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MITIGATION OF FLOODING BY IMPROVED DAMS AND DYKES

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ABSTRACT

After the past flood disasters in Europe, safe and modern levee cross-sections with geosynthetics have been carried out. The use of filter nonwovens between the levee core and the exposed drainage and ballast berm at the inner levee embankment or the arrangement of geosynthetic clay liners (bentonite mats, GCLs) at the outer levee embankment are included as well-established alternatives in current guidelines. In addition, the efficiency of stabilization measures with geosynthetics integrated in the levee was investigated and a high stability of these construction methods in case of overtopping was documented. Erosion at the inner levee embankment and unexpected levee failures can be prevented and/or be delayed. The potential that such levee breaks by forming a levee gap is minimized, because the levee body cannot be eroded. The approach to improve the safety of levees dramatically by integrating different geosynthetics in the levee cross-section could significantly reduce the danger and potential flooding damages in many other parts of the world.

INTRODUCTION

In recent decades several major flood events have shown the vulnerability of flood protection structures all around the world. Frequently, the overtopping of flood protection dikes has caused total failure of the dike. Consequently, the polders were flooded and damaged not only real assets but also claimed human life. Particularly, long lasting flood events and locally concentrated extreme precipitation and flow events were responsible for this damage (Heerten & Horlacher 2002). Locally and regionally, the threats and risks are increasing, as forecasted by several hydrological scientists and researchers (Hennegriff et al. 2006, KLIWA 2006).

In the aftermath of past disastrous flood events in Germany and other European countries, it became evident that levees are part of the society's infrastructure and need careful control and maintenance. Immediately after major flood events the willingness to improve flood protection structures is great and (tax) money is available. These programs to improve the flood protection should consider the present technical improvements e.g. for the construction of levees. The improvement of levee cross-sections by using different geosynthetics has developed to be state-of-the-art. The use of nonwoven filter materials to form a filter-stable, erosion-resistant transition between levee core and the air-side drain and ballast body or the arrangement of geosynthetic clay liners (bentonite mats) as a water-side surface seal have already become anchored as established alternatives in current regulations. Beyond the three-zone levee, the effects of geosynthetics integrated into levees as safety measures have been investigated and documented to have a high resistance capability during overflow load conditions. Erosion processes on the inner embankment and the risks of unexpected levee breaches can be minimized with geosynthetic construction techniques; geosynthetics can also be employed as support facilities for emergency reinforcing measures.

Erosion from within embankments and sudden breaches to the surface of dikes can be prevented with knowledge and implementation of geosynthetics. Thus, these technologies provide not just structural defenses but more time for evaluating risk and providing emergency response to populated areas that are threatened by rising water levels.

GEOSYNTHETIC CLAY LINERS (GCL, BENTONITE MATS)

General

Towards the end of the 1980s, a new class of construction products - needle-punched GCLs - was developed for geotechnical containment applications. The needle-punch manufacturing technique allowed bentonite clay to be sandwiched between geotextiles. This created an industrially produced alternative barrier to conventional construction techniques made of thick layers of compacted clay.

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Actually, geosynthetic clay liners are widely used in landfill sealing systems and many other applications all over the world. The total use of needle-punched GCLs with a GCL product market share of about 95% is estimated to be close to 1.000.000.000 m² since introduction in the late 80s of the last century. In early days the coffer dams to separate the canal section for repair and the secondary seal beneath the asphalt seal of the Bavarian Lech Canal were the first major applications back then to employ this new construction product in hydraulic engineering construction projects (Fig. 1) as replacement of classical compacted clay liners.

Fig. 1   Coffer dam at the Lechkanal sealed with needle-punched geosynthetics clay liner (GCL), 1989

In the last 15 years extensive tests concerning the permeability behaviour in case of desiccation and re-hydration (structure healing process), ageing and system efficiency have been carried out. Thus, the GCL is the most carefully tested and investigated mineral sealing element in the field of environmental protection and hydraulic engineering. Ongoing lysimeter trials and field excavations are confirming a long-term efficiency (Bluemel et al. 2002, Fleischer et al. 2007).

