# GEOMEMBRANE SYSTEMS IN THE NETHERLANDS AND ABROAD - RISKS AND LESSONS-LEARNED

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ABSTRACT: This article gives an overview of risks and lessons learned about geomembrane constructions in The Netherlands and abroad. Subjects that will be discussed will include risk-assessments and quantification of risks regarding geomembranes, welding procedures, stability issues of slopes, backfill and retaining structures, installation damage by handling and weather circumstances, and external influences after completion. The aim of this paper is to emphasize an integral approach during the entire process and importance of acknowledging quality risks to all involved companies. The success of a watertight and durable installation will depend on an integration of design aspects, materials, construction issues and quality assurance. To avoid risks during lifetime attention shall be given to proper restrictions, maintenance issues and monitoring of leakage/durability. The article presents examples, to illustrate risks and lessons learned.

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## 1 INTRODUCTION

The success of realizing a watertight and durable geomembrane construction depends on a lot of factors. Some of these factors can be recognized and avoided in an early stage. However based on specific project circumstances the factors can differ. Risk determination shall be in cooperated in the total process. In terms of risk analysis we can divide the construction process in 3 important stages, with examples of important risk factors:

1. Design stage (geotechnical, geohydrological and environmental investigation of soil and water conditions, choosing material properties, design layout, detailing, etc.)
2. Construction stage (proper procedures for inspecting the subsoil/backfill directly adjacent to the barrier and removing all irregularities and stress concentrations, procedures for installing/welding the geomembrane, proper CQA, etc.)
3. Maintenance stage (proper maintenance of drainage/dewatering systems, leak management, knowledge management of the harmfulness structure and measures to ensure no harmful activities, legislation, calamities with aggressive fluids/fire, etc.).

The common denominator in all three stages mentioned above will be the limited knowledge of geomembrane systems, material properties and procedures. A lack of knowledge by companies involved means that potential risks are not being recognized at an early stage resulting in a possible major impact to the final installation and harming the integrity of the geomembrane construction during the building process or even years after completion. Based on the harmful properties the following main risks can be distinguished.

- Suitability of the *in-situ* soil material for back fill on the geomembrane (admixture with cohesive or organic soil, presence of sharp stones or tree roots, possibility of reaching the required degree of compaction);
- Presence of environmental pollution in soil or groundwater (affecting durability of geomembrane);
- Influence of weather conditions (rain, sunlight, UV-radiation, frost, wind conditions, etc.) during welding and in the long term;
- Damage of the geomembrane during construction by handling or events after installations by personnel (smoking, footwear, waste), equipment (mechanical damage by cranes, trucks, dozers) or vandals (unauthorized persons who entered the construction area causing damage).
- Damage of the geomembrane by stability problems such as subsidence or differential settlement, caused by external water pressures versus the backfill levels, gas development, excavations in the backfill material above the geomembrane, external loads, etc.
- Damage of geomembrane during lifetime by a calamity with fire, aggressive liquids, external pollutions from adjacent sites (maintenance), mowing activities, planting trees.

An example of severe damage is given in figure 1. A situation of unacceptable excessive wrinkles is given in figure 2. Covering these excessive wrinkles will result in sharp folds, likely to give durability problems on the long term, due to stress concentrations.

Figure 1. Slope failure by stability problems after finishing the geomembranes caused by external water

Figure 2. Unacceptable excessive wrinkles in geomembrane caused by thermal expansion down a

| | |
|---|---|
| pressures versus insufficient backfill levels [Genap] | slope [Scheirs] |

Knowing the agencies that are damaging to geomembranes, risks are inevitable so the main issue is how to incorporate risk awareness during the different stages. This awareness can be done by executing an exhaustive risk assessment taking all aspects into account.

## 2 INTEGRAL APPROACH

The success of a watertight and durable installation will depend on an integration of design aspects, materials, construction issues and quality assurance. An integral approach starts in the subsequent design phases of project preparation. An integrated approach and design aims to customer needs, engineering, spatial planning and effects to integrate into any design stages. This takes into account feasibility and construction methods, permits, management and maintenance, and affordability. In addition, sustainability principles are integrated (durability, cradle-to-cradle) and value engineering is applied. Locating the geomembrane structure in a central position, factors of an integral approach can be visualised as given in figure 3.

