthetic is not covered by a layer of soil, or is covered by only a very thin layer of soil or a layer of soil that could be eroded or otherwise removed, should identify all possible sources of fluids capable of uplifting the geosynthetic.
- Geosynthetics are often placed horizontally and normal stresses develop on top of them. As a result, in case of localized subsidence of the underlying medium, geosynthetics sag, stretch and may rupture. Examples include: (i) sludge pond cover system that exhibited localized subsidence during construction under the weight of equipment due to lack of bearing capacity of the sludge, which resulted in the opening of GCL overlaps, while the unreinforced PVC geomembrane elongated without damage (*Badu-Tweneboah et al*., Section 5.3.4); bursting of geomembrane over localized subsidence of soil due to dissolution of soil with high carbonate content (*Giroud*, Section 2.4.2), or collapse of karstic soil (*Giroud*, Section 2.4.3), or pipe crushing (*Giroud*, Section 2.4.4). Engineers designing a geosynthetic application should be knowledgeable in geotechnical engineering to be able to identify all possibilities of localized subsidence and to make a reasonable assumption of the areal extent and depth of the subsiding area. Then, quantification of the geosynthetic strain and tension is relatively easy thanks to available analytical methods (Giroud 1982a; Giroud et al. 1990a; Giroud 1995b).

- All polymers have a large coefficient of thermal expansion-contraction (i.e. about ten times as large as that of usual construction materials such as concrete and steel). However, polymers that are drawn (i.e. stretched in a controlled manner to make fibers and geogrid ribs) do not expand and contract much (and may even shrink, but in an irreversible manner, when heated excessively). As a result, geonets and non-reinforced geomembranes significantly expand or contract when temperature increases or decreases, respectively; in contrast, geotextiles, geogrids and reinforced geomembranes do not exhibit significant thermal expansion and contraction. Thermal expansion of geomembranes results in wrinkles (Section 5.4) and thermal contraction results in geomembrane tension, which may cause tensile failure (in the case of geomembranes that become stiffer at low temperature) or stress cracking (2.3.2).

Based on the above examples, it is clear that geotechnical engineers designing structures incorporating geosynthetics should learn about a number of failure modes specific to geosynthetics in order to avoid failures.

7.3.3 *Failure modes due to geosynthetic degradation*

The failure modes due to geosynthetic degradation are discussed in detail in Section 6.2. These failure modes include: fire, heat, ultraviolet radiation, radioactivity, chemicals, cracking, and delamination and blistering.

7.3.4 *Failure modes due to interaction between geosynthetics and adjacent materials*

Interaction between geosynthetics and adjacent materials may involve mostly normal stresses (intimate contact and intrusion), shear stresses (interface shear strength), and tensile stresses (soil-geosynthetic displacement interaction). Examples and comments follow:

- Intimate contact is an important requirement in many geosynthetic applications: in these applications, the geosynthetics need to be in intimate contact with the adjacent soil to properly perform their function. This requirement results from the fact that a two-dimensional material, the geosynthetic, is placed against a three-dimensional material, the soil. Lack of intimate contact explains a number of failures. A geosynthetic may not be in intimate contact with the adjacent soil if it lacks flexibility or if it has not been applied against the soil with sufficient pressure. Examples include: (i) in the case of composite liners, wrinkles due to thermal expansion prevent geomembranes from being in intimate contact with the underlying low-permeability soil (compacted clay or geosynthetic clay liner), thereby preventing the formation of an effective composite liner (Section 5.4): (ii) wrinkles promote the mechanism of desiccation that deteriorates the clay component of a composite liner (Section 6.1); (iii) failures of geotextile filters due to lack of intimate contact between the geotextile filter and the adjacent soil are a typical mode of failure of geotextile filters (Giroud et al. 1977, Giroud 1989, 1996, Section 3.3.1) and (*Vertematti, Koerner and Koerner*, Section 3.3.2); (iv) failure of an asphalt overlay due to lack of intimate contact between the geotextile and the underlying pavement and between the geotextile and the overlay (*Guram, Baker and Marienfield*) (Section 5.8.2); (v) failure of a geomembrane liner that had been installed too far from the corners of a reservoir and, as a result, underwent excessive strain during the first filling of the reservoir as it was forced to move toward the reservoir corners by water pressure (Giroud 1993, *Giroud and Stone*, Sections 2.5 and 5.3.5); and (vi) failures of bank protection systems due to lack of contact between the geotextile filter and the soil (*Gustin*, *Heerten*, Section 3.3.3) and (Giroud 1993, *Giroud*, Section 3.3.4).
- When two geosynthetics are in contact, one of them may intrude (i.e. partly penetrate) into the other. This is the case in particular for geotextiles penetrating into geonets, thereby reducing their hydraulic transmissivity (Section 3.7). Another example of intrusion is the case of geonet strands indenting into geomembranes, thereby locally reducing the geomembrane thickness. However, this case is rare (*Laine and Darilek*, and *discussion by Giroud et al. of Laine and Darilek's paper*, Section 5.6.3).
- Geosynthetics are more or less smooth. At best, the shear strength at a geosynthetic-soil interface is equal to the shear strength of the soil. Therefore, in general, the presence of geosynthetics creates one or several planes of low shear strength. These planes increase the risk of instabil-

ity. Instability of a soil, waste or ore slope or mass is one of the main causes of failures associated with geosynthetics. Also, asphalt overlays may fail by sliding due to insufficient interface shear strength. Examples of failures linked to interface shear strength are as follows: (i) liner system on slope (*Richardson et al., Stark et al., Bonaparte et al., Vander Linde et al., Frobel and Comer, Luettich et al., Datye and Gore,* Girard et al. 1990, Giroud 1993, Section 4.2.3), waste slides (Section 4.2.2), ore heap slides (*Smith, Breitenbach, Smith and Giroud,* Section 4.2.4), asphalt overlays (*Guram, Baker and Marienfield,* Section 5.8.2) and (*Wilmers,* Section 5.8.3).

- When geosynthetics are used for soil reinforcement, a certain geosynthetic strain is required to mobilize the geosynthetic tension. This strain requires a displacement of the soil, which may cause a deformation of the geosynthetic-reinforced soil structure. The deformation of the structure may affect its serviceability to the point that it may be considered that the structure failed. A similar situation exists with the mobilization of interface shear strength. Examples of such failures are: (i) excessive deformation of geosynthetic-reinforced soil walls (Sections 4.5.3) and (*Bathurst,* Section 5.9.2); (ii) excessive deformation of a temporary access road (Giroud 1993, Section 5.9.3); (iii) failure of an embankment due to the fact that the reinforcing geotextile was installed with wrinkles, which required excessive soil displacement to mobilize the geotextile tensile strength (*Gale,* Section 5.9.4); and (iv) landfill failure where the displacement required to mobilize the peak interface shear strength was significantly less than the displacement required to mobilize the peak shear strength of the waste (*Stark et al.,* Section 4.2.2).

7.4 *Conclusion on failure modes associated with geosynthetics*

The review of modes of failure associated with geosynthetics presented in Section 7 shows that the forces involved are known and the mechanisms are easy to understand. Many of them are similar, or related, to the mechanisms of failure that are familiar to geotechnical engineers. After all, the most common causes of failures of structures incorporating geosynthetics are gravity and water pressure. Also, as a result of cooperation between geotechnical engineers and polymer scientists, the modes of failures that are associated with the polymeric nature of geosynthetics have been identified and geotechnical engineers are becoming aware of these mechanisms. Therefore, one may wonder why there are still failures of structures incorporating geosynthetics. This is addressed in Section 8.

8 SITUATIONS LEADING TO FAILURES

8.1 *Overview: excessive expectations*

An analysis of the reasons behind the observed failures of structures incorporating geosynthetics shows that many failures result from the fact that design engineers, generally, or contractors, sometimes, put themselves in a situation that increased the probability for failure. It appears that, in many cases, excessive expectations regarding the geosynthetics led to negligence at the design stage, or irrational decisions at the design or construction stages.

When confronted with a relatively new technology such as geosynthetic engineering, some engineers are reluctant to use the new technology while others are overly enthusiastic and believe too easily (sometimes encouraged by overzealous salespersons) that the mere fact of using a geosynthetic will automatically solve all problems. The former miss opportunities for better designs, while the latter are potentially dangerous because, as a result their excessive expectations, they may be inclined to neglect consideration of failure modes when they design.

Excessive expectations can lead to various types of design mistakes including: (i) design is neglected based on the belief that the geosynthetic will solve the problem regardless of the design (see Section 8.2); (ii) basic design steps that are usual in geotechnical engineering are omitted as if there was no relationship between geosynthetic engineering and geotechnical engineering (see Section 8.3); (iii) the fact that geosynthetics may have a detrimental effect on the structure is ignored in design, whether the geosynthetic is useless (see Section 8.4) or useful (see Section 8.5); (iv) using two geosynthetics instead of one may have detrimental consequences (see Section 8.6); (v) all geosynthetics are considered equal (see Section 8.7), which is wrong, but consistent with the fact that they are all assumed to make miracles; and (vi) even when it has been shown that a failure may happen, those who are overly enthusiastic about geosynthetics may not take the failure potential seriously, or those who have been trained to believe only in precedents do not believe the failure may happen if the same type of failure has not happened before (see Section 8.8). These various situations that lead to failures of structures incorporating geosynthetics are discussed below.

8.2 *The use of a geosynthetic does not replace an adequate design*

As indicated in Section 8.1, some overly enthusiastic users of geosynthetics tend to act as if they were thinking that the mere fact of using a geosynthetic will automatically solve all problems. As a result, they may underestimate the need for design of geosynthetic applications. Examples follow.

