The "zero leakage" approach and German regulations for geosynthetics used in landfill liner and capping systems

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ABSTRACT: An approach to achieve "zero leakage" is discussed with respect to the experience in Germany, where strict regulations for landfill lining and capping systems have been developed and issued because of large environmental problems related to landfills that accumulated in the 1970's and 1980's. These regulations for landfills and geosynthetics which are used in landfill liner and capping systems are shortly described. The main certification requirements for the products as well as conclusions for their use are presented. Using a thick, high quality HDPE geomembrane (GMB), which is installed free of residual waves and wrinkles in intimate contact with a compacted clay liner (CCL) or geosynthetic clay liner (GCL) of very low permeability, by a qualified, experienced, well equipped and properly third-party controlled installer and which are protected by heavy protection layers designed with respect to long-term performance of the GMB, may result in a liner or capping system of practically no leakage. This is demonstrated by analyzing results of measurements obtained from permanently installed leak detection systems in combination with HDPE GMBs.

Keywords: HDPE geomembrane, landfill liner, leak detection, regulations

1 INTRODUCTION

Already in the year 1989 the Federal Institute for Materials Research and Testing (BAM) issued for the first-time certifications for geomembranes for landfill lining systems. Afterwards the BAM approvals for geosynthetics were established increasingly as part of the authorization procedures for landfill containment systems. The variety of geosynthetics used in the field of landfill engineering has increased rapidly in recent years. Since 2009, according to the German Landfill Ordinance the BAM is responsible for the certification of geosynthetics, polymers and leak detection systems which are applied in landfill liner and capping systems (N.N. 2009). For a certification, it has to be demonstrated that the geosynthetic product will fulfil its function over a period of at least 100 years. Leak detection systems for convection barriers have to retain their function for a period of at least 30 years. To accomplish this requirement all possible external impacts and interactions between components of the system have to be taken into account. In this way, the German Landfill Ordinance describes the German state of the art for geosynthetics in landfill construction in general terms. The BAM certification guidelines for geosynthetics and leak detection systems transfer this general description of the state of the art in applicable detailed requirements. To fulfil the requirements of the Landfill Ordinance the guidelines of the BAM not only consider the products themselves. The guidelines also take the quality assurance during production and on construction side into account and put demands on the procedures in these areas.

There is much debate in the GMB community about the issue of leakage through landfill liners with a GMB component. The very old assumption "all liners leak" (Peggs and Giroud 2014) is still readily accepted by many geotechnical engineers (Peggs 2015). However, is the assumption actually true? We wish to show that it is possible to avoid leakage by engineering methods to an extent, that it may be considered as zero with respect to any practically relevant concerns. In Germany, the regulations focus on a “zero leakage” approach. The approach stems from the environmental concerns of many citizens’ initiatives. It transpired that it was actually impossible to agree upon an acceptable amount for waste water leakage and even though, it would had been impossible to reliably determine and control it. The approach is nowadays enforced by very restrictive German regulations (water resources act) concerning ground water protection.

2 PRINCIPLES OF THE APPROVAL OF PRODUCTS AND DEVELOPMENT OF THE GUIDELINES

The BAM is responsible to define tests and testing criteria, to include provisions into the certification document and in addition to stipulate requirements regarding installation procedure and quality management. The certification holder is the manufacturer of the geosynthetic product. The approval is given based on investigations by BAM as well as by the manufacturer and on testing results from accredited laboratories. For the certification one of the basic requirements is that the geosynthetic product is produced with well-defined and reproducible properties. Thus, a sophisticated quality management system is needed. In addition, not only production control, but also a quality assurance for the installation is necessary.

The BAM guidelines are based as far as possible on available standards or other regulations. However, concerning long term behaviour BAM had to develop new testing procedures, because applicable standards are not available. This comprises for example: long term water flow capacity of geosynthetic drains, long-term shear strength of structured geomembranes, GCL, and geocomposite drains and so on, long-term behaviour of geogrid pull-out resistance, long-term properties of welds etc.