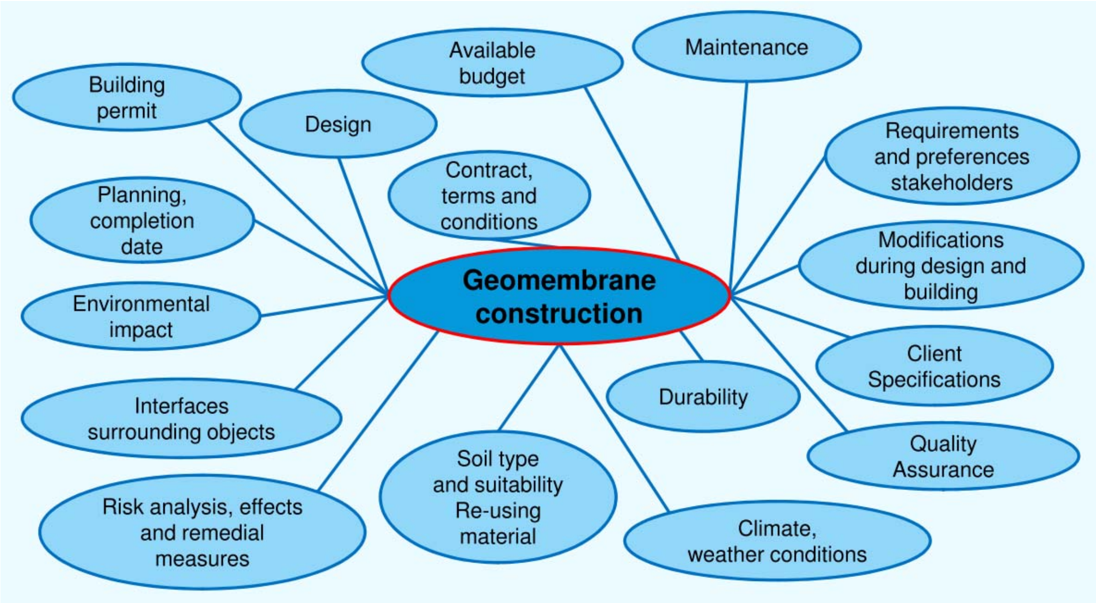


Figure 3. Notable issues for an integral approach locating the geomembrane in a central position *[Gerritsen]*.

The issues shown in the sketch will influence decisions in the design and construction method. Explanation to the issues of an integral approach is given below.

- Desired lay-out after completion (landscaping, architectural design, e.g. major importance in case of infrastructural projects).
- Desired durability / lifetime of the structure (e.g. 50, 75 or 100 years). Test proven the lifetime is applicable, knowing the (local) project circumstances.
- Building permits, available working and building space (work limits, based on building license and spatial planning).
- Environmental impact (construction with large dewatering installations or choosing a construction method without dewatering, submerging).
- Soil type and stratification (sand, clay, peat, stones, etc.) and suitability for reusing the material in or around the geomembrane (major importance in case of a vertical ballasted geomembrane).

- Presence of environmental pollutions in soil or groundwater, which could harm the durability of the construction during lifetime.
- Interfaces with surrounding objects (connections to intersecting roads, foundations, pipelines and cable connections, etc.).
- Management and maintenance issues (reduction of maintenance costs, reduction of risk impacts after completion, feasibility of proper maintenance, replacement or adjustment of the structure during lifetime).
- Direct and indirect building costs, available budget.
- Schedule, planning and completion date.

For the construction stage it can be stated that open and active communication between all involved parties (client, contract manager, supervision staff, engineer, main and subcontractors, QA) is of major importance. Special attention shall be given to the interfaces of different disciplines by main and subcontractors. For a large project the main contractor will engage a lot of subcontractors, like foundation works, groundwork, form workers, carpenters, concrete fixers, pouring concrete firms, dive company's (in case of wet works), cable companies, road and asphalt builders, etc. Knowledge of geomembrane systems can be present with the geomembrane supplier or QC, but finally all sub-contractors and personnel in the working area should have instructions about the 'do's and don'ts during the building process. This implies that toolbox-meetings are necessary to inform everybody about the procedures to ensure personal safety conditions, but also conditions to ensure the safety and integrity of the geomembrane, also after completion and finalizing the project at surface levels.

## 3 RISK ASSESSMENT

Factors listed above can cause a negative influence on the geomembrane construction, harming the integrity, durability or functionality of the structure through the entire life cycle. Direct or gradual developing damage of the geomembrane can cause leakage and if not controlled total failure of the construction may occur. It shall be evident, severe damage or total failure should be avoided by recognizing the risks at an early stage. Regarding the life cycle risks can be divided to the three main stages of a structure, knowing the design, construction and maintenance stage (see table 1).

| **Phase** | **Risk issue** |
|---|---|
| Design | Geomembrane material selection. |
| | Maximum design water levels during construction and completion stage. |
| | Feasibility of local excavations within the geomembrane. |
| | Presence of environmental pollutions. |
| | Stability of slopes/retaining structures, especially in case of stacking several geotextiles. |
| | Feasibility re-use local excavated material around the geomembrane. |
| | Connection type/detailing to structures. |
| Construction | Quality of welding (on site/off site). |
| | Weather conditions (rain, sunlight, UV-radiation, frost, wind conditions, etc.). |
| | Installation damage by handling personnel, equipment or vandalism. |
| | Stability problems caused by external water pressures, loads, etc. |
| | Suitability subsoil (i.e. sub grade) to apply geomembrane. |
| | Backfill method and backfill material quality. |
| | Local excavation within backfill material (drainage pipes, sewage, etc.). |

| | |
|---|---|
| Completion and Maintenance | Damage by a calamity with fire or aggressive liquids. |
| | Gradual damage by external pollutions from the containment or adjacent sites. |
| | Damage/puncturing geomembrane by human activities (drilling, digging, foundation works, etc.). |
| | Lack of maintenance to drainage and sewage systems. |

Table 1. Risk assessment based on project phases

About risk management notable opinions exists: it is complicated, expensive, fill exercise, it takes a lot of time and have little effects. You can also see risk differently: as structured approach to achieve successfully goals despite presence of risks. Targeted risk management, according to *Van Staveren 2006* is useful and necessary because we are confronted almost daily with underlying risks and uncertainties. There are many approaches to risk management. One approach is the project risk management method (RISMAN). This method distinct several steps: (1) determine goals, (2) identify risks, (3) classify risks, (4) whether or not to take measures, (5) evaluating effectiveness and (6) report.