- Failures of reinforced-soil walls have occurred due to insufficient amount and/or length of reinforcement (*Watn, Al Hussaini*, Section 4.3.5; *Frost*, Section 4.5.3).
- The failure of a drainage system incorporating a geocomposite drain resulted from the fact that the entire drainage system was undersized. (*Sprague et al.*, Section 3.8).
- The failure of an experimental erosion control systems for a torrent bed was due to the fact that insufficiently strong geosynthetics were used. (*Jacotot et al.*, Section 5.7.1).
- The failure of geomembrane tubes for a coastal protection system was due to the fact that the large sand-filled geotextile tubes that were used were not properly designed (*Richardson*, Section 5.7.2).
- The failure of a geomembrane liner for a phosphoric acid pond on a soil with a high carbonate content was due to the fact that the design was based on the assumption that the geomembrane liner would be totally impermeable and therefore dissolution of the soil by phosphoric acid would no occur (*Giroud*, Section 2.4.2).
- The failure of a haul road where the specified geogrid was replaced by a geotextile has been reported (*Bostian et al.*, Section 5.8.6). In fact, in that case, the haul road would have failed with any geosynthetic approximately equivalent to the specified geogrid, because the design was inadequate.

The above examples show that geosynthetics do not make miracles and should not be expected to make miracles. A design that relies on unrealistic expectations about geosynthetic performance is flawed and could lead to failures. After the failure has occurred, the geosynthetic should not be used as a scapegoat for the failure.

8.3 *Design steps that are usual in geotechnical engineering should not be omitted*

Failures occur when designers focus exclusively on the design of the geosynthetic aspects of an application and omit the more usual aspects of the design, i.e. the design aspects that involve geotechnical engineering. This may happen, in particular, if a structure is redesigned to replace an original structure component that did not include geosynthetics by a component with geosynthetics. In such cases, it is possible that additional geotechnical design is required (whether the original design is deficient or not). It may simply happen that unrealistic expectations regarding geosynthetics lead the design engineer to think that all problems are solved as long as the geosynthetic application is designed, thereby ignoring that the geosynthetic application is in a geotechnical environment that requires investigation and design. Some examples are presented below:

- *Insufficient site investigation*. The failure of a portion of riverbank protection system incorporating a geotextile filter was due to the biological clogging of the geotextile (*Davis et al.*, Section 3.4.2). The risk of biological clogging was not recognized because of insufficient site investigation.
- *Insufficient site investigation*. The failure of a modular-faced reinforced soil wall was caused by excessive water supply due to poor surface drainage in an adjacent street and soil profile different from expected (*Bernardi*, Section 4.5.3). Both site characteristics were unknown to the design engineer due to insufficient site investigation.

- *Insufficient site investigation*. In an ore heap leach pad, a deep-seated slide occurred, involving movements of the ore and the foundation soil (Van Zyl 1993, Section 4.3.3). Because of inadequate sub-soil investigation, the design engineer had not realized that the critical slip surface could be deep-seated.
- *Basic geotechnical engineering consideration ignored*. The failure of the geomembrane liner for a large reservoir was caused by the crushing of a pipe located in the soil underlying the liner (Giroud 1993, Section 2.4.4).
- *Basic geotechnical engineering consideration ignored*. The collapse of a section of the modular facing of a reinforced-soil wall located on a slope was caused by erosion of the soil at the toe of the facing (*Gourc et al*., Section 4.7.2). Erosion should always considered as a potential source of problems for a foundation resting on a slope.
- *Basic geotechnical engineering consideration ignored*. A geosynthetic-reinforced soil wall collapsed as a result of global or compound instability, aspects of the design that had been omitted by the designer who focused on the internal and external stability of the reinforced soil wall (*Berg and Meyers, Valentine and Damm, Giroud and Beech*) (Section 4.3.4). In other words, the designer focused on the geosynthetic aspect of the design (i.e. the design aspects involving only the geosynthetic-reinforced soil) and not on the design aspects involving the surrounding soil (i.e. the geotechnical aspect of the design).

Based on the above examples, it is clear that usual design steps should not be omitted from the design of structures incorporating geosynthetics. These usual design steps include, for example: site investigation for all types of structures, in particular to identify sources of water and soil profile; deep-seated failure analysis; global and compound stability analyses; evaluation of strength, compressibility and bearing capacity of the soil underlying the considered structure; erosion consideration, especially for structures located on slopes; and many other typical geotechnical engineering activities. As paraphrased from *Frost et al*., a structure incorporating geosynthetics should not be regarded as a prefabricated system that is simply inserted in the field without consideration of the site conditions

8.4 *Useless geosynthetics may have a detrimental impact on the structure*

Sometimes geosynthetics are used in structures where they are not needed. This happens when overzealous salespersons manage to convince designers or contractors to use a geosynthetic they do not need, or when an overly enthusiastic design engineer specifies a geosynthetic "as an extra precaution", assuming that a geosynthetic can only add to the performance of the structure. It is important to recognize that, even though a geosynthetic is useless, it may have a detrimental effect on the performance of a structure. Examples are given below.

- *Slide caused by additional geosynthetic*. A geotextile added to the liner system for a landfill caused a slide (Section 4.2.3).
- *Flow capacity reduction due to additional geotextile*. The leachate collection system of a landfill was mad ineffective by an extra length of geotextile filter (Giroud 1993) (Section 3.7.2).
- *Clogging due to additional geotextile*. A geotextile "filter" added to a perforated pipe was about to become clogged (Giroud 1993) (Section 3.2.3)..

The following lessons can be learned from the above examples:

- Common sense, which indicates that adding a geosynthetic can only improve the performance of a structure, is wrong. An additional geosynthetic can be detrimental. Similarly, extending a geosynthetic beyond the area intended by the design engineer may cause a serious problem, because a geosynthetic may be beneficial in one area (where it is needed and specified) and detrimental in another area.
- Specifications must be as precise as possible. Ideally, engineers who prepare specifications should address problems that would result from potential misinterpretation of the specifications during construction. For example, there are cases where a minimum and a maximum geosynthetic length, width, or overlap should be specified, not only a minimum. In some cases, it is recommended to include in the specifications a warning against certain specific uses of a geo-

synthetic if experience dictates that, in the considered applications, contractors are tempted to use an extra geosynthetic, not knowing that it can be detrimental.

- Installers should be instructed not to place extra geosynthetics as they may cause problems such as clogging of drainage systems and slip surfaces. Installers should be instructed not to add a geosynthetic or extend the area covered with a geosynthetic during construction without being authorized by the design engineer.
- Design engineers should visit construction sites to learn about typical mistakes made during construction. This helps them write better specifications.
- The presence of the design engineer at the construction site may help prevent mistakes that could lead to failures.

8.5 *Useful geosynthetics may have a detrimental impact on the structure*

It is important to recognize that a geosynthetic, even when it is useful and performs its intended function, may have a detrimental effect on the performance of a structure. This may happen as part of the function performed by the geosynthetic (e.g. the geosynthetic may require some soil deformation to mobilize its strength and it happens that this soil deformation has some detrimental impact on the structure) or because the geosynthetic happens to perform an additional function which was not recognized by the design engineer. It is, therefore, important to identify all functions performed by the considered geosynthetic, and understand the requirements for the geosynthetic to perform these functions. The following examples illustrate this point:

- *Low interface shear strength due to the presence of geosynthetics*. Numerous slides in landfills equipped with a geosynthetic liner system have been caused by low interface shear strength associated with the presence of geosynthetics (*Chang et al., Ouvry et al., Stark et al.)* (Section 4.2). Also, the presence at an interface of bentonite particles from an adjacent GCL may reduce the interface shear strength. In fact, low interface shear strength is one of the main causes of failures of structures incorporating geosynthetics.
- *Bentonite particles migrating from a GCL and clogging a geonet drain*. This mode of failure has not been observed, but it could happen.
- *Geosynthetic blocking ground water drainage thereby causing pore pressure buildup*. Geomembranes and geosynthetic clay liners are used as liners because they have a low permeability. However, due to this low permeability, they may block natural drainage paths. As a result, pore pressure may develop under the liner, causing the liner to be uplifted (*Datye and Gore*, Section 4.2.3) or the slope to become globally unstable (*Bonaparte et al.*, Section 4.2.3). In the same category belongs the classic case of geotextile roadway separators that are not sufficiently permeable and retain water beneath them, leading to failures. Clearly, geotextile separators must be designed for performing the secondary function of filtration.
- *Failures caused by geosynthetic transmissivity*. Failure of structures incorporating geosynthetics can be caused by water or air conveyed by a transmissive geosynthetic while it performs the intended function (which is not related to fluid transmission). In other words, a geosynthetic, while it performs the function it is supposed to perform, may perform other functions, which may be detrimental to the structure. Examples include: excessive leakage through a dam, where water was conveyed from the reservoir through the dam by a transmissive geotextile (*Levillain*, Section 2.6.1); and development of blisters in asphalt overlay due to humid air conveyed by woven geogrids used to reinforce the pavement (*Wilmers*, Section 5.8.5).
- *Failure resulting from a function temporarily performed by the geosynthetic*. Excessive deformation of the geotextile separator for an airport taxiway due to the temporary use of the aggregate layer overlying the geotextile as an unpaved access road (Giroud 1993, Section 5.9.3).
- *Failure caused by incorrect geosynthetic placement*. Collapse of an earth dam due to internal erosion caused by water that was conveyed from the reservoir to the dam due to preferential paths (*Sembenelli*, Section 2.6.2): (i) the folded connections between adjacent geomembrane sheets were not sufficiently watertight and provided preferential paths for water from the reservoir; and (ii) the connection between the geomembrane and clay at the toe of the dam created preferential paths for the water from the reservoir.

- *Failure caused by incorrect geosynthetic placement*. False leakage detection in two landfills due to water that had penetrated into the anchor trench at the top of the slope and reached the geonet leakage collection and detection system (*Gross et al*., Section 2.6.3).