2.1 *Advisory board*

Based on the German Landfill Ordinance the BAM has developed detailed requirements for geosynthetics in close cooperation with an advisory board of landfill experts from state authorities, landfill authorities, universities, testing institutes, engineering and construction companies, manufacturers of geosynthetics, third party controller and testing institutes. The advisory board counsels the BAM during the preparation of the certification documents which describe the products, responsibilities of the manufacturer and the requirements on the product and on use and installation. With respect to the variety of geosynthetics products the advisory board has established the following working groups (WG) to discuss the certification guidelines: WG geotextiles for filtering and separation, WG leak detection systems, WG geogrids, WG geomembranes and WG third-party-control on construction site. The results of the working groups will be discussed, decided and approved in the advisory board.

2.2 *Publication of the certification guidelines and other documents*

All completed documents such as certification guidelines, recommendations and testing specifications which are approved by the advisory board will be published on the website and in the Official Gazette of the BAM. Some of the guidelines, i.e. the certification guideline for geomembranes, are available in English language (webpage: http://www.tes.bam.de/en/mitteilungen/abfallrecht/index.htm).

2.3 *Geosynthetic installers*

The proper installation of geosynthetics and plastic components is an important condition regarding the durability of geosynthetic products. For this reason, the requirements to the installation companies are a crucial item with respect to the demands of the German Landfill Ordinance. Therefore, the installation companies must be highly qualified. Installation companies should have a great experience and suitable equipment to be able to install the products properly. The necessary qualification, equipment and experience of an installation company could be proved by the recognition by a quality supervision organization. Manufacturer associations such as the AK GWS e. V. (*Arbeitskreis Grundwasserschutz* registered society) and the AGAS e. V. (*Arbeitsgemeinschaft Abdichtungssysteme* registered society) offer a quality supervision system based on the respective guideline of the BAM. The certification guidelines require for geomembranes, for geosynthetic drains and for protection layers to be installed by such qualified installers. This request is also valid for geotextiles and geogrids whenever these products are installed in connection with a geomembrane. Otherwise, in cases that these products are installed into systems without geomembranes or in a different context, the construction workers which actually perform the installation have to be trained by a qualified person.

2.4 *Third-party inspectors*

It is well known that the third-party control is of immense importance for flawless GMB installation (Cadwallader and Barker 1986). The BAM supports the activities of third-party inspectors. Tables of requirements for the type and numbers of onsite tests were included into the certification guidelines. The requirements of these tables are obligatorily for the installation of the products. Accreditation according to ISO/IEC 17020 for the inspection body and ISO/IEC 17025 for the laboratory is required. The requirements, on which the accreditation is based for third party control, are published on the website of the BAM together with examples of the relevant inspection instructions, examples of quality control plans and reports (BAM 2017). The third-party inspectors which are organized in the AK GWS e. V. have formed a working group. This working group helps to solve problems which arise by putting into action the requirements of the third-party control guideline and the demanded accreditation of the third-party inspectors according to DIN EN ISO/IEC 17020 and DIN EN ISO/IEC 17025. Furthermore, the procedures of the third-party inspection on the construction site shall become more transparently and better comparable. The quality in third-party control shall be standardized and raised. To achieve these aims for example round robin tests are done.

3 REQUIREMENTS ON HDPE GMBS

Only HDPE GMBs have been certified so far, which have high stress crack resistance and are properly stabilized by antioxidants against oxidative degradation. In this respect the requirements in the certification guidelines (BAM 2017) are comparable to those based on the GRI standard GM13 (GRI 2015). However, there are differences with respect to other properties. In geotechnical engineering, HDPE GMBs with different thicknesses are used and there is an ongoing discussion about the minimum thickness necessary. One has to choose the optimum between mechanical robustness, stress crack and oxidative resistance, performance during installation and, above all, welding on the one hand and financial expenditure on the other hand. Mechanical robustness, stress crack resistance and even oxidative resistance significantly increase with thickness. Welding, especially extrusion welding, can be much easier and more reliably performed with thicker GMBs. There is consensus that under no circumstances the HDPE GMB should be thinner than 1.5 mm. However, there are many reports about regular problems with extrusion welding of 1.5 mm thick HDPE GMBs (Hein et al. 2003). Usually, a thickness of minimum 2.0 mm thick is recommended. In the German Landfill Ordinance the thickness has to be at least 2.5 mm.