For GCLs a self-healing process after desiccation is verified under sufficient surcharge (soil cover thickness). Due to the extreme swell capacity of sodium bentonite with fresh water shrinkage cracks are reversible, if there is a sufficient surcharge, too. Sodium-bentonite needs only 1 litre/m² of water to swell again and to be sealing-efficient with a corresponding surcharge. This effect is a very important performance characteristic and can lead to an increase of system efficiency as dykes are not subject to a permanent water infiltration.

Aside from applications for environmental protection, there have also been many important water-related hydraulic engineering structures successfully realized with needle-punched bentonite mats over past decades and advanced product developments have been made for underwater installations (BAW 2002). Needle-punched bentonite mats have gained widespread acceptance for levee improvement projects because these products create a simple, effective, economical seal for a levee that simultaneously provides erosion protection for the levee body (Heerten & Horlacher 2002, Heerten 2003a). Following the Elbe River floods that took place in Germany between 2002 and the end of 2005, about 150 levee reconstruction projects are known, being carried out in this period, in which about 2.2 million m² of needle-punched nonwovens, about 300 000 m² of geogrids and about 700 000 m² of geosynthetic clay liners (bentonite mats) have been employed (Heerten 2003b, Heerten & Werth 2006). One example is shown in Fig. 2. In the meantime, needle-punched geosynthetic clay liners are considered as state-of-the-art construction materials in levee/dyke construction (German Association for Water, Wastewater and Waste, DWA 2005) in Germany and show increasing acceptance and use also in other countries.
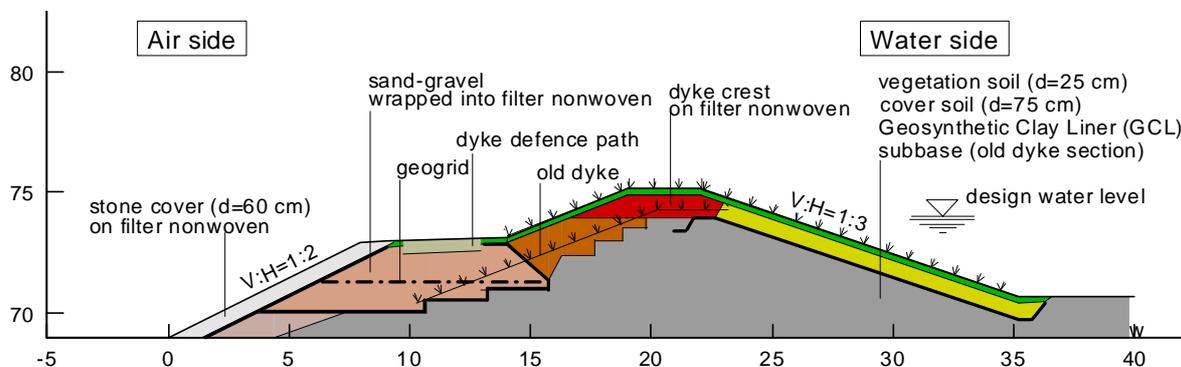

Fig. 2   Standard cross-section of a reconstructed Elbe levee near Bösewig / Sachsen-Anhalt
(Heerten & Werth 2006)

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Levee seal – current excavation results

The installation of a GCL can be carried out in a simple manner with a minimum use of technical equipment. After installation of the profiled bedding the GCLs are unrolled and overlapped. Afterwards the GCL is covered with soil.

According to DWA (2005), a cover layer thickness of 80 cm is recommended for both types of mineral sealing system in order to withstand climatic influences. Bentonite mats offer the advantages of low sensitivity to settling without degradation to seal characteristics, consistent quality even after installation, as well as good friction behavior for steeper embankment slopes. However, the potential effects of root penetration and/or rodent infestation must be given attention just the same as with classic seals made of cohesive soil. These effects can be counteracted by the design of the levee's project-oriented cross-section geometry, the use of non-cohesive cover layers unattractive to burrowing animals (Fig. 3) or by additional engineering measures. Further information about planning and building with geosynthetic clay liners can be found in Federal Waterways Engineering and Research Institute (BAW 2006), German Geotechnical Society (DGGT 2002), Heerten (2007a) and Saathoff & Werth (2003).