The following lessons can be learned from the above examples:

- A geosynthetic, even though it performs a useful function, may have a detrimental impact on the performance of a structure: it can impair its stability, convey undesirable water, etc.
- It is important to understand both the characteristics of geosynthetics that can affect the performance of a structure (e.g. interface shear strength, low-permeability, tensile modulus, hydraulic transmissivity) and the geotechnical mechanisms that can be mobilized by the geosynthetics (e.g. pore pressure buildup, deformation, water flow).
- It is important to identify the function of the geosynthetic, and to understand the mechanisms involved when the geosynthetic performs its function. If a geosynthetic must perform two functions, one during construction (e.g. reinforcement), the other in service (e.g. separation), this may cause problems that the designer engineer must foresee and solve at the design stage.

8.6 *Geosynthetic redundancy may have a detrimental impact on the structure*

Those who are overly enthusiastic about geosynthetics (or have unrealistic expectations about geosynthetics) may believe that adding a geosynthetic to an existing structure may only improve the structure. This is not always the case as illustrated by the case history presented in Section 5.5.4 (Giroud 1993; *Giroud*). This case history shows that two liners are not necessarily better than one, contrary to what common sense would dictate.

Clearly, adding a geosynthetic to an existing structure without reviewing the design may cause problems. Common sense, which indicates that two are always better than one, is wrong.

8.7 *Not all geosynthetics are equal*

Not all geosynthetics are equal. Geosynthetics of the same type are not necessarily equal (i.e. two geonets are not necessarily equal). Even when geosynthetics appear similar, they may have different properties. Considering that “all geosynthetics are equal” leads to two types of problems: (i) a geosynthetic that is not equivalent to the specified geosynthetic may be considered equivalent; and (ii) instead of measuring the properties of a considered geosynthetic, properties are “borrowed” from another geosynthetic considered equivalent, although it is not. These two points are further discussed below.

Often, a certain geosynthetic is specified for a project, and the specifications indicate that an equivalent geosynthetic can be used. The specifications should indicate that, if the “equivalent” geosynthetic does not have properties (obtained from tests performed by an accredited laboratory) that are *identical* to those of the specified geosynthetic (with a small tolerance), an equivalency demonstration (including theoretical analyses and laboratory tests) should be provided. Equivalency demonstrations should be performed rigorously; an example of the significant difference between a rigorous equivalency demonstration and an approximate equivalency demonstration is provided by Giroud et al. (2000b). As shown in the examples given below, failures have been reported that are due to the fact that the “equivalent” geosynthetic that was selected was not actually equivalent.

Considering that all geosynthetics are equal leads to using published properties instead of conducting project specific tests. This approach is dangerous, because there may be significant differences between materials that look similar. For example, an error of only a few degrees on the interface friction angle may cause slope instability, which has happened in several cases. Also, assuming on the basis of common sense that the interface friction angle is always greater with a textured geomembrane than with a smooth geomembrane can be wrong. Rubbing the hand against a geomembrane gives some indication of the friction at the hand-geomembrane interface, but gives no indication of the friction at the interface between the geomembrane and the adjacent material in the field. This was confirmed by a full-scale test and related laboratory tests (Giroud et al. 1990b, 1990c) where a geonet had a greater interface shear strength with a smooth geomembrane than with a textured geomembrane.

Examples follow:

- *Biological clogging of a geotextile filter in a riverbank protection system.* The failure of a riverbank protection system incorporating a geotextile filter due to the biological clogging of the geotextile was described in a case history presented in Section 3.4.2 (*Davis et al.*). The specified geotextile filter had been replaced by an "equivalent" geotextile that was significantly more susceptible to biological clogging than the specified geotextile. Although a major mistake in that project was the insufficient site investigation as pointed out in Section 8.3, the replacement of the specified geotextile by another geotextile contributed to the failure.
- *Waste slide in a landfill.* A large waste slide occurred in a landfill where the interface shear strength was overestimated based on published values (*Ouvry et al.*, Section 4.2.2).
- *Liner system slide in a landfill.* During the design of several waste disposal landfills, the interface friction angle between adjacent geosynthetics was estimated on the basis of published test data or results of tests on similar geosynthetics conducted for earlier projects. In one of these landfills, a major slide of the liner system occurred near the end of construction (Giroud 1993, Section 4.2.3).
- *Clogging of drain by soil particle migrating through a geotextile filter.* In a dewatering system, the rightfully specified nonwoven geotextile was replaced by a woven geotextile with larger openings. As a result, soil particles migrated through the geotextile and clogged the gravel drain (*Christopher*, Section 3.5.1).

The following lessons can be learned from the above examples:

- Geosynthetic properties should not be estimated, they should be measured. This is particularly true in the case of interface friction angles, because this property, which often plays a critical role in the performance of structures, is difficult to estimate. Furthermore, a slight error on the interface friction angle may lead to the belief that a slope is stable when it is not.
- A specified geotextile should not be replaced by another geotextile without approval by the design engineer.
- As more and more geosynthetics are available on the market, the probability increases that there are significant differences in properties between geosynthetics that may appear to be identical.

8.8 *Disbelief in potential failure*

It is hard to believe that a mode of failure that never happened in the past could happen, even if this mode of failure is predicted using a rational analysis. Indeed, geotechnical engineers are accustomed to learn from precedents, which is consistent with what common sense would dictate. However, it should be noted that, while such an attitude may be justified in a relatively old discipline such as geotechnical engineering, it is not appropriate in a relatively new discipline such as geosynthetic engineering. This is illustrated by the case history of a geomembrane liner in an underground reservoir presented in Section 2.5 (Giroud 1993, *Giroud*). The failure was predicted, described in writing, and quantified by the design engineer. However, such failure mode had never occurred before and the recommended precautions were ignored. They were taken only after the failure had occurred twice.

The following lessons can be learned from the above case history:

- In a relatively new discipline such as geosynthetics, the fact that a certain mode of failure did not occur before is of limited value. Those who claim to have experience in a new discipline often do not; those who have experience often did not have the time or the means to analyze it and, therefore, did not learn. To be valuable, experience must be complemented by rational analyses.
- If a rational analysis based on adequate data shows that a failure can occur, then it is likely to occur. (The only reason that would prevent such a failure from occurring would be the presence of hidden factors of safety.) The engineer who predicts a failure through a rational analysis should believe the results of the analysis, regardless of past experience and common sense. The engineer should, therefore, take the risk of failure seriously and should convince the owner that the failure is likely to occur even if the predicted mode of failure has not been observed before.

- Common sense can be wrong, as well as it can be right. Since the basis for common sense is not known, it is not possible to distinguish between the good and bad aspects of common sense. As a result, common sense is not reliable.
- A rational analysis is the only reliable way to make sound decisions.

9 LEARNING FROM FAILURES

9.1 *Overview*

The title of this paper includes two essential words: *lessons learned*. Accordingly, many case histories were presented, and lessons were learned from these case histories. These lessons were learned from the viewpoint of the design engineer, which is natural because design plays a central role in failures, as indicated in Section 9.2. However, mistakes during construction also play an important role in the development of failures, and it is useful to summarize the lessons learned regarding construction, which is done in Section 9.4. In addition to learning lessons from failures, lessons were learned about failures; these lessons are summarized in Section 9.5. However, before these two summary sections, two discussions are presented.

The first discussion (Section 9.2) addresses the impact of design on failures associated with geosynthetics; in this discussion, it is indicated that failures often result from design flaws and reasons for design flaws are reviewed. Recommendations are made to improve designs; one of them is to learn from failures. Accordingly, the second discussion (Section 9.3) addresses the importance of learning lessons from failures and mentions general lessons that can be learned. Then, specific lessons are listed in the two summary sections mentioned above (Sections 9.4 and 9.5).

9.2 *Impact of design on failures associated with geosynthetics*

9.2.1 *Importance of design in failures*

Structures incorporating geosynthetics are the results of the direct efforts of manufacturers, design engineers, and contractors (in addition to indirect efforts of others such as owners, distributors of materials, and quality assurance providers). Therefore, failures of structures incorporating geosynthetics result from actions by these three categories of individuals. Accordingly, three categories of failures are often considered: material failures, design failures, and construction failures. However, it should be noted that material failures generally result from a misuse of materials rather than from an inherent flaw of the materials. For example, the development of holes in geotextiles exposed to sunlight for an excessive period of time is indeed a material failure, but it is generally not imputable to the geotextile manufacturer; rather, this problem generally results from a decision by the design engineer, the contractor or the facility operator. Essentially, geosynthetic materials are what they are, and it is up to design engineers (and, to a certain degree, to contractors) to learn about geosynthetics and their limitations. Similar comments can be made about mistakes made during construction. Certainly, many of these mistakes are made by the contractor; however, it should be noted that a number of construction mistakes result from inadequate designs or specifications, unclear construction drawings, failure by the design engineer to communicate with the contractor, and failure by the design engineer to educate the contractor and familiarize him/her with certain features of structures incorporating geosynthetics that are not familiar to many contractors. Clearly, the design engineer plays a central role in the design and construction of structures incorporating geosynthetics, and, consequently, in their failures.

The importance of design in failures is illustrated by the following data from a study of 83 problems (some of them failures) that occurred in 73 modern landfills in the United States. The term “modern landfill” refers to a landfill designed with components substantially meeting current State and Federal regulations, and constructed and operated in accordance with the US state of practice (including construction quality assurance) from the mid-1980s forward. The statistical distribution of the problems is as follows (*Gross et al.*):

- 75% of the problems are related to landfill covers and liners, and 25% to leachate control systems; and
- the problems related to covers and liners break down into 60% structure behavior problems (i.e. 45% stability and 15% deformations) and 40% material problems (i.e. 25% defects and 15% degradation).

From the same database, the following breakdown has been obtained regarding the origin of the problems: design, 50%; construction, 35%; and operation, 15%. It should, however, be noted that the percentage attributed to construction would have been higher if the landfills had not been constructed with construction quality assurance. Nevertheless, these data confirm the comment made above that design is a major cause of failures. Accordingly, the emphasis is on design in the discussion that follows.

9.2.2 *Inadequate design effort*

The author reviewed a number of failures, and found that, in many cases where a failure occurred (including cases where construction and operation mistakes significantly contributed to the failure), the design effort was not sufficient. In particular, some potential failure scenarios were not considered, and materials' properties were not properly evaluated.