In section 3.3, we discuss the importance of an installation free of waves and wrinkles for zero leakage. To achieve this goal, one has to take into account the dimensional stability or shrinkage behavior of the GMB as an important property. During the production (extrusion and calandering) orientation and related stresses are imposed on the product and locked in during the cooling procedure. Later on, the orientation and stresses relax to a degree during transport and installation, especially when exposed to higher temperature on the installation site. The relaxation leads to an “intrinsic” waviness of the GMB. Therefore, inferior dimensional stability can cause serious problems for welding and wrinkle-free installation.

The following method of measuring the dimensional stability may be used to characterize this effect. Quadratic specimens (plates) with 100 mm edge lengths are cut from the GMB. The edges must be right-angled and the lateral faces must be even. The specimens are kept in an oven at 120 °C for one hour. The edge length (l_{before} and l_{after}) of the plates before and after heating in the oven is measured in the extrusion direction and crosswise and the percentage of change of length with respect to the initial length is calculated for each direction and rounded to ‰-values.

$$\delta l = \left(\frac{l_{before} - l_{after}}{l_{before}} \right) \cdot 100, \qquad (1)$$

The certification guideline requires that the absolute value of the dimensional change in extrusion as well as in cross extrusion direction must be ≤ 1.0 % for smooth GMBs and ≤ 1.5 % for GMBs with an embossed surface pattern. However, the absolute value of the difference in the dimensional changes along the width has to be significantly lower than 0.6 %. The BAM certification guideline sets in addition a limit on the appearance and waviness after production, which is checked at the beginning and end of a production run. The maximum clearance between the GMB and level supporting surface is measured over a length of 10 m when rolled out over a length of 12 m. The measured value must be 5 cm at most.

Figure 1 (right) shows the appearance of the same GMB after installation. Since shrinkage in the extrusion direction is large at the edges but small in the middle, a typical “bulginess” of the GMB occurred. A wrinkle-free installation would be impossible, even with elaborate installation techniques. Therefore, not only thickness and the related mechanical robustness but also low intrinsic waviness is an important prerequisite for an installation, which avoids holes.

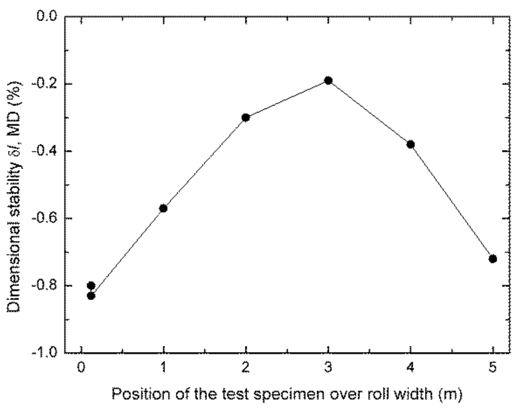

Figure 1. Dimensional stability in the extrusion direction measured along the width of the GMB (left). Intrinsic waviness of the GMB after deployment on the installation site (right).

3.1 *Installation*

Below, we make comments about the state of the art of GMB installation as used in German landfill construction. Clearly, there is a large variety of the extent to which the requirements are actually fulfilled. Yet, as it is shown in the next section, a sealing system free of holes is realized in many cases.