Fig. 3   Covering Bentofix® GCL with locally available fine gravel to ward off burrowing animals

With regard to mineral sealing layers (CCLs and GCLs) in landfill sealing systems, concerns about desiccation for mineral layers and ion exchange for bentonite have been reported and discussed (Heerten & Koerner 2008). In contrast to compacted clay liners (CCLs) needlepunched GCLs show very good "self-healing" performance after desiccation, especially due to the small amount of water needed (approx. 1 l/m²) under a soil confining stress of 15 kN/m². The author also discovered during several excavations in the past years that ion exchange occurred during the first 2 - 3 years (Heerten & Reuter 2006) and that the self-healing was extremely evident with the excavated GCLs which had powder bentonite sandwiched between the geotextiles.

Excavations of bentonite mats at the German levees Lippe / Haltern-Lippramsdorf (a) in the Ruhr region as well as on the Kinzig near Offenburg (b) at the southern Rhine were carried out recently. The bentonite mats at these locations have been in place for 6 and 12 years respectively. The excavations were performed with the professional accompaniment of ICG Leonhardt - Veith GmbH & Co. KG, geotechnical engineering consultants, as well as representatives of the Karlsruhe office of the BAW. The results of these excavations were presented at the water engineering colloquium 2007 held at the Technical University Dresden (Fleischer et al. 2007). Subsequent laboratory investigations were aimed at assessing possible material changes that may have taken place over the multi-year deployment. In comparison to unused virgin products these excavated samples exhibited no significant quality differences (Fleischer et al. 2007), thus confirming the fully functional condition of the installed bentonite mats. The bentonite mat samples taken exhibited permeability coefficients of k = 2.5 × 10^{-11} m/s to 8 × 10^{-11} m/s, even after laboratory proved ion exchange a hydraulic capability corresponding to the suitability tests prior to installation. Geosynthetic clay liners in a levee not being placed between drainage layers as it is a standard for landfill sealing systems show no influence or evidence of changing water content with regard to desiccation or self-healing. The implementations of both old levee improvement measures, (a) and (b), are presented below.

Lippe levees (GCL excavation after 12 years deployment period)

This levee was improved in 1994. It is located in an area of mining subsidence and it is built along both sides of the Lippe River in the vicinity of Haltern-Lippramsdorf and Marl in the Ruhr region. These levees were improved in 1994 for floodwater protection of surrounding residential areas and the nearby Auguste Victoria

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mine. The improvement raised the levees by 50 cm. The project was commissioned by the Lippe Association who has tailings in the area left over from coal mining activity. A seal on the levee was necessary for both levee stability as well as for ecological reasons (leaching from tailings). The procurement of clay or loam soils was deemed to be uneconomical and would have necessitated extensive installation and monitoring overhead on the 1:n = 1:2 grade embankments during construction. Furthermore, construction time was limited to the months of low rainfall. These prevailing conditions led to an alternative; to lay out a shear-force transmitting, needle-punched geosynthetic clay liner as a sealing element on surfaces at both sides of the Lippe River then to cover this with a 40 cm thick layer of sand, crushed stone and topsoil (Fig. 4). At the southern levee, newly located tail piles were encircled with GCL. Steel sheet piling was installed along the foot of the northern levee to which the GCL was attached. These conditions provided further incentive for a solution with subsidence-insensitive GCL as connections to rigid structures can be accomplished readily and produce a very tight seal.

Kinzig levees (GCL excavation after 6 years deployment period)

As early as 1987, the Southern Upper Rhine / High Rhine Water Authority began work to upgrade the 160 km long levees on the Kinzig (some parts then over 100 years old) to current state-of-the-art conditions. Floodwater events in 1990 and 1991 had already revealed critical levee leakage at several points. An extensive program for Kinzig levee reconstruction was formulated which was to be carried out in 2000 and 2001 that had the objective of creating a state-of-the-art structure. This program included plans to raise defined sections of the levee an average of between 60 cm and 80 cm, a reinforcement of the levee, and to place a needle-punched, shear-force transmitting geosynthetic clay liner on the levee's water side (Santo 2003). On the 1:n = 1:2.8 grade embankment, GCL was laid in sections of 100 m each then covered with a 60 cm thick layer of compacted fine gravel (as an intermediate layer to ward off burrowing animals). These layers were subsequently covered with a final 20 cm layer of topsoil then planted with grass. The gravel was taken directly out of the Kinzig's bed, which also represented an important maintenance function. On the left side near the town of Weier, a total of 36 000 m^2 geosynthetic clay liner was installed as a levee seal (Fig. 5). From the standpoint of water authorities, the cost of delivery for a mineral sealing material would have made a loam seal uneconomical. Implementation and quality assurance was done with the consent of a geotechnical expert and the BAW.