The facts that budget and time are limited are often mentioned as reasons why design efforts are insufficient. This is certainly true in a number of cases, and owners who restrict the allocated budget and time to the point that the design engineer cannot work in good conditions should not expect a first class design. It should be noted that engineers should never take assignments if they lack the budget or time to do a proper design, because they are liable even if they agree to work for free. Lack of experience of the design engineer is also mentioned as a reason for inadequate design. It is clear that design teams that do not have experience in geosynthetic engineering should use some help from experienced designers.

However, it is important to note that there are a number of cases where mistakes were made by experienced design engineers with an adequate budget and enough time for design. Based on the author's experience, important mistakes that characterize insufficient design effort, i.e. the fact that some potential failure scenarios were not considered and the fact that materials' properties were not properly evaluated, often result from lack of communication between the various parties involved, lack of discussion within the design team, and lack of focus on important issues. These aspects are discussed below.

9.2.3 *Reasons for inadequate design effort*

Lack of communication between parties involved. As shown by several examples in this paper (*Berg and Meyers,* Section 4.3.4; *Christopher,* Section 3.5.1; *Giroud and Beech,* Section 4.5.3; *Rowe and Seychuk,* Section 3.6.2), a number of failures were caused by lack of communication between owner, manufacturer, material supplier, design engineer, and contractor. The worst case is when there are two teams of design engineers who do not communicate (*Berg and Meyers,* Section 4.3.4). The detrimental effect of such lack of communication is obvious. A more subtle, but equally dangerous, situation is discussed below, the lack of communication between members of the same design team (Section 4.3.2).

Lack of discussion within the design team. Discussion within the design team is essential because various engineers may have different opinions or may prefer different approaches, due to the complexity of the technical issues sometimes associated with the use of geosynthetics. Discussion within the design team is successful only if every technical issue is thoroughly and *openly* discussed by *several* knowledgeable individuals. It is important to emphasize two words: *openly* and *several*. First the word "openly": the author of this paper has seen a design team that was making mistakes because project engineers were afraid of making comments to the production-driven project manager (Section 4.3.2). Then, the word "several": the author of this paper knows of a major failure that happened because the project manager always avoided exposing his design decisions to criticism by the members of the design team and never encouraged round-table discussions (Section 4.3.2). This type of attitude is dangerous because geosynthetic applications are so diverse and many of them so complex that it is not possible for one person to have the right answer to all technical issues.

If the design team does not have all the expertise required to conduct a fruitful discussion, it is far less expensive to hire an outside expert as a peer reviewer than to have a failure. As pointed out by Berg (1993), a well planned peer review "permits to identify potential design problems in the early stage of the project, in time to take corrective action." Even when the design team has all the required expertise, an independent opinion may be useful. Also, when a design team is facing a difficult issue or decision, the presence of an outside expert requires the team to make a formal presentation which can only help clarify the issue. Finally, in cases where an overbearing project manager discourages discussion (usually unconsciously) between team members, the presence of an outside expert at a meeting, if only for one day, will encourage discussions. In the case of the major failure mentioned above, the author of this paper believes that such a meeting would have opened the much needed discussion that would have avoided the major failure that happened. Indeed, the investigation showed that the project manager had not listened to members of the team who had envisioned the failure mechanism; he would have had to listen if a round-table discussion had taken place in the presence of an outside expert.

Lack of focus on important issues. There are too many design reports where the design engineers present in great detail the aspects of the design they like most, such as some calculations and test results, and do not put any special emphasis on the important decisions made during the design process, in particular the decisions related to the key aspects mentioned in Section 9.2.2: the identification and analysis of potential failure scenarios, and the evaluation of materials' properties. This is regrettable because, if important decisions are emphasized and documented in detail in the design report, they are more likely to have been taken rigorously and they are more likely to be peer-reviewed. For example, if it is understood that the justification for the evaluation of key material properties will be emphasized in the design report and that the process leading to the selection of property values to be used in design calculations will be documented in detail in the design report, it is likely that this selection will be made with great care, possibly with the help of, or the review by, an outside expert. The key point here is that the important design decisions should be formally documented: not only documented in a company peer review log, but documented in the design report.

9.2.4 *Improvement of design quality*

Design quality control. The approach described above can be called design quality control, because it is similar to construction quality control (voluntary, provided by installer), but not to construction quality assurance (mandatory, provided by third party). Design quality control is more formal than the peer review system typically practiced by design firms, i.e. design quality control includes: (i) a formal process for important design decisions, including round-table meetings, typically with outside experts; and (ii) a formal and detailed documentation in the design report (and not only in confidential company logs) of the process leading to important design decisions. Clearly, design quality control does not require much additional effort compared to typical peer review. In fact, design quality control is practiced occasionally by certain design teams, and lends credibility to their designs. For example, the selection of an "equivalent" geosynthetic is done more seriously and carries more weight when the steps leading to the selection are documented in the design report. Design quality control has other benefits for design firms, as discussed below.

Benefits of design quality control. Design quality control is obviously beneficial to the owner because it results in safer designs. Design quality control is also beneficial to the designer because: (i) safer designs minimize the risk of litigation, thereby protecting the design firms; and (ii) the participation of the entire design team in important design decisions (including meetings with outside experts) educates the design engineers and is, therefore, beneficial to future designs. Design quality control can be as beneficial to design firms as construction quality assurance to geomembrane installers. It is appropriate, at this point to learn a lesson from the history of the geosynthetic discipline. In 1983, geomembrane installers were reluctant to accept construction quality assurance. However, they quickly understood they were major beneficiaries of construction quality assurance.

By placing emphasis on important decisions such as failure mechanisms and materials' properties, design quality control encourages the designers to consider site conditions. As a result, design quality control should benefit designers by discouraging the market-driven practice of copying past designs. It can be understood that some owners, due to the highly competitive market, would like to decrease design costs by reusing old designs. However, copying a past design is dangerous and has been responsible for failures. The design of structures incorporating geosynthetics, such as landfills or retaining structures, must be project-specific because sites are different and, therefore, it is dangerous to consider that a structure incorporating geosynthetics can be "imported" to a site without considering the site conditions. Also, copying a design detail without understanding its intent can lead to a failure. Furthermore, past designs should not be copied because they may be obsolete, as: (i) new materials become available; (ii) new design methods become available due to analytical developments and lessons learned from failures; and (iii) designers become increasingly aware of some potential failure scenarios which may not have been considered in the past design that is being copied. Past designs can be used as partial models, but should not be copied.

Design quality control and regulations. Design quality control does not have to be mandated by regulations, but it could be encouraged by regulators. For example, regulators could issue a notice of deficiency for designs that do not document important decisions and the peer review process related to these decisions. Increased safety is more likely to result from regulators who challenge design engineers to work at their full capacity than from regulations that limit the engineer's freedom. For example, regulations that prescribe design parameters such as a maximum slope angle for a landfill slope may be counterproductive as they may give a false sense of safety. Clearly, it would be preferable to have regulators who encourage design quality control rather than regulations that prescribe minimum values for parameters. In the first case, engineers are encouraged to do good designs — while, in the second case, overconservatism and overconfidence are encouraged.

Some regulatory agencies have sponsored the development of design methods (e.g. for geotextile filter selection, for water infiltration into landfills, and for geosynthetic-reinforced soil walls). When these methods are widely used, they provide agencies and peer reviewers with a tool they can use to compare designs objectively, which is beneficial to design quality. However, design engineers should be, and feel, free to use other methods in parallel.

9.3 *Learning lessons from failures associated with geosynthetics*

9.3.1 *The importance of learning lessons*

Failures of structures incorporating geosynthetics are essential for calibrating designs, but they are rare. Therefore, no opportunity should be missed to learn from failures. Unfortunately, many of the lessons that could be learned cannot be published because they have to remain confidential due to the litigious atmosphere that often surrounds forensic analyses. When case histories of failures can be published, it is important that they are properly interpreted and that the right lessons are learned. These points are discussed below.

9.3.2 *Impact of litigious atmosphere on the possibility of learning lessons from failures*

The litigious atmosphere that surrounds forensic analyses can be positive or negative: (i) it is positive because it provides an incentive for opposite viewpoints to be expressed; and (ii) it is negative because it discourages open discussion and fruitful sharing of information. When a failure occurs, opposite teams are formed where lawyers play a major role. Engineers of one team are discouraged from communicating with engineers of the opposite team. As a result of this atmosphere, many interesting case histories are never published, and useful lessons are lost. Certainly, engineers and lawyers should work together, and while lawyers should prevail regarding legal matters, engineers should prevail regarding technical matters. However, it is discomforting to see that the civil engineering profession, which has been a leading profession over the centuries, does not have a leadership role in the case of failures. When a failure occurs, civil engineers should not become soldiers fighting under lawyers' command, but should remain what they ought to be, the leaders of civil engineering. If engineers want to achieve better designs through open discussion of technical issues and peer review, they should adopt a cooperative attitude during forensic analyses. Great lessons would be learned if forensic analyses were not battlefields where nobody listens, but forums where various analyses and opinions are discussed with a view to draw objective conclusions. From this viewpoint, grievances settled through arbitration conducted by a technically competent arbitrator are more satisfactory, and owners should be encouraged to add arbitration clauses to contracts. In fact, in certain countries, an expert is always appointed by the court to conduct a non-binding arbitration. This is a very effective system: it helps settle cases and often avoids lengthy litigation.

9.3.3 *Importance of learning lessons established on a rational basis*

When case histories of failures are available, it is important that they be published. These cases histories often make good reading, as it is entertaining to read about mistakes made by others. However, learning lessons from failures means more than reading anecdotes. The right lessons can be learned only if the failures are rationally analyzed. As indicated below, general lessons can be derived from the experience gained by the author of this paper in analyzing failures of geotechnical structures since 1964.

The most important lesson learned by the author in his career is the following: in all of the forensic analyses in which the author has been involved, it was possible to rationally explain what had happened. From this fact, lessons can be drawn: two lessons for experts performing forensic analyses, and two lessons for design engineers.