Before the GMB installation can start, the subgrade (or supporting layer), on which the GMB will be deployed and welded, has to be produced and its surface prepared. Particle shape, particle size and particle size distribution of the supporting layer material must be selected in order that the loads, which occurred during construction and use, do not result in inadmissible deformations by indentations and imprints in the GMB. Therefore, the BAM certification guideline contains material-technical and geometrical criteria for the surface of the subgrade and the mineral component in the composite liner. The subgrade surface must be stable bearing, homogeneous, fine-grained and free of holes. Gravel particles with a diameter > 10 mm and foreign particles have to be removed. All finer gravel components must be embedded in such a way that they are surrounded on all sides by cohesive subgrade material. Gravel particles and foreign particles must not lie on the surface. Generally, abrupt changes in height should be smoothed to a large extent. As a reference point a permissible height of 0.5 cm is considered for steps (impression differences). Unevenness, when measured beneath a lath (straight edge) of 4 m in length resting on the surface, may not exceed 2 cm. The production of such a surface requires a substantial constructional engineering input (Averesch and Schicketanz 1998).

As a general rule, the GMBs have to be installed in such a way that as few welding seams as possible are necessary and that dual hot wedge seams. GMB installation requires a certain amount of time: the welding of a 100 m long seam at a typical welding speed of approximately 1 to 1.2 m/min, with preparation and testing, takes about 2.5 to 3 hours. Each dual hot wedge seam is tested over the entire length by air pressure tests with about 5 bar. Peel tests are performed on the seams of the test weld or predominantly on samples from the beginning and end of the seam. Various geometric parameters of the seams are measured on test specimen. In addition, they are measured non-destructively on the on-site seams by ultrasonic tests. Thereby the cutting of test holes and patching is avoided. Site conditions, welding parameters and test results are recorded in standard forms.

An installation method, which uses the temperature gradient over the day, can guarantee the intimate contact of the GMB with its subgrade to a large extent. A change in temperature of 10 °C between night and day can alter the length *L* of a HDPE GMB section due to thermal elongation and contraction by an amount to 2 m for a 100 m long section. Therefore, if a GMB, which is acclimatized to the temperatures of the warmer time of day, is aligned, installed with minimum undulation and welded, it will pull itself smooth as it cools during the night. Installing a geotextile and fine gravel or a heavy sand mat as protection layer and backfilling with the coarse gravel drainage material (base liner) or installing a geotextile protection layer (or a geocomposite drain) and backfilling with a layer of reclamation earth (capping) will fix the GMB and realizes the intimate contact. It is very important to ballast the geomembrane at the correct time. The waviness of an uncovered area of a GMB will increase significantly over time and after a certain period it will be impossible to achieve intimate contact. The certification guideline requires that a sufficient load must generally be applied on the same or the following day and at the latest on the second working day after the installation of the GMB.

3.2 *Evaluation of measurements with leak detection systems in landfill cappings*

Permanently installed Leak Detection Systems (LDS) are applied in German landfill cover systems in combination with HDPE GMBs (Wöhlecke and Müller 2014). Such a combination can be equivalently used as a substitute for a composite liner system. LDS are able to detect and localize defects in barriers such as cracks and holes with respect to their size and occurrence. LDS used in German landfill constructions are based on well-known and in different versions applied electroresistive measuring techniques and sensors (Darilek and Laine 1999). Such kinds of LDS make use of the insulating behavior of the HDPE GMB and the change of electrical potentials in the area of a defect. Instead of the flow of water the flow of electric current is measured. Therefore, an external voltage must be introduced into the barrier system during a measurement. If the conditions are not particularly unfavorable, a hole can be detected electrically much earlier and with higher accuracy than by any monitoring of any hydraulic effect. The LDS are certified by the BAM for this application (BAM 2017).