| Risk assessment | | | Quantification Initial risk | | | | Risk management | Quantification Risidual risk | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Risk | Cause / explanation | Consequence | u | K | T | p x (K+T) | Precautionary actions | p | K | T | p x (K+T) | Risk carrier |
| Stability failure backfill material slopes geomembrane during construction stage. | 1. Improper groundworks backfilling method (backfill levels, slope inclinations, compaction rate, suitability of backfill material).<br>2. Friction geomembrane/geotextiles lower than expected.<br>3. Improper management water control (high groundwater levels, rainfall, pump failure). | 1. Stability failure embankments on geomembrane.<br>2. No horizontal/vertical balance geomembrane causing whales/uplift.<br>3. Geomembrane damage by stability shearing, complex recovery. | 4 | 5 | 5 | 40 | 1. Description methodology groundwork backfill (method statement).<br>2. Laboratory testing of friction angle geomembrane - geotextile interface.<br>3. Increase of backfill levels and checking by supervision staff.<br>4. Decreaing groundwork slope inclination.<br>5. Active water control by monitoring (standpipes with digital divers / hand readings).<br>6. Installation proper dewatering devices with enough capacity (filters / pumps / drains).<br>7. Alarm system in case of pump failure. | 1 | 5 | 5 | 10 | Contractor, Sub-contractor, Client, Engineer |

Remarks: p = occurence probability, K = cost effect quantification, T = time effect quantification

Table 2. Example risk assessment ‘Stability failure backfill material at geomembrane’ with quantification of initial and residual risks *[Gerritsen]*.

For risk management technical risks are to be classified. Each identified risk can be rated to the occurrence probability and impact effecting costs and time. Also precautionary actions and residual risks are assessed. The table below according to the method RISMAN shows the manner of risks qualification for an example risk ‘Stability failure backfill material slopes geomembrane during construction stage’. Based on ranking top risks can be determined and actions can be taken to control the risks to an acceptable level. For obtaining an active risk management during the building process it is important the risk assessment is lively and updated as risks can change, for example the occurrence of new risks or change in classification based on new circumstances.

## 4 EVALUATION OF RISKS

In the paragraphs below 5 issues are described more in detail and illustrated with pictures from engineering, construction and inspection practice.

### 4.1 *Welding quality*

Welds and seams can be designated as the weakest points of a geomembrane. According to *Scheirs 2009* seams are regions with high stress concentration due to defects in seaming operations, the heat-affected zone (HAZ) and residual stresses. The welding quality depends on a lot of factors, knowing the presence of contamination on the geomembrane welding surface (soil/moisture), weather conditions, workmanship of the personnel involved, material selection, and proper inspection. In figure 4 to 7 several examples are given of defects designated at welds and seams.

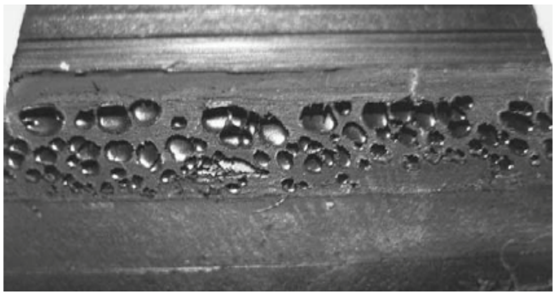

Figure 4. Example of moisture causing weld failure in a HDPE weld [Scheirs]

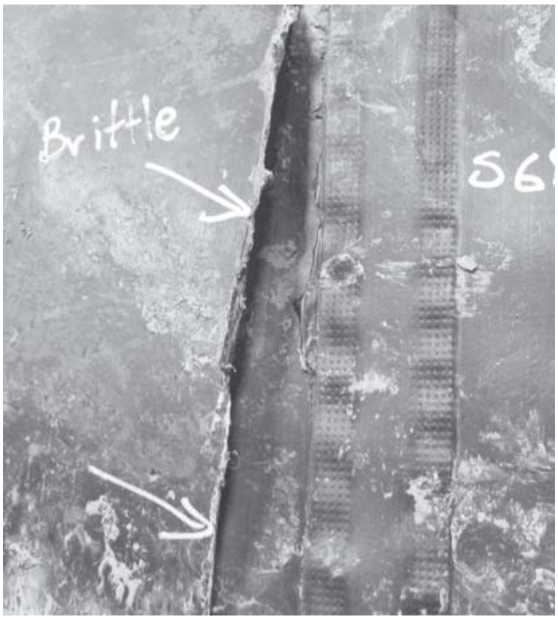


Figure 5. Example of stress cracking on edge of overheated weld [Scheirs]


Figure 6. Example of poor nip roller tracking in a HDPE wedge weld [Scheirs]


Figure 7. Example of overheating a HDPE Weld [Scheirs]

Obtaining a high quality weld will require serious craftsmanship and experience. Installation companies need to train their personnel themselves in company or on the job. Welders can be qualified by means of a certification issued by a notified body. To ensure the quality of personnel the project and contract specifications can regulate the employment of certified welders only. Factors to take into account to ensure welding quality are:

1. Weather conditions. The humidity plays an important role. It should not exceed 80%. Wind, rain and pollution by means of mud or sand (blown by the wind into the joint) will influence the quality of the welding.
2. Welds are adversely influenced by frost and high temperature. Therefore it is very important to check on the temperature of geomembrane during the installation process.