Two lessons for experts performing forensic analyses. The first lesson for experts performing forensic analyses is that it is easier to explain failures than to do a good design. Consequently, experts performing forensic analyses should not be arrogant and should realize they have a responsibility to share what they have learned.

The second lesson for experts is that they have a duty to rationally explain failures. Experts should refrain from using meaningless concepts and phrases such as "engineering judgment" and "common sense". These phrases essentially serve as camouflage for failure to perform a rational analysis or are used as a screen to hide the laziness inspired by the difficulty inherent to rational analyses. The necessity to rationally explain failures is particularly compelling when a claim is settled by arbitration, as arbitrators must found their decisions on a sound basis. Clearly, rational explanations of failures prevent arbitrators from making arbitrary decisions.

Two lessons for design engineers. The lessons for designers can be introduced as two "principles". For those who have heard these lessons repeated many times, they have become "the two Giroud's principles".

> *The first Giroud's principle is that, if a design engineer predicts a failure using a rational method, the failure is likely to occur and, therefore, the design engineer should believe the prediction.*

This is a lesson that the author of this paper learned the hard way, as described in the case history presented in Section 2.5. In 1980, the author, who was designing a project, predicted a failure using a rational analysis, but other parties involved in the project thought that the prediction by the author was just an academic exercise that had nothing to do with reality. The author insisted his analysis was rational, but he had to acknowledge that there were no facts to prove that the failure prediction derived from the analysis was correct since the predicted mode of failure had never been observed before. As a result, the author could not convince the other members of the team (in part because he respected experience and, therefore, was not fully convinced himself by the prediction he had made). Construction was completed without the precautions recommended by the author and the failure occurred as predicted.

The lesson is clear, if a failure is predicted using a rational method, the prediction should be believed; and the failure is likely to occur, even if this mode of failure has never occurred before. This does not necessarily mean that the failure “will” occur (because many factors can increase a factor of safety by a decimal point), but it certainly means that *most experts will be able to explain the failure if it occurs*. This leads to second Giroud’s principle.

> *The second Giroud’s principle is that a design engineer should never take a risk such that, if a failure occurs, it can be explained by an expert using rational methods.*

Indeed, that would be at least very embarrassing and could cause the engineer to incur liability.

The author found that these two principles presented above as Giroud’s principles are very useful in helping design engineers resist excessive pressures from overdemanding clients or from overzealous project managers, two situations that may lead some engineers to make mistakes that could lead to failures for which they would be held liable.

9.3.4 *Importance of learning lessons from the field*

As pointed out in Section 9.2.1, a number of the mistakes made during construction are due to inadequate design. Therefore, it is important that design engineers visit construction sites to understand working conditions in the field. Also, design engineers should not miss any opportunity to see failures in the field firsthand. While learning from failures by reading published case histories is irreplaceable because of the extent of knowledge that can thus be acquired in a relatively short period of time, it is important for design engineers to go to the field, especially to see failures — just as reading stories about exotic countries does not provide a full experience if the reader of these stories does not visit at least some of the countries. A design engineer who often goes to the field is better prepared for design than a design engineer otherwise equally qualified who never goes to the field. A design engineer who has seen a failure is better prepared for design than a design engineer otherwise equally qualified who has never seen a failure. A design engineer who has seen a failure and has written a report about the failure is better prepared for design than a design engineer otherwise equally qualified who has seen a failure, but has not written a report about it.

The author of this paper had the opportunity, early in his career (in the mid 1960s), to learn how important it is to go to the field thanks to the sense of humor of a seasoned consulting engineer for whom he was doing some design work. The seasoned consulting engineer told him one day: “You seem to like what you do and you probably want to make a career in geotechnical engineering. If this is the case, believe me, never, never go to the field!” As the author, then a young engineer, was surprised, to say the least, having learned that geotechnical engineering is an “outdoor sport” and having already been in the field a number of times, the seasoned consulting engineer added “Yes, never go to the field if you want to stay in this profession, because you will be disgusted when you see what ‘they’ do with your neat designs!”

Since that time, the author of this paper has been countless times to the field. Every time the author has to go to the field to see a failure, he reads what is available on the project and, before going to the site, develops a scenario, often wrong, always useful. Design engineers going to the field to see a failure should have in mind a number of preconceived ideas (possibly conflicting) about what happened. It may be a waste of time to go to the field with an empty mind. But, of course, engineers must be prepared to change their mind based on the observations made in the field, and, when coming back to the office, must also be prepared to change their mind based on the analyses made in the office and/or in the laboratory. Finally, it is important to stress that engineers should not go the field only to see failures. As pointed out by Thiel (1999) “Engineers need to learn how things are built in the field. They need to learn how the equipment moves dirt, compacts, the *art* of moisture conditioning soils, the *art* of coordinating mass excavations and fills, the limitations of equipment on slopes, the limitations of welding pipes and geomembranes, how roll goods are deployed, etc. Only by knowing how things are built will they be able to create really effective designs.” In fact, design engineers visiting construction sites generally enjoy the visit and are amazed by the magnitude of the efforts and the variety of materials.

9.3.5 *Conclusion on learning lessons*

An essential lesson is that many failures are due to improper design and, therefore, design engineers must make efforts to improve design quality. This includes learning from failures. The lessons learned from failures should not only be the technical lessons summarized hereafter in Sections 9.4 and 9.5, but also the more general lessons presented above in Section 9.3, i.e. not only technical lessons to increase knowledge but also professional lessons to better use knowledge.

Examples presented in this paper show that many failures of structures incorporating geosynthetics are due to mistakes made during construction. Many of these examples show that many of the mistakes made during construction are due to failure at the design stage to foresee problems that could occur at the site. Therefore, the comments presented in Section 9.4 should benefit design engineers as well as contractors.

9.4 *Summary of lessons learned regarding construction*

The "lessons learned" presented in Section 9.4 are derived from the examples and case histories presented in Sections 2 to 6, and occasionally a few additional comments based on the author's field experience.

9.4.1 *Geosynthetic selection*

The following comments can be made regarding geosynthetic selection at the construction stage:

- If the contractor is allowed to substitute an "equivalent" geosynthetic for the specified geosynthetic, the contractor should do so only with great precautions, because many geosynthetics that appear to be similar are not. The design engineer or a qualified consulting engineer should be involved in evaluating the equivalency. Contractors should learn that simply comparing tables of geosynthetic properties is not sufficient to establish equivalency between two geosynthetics. Furthermore, contractors should not believe that two geosynthetics are equivalent only on the basis of claims by geosynthetic suppliers.
- If a contractor wants to add a geosynthetic that is not in the construction drawings, the contractor should do so only if the proposed geosynthetic addition is reviewed by the design engineer or a qualified consulting engineer.
- If possible, the contractor should prefer geosynthetics available in wide rolls to minimize the number of seams or overlaps.

9.4.2 *Geosynthetic storage and placement*

The following comments can be made regarding geosynthetic storage and placement:

- Geosynthetics should be stored in a clean place. For example, clogging of geonets due to dust or mud has occurred during storage.
- Geosynthetics should be placed on an adequately prepared soil surface. In particular, the soil surface should be free of elements likely to damage the geosynthetic. Also, the soil surface should not have abrupt changes in grade likely to cause stress concentration in the geosynthetic.
- Needle-punched nonwoven geotextiles placed in contact with geomembranes should be free from needles.
- If a geomembrane liner is placed on a horizontal pond floor made of a rather low-permeability soil and if the geomembrane is not covered with a layer of soil or other material, there is a high risk that the geomembrane will be uplifted by air entrapped on high spots of the pond floor during the first filling of the pond.
- To minimize the risk of stress concentration, the number of seams should be minimized. This can be achieved by using geosynthetics available in wide rolls (as mentioned in Section 9.4.1) and by minimizing the number of samples taken for destructive testing. Also, samples for destructive testing should not be taken at locations where high tensile stresses are likely to develop, such as the top of slopes and the vicinity of rigid structures.
- Geomembrane liners, and sometimes geotextiles, should possess the tensile strength required to resist wind uplift and should be secured using sand bags, anchor trenches, anchor benches, or

other appropriate means. If a geomembrane is designed to be uplifted by wind, it should not be attached to a fixed structure, such a gas vent, in an area where it should be free to be uplifted.

- Contractors should be aware that there are some applications where it is essential that the geosynthetic be in intimate contact with the adjacent material (see Section 9.4.3). In these applications, the surface of the material on, or against, which the geosynthetic is to be placed should not have irregularities that may prevent intimate contact between the geosynthetic and the material.
- Contractors should be aware of the influence of weather during construction on the quality of the installed geosynthetic (see Section 9.4.5).
- Workers and visitors should refrain from any activities that could damage installed geosynthetics.

9.4.3 *Intimate contact between geosynthetic and adjacent materials*

Intimate contact between the geosynthetic and the adjacent material is essential to the performance of the geosynthetic in some applications. Some examples follow:

- A geotextile filter must be in intimate contact with the adjacent soil. In the case of drainage trenches, this can be achieved by using a flexible geotextile and filling the trench with relatively small stones. In the case of a relatively rigid edge drain, sand should be poured in the space between the edge drain filter and the walls of the trench. In the case of bank protection, intimate contact can be achieved by using a flexible geotextile with a layer of relatively small stones between the geotextile and the rocks or blocks.
- A geomembrane placed on top of a layer of compacted clay to form a composite liner must be in intimate contact with the clay. It is, therefore, important to place the geomembrane with wrinkles as small as possible (because small wrinkles tend to flatten under the weight of overlying layers).
- A paving geotextile, used on an existing pavement prior to placing an asphalt overlay, must be in intimate contact with the existing pavement. Furthermore, there should be a sufficient amount of asphalt tack coat to impregnate the geotextile and bind it to the existing pavement and the asphalt overlay. The intimate contact between the geotextile and the existing pavement can be achieved by rolling the geotextile (after the tack coat application) with a pneumatic roller. A steel roller is too rigid to ensure intimate contact.
- A geomembrane liner used in a concrete tank should be placed in intimate contact with the corners of the tank to ensure that it will not burst during filling.