The efficiency of a LDS is defined in terms of what minimum leak size can be detected and with what spatial resolution. The detection limit of a leak monitoring system is the minimum size of a hole in the GMB, assumed to be circular, that can be detected by the leak monitoring system with certainty under normal conditions. For a certification, the leak detection system must be able to detect a circular hole of at least 5 mm diameter (corresponding to an area of 20 mm² per hole) with 100% probability. The manufacturer and operator of permanently installed LDS with their relevant decades of experience can add valuable information to our discussion by providing data from the examination of the barrier-system after the whole construction process and during use. Such data was provided by the SENSOR Dichtungs-Kontroll-Systeme GmbH, Germany to the authors. The putting into operation of the LDS usually starts with a control measurement of the performance of the LDS itself. For this the third party controller “secretly” drills small holes into the GMB capping, which have to be localized by the LDS. Then, there is an approval measurement after the end of the construction of the capping system. After that, there are regular measurements at some time intervals of the performance of the capping system during operation and after-care of the landfill. The certified LDS contain a “self-control” procedure: Before each measurement, it is checked whether the cables, sensors and electronic equipment are functioning correctly. Therefore, the data provided by SENSOR may be considered to be reliable.

Figure 2 shows the results of 14 years of controlling capping systems with permanently installed LDS in German landfill cappings. The data include the results of the approval measurement and the regular interval measurements until the year 2015. Data from 32 landfills with an overall capping area of 1,276,500 m² became available. There were only six failures found, which means a failure density of only one defect nearly every 21.3 ha. This is in fact negligible. In 26 of the 32 construction sites no defects were determined at all. On the remaining six construction sites only one defect per capping system could be found. No details were given for one of these defects. All other defects were located outside the seams in the panel area of the GMBs and were caused by physical impact. Failure to poor craftsmanship or material problems (stress cracking) were not relevant. One of the defects was deliberately and “secretly” introduced during the construction process with the perspective of a second validation of the construction later on. Two defects were due to puncturing by sharp objects. A quite large 1 cm diameter defect was created by an excavator shovel. For one hole of 1 cm diameter no further information about the origin was available. The 32 landfill capping systems were built with certified HDPE GMBs according to the requirements of the landfill ordinance and the certifications were mandatory. Taking all landfill, there were on average only 0.05 relatively small holes per hectare. This supports our view that the zero leakage approach is actually achievable.