In general the geomembrane should be welded with a minimum geomembrane temperature of 5 ° Celsius. A temperature of 0° Celsius is advised as minimum temperature for all handling procedures of geomembranes (see figure 17). The occurrence of low temperatures can be of major importance in a project planning. In many countries the winter months are to be too cold to install geomembrane liner. Most projects start with an optimistic time schedule, but related to delays of preparation works the start of installation of liner material can easily be delayed, such the planning become critical and bad weather influences are unavoidable. Besides low temperatures, also high temperatures are to be considered. The upper limit of temperatures are to be derived on geomembrane material and the local circumstances, as these will cause changes to the physical properties of the geomembrane and thus of the quality of the welding. For example the maximum temperature for welding PVC-p material can be set to 35° Celsius. It's advised not to weld geomembrane strips in case of more than 10° Celsius to avoid bridging, wrinkles and undesirable stresses in the weld.

3. If there are changes of temperature during the welding process the installer needs to verify his welding parameters, in particular the welding machine temperature, pressure and welding speed. For example when the weather changes from cloudy to sunny weather, the temperature of a (black) geomembrane can heat up very quickly, influencing the weld parameters. A new trial weld needs to be executed in order to be sure that the machinery is adjusted properly to the changed circumstances. Visual inspection shall not be enough because the quality of the joint cannot be judged properly.
4. In terms of the machinery we recognize the importance of good maintenance of the welding machines. The machine shall be cleaned after usage and it shall be free from any pollution to the heating and pressure rollers, as this will have a negative influence on the quality of the weld. The electrical parts are vulnerable for interruption and a machine that is not running flexible and without friction will cause a bad weld.

### 4.2 *Suitability excavated and re-use soil material*

A lot of geomembranes are used and installed as underground barrier in the subsoil. This will imply excavations and backfill with soil/stone material, resulting in damage risks to the geomembrane. Based on electrical leak location surveys performed by *Nosko et al. 1996* it was assessed that about 20% of the leaks occur at seams (improper welding), but over 70% (!) of leaks occur when the liner is covered by soil or stone. Based on these values and practical experiences the quality of groundwork's is showing a factor which is under-estimated in a lot of projects. The covering operation has to be seen as a very critical stage for the geomembrane.

Figure 8. Presence of an un-expected dumpsite with ceramic material and environmental pollutions at a project site with a planned submerged geomembrane [Gerritsen].

Figure 9. The presence of sharp/big stones without protective geotextiles will significantly increase the risk on damaging the geomembrane [Gerritsen].

Related to this issue many examples in projects are known, observing worse circumstances during the excavation or covering stage (see figure 8 and 9). In case these circumstances are neglected and no actions are taken, this can result in direct physical damage to the geomembrane.

Soil types can be derived in several classifications, knowing for example sand, clay, loam, peat, gravel, rock, etc. However based on the geological history all kinds of mixtures and stratifications can be found all over the world, like silty sands, organic clay, etc. The interpretation and evaluation of soil properties and stratification is the expert field of geotechnical engineers, showing a strong connection to geotextile applications. Installing a barrier deep in the subsoil will cause major groundwork and soil materials stocked in a depot. Most desirable material to use around a geomembrane, will be clean sand with specifications given in table 1 (minimum specification) or table 2 (optimum specification). Sand which satisfies to these specifications is not harming the barrier (punctures) and the sand given in table 2 will be suitable to reach a good compaction rate. Values given are inter alia based on standard contract specifications used in the Netherlands *(CROW, 2015).*

| Nr. | Specification |
|---|---|
| 1 | The material shall exist of mineral material, geotechnical classified as 'clean sand'. |
| 2 | The content of mineral particles through sieve 63 microns of the sieve fraction by 2 mm shall not exceed 15%. |
| 3 | If the referred content in (2) is 10 to 15%, in addition, the content of mineral particles through sieves 20 microns of the sieve fraction by 2 mm not exceeding 3%. |
| 4 | The material through sieve 2 mm allowed the loss on ignition not exceeding 3%. |
| 5 | The material should be free of any admixture or environmental pollutions. |
| 6 | The maximum particle size shall be 3 mm. |

Table 3. Specification of optimum sand around geomembranes - suitable for compaction and projects with high requirements to functioning (e.g. infrastructure).

| Nr. | Specification |
|---|---|
| 1 | The material shall exist of mineral material, geotechnical classified as 'clean sand'. |
| 2 | The content of mineral particles through sieve 2 microns (experiment 1) is at most 8%, and the content of mineral particles by sieve 63 microns (test 2) shall not exceed 50%. |
| 3 | The material should be free of any admixture or environmental pollutions. |
| 4 | The maximum particle size shall be 3 mm. |

Table 4. Specification of minimum sand around geomembranes - suitable for embankments/backfill.

However depending on the site conditions the soil characteristics does not meet the optimal characteristics, and better material is not available in the far region. The geomembrane has however to be installed and most desirable will be the re-use the material in or around the geomembrane. Purchase and transport of new material will be a major cost factor in all projects, and mostly not cost-effective and not desirable related to the $CO_2$-footprint. This means that sometimes material has to be used that is less suitable for application. In such cases a lot of attention shall be given in the design stage (soil investigations, determine properties) and construction stage (earthmoving plan, equipment, compaction rates). Measures that can be taken:

1. Application of a protective layer of guaranteed clean sand above or below the geomembrane (minimum thickness 0.5 m, but preferable 1.0 m).
2. Mechanical sieving of the material to remove spoil/admixtures.
3. Application of protective geotextiles at / below the geomembrane.