Fig. 4 Lippe River levee reconstruction (1994): Installing Bentofix® GCL as a levee seal
(Saathoff & Werth 2003)

Fig. 5 Kinzig River levee reconstruction (2001)

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GEOTEXTILE AND GRAIN FILTERS

As shown in Fig. 2, filter geotextiles are commonly used in present cross-section design of levees. But what are suitable geotextile filters and how are geotextile filters to be designed compared to grain filters? A filter used in geotechnical and hydraulic engineering must meet the almost contradictory retention and permeability criteria. Still today most designers wrongly assume that retention and permeability are the only criteria which are required for a geotextile filter design, and possibly tensile strength requirements or other typical product values out of data sheets are additionally specified. But it is important to point out that thickness, mass per unit area and elongation at break are very important requirements for filtration design (thickness) and installation robustness (mass per unit area / elongation at break), too.

A designed or checked (field test) high installation robustness with no risks of puncturing of the geotextile filter during installation is the precondition with regard to the designed and specified "opening size" of the geotextile filter! **It makes no sense to debate "opening size" and to accept the risk of puncture!**

State-of-the-art grain filter design

Dealing with filtration and filter design it has to be basically considered that the filter elements are the pores in the filter structure and not the elements formung the pores.

Grain size diameter, uniformity of the grain size distribution, shape of the grains and package density of the grains indirectly define the pore structure and the pore size distribution of the grain filter material. The most comprehensive approach for the actual dimensioning of granular filters for non-cohesive soils is given by Ziems (1968), indicating a permissible distance ration A_{50} of the grain diameters d_{50I} (base material) and d_{50II} (filter material), depending on uniformity U_I (base material) und U_{II} (filter material) in a design diagram (Fig. 6). By Teindl (1980) it was shown with regard to Ziems' design diagram that the very often used Terzaghi filter rules are on the uncertain side when $U_{II} > 2$. But this is in good accordance with Terzaghi's basic work, because he himself limited his filter rules to soil/filter materials with $U < 2$!
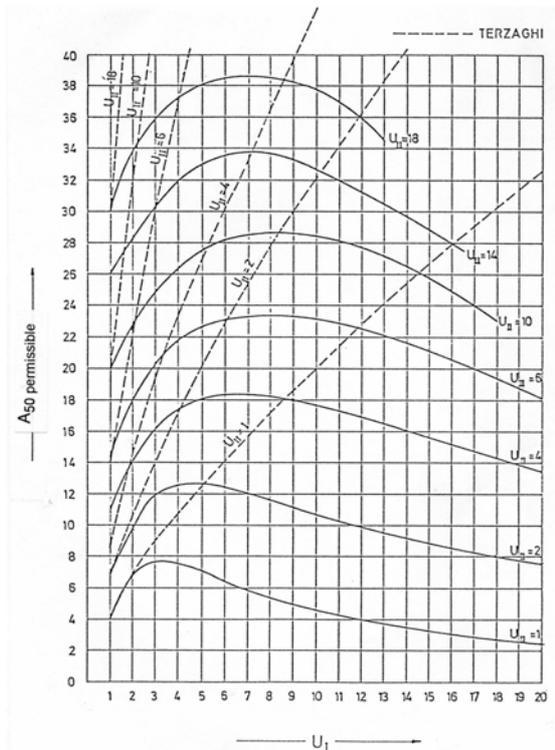

Fig. 6   Diagram by Ziems for the dimensioning of granular filters compared to the filtration rules by Terzaghi
(Teindl 1980)

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According to Wittmann (1980) safe filter conditions with the distance ratios A_{50} given in the Ziems diagram are only achieved in conjunction with a sufficient filter thickness. The calculation of the pore structure and filtration length for a given filter application is a very complex approach, but Wittmann (1980) pointed out that a safe filter design according to the approved Ziems diagram will only be achieved with the following requirement on the filter thickness:

$$t_F \geq 25 \cdot d_{50II} \qquad or \qquad t_F \geq 100 \cdot d_{10II}$$

with t_F = thickness of the filter layer

The state-of-the-art design practice of granular filters will follow the approach:

Make full use of the allowed distance ratio A_{50} between base and filter material
- to create the filter as coarse as possible
- to minimize the number of filter layers
- to ensure the highest water permeability
- to avoid filtration by surface retention (sieving) with the hydraulically unfavourable danger of a filter cake
 formation.