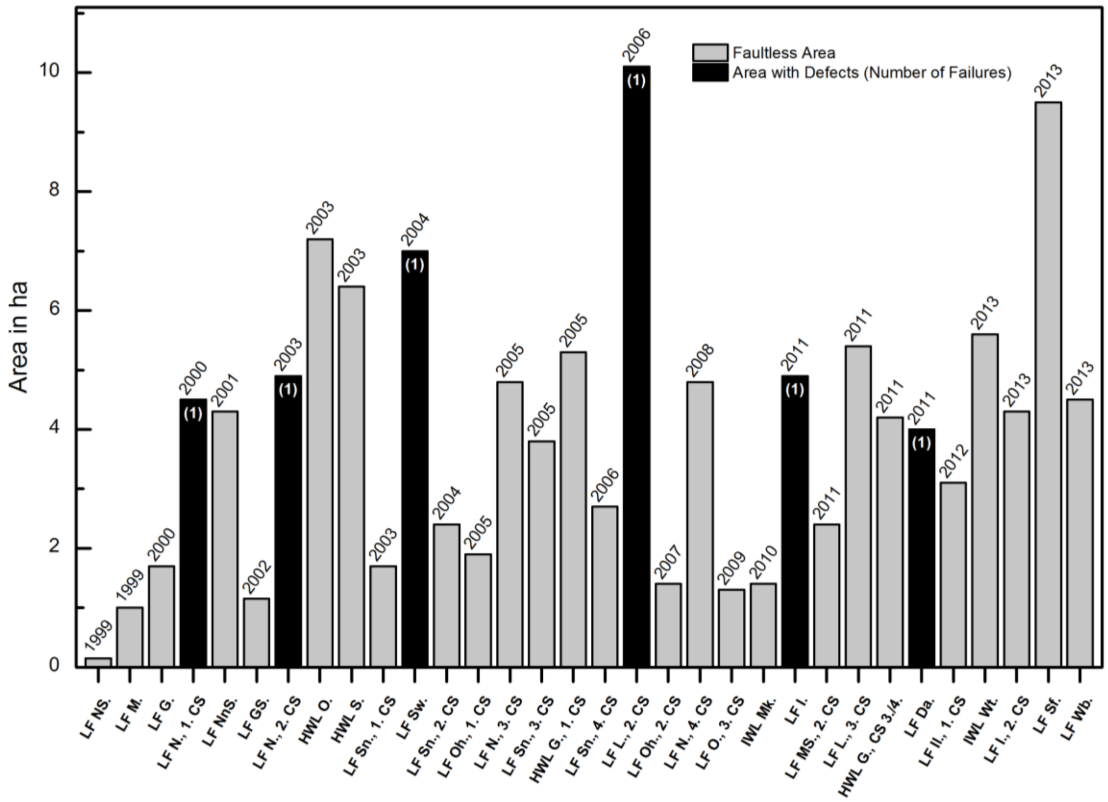

Figure 2. By LDS monitored areas of landfill cover systems of anonymized landfills in Germany. The year of the construction project is indicated above the bars. Abbreviations: LF = Landfill; HWL = Hazardous Waste Landfill; IWL = Industrial Waste Landfill; CS = Construction section.

Beside landfills, LDS are used for container constructions, leachate reservoirs, sealing of basins, floors of storage halls and other applications. In these cases, the zero leakage approach is not applied regularly. Data for an overall area of 129,670 m² HDPE GMBs were provided by SENSOR for such applications. 106 defects were found in 4 projects with 1,100 m². An unqualified and un-experienced installer was responsible for these projects. In all other projects, 20 defects were found, which is 1.6 holes per hectare. If the subgrade has a high permeability, such a number of holes may lead to a significant amount of leakage.

3.3 *Leackage through composite liner systems*

The leakage through a hole in the GMB, i.e. the volume of water flowing through the hole divided by the time duration of the flow, strongly depends on the contact with and the properties of the GMB subgrade. A detailed discussion is given in (Müller 2007). Quite often formulas are used for quantitative estimates of the severity of a hole, which are based on a model, where it is assumed that the water can flow freely within a gap between subgrade and GMB (Giroud and Bonaparte 1989a, 1989b; Jayawickrama et al. 1988). Arguments in favor of this model are as follows: the subgrade would usually be a soil or sand-gravel layer without being specifically rolled or scraped, or prepared in any other way. Pores, wheel marks, cracks, impressions, outstanding gravels, overlying gravels, foreign particles would shape the surface. No great importance would be attached to the surface contact of the GMB. Due to temperature differences during the course of a day, the GMBs would develop a large number of waves which would be covered during ballasting. Obviously, the model only applies to an installation practice, which allows bad subgrades, waves and wrinkles and insufficient covering.

On the other hand, it was shown that with a reasonable flat surface of the subgrade and a GMB free of waves an intimate contact is easily obtained by a relatively small overburden. Under this condition, the flow is located near the hole and the flow rate is essentially determined by the permeability of the subgrade (J. Walton et al. 1997; J. C. Walton and Sagar 1990). Therefore, a subgrade of low permeability will strongly reduce the flow rate and the leakage through a hole.

The waviness of the GMB is very important with respect to leakage through a GMB (Müller 2007; Rowe 2012). It is important to note that the HDPE material is incompressible. Therefore, waves cannot be smoothed out by ballasting the GMB. At least a small residual wave will remain. Larger waves or a number of waves are pushed together and standing folds, lying flat folds or mushroom-shaped waves are produced by ballasting (Koerner et al. 1999). These type of waves and wrinkles typically emerge when GMBs are installed over large areas, remain uncovered over long periods of time and are finally backfilled (Rowe et al 2012; Take et al. 2007). The various types of residual waves and wrinkles will form a network of channels in which water can freely flow. In the flat areas in between and bounded by the network of waves usually a quite intimate contact between GMB and subgrade is found. The effect of such a network on the flow through holes in the GMB is discussed in (Müller 2007; Rowe 2012).