The subsoil on which the geomembrane will be installed needs to be clear from sharp subjects which may puncture through the geomembrane. In figure 10 to 12 several examples are given of unacceptable sub grades. The starting point for suitability of soil material adjacent the geomembrane shall be that the material is free of admixtures with sharp stones, desiccated sub grade, boulders, concrete blocks, tree roots, construction waste (wood, beams, steel rebar, nails, piles, drainage or sewage pipes, foundation materials etc.). In case of building in urban areas with a long history or reconstruction works it can be presumable the excavated soil and surface will not be clean enough. In case of admixtures the material can be mechanical sieved by on plant installation or sieving equipment (see figure 13). In case the sand material has a lot of fines (problem of reaching the required degree of compaction) the fines can be removed. The same extraction can be done by presence of too much coarse material (gravel/boulders).

Figure 10. Unacceptable desiccation of clay sub grade [Scheirs]

Figure 11. Unacceptable damage to sub grade and improper working method by construction equipment [Scheirs]

Figure 12. Unacceptable sub grade for direct (HDPE) geomembrane installation [Scheirs]

On the other hand measures can be taken to protect the geomembrane additional. Since 2012 state-of-art geomembrane applications in The Netherlands are provided with protective non-woven geotextiles on both sides (bottom/above), see figure 14. In case of non-woven protective geotextiles attention should be given to the material type (polypropylene / polyester), minimum density, dynamic cone drop resistance and static puncture resistance. In case of dry construction methods the non-woven protective geotextiles exists of polypropylene (PP), specified with a minimum density of 500 gram/m$^2$. In case of wet construction methods (submerging) the non-woven protective geotextiles exists of polyester (PET), specified with a minimum density of 1000 gram/m$^2$. An interesting research paper by *Austin 2014* demonstrated that non-woven PET-material does have a higher protective level in comparison with PP-material, based on 3D-scanning of the effects by a standardized profiled plate. Related to high risks of covering geomembranes by backfill material, the best standard should be that geomembranes are to be embedded by non-woven protective geotextiles at all times. Applying a good quality non-woven will reduce the risk of perforations of the geomembrane significantly.

After placing a non-woven protective geotextile and a first layer of back fill contractors tend to use their internal transport to drive over this back fill. At least 50 centimetres should be taken into account as a minimum before driving on top of the geomembrane, but preferable a thickness of 100 centimetres to ensure enough load spreading from equipment (see figure 14).

Figure 13. Example of proper mechanical sieving equipment to extract rubbish/admixtures before re-using the material within a geomembranes [G.M. Damsteegt]

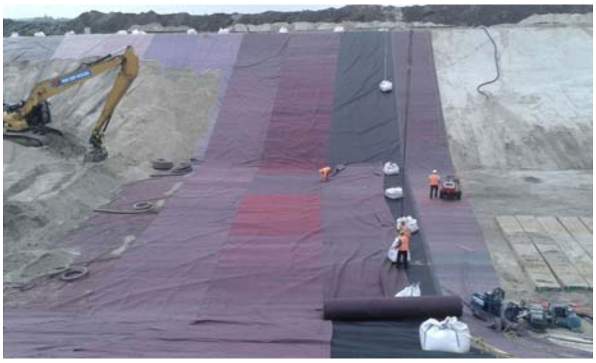

Figure 14. Example of proper installation using a protective non-woven geotextile at the subsoil and topside of the geomembrane, working sequence with excavation works and installing method at large slopes [Genap]

### 4.3 *Stability of slopes, backfill and retaining structures*

To ensure a safe situation during the design and building process a lot of attention should be paid to the stability of slopes, backfill and retaining structures. In case stability is not assured this will have major effects to the project. In case of (geotechnical) slope failure adjacent to geomembrane constructions damage to sealing is almost inevitable. Worst case this can result to a total loss of the geomembrane sealing and major effects to costs, planning, etc.

Geomembrane systems are widely used in the Netherlands as watertight artificial barriers in underground construction of roads, rail- and waterways. High water tables up to the surface make it challenging to install the geomembrane system deep below the surface. In the Netherlands submerged geomembrane systems have been installed down to a depth of about 27 metres below the surface and groundwater table. In dry conditions depth are reached up to 18 meters below the surface, using methods for dewatering the building pits. In dry conditions slopes are generally set to 1 to 2 (vertical : horizontal), however also examples are know of using steeper slopes up to 1 to 1.5 or even 1 to 1. In wet conditions slopes are generally set to 1 to 3 (vertical: horizontal). With special evaluations also wet conditions are known with realising steeper slopes using water overpressure during the excavation stage.

In the stability of slopes/retaining structures, related to the construction of geomembranes factors are of major importance:

- Soil layers characteristics (loose to dense sand, weak to stiff clay, loam, peat, etc.) and derived strength parameters.
- Presence of groundwater and conditions (differential levels, flows, confined pressures), ability of dewatering devices (deep wells, filters, etc.)

- Presence of uniform loads (equipment, trucks, crane platforms, storage or soil stocking next to the building pits).
- Sequence of applying backfill above a geomembrane;
- Properties of geotextile structures in the subsoil and interface strength, elongation properties, fixing to structures.

Factors above should to be taken into account and assessed by a geotechnical and geosynthetic expert. This shall be done during the design stage, but assessments shall also take place during the building process. Conditions during the construction are to be checked and compared with the assumptions made during the design. In case those conditions are differential during the building stage and not recognized, this can easily lead to risks or failure to the geomembrane.