9.4.4 *Geosynthetic connections*

The following comments can be made regarding geosynthetic connections:

- Geosynthetic overlaps should be sufficiently wide that they will not separate even in case of settlement of the underlying soil. If overlap separation cannot be avoided, the overlaps should be replaced by seams.
- Overheating of a geomembrane during seaming should be avoided.
- Connections of geosynthetics with structures or elements of structures should be such that they will not be damaged by differential settlements. This applies, in particular, to connections of geomembrane liners to appurtenances and connections of reinforcing geosynthetics to facing elements of reinforced soil structures. Geotechnical engineers must review connections very carefully because they are sometimes designed by individuals who have an insufficient knowledge of geotechnical engineering and who, therefore, do not realize that even a small amount of differential settlement may cause the connection to fail.
- In case of high hydraulic gradient, geotextile filters and geomembrane liners should be seamed, not overlapped. Also, in case of high hydraulic gradient, the connection between a geomembrane liner and a clay liner or a clay-filled anchor trench should be done with great care. It is preferable, if possible, to avoid this dangerous situation and to move the connection to a location where the hydraulic gradient is small, such as at the top of a slope.

- The extremity of a geotextile likely to convey undesirable water should be sealed. This is the case, for example, at the toe of a dam or the anchor trench of a landfill. Also, needle-punched nonwoven geotextiles and woven geogrids used in pavements should be impregnated with asphalt to prevent the geotextiles or the geogrids from conveying water into the pavement.

9.4.5 *Influence of weather and other external conditions on geosynthetics*

The following comments can be made regarding the influence of weather and other external conditions on geosynthetics:

- Geotextiles should not be exposed to sunlight for more than a few weeks, unless planned otherwise at the design stage. Exposure to sunlight may result in severe degradation of many geotextiles.
- A composite liner that consists of a geomembrane on compacted clay should not remain exposed on a slope, because desiccation and cracking of the clay may occur.
- Geomembrane seaming should not take place under adverse weather conditions because it has been shown that the number of geomembrane seam defects increases under those conditions.
- A geomembrane liner should not be placed on a low-permeability soil having a water content higher than specified (in particular after a rainfall) because this may result in a significant decrease in the interface shear strength, which could cause a catastrophic slide.
- Thermal expansion of geomembranes causes wrinkles, which are undesirable for several reasons: (i) they can be damaged by placement of soils on top of the geomembrane; (ii) they prevent intimate contact between a geomembrane and the underlying clay in a composite liner; and (iii) in landfills, they impede the flow of leachate in leachate collection layers. When it is important to minimize wrinkles, it may be necessary to install geomembranes at night and to cover them with soil before the temperature increases. Alternatively, geomembranes that are less likely than others to exhibit wrinkles can be selected, i.e.: (i) geomembranes with a white upper surface and/or a textured lower surface; (ii) geomembranes with a low bending modulus (i.e. flexible geomembranes); (iii) geomembranes with a small coefficient of thermal expansion, such as reinforced geomembranes; and/or (iv) heavy geomembranes, such as bituminous geomembranes.
- Thermal contraction causes tensions in geomembranes exposed to low temperatures. When it is important to minimize tensions, it is desirable to place geomembrane liners with some slack, which is in contradiction with the no-wrinkle requirement mentioned above. Alternatively, the geomembrane may be installed flat at a relatively low temperature (provided that the low temperature is compatible with seaming quality).
- As indicated in Section 9.4.2, geotextiles and geomembranes can be uplifted by wind and they should be secured.
- Contractors should be made aware that geofoam blocks may catch fire if the geofoam is not of the flame-retardant type. Therefore, precautions should be taken when performing activities such as welding. Also, in case of thunderstorm, lightning may set fire to geofoam and other geosynthetics.
- Geonets should not be exposed to dust during construction, as they may get clogged.
- If precipitation water (i.e. rain, hail, snow) accumulates in a geonet used as a leakage collection and detection layer, this water should be allowed to drain or evaporate prior to placing overlying materials. If not, false leakage detection will occur at the beginning of landfill operation.

9.4.6 *Placement of materials in contact with geosynthetics*

The following comments can be made regarding the placement of materials in contact with geosynthetics:

- Geomembranes are more damaged by placement of the overlying materials than by any other construction activity. Therefore, it is important that this construction activity be conducted with maximum care and construction quality assurance. Furthermore, the integrity of the geomembrane could be checked after placement of the soil layer by using the electric leak location method or conducting a ponding test.

- To minimize the risk of geomembrane damage by overlying materials, it is advisable to select overlying materials that are least likely to damage the geomembrane: (i) when granular soil is used, the particles should be as small as possible; (ii) if necessary, a thick needle-punched geotextile acting as a cushion should be used between the geomembrane and the granular soil; and (iii) when reinforced concrete is used to protect a geomembrane (as on the upstream face of dams) fiber-reinforced concrete should be preferred to the traditional concrete reinforced with steel bars. Also, lightweight equipment should be used as discussed below.
- Clear specifications and instructions should be given to the contractor to minimize damage to geosynthetics used for soil reinforcement.
- Fresh concrete should not be placed in contact with a polyester geotextile, because of potential degradation of the polyester by hydrolysis.
- Contractors should be made aware that placing a geotextile in contact with a geonet can significantly reduce geonet transmissivity and should be done in strict accordance with specifications.
- Placement of soil layers overlying geosynthetics may cause soil settlement or bearing capacity failure if the soil supporting the geosynthetics has high compressibility and/or low strength. The resulting deformation of the soil surface may cause geosynthetics or seams to rupture, or may cause geosynthetic overlaps to separate. Lightweight equipment should be used to place the soil overlying the geosynthetics.
- A bulldozer that pushes a soil layer against a geotextile overlap may cause the overlap to separate. Therefore, the direction of soil placement with respect to geotextile overlaps should be specified.
- A bulldozer that pushes a soil layer downward on a liner system on a slope may cause veneer instability. Therefore, the direction of soil placement on a slope should be specified.
- Construction equipment that maneuvers and brakes on a soil layer overlying a liner system on a slope may cause veneer instability.
- Vibratory rollers should be used with caution on a soil layer overlying a liner system on a slope because the vibration may cause veneer instability.
- When a high strength geotextile is used to reinforce an embankment constructed on soft soil, care should be taken during placement of the soil on the geotextile to not create wrinkles in the geotextile. These wrinkles would prevent the geotextile from mobilizing its strength, which could cause an embankment failure.
- When ore is placed on a leach pad with a slope (e.g. 5%), the ore should be placed in the up-slope direction, because if there is any departure from the designed slope (e.g. 6% slope) the factor of safety increases in case of up-slope placement and decreases in case of down-slope placement.

9.4.7 *Required soil deformation*

The following comments can be made regarding the required deformation of a soil associated with a reinforcing geosynthetic:

- Contractors should be made aware of the need for reinforcing geosynthetics to deform to mobilize their strength when they perform the reinforcement function. For example, contractors should learn that the facing of geosynthetic-reinforced soil walls moves laterally during and after construction.
- Contractors should be made aware that the facings (particularly the “wrap-around” facings) of vertical, or quasi vertical, geosynthetic-reinforced soil walls deform and, as a result, may come in contact with adjacent structures if not enough space was left between the facings and the adjacent structures.
- Contractors should be made aware that a geosynthetic-reinforced unpaved road must exhibit ruts for the geosynthetic tension to be mobilized. This requirement may cause grading problems if a temporary unpaved road is to be eventually incorporated in a permanent road.
- Contractors should be made aware that it is important to place reinforcing geosynthetics under tension, if possible, or, at least, without slack to minimize the required geosynthetic deformation to mobilize its tension.

9.4.8 *Impact of geotechnical problems on structures incorporating geosynthetics*

The following comments can be made regarding the impact of geotechnical problems on structures incorporating geosynthetics:

- The soil of reinforced soil structures must be properly compacted. In particular, if cohesive soil is used, this soil should be compacted at the specified water content and, in particular, should not be compacted too dry.
- Temporary excavations done to construct structures incorporating geosynthetics should be stable.
- No excavation should be done near the toe of a structures incorporating geosynthetics, unless approved by the design engineer. Also, the toe of structures incorporating geosynthetics must be protected against erosion.
- Surface drainage must always be effective because excess water is a common cause of failure of structures incorporating geosynthetics as well as geotechnical structures.
- When geosynthetics are supported by a material that is highly compressible or has a low bearing capacity, only lightweight construction equipment should be used.

9.5 *Summary of lessons learned regarding failures*

The "lessons learned" presented in Section 9.5 are derived from the examples and case histories presented in Section 2 ato 6, and occasionally a few additional comments based on the author's experience.

9.5.1 *Prediction of failures*

The main lessons regarding the prediction of failures can be summarized as follows:

- Most failures can be predicted using rational analyses based on principles of physics and mechanics, fundamental knowledge of geotechnical engineering, understanding of functions of geosynthetics, and a good knowledge of geosynthetic properties.
- The design engineer who predicts a failure using rational analyses should believe the results of the analyses and convince other parties (i.e. the owner, contractor, etc.) that the failure is likely to happen.
- The design engineer who makes a prediction based on a rational analysis must not be impressed by experience from others, because there are only a few people who really have experience in the field of geosynthetics. The most dangerous of those who have experience are those who rely only on common sense instead of using rational analyses to draw lessons from their experience.
- Most failures are easy to explain, but some are difficult to predict. Therefore, engineers must learn from case histories describing failures.