From these considerations it follows, that leakage through a hole will be extremely low, if the subgrade has a flat surface and a very low permeability and if installation takes care to avoid waves and wrinkles to a large extent. Therefore, the liner and capping systems of the German landfill class 2 (residues of thermally or biologically treated municipal waste) and of landfill class III (industrial and hazardous waste) have to be realized as composite liner with a GCL or a CCL of very low permeability and the regulations include strict requirements with respect to surface properties of the subgrade and wrinkle-free installation. Taken the frequency of the occurrence of small holes in the GMB as obtained in section 4 as representative values, the composition of the GMB in intimate contact with a low permeability CCL or GCL would indeed lead to a negligible overall leakage of the liner system.

3.4 *Protection layers*

The vast majority of GMB faults, which were found in various kind of leak detection measurements in other countries and/or in other field of applications (namely more than two third of all faults typically found) were caused during installation of subsequent layers, i.e. during construction but after the GMB installation (Nosko and Touze-Foltz, 2000). Therefore, it would be certainly important to cover the GMB as soon as possible with a heavy, highly effective protection layer. It protects the GMB from perforation by sharp-edged or pointed objects during the construction work following the installation.

However, in this section our focus is on the occurrence of holes in the long term. The formation of holes after proper installation will be triggered by the formation of stress cracks at points of large deformation and local stress concentration. Oxidative degradation will accelerate this process since it reduces strongly the resistance of the GMB against environmental stress cracking. GMBs must be protected against deformations by coarse objects with sharp edges and points, which will cause stress concentrations. An inappropriate GMB subgrade and, mainly, the gravel drainage layer (base liner) or the earthen reclamation layers (capping) above the GMBs contain gravel, stones or even foreign bodies of various sizes. Under dynamic and static loadings during the construction phase or in use, these objects may cause unacceptably large indentations and imprints with high local deformations. Therefore, a protection layer properly designed with respect to these impacts has to be placed over the GMB as part of the installation to avoid the formation of holes in the long run. The type and design of the protective layers depends on the characteristics of the neighboring layers and the loading conditions. However, in all cases, one has to ensure that deformations imposed by indentations and imprints do not exceed the permissible local limiting strain values for the service life of the structure. A detailed description of the respective test methods for protection layers, the permissible strain limits and the types of protection layers are given elsewhere (Müller 2007; Seeger and Müller 2003).

The requirements for protection layers for HDPE GMBs in the base liner strain is ≤ 3 % bi-axial. It can easily be achieved even under very high loads with geotextile containers filled with fine sand, which form rolls of about 2 cm thickness. Very thick nonwoven geotextiles have to be used to achieve comparable protection efficiency. The design approach is described in detail in (Seeger and Müller 2003). Beside the perfect protection performance, the sand rolls are heavy enough to realize a quick ballasting of the GMB, which is so important for avoiding waves and wrinkles.

4 CONCLUSIONS

It is not the case that all liner systems necessarily leak. This was shown by an evaluation of leak detection measurements on latest technology GMB capping and liner systems. It is possible to accurately describe the relevant factors for leakage. They are related to the properties of the GMB, the properties of the surface and permeability of the subgrade, the welding and installation, the intensity of quality control, the design of protection layers, the procedures of the backfilling, the careful planning of penetrations and constructions. It is possible to avoid the problems of leakage by engineering methods. Clearly, the procedures and requirements described above are cost-intensive. The installation speed is small, on average about 1,000 m²/(days of installation and crew). However, a fair cost-benefit-comparison would have to take into account various externalities, which are difficult to estimate realistically and are often omitted. These are, for example, the costs of ground water pollution as well as remediation and follow-up care of contaminated sites in the long run.

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