Special attention should be given to the assessment of the stability of slopes in case of stacking several geotextiles. This issue of interface strength is of major importance in case geomembranes are covered by non-woven protective sleeves. The interface strength between geotextiles can be remarkable lower than the normal geotextile-soil interface strength. Reduction to the interface strength can cause a preferred failure plane along the geotextile structure. Based on laboratory test the interface strength can be determined. Measures can be taken to increase the interface strength by using textured geomembranes. The application of textured geomembranes is quite common in environmental applications (dumpsites), knowing the critical slope stability of the top sealing at low effective soil pressures.

The presence of groundwater is affecting in a prior case the stability of slopes and retaining structures. Groundwater can be seen as a ‘sneak murderer’ for building pits, so also in the construction of geomembranes. The conditions of groundwater are of major importance, and also the proper working of dewatering devices (deep wells, filters, etc.). In case the dewatering devices (pump generators) fail, a quick build up of water pressure can occur, this can cause severe problems to the stability of geomembrane construction. Also excessive rainfall can lead to problems by rapid increasing groundwater levels, exceeding the design water levels or overflow of the working area. Another failure mechanism can be leakage through retaining walls (sheet piles). In the Netherlands several cases are known of groundwater conditions which damaged the excavated slopes or already installed geomembrane structure during the construction process (see figure 15 and 16). These situations are unintentional.

Figure 15. Risk to instability soil backfill and severe damage geomembrane, using a wrong backfill sequence at the geomembrane structure [Ref. Dutch directorate for public Works and Water Management]

Figure 16. Geomembrane whales due to uplifting water pressure below the geomembrane related to improper backfilling levels [Genap].

A returning issue for excavations in wet conditions (below the groundwater, familiar in The Netherlands) is the water level to be maintained in the building pit. Soil will be removed hydraulic method (dredging) or mechanical method (crane). In last case soil is excavated but water is also removed by loading saturated soil on trucks. Depending on the permeability of the soil, water will flow from the adjacent areas to the building pit. In case the flow is limited by low-permeable soil layers the water level in the building pit can drop significantly. Water flow through the excavation surface can lead to (geotechnical) failure (micro of macro stability, uplift, welling, retaining wall deformation or worse collapse). One of the preventive measures which can avoid problems should be to increase the water level in the building pit to a higher level than the surrounding area. In this way there is always an overpressure, which is maintaining the stability. In case the geomembrane is submerged also an overpressure of water is applied within the geomembrane. This overpressure of 0.1-0.3 m shall be taken into account on formwork and retaining walls, as these can have a significantly effect on the deformation of retaining structures, used in cases of limiting space by using vertical boundaries and fixations of geomembranes *[Gerritsen, et al., 2014]*.

### 4.4 *Installation damage by handling and weather circumstances*

During the construction stage the geomembrane remains very sensitive for damage, knowing it can be exposed to all influences from transport, handling, weather influences, etc. During transportation and off loading full rolls may be damaged by means of insufficient packaging or due careless handling by drivers of fork lifters or cranes. Also the storage area of unpacked geomembrane rolls, shall be kept save from heavy equipment preferable by applying closed building fences around the storage area.

Depending on the site conditions packed geomembrane rolls shall not be stored in full exposed weather conditions, but preferable below roofing or conditioned building. In warm regions the temperature and UV-radiation can affect the quality of the geomembrane. In cold regions / winter periods frost can harm the geomembrane significantly, if handled with material temperatures minus 0° Celsius (see figure 17). The material can easily break and full sheets/rolls are to be rejected and regarded as waste.

Wind may influence the quality as well since a firm wind blow may blast away the uncovered geomembrane. The geomembrane should not be installed during high wind speed > 5 Bft and assure sufficient back fill after unrolling before final back fill is placed. In case of suddenly strong or increasing wind speed, this can cause intense safety risks for personnel and quality issues to the geomembrane (see figure 18).

Figure 17. Low temperature with frost during the unpacking and installation of a PVC-p geomembrane given delays around wintertime [Gerritsen].

Figure 18. Major effect of wind influence at an uncovered geomembrane field, causing intense safety risks for personnel and quality issues to the geomembrane [Genap].

Related to the placement of backfill there are examples of damage related to the improper placement of backfill in comparison with weather circumstances. Placing improper backfill during warm conditions on top of the membrane means avoid back filling the folds in the geomembrane as HDPE is known for its great expenditure (shrinkage and expansion) depending on variation in temperature. Common folds lead to a sharp fold which accordingly may cause a stress fracture in the geomembrane in the long term. Damage caused by folds, wrinkles and stress cracking is described by *Peggs 2003*.

The geomembrane can also be harmed by actions of the personnel themselves, for example by smoking, wearing improper footwear or inclusions with sharp stones (see figure 22), falling tools like knifes and scissors, effects of heat blowers, movement of a electric generator, or leaving waste. Another factor of damage can be the pulling to geomembrane sheets with strong forces (ropes, winches, big bags); in case the geomembrane is not exactly positioned in the right place. The geomembrane can be harmed by sharp edges of construction objects, like geonets (see figure 21), steel sheet piles or anchoring systems. Another cause is the impact of heavy equipment used on the construction site, causing mechanical damage by cranes, trucks, dozers (see figure 19 and 20).