The as-coarse-as-possible approach for the grain filter design leads automatically to a deep filtration characteristic of the filter.

In general the distance ratio A_{50} out of the Ziems diagram (Fig. 6) shall be larger than 4 to avoid filter cake formation and surface filtration which, if occurring, can lead to a dangerous reduction in permeabiltiy in the soil-filter system up to 4 order of magnitude. A possible reduction in permeability will cause additional hydraulic head and can be dangerous for the safety of the geotechnical or hydraulic structures. This is clearly indicating that too small pores in a filter layer can lead to a risk and must be avoided. Surface filtration with filter cake formation therefore must be avoided in filter design and application.

State-of-the-art geofilter design

Actual design and specification

The current practice of the geotextile filter design very often only asks for an opening size and a water permeability or permittivity to be determined. A thickness requirement for geotextile filters is still quite unknown and specification criteria to avoid puncturing during installation are widely missing, too.

The openig size $O_{90,w}$ (= the effective opening size of the geotextile where 90% of the well defined test soil is retained in the wet sieving test, DIN EN ISO 12956 Geotextiles and geotextile related products – Determination of the characteristic opening size) is usually required to be smaller than a factor x multiplied by a defined grain-size distribution parameter of the base material.

$$\mathbf{O_{90,w} < x \cdot d_y}$$

This design criteria has no limits for the smallest size of pores to avoid filter cake formation and surface filtration by selecting a geotextile filter. As a consequence the geotextile filter may clog or block with a decrease in permeability up to 4 order of magnitude as known and described also for grain filters (Heerten 1993). A simple permeability criterion for geotextile filters that the permeability of the geotextile should be 10 to 100 times the permeability of the base soil is not enough for good design and performance of a geotextile filter. Therefore design and specification criteria for geotextile filters have to consider

- a limit for small pores
- a thickness / filter length requirement
- a safe installation criterion to avoid puncturing.

Analogies grain filter / geotextile filter design

Sufficient pore size and thickness requirements of the geotextile filter can easily refer to grain filter design by considering **a pore size analogy and a thickness analogy** comparing grain filters and <u>needle-punched nonwoven geotextile filters</u>. Only for this type of geotextile filters this comparison is possible, because of the

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three-dimensional pore structures in both alternatives, the grain filter and the needle-punched nonwoven geotextile filter (NP-NW-GTX filter). The basic idea of the pore size / thickness analogy approach simply is to offer "the same" pore structure for the filtration job by a grain filter or a geotextile filter, considering that the filter elements are the pores and not the elements (grains/fibres) forming the pores.

Compared to grain filters, also NP-NW-GTX filters can have a wide-spread pore size distribution and very different pore sizes when using staple fibres (cut fibres) of different diameter. Some special pore size distribution investigations were carried out and show the difference in pore size (Heerten 1992).

The results (Table 1) show that nonwoven (NW) needle-punched (NP) staple fibre (SF) geotextiles (GTX) can be produced in a wide range of pore size distributions to fulfill the demand for different pore sizes in analogy to the grain filter design for different filter applications. The pore size distributions refer to grain filters ranging from medium sand to medium gravel!

Table 1: Investigated pore sizes of nonwoven needle-punched staple fibre geotextiles (NW-NP-SF-GTX) using the mercury intrusion method compared to $O_{90,w}$ determined by wet sieving

Test specimen	O_{10}	O_{90}	$O_{90,w}$
	(mm)	(mm)	(mm)
Terafix 600	0.06	0.3	0.08
Terrafix 601 S	0.075	0.8	0.15
Secutex 444	0.07	1.1	0.26
Depotex 755 GG	0.08	3.0	0.53

O_{10} :   10 % pores are smaller
O_{90} :   90 % pores are smaller

By using the "pore-channel-diagram" developed by Teindl (1980) and the results of the pore size distribution of a NW-NP-SF-GTX filter (Heerten 1993) it is easy to receive an $