9.5.2 *Prevention of failures*

The main lessons regarding the prevention of failures can be summarized as follows:

- Geosynthetics should not be expected to make miracles in spite of claims by overzealous salespersons. Geosynthetics must be treated like other construction materials, and it must be recognized that, in come cases, geosynthetics may have a detrimental effect.
- Properties of geosynthetics must be measured and not estimated, because geosynthetics that seem identical often have different properties. Tests used to measure geosynthetic properties must be carefully selected because tests that are not representative of the field situation give results that are incorrect.
- At the design stage, design engineers must consider all potential mechanisms of failure of structures incorporating geosynthetics. To that end, they must keep themselves abreast of observations made by others on the performance of structures incorporating geosynthetics, and they must learn about new design methods. It should be noted that the presence of a geosynthetic makes possible some new mechanisms of failure, without eliminating most of the traditional mechanisms of failure.
- To keep themselves abreast of modes of failures observed by others, design engineers must, of course, listen to presentations and read papers on this subject (Giroud 1977a, 1977b, 1983a,

1983b, 1984a, 1984e, 1984f, 1993, 1999). They must also learn about the design and construction of structures incorporating geosynthetics that perform satisfactorily (Raymond and Giroud 1993).
- Design engineers must write specifications that are complete and precise and that address problems that might occur during construction.
- The design engineer should be present or represented at the site during important phases of construction.
- It is necessary to educate designers and contractors on the potentials and limitations of geosynthetics. Regarding designers, this means that, among other things, they should learn from polymer specialists, learn from failures, learn regarding installation constraints for geosynthetics, and educate contractors.

9.5.3 *Action in case of failure*

The main lessons regarding action to be taken in case of failure of structures incorporating geosynthetics can be summarized as follows:
- A complete investigation must be undertaken. This investigation should address all aspects of design and construction and should not be limited to aspects related to geosynthetics. The investigation should be conducted in a way that makes it possible to adequately review all possible failure mechanisms.
- Parties that conduct independent investigations of a failure should be required to communicate at some stages of their investigations. In particular, observations should be compared and an agreement should be reached on tests to be conducted.
- If the investigation includes tests, the tests must be representative of the field conditions. Some tests may give the illusion of being representative. The fact that a test is performed in the field does not guarantee that it will be representative. Some laboratory tests are more representative of field conditions than some field tests. Clearly, on this point, common sense may be wrong.
- One should not automatically take the position that geosynthetics are responsible for failures and can be used as scapegoats. Taking such a position may lead to selecting inappropriate remedial measures.
- If it appears that the design of a structure is flawed, one may take advantage of the repair work to improve the design, instead of systematically reconstructing the structure as it was before.
- On the pretext that the failure was associated with a geosynthetic, one should not systematically eliminate geosynthetics when designing remedial measures. In reality, failures of projects built with geosynthetics are generally repaired successfully using geosynthetics.

9.5.4 *Responsibility in case of failure*

The main lessons regarding responsibility in case of failure can be summarized as follows:
- In case of a failure of a structure incorporating geosynthetics, one should not automatically assume that the supplier and/or installer of the geosynthetics are responsible. Experience shows that observed failures are often due to a number of other causes.
- The designer of a project must take all possible precautions at the design stage to avoid the situation where, if a failure were to occur, any expert would be able to explain it using methods that were available at the time when the project was designed.
- Those who dare writing papers on lessons from observation of failures must avoid, when they design projects, to be in a situation where they could eventually be accused of ignoring what they teach. Alternatively, they should abstain from designing projects.

10 SUCCESSES OF GEOSYNTHETICS

10.1 *Overview*

In Sections 1 to 9, failures of structures incorporating geosynthetics have been discussed extensively. It is important to put these failures in perspective. As indicated in Section 1.12, 15 billion

m^2 of geosynthetics have been used in several million projects with only 0.1% significant failures. Clearly, this is a remarkable success, which can be summarized as follows:

- *Applications*. Today, geosynthetics are part of the geotechnical landscape. They have pervaded all branches of geotechnical engineering, as shown in a compilation of case histories (Raymond and Giroud 1993). Geosynthetics have been used in a wide variety of applications, from very small to very large projects; this flexibility has contributed to their success.
- *Design*. For all of the applications of geosynthetics, there are design methods, most of them satisfactory. This considerable body of knowledge was developed in a remarkably short period of time. In the context of this paper, it is interesting to note that some of the most successful design methods were developed in response to challenges presented by the analysis of failures.
- *Construction*. Construction of structures incorporating geosynthetics has become very reliable, thanks in part to the use of construction quality assurance. Remarkable construction techniques have been developed, for example for installation of geomembranes on the vertical face of concrete dams, or for underwater placement of geosynthetics.
- *Performance*. As indicated above, the number of failures has been relatively small. Therefore, past performance of structures incorporating geosynthetics can be considered very satisfactory. Future performance can be expected to be excellent due to the considerable knowledge accumulated in the past decade on durability of polymeric materials and on the accurate prediction of important aspects of their long-term behavior, such as creep.

What are the reasons for the success of geosynthetics? First, and most obviously, geotextiles have been successful because manufacturers have aggressively developed and marketed them, and because contractors, designers and owners have elected to use them. The reasons for early usage of geosynthetics are discussed first (Section 10.2). Then, fundamental reasons that help understand why geosynthetics are here to stay are presented (Section 10.3).

10.2 *Reasons for the early successes of geosynthetics*

10.2.1 *Influence of contractors*

Early successes of geosynthetics may be credited to a large extent to contractors. They adopted geotextiles first, then geosynthetics, because they found immediate benefits in using them. Thanks to geosynthetics, construction is easier, and both earthwork and transportation time and costs are reduced, as discussed below:

- In some projects, the use of geosynthetics allows construction which would otherwise be difficult, if not impossible, such as road construction over a very soft soil. Also, road construction with geosynthetics is less weather-dependent (trucks are less likely to get bogged down when a geosynthetic is used). In applications such as filtration, construction time is reduced because a geotextile filter is easier to install than a granular filter.
- When using geosynthetics, the amount of earthwork is often reduced, e.g. geosynthetic drains and geotextile filters are less bulky than their granular counterparts and geosynthetic reinforcement allows the construction of smaller structures. Alternatively, the cost of earthwork is reduced because geosynthetic reinforcement permits the use of soils of a lesser quality than the soils used in conventional structures or in steel-reinforced soil structures.
- Transportation costs can be significantly reduced by replacing hundreds of tons of granular material by a few rolls of geosynthetic. Transportation costs can be further reduced if the incorporation of geosynthetics in a structure results in the use of local soils. Reduced transportation is also beneficial from an environmental standpoint since the noise and dust associated with transportation of construction materials are reduced.

The above comments apply primarily to road construction, an area where the influence of contractors on the development of the use of geosynthetics was significant. The use of geotextiles in road construction was the first large market for geosynthetics (while the first applications of geosynthetics were geotextiles in coastal protection, where the need for geotextiles is clear, but the market is smaller).

10.2.2 *Influence of designers*

Designers have not been as quick as contractors to adopt geosynthetics because they do not have the same opportunity to enjoy immediate benefits. Furthermore, they often do not even have an incentive to recommend less expensive solutions. However, with the emphasis now placed on “value engineering”, there is a greater incentive for designers to prepare less expensive designs. Contractors, on the other hand, always had a high incentive to decrease the cost of a project, and they are also in the best position to evaluate savings resulting from easier and more efficient construction procedures. This is especially true in road construction where access to the construction site is of prime importance.

Some of the reasons for the early uses of geosynthetics by designers are listed below:

- Geosynthetics present an easy solution to problems with which designers have long been struggling, such as filters for coastal protection. Sand filters wash away and are difficult to construct under water, while geotextile filters are not sensitive to erosion and are easy to place, even under water. Therefore, it is not surprising that the first uses of geosynthetics were geotextiles in coastal protection.
- Geosynthetics open new possibilities for innovative design and, in some of the first uses of geosynthetics, the motivations of the designer were nothing but sheer curiosity and desire to try something different. This was more possible in countries where there was no prevalent litigious atmosphere, unlike some countries where designers fear litigation.
- Geosynthetics may increase the reliability of a structure in which they are incorporated because: (i) the quality control of their placement is easy; (ii) their installation is not significantly affected by weather; (iii) their properties are more uniform and reliable than soil properties; and (iv) they mitigate some soil defects by bridging weak spots, separating layers which would tend to mix, etc. As a result, the designer knows that the structure is built as designed and will likely perform as predicted.

The above reasons that motivated the designers are complemented by fundamental reasons, discussed in Section 10.3, which affect designs.

10.2.3 *Influence of owners and agencies*

To a large extent, the success of geosynthetics is due to owners — often large agencies — who dared to use them in the early days. Motivations of owners are a combination of contractors’ and designers’ motivations. Like contractors, owners are interested in low cost, and, like designers, they are interested in reliability and, sometimes, in experimentation. Some of the most spectacular geosynthetic installations can be credited to daring and visionary owners playing the same role as the Babylonian State/Church three thousand years ago when the ziggurats — the first reinforced-soil structures — were constructed. In many countries, large agencies and private companies have set the example in the fields of roads and highways, dams and land reclamation, waterways and coastal works, railways, electric power, protection of the environment and waste management, mining, etc.

Also, the regulations prepared by some agencies have played a key role in the development of some of the uses of geosynthetics. The most notorious example is the use of geomembranes in waste disposal landfills.

10.3 *Fundamental reasons for the success of geosynthetics*

In addition to the technico-economical reasons discussed above, there are other reasons for geosynthetics to be used in geotechnical engineering. These are fundamental reasons.

10.3.1 *The need for two-dimensional materials*

The first fundamental reason for the success of geosynthetics stems from the fact that geotechnical engineering structures are three-dimensional and are built with granular materials, which consist of discrete particles. Clearly, there is a gap between the three-dimensional geometry of the massive geotechnical structures and the relatively small particles used to construct them. It may, therefore, be concluded that geotechnical structures should benefit from the use of two-dimensional materials in conjunction with granular materials. In summary, there is a need for two-dimensional materials in the three-dimensional geotechnical engineering structures.

The properties of granular materials are obviously complemented by those of two-dimensional materials such as geosynthetics. For example, the integrity of layers of granular soils can be disrupted by erosion, settlements, and earthquakes, while a geosynthetic layer tends to remain continuous. Clearly, geosynthetics provide continuity to geotechnical structures, which enhances their safety.