Figure 19. Mechanical damage to a geomembrane anchoring trench by using wrong backfilling equipment (crane) and less instructed personnel on site [Gerritsen]

Figure 20. Mechanical damage of a woven protective geotextile by handling of heavy equipment, given a direct threat to the geomembranes behind [Gerritsen]

Figure 21. Sharp cut end of geonet causing puncture of geomembranes [Scheirs]

Figure 22. Stones in tread of work boots causing puncture of geomembranes [Scheirs]

A special remark is made about influence of vandals. These are unauthorized persons who have entered the construction area causing damage during night-times and weekends. Several examples are available of people who entered a construction site, throwing objects like sticks, stones or waste directly on the geomembrane, causing stake puncturing. There is an example in The Netherlands just before submerging a geomembrane during a final inspection of the bottom of the building pit a scuba diver found a bicycle. Based on these examples the common practice is that construction sites during the critical situation of an uncovered geomembrane are increasingly protected by fencing and security guards. Also security cameras are unfortunately becoming common at construction sites.

### 4.5 *External influences after completion*

After completion of the installation it may seem that the geomembrane is save for lifetime. However, during the entire lifecycle all kind of influences can harm a geomembrane. Special influences to be listed are:

1. Damage of geomembrane during lifetime by a calamity with fire or aggressive liquids.
2. Gradual damage by external pollutions from adjacent sites.
3. Damage/puncturing geomembrane by human activities (drilling, digging, foundation works, planting of growing trees, etc.).
4. Lack of maintenance to drainage and sewage systems.

The feasible damage of a geomembrane by a calamity with fire or aggressive liquids is the case for geomembranes used in the subsoil for infrastructural or railroad projects. At the track above the geomembrane calamity's can cause serious damage to geomembrane material, for example by accidents with trucks/trains loaded with aggressive liquids. For major road constructions it can be regulated that an extra calamity geomembrane shall be applied at a shallow depth below the road or railway construction. An alternative can be applying a very tight and cohesive clay-layer at the surface to avoid aggressive fluids to penetrate into the soil.

Gradual damage by external pollutions can be caused by aggressive pollutions stored in a waste disposal. In case of infrastructural barriers migrating water pollutions from adjacent sites can gradual harm the integrity of the geomembrane. An example of this phenomenon is described as special case study of 'Doornboslaan Breda' in chapter 5. Impairment of the geomembrane by VOC-pollutions resulted in a durability failure with need for replacement of the barrier in 2016.

Figure 23. Geomembrane perforation below a underground railway track by installing earth pins for deelectrification [Dutch railway authorities]

Figure 24. Inspection of a water collection cellar, observations of an increased influx (leakage) with external iron rich groundwater, blocking the total drainage system within a geomembrane construction [Municipality of Zwolle]

Damage/puncturing geomembrane by human activities is a likely cause for damage. The existence of a barrier is often 'forgotten'. Examples can be drilling, digging and foundation works. Examples are available of placing foundations for a large advertising column through a geomembrane liner. Also planting trees can harm the integrity on the long term. For the first years trees are small, but after 10-20 years the root systems can be enormously wide and deep. Another example is the geomembrane perforation below an underground railway track by installing earth pins for de-electrification (see figure 23). For this case several tests and evaluations have been carried out to find the best solution, knowing removing the pins, injection techniques or maintain the pins at location (perforated). From a test set-up it was concluded the best way was to maintain the pins, knowing a minimum of leakage.

At most geomembrane systems drainage and sewage systems are installed to collect rainfall water or leakage water. These systems are to be maintained and regular inspected. A learned-lesson is the case of a 15 year old geomembrane failure 'IJssellaan Zwolle Netherlands'. Observations were made of an increased influx (leakage) with external iron rich groundwater, blocking the total drainage system within the geomembrane construction (see figure 24). As remedial measure the leakage was treated with injection measures, however this was finally increasing the leakage. Water on the road construction result in winter times in an uncontrollable and dangerous situation for traffic driving through the underpass. Finally the barrier was replaced by a traditional concrete construction in 1995.

## 5 CASE STUDY: DOORNBOSLAAN BREDA NETHERLANDS

### *45 year old geomembrane durability failure Doornboslaan Breda Netherlands*

During the early '70's a geomembrane barrier system was used to create an artificial water tight sealing of the underground construction for access roads to a railway underpass close to the city centre of Breda located in the Netherlands. Used for civil engineering purposes the building technique of using a barrier was quite innovative for that time. Above the geomembrane a backfill of sand was used to ensure stability against uplift. Typical cross sections of the old structure are given in figure 25 and 26.

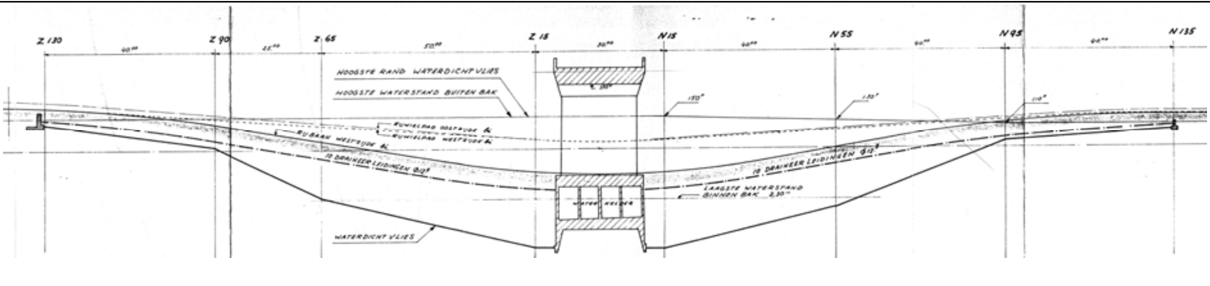


Figure 25. Longitudinal section railway underpass, access roads constructed with a geomembrane barrier system ballasted with backfill, in the middle a concrete construction with 4 track railway [Technical drawing, Dutch Railway Institute, 1968].