One step beyond continuity is the combination of continuity and tensile strength, which allows geosynthetics to confine the soil. As a result, when geosynthetics are used, some structures can be stable and perform satisfactorily while they are theoretically at the verge of failure. For example, this is the case of geosynthetic-reinforced unpaved roads where, under repeated loads, the soil can work safely at its plasticity limit. This is possible only because a two-dimensional flexible material with tensile strength, the geosynthetic, provides confinement to the soft subgrade soil. It is known that, without confinement, a soil collapses when the load reaches the plasticity limit.

Finally, from a more practical — yet still fundamental — viewpoint, geotechnical structures are often large masses including layers of materials, and thin two-dimensional materials are obviously useful, either as an interface between layers having different characteristics, or as a liner or protection at the surface of the mass.

10.3.2 *The availability of two-dimensional materials*

The requirements for two-dimensional materials to be used in geotechnical structures are governed by the flexibility of geotechnical structures. Geotechnical structures are flexible and subjected to differential movements. Therefore, materials used in geotechnical structures should be flexible. This is true, in particular, for the two-dimensional materials used in geotechnical structures. By definition, “membranes” are two-dimensional and flexible. Therefore, the two-dimensional materials to be used in geotechnical engineering should belong to the category of “membrane-like materials”.

There is a lack of appropriate membrane-like materials in nature, and geosynthetics, since they are two-dimensional and flexible, are the best materials to fulfill the needs indicated above:

- There are very few natural membrane-like materials. Animal hides have been used in earth construction in antiquity and in the Middle Ages, but they are small and usually biodegradable.
- Fascines made of willows, coarse mats made of palm fronds, jute fabrics, etc., have been used in soil structures since antiquity. These materials can be made as large as needed, but they are usually biodegradable, and they are expensive because their fabrication is labor intensive.
- Geosynthetics are flexible two-dimensional materials, they can be made as large as needed, and they are not biodegradable. Therefore they fulfill all requirements to satisfy the need for membrane-like materials discussed above.

Clearly, the second fundamental reason for the success of geosynthetics is that the geosynthetics are the only materials that meet the fundamental need for flexible two-dimensional materials in geotechnical engineering.

10.3.3 *The structure of two-dimensional materials*

As discussed above, an efficient way to build a tri-dimensional structure is to incorporate two-dimensional materials in that structure. Similarly, an efficient way to make two-dimensional materials is to combine one-dimensional materials (fibers, or drawn ribs), because making fibers (or drawn ribs) is one of the most efficient ways to use a given amount of matter since, as a result of molecular orientation, the strength of a fiber (or a drawn rib) is much higher than the strength of the original polymer. In summary, building a three-dimensional mass using two-dimensional materials made from one-dimensional elements is a very efficient way to use matter, especially if the one-dimensional elements have high molecular orientation. This explains the success, in soil reinforcement, of geotextiles and other molecularly oriented materials such as geogrids.

The above discussion on the efficient use of matter in geosynthetics, using soil reinforcement as a example, is corroborated by the following comments on the performance of a nonwoven geotextile used for filtration. Calculations show that a nonwoven geotextile and a sand having the same opening size (i.e. distance between fibers or particles that govern the filtration capability) have approximately the same permeability. The same calculations also show that the density of the geotextile would be about one-tenth of that of the sand because the geotextile has a much higher porosity that the sand, and polymer density is much lower than mineral particle density. As a result, a geotextile has the same filtration characteristics as sand, but with ten times less matter. In addition, the thickness of a geotextile filter is usually 100 to 1000 times smaller than the thickness of a sand filter, which is possible because of the continuity resulting from the structure of the geotextile. As a result, the weight of a geotextile filter is typically 1000 to 10 000 times smaller than the weight of a sand filter having the same filtration characteristics.

10.4 *Conclusion on the success of geosynthetics*

Clearly, the success of geosynthetics is explained by three fundamental reasons: (i) there is a need for two-dimensional materials in geotechnical engineering; (ii) geosynthetics are the only available materials that meet the requirements for two-dimensional materials in geotechnical engineering; and (iii) many geosynthetics are two-dimensional materials made with one-dimensional elements, which is a very efficient use of matter.

In conclusion, when used as reinforcement, drainage or liners, geosynthetics are, respectively, the muscles, the veins and the skin of the Earth. Never before have construction materials displayed such versatility and performed such fundamental functions. Geosynthetics are therefore here to stay.

11 CLOSURE

Geosynthetics engineering is a relatively new discipline; however, it has all the attributes of a full-fledged discipline because it has failures. A discipline needs failures to progress, because failures are an excellent way to calibrate designs, to challenge engineers to learn lessons, and to motivate them for design and construction quality. Fear of failures encourages engineers to work better.

Some people do not want to discuss failures associated with geosynthetics because failures have a negative impact on the credibility of the geosynthetic discipline. Indeed it is true that discussing failures may have a short-term negative impact, but openly discussing failures is a long-term investment because it is an excellent way to increase designers' knowledge and minimize the risk of failures in the future. The author of this paper used the opening speech of the International Conference on Geomembranes in 1984 (Giroud 1984b) to denounce the poor quality of installed geomembrane liners with maximum visibility. He was criticized for that and his slogan "all liners leak" was repeated thousands of times, not always in a constructive manner. However, this denouncement contributed to the development of liner construct quality assurance, which is now widely recognized as having been the main factor in establishing the respectability enjoyed today by the liner industry and the geomembrane branch of the geosynthetic discipline.

To those who believe that failures should not be openly discussed, it should be pointed out that geosynthetics are not always — in fact not often — the cause of the observed failures of structures incorporating geosynthetics, and they should not be used as scapegoats. Most of the failures discussed in the examples and case histories presented in this paper were not caused by a geosynthetic; they are only failures of structures incorporating geosynthetics. Failures of structures incorporating geosynthetics do not occur because geosynthetics are not good, but because geosynthetics are used extensively. As indicated in Section 1.12, the percentage of significant failures of structures incorporating geosynthetics is less than 0.1%, which is small. It may also be noted that the review of failures associated with geosynthetics presented in this paper shows the success of geosynthetics in the following ways: first, geosynthetics are used in virtually all branches of geotechnical engineering; and, second, the failures of structures incorporating geosynthetics are usually repaired successfully using geosynthetics. It is possible that structures incorporating geosynthetics are safer than traditional geotechnical structures, i.e. structures that do not incorporate geosynthetics, in part because of the reliability of geosynthetics (which are manufactured with quality control) compared to soils. Also, it is clear that geosynthetic reinforced-soil structures are safer than conventional structures as discussed in Section 10.

A discipline is mature when it can openly discuss its failures. The fact that failures of structures incorporating geosynthetics are so openly discussed today is a sign that the geosynthetic discipline is mature. The geosynthetic discipline is mature today, not only because it has developed an impressive and consistent body of rational knowledge in a rather short period of time, but also because it has early in its history started discussing its failures. At this point, the beneficial example set by the geotechnical engineering discipline must be acknowledged. Lessons learned from failures of foundations, slopes, and embankment dams, are famous, and the *lessons learned from failures associated with geosynthetics*, which are the backbone of the paper, belong to the same engineering tradition.

Geosynthetics have been successful in pervading geotechnical engineering. As a result, geosynthetics have been involved in a wide range of geotechnical structures, which has created a wide variety of opportunities for failures. The wide variety of failures associated with a wide range of geotechnical structures provides many opportunities to learn not only about geosynthetics, but also about geotechnical engineering. Therefore, it is hoped that the *lessons learned from failures associated with geosynthetics* will be considered to be an important addition to the thesaurus of geotechnical failures, and will contribute to a deeper understanding of geotechnical engineering.

It is always entertaining to learn about, and from, failures, especially if the failures result from mistakes made by others. However entertaining it may be, learning from failures is not easy. First, it requires the availability of a number of well documented case histories, which is not easy considering the confidentiality of so many interesting cases, and knowing that those who are busy analyzing important cases do not have much time to write. Furthermore, learning from failures requires a strict intellectual discipline. Forensic analyses should be based on rational deductions conducted with Cartesian rigor. It is clear from many examples presented in this paper that common sense should not be used in forensic analyses. It has been shown in this paper that common sense is a random process that can have credibility only with those who prefer a veneer of satisfaction to the depth of understanding, and who prefer the comfort of illusion to the rigor of logic. To learn technical lessons, common sense is a common temptation that does not make sense.

Common sense is not only dangerous in forensic analyses, it is also dangerous in design and construction. Indeed, this paper shows, on the basis of numerous examples and case histories, that decisions based on common sense were involved in the process that led to many of the observed failures. It appears clearly that common sense cannot serve as a basis for rational decisions in a scientific discipline such as geotechnical engineering. This paper also shows that common sense, because of its preference for traditional solutions, is particularly detrimental in the case of novel technology such as geosynthetics engineering. It is clear that the use of common sense must be banished from all scientific disciplines, in particular those which are under development. But, understanding this recommendation may require more than common sense.

As mentioned many times in this paper, it is important to educate designers and contractors on the possibilities and limitations of geosynthetics. Learning from failures is the best way to decrease the number of failures in the future. Therefore, this paper should hopefully help reduce the number of failures. Society at large will benefit because of a decreased number of claims relative to the total number of structures constructed with geosynthetics. The geosynthetic discipline will benefit because its credibility will increase. The author of this paper will benefit because he will not have to write an update. Finally, this paper should benefit those who have read beyond the following sentence, which is repeated from the first paragraph of this paper:

> *Geotechnical engineers who do not learn from mistakes made by others*
> *will learn from their own mistakes.*

12 DEDICATION

The author would like to dedicate this paper to D. Cazzuffi for his relentless and enthusiastic efforts for promoting and developing the geosynthetics discipline at the international level.

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Note: References which appear in the text in italics are those of papers included in the book on lessons learned from failures in preparation by J.P. Giroud. Other references are as follows.

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