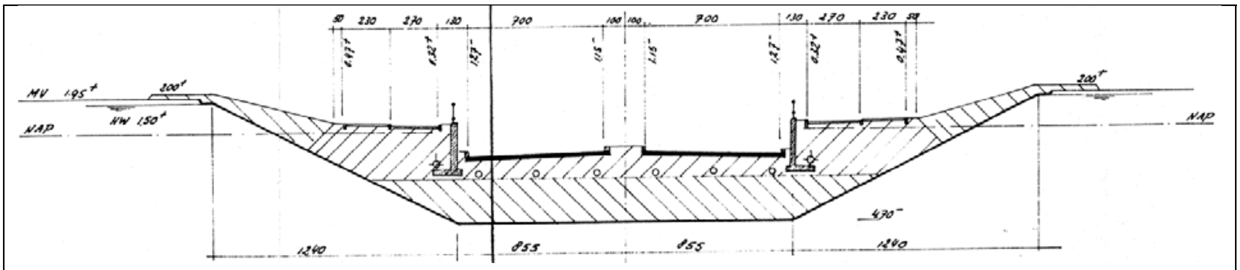

Figure 26.Cross-section access roads constructed with a geomembrane barrier system ballasted with backfill [Technical drawing, Dutch Railway Institute, 1968].

The barrier system existed of PVC-p (weakened) material, with a nominal thickness of 0.4 mm. In 2009 and 2010 investigations were carried out by several trial pits to obtain more information about the durability of the geomembrane system in place (see figure 27 and 28). Based on several trial pits and material tests the condition of the original 45 year old geomembrane was quite bad, knowing wrinkles, brittle cracks and water inflow. Based on tests and observations it was concluded the remaining lifetime of the geomembrane was ended.

Figure 27. Investigation of 45 year old 0.4 mm geomembrane in trial pit, observing an irregular surface, wrinkles and cracks and water inflow [Witteveen+Bos / Kiwa, 2010]

Figure 28. Close up brittle crack in the 45 year old 0.4 mm geomembrane, causing water inflow [Witteveen+Bos / Kiwa, 2010]

Reasons for the loss of functionality of the geomembrane can be found in the source material (quality of the geomembrane), 0.40 mm small thickness and likely the construction way with wrinkles/sharp edges and irregularities in the adjacent backfill (stones). Another major reason can be found in an exposure to severe groundwater pollutions nearby. Next to the geomembrane was over a period of around 30 years a laundry factory located, causing a historic groundwater pollution of VOC. The chemical properties of VOC are having a higher volume weight than water, so pollutions of VOC are gradually descending to deeper aquifers. Around 2012 investigations turned out pollution depths of 10-25 m-surface, but from historic point of view the pollution was likely around and exposing the geomembrane decades before. Exposure to this kind of pollutions is causing an increased loss of plasticizers, which reduce the lifetime of geomembranes significantly. As the Client was planning to built a high speed public transport line, which should cross the geomembrane, it was strongly advised not to build new structures in or next the severe attacked geomembrane. In consultation with the Client (municipality of Breda) decisions were taken to replace the geomembrane over the full length of the road underpass, combined with the construction of two crossing viaducts. Based on a comparison of several building techniques it was chosen to replace the structure with a new geomembrane with state-of-art techniques and building methods, successfully finalized in 2016. To ensure a durable sealing a new high-quality geomembrane PVC-p, with a nominal thickness of 1.0 mm was submerged in large building pits, protected by non-woven heavy duty protective geotextiles 1000 gr/$m^2$.

## 6 CONCLUSIONS

The success of realizing a watertight and durable sealing will depend on a good understanding of design aspects, materials and on quality assurance during the building process. Risk determination shall be in cooperated in the total process. In terms of risk analysis we can divide the construction process in three important stages: the design, construction and maintenance stage. The common denominator in all three stages mentioned above will be the limited knowledge of geomembrane systems, material properties and procedures. A lack of knowledge by company's involved means that potential risks are not being recognized in an early stage resulting in a possible major impact to final harming the integrity of the geomembrane construction during the building process or even years after completion.

An integral perspective is necessary to obtain a durable geomembrane construction. For the construction stage it can be stated that open and active communication between all involved parties (client, contract manager, supervision staff, engineer, main and subcontractors, QA) is of major importance. Special attention shall be given to the interfaces of different disciplines by main and subcontractors.

The installation of geomembranes as underground barrier in the subsoil will imply excavations and backfill with soil/stone material, causing a strong interface with damage risks to the geomembrane. Based on surveys and practical experiences the quality of ground works is showing a factor which is under-estimated in a lot of projects. The covering operation has to be seen as a very critical stage for the geomembrane. Related to the high risks of covering, the best standard should be geomembranes to be embedded by non-woven protective geotextiles at all times. Applying a good quality non-woven will reduce the risk of perforations of the geomembrane significantly by external influences as well during the construction stage as well after completion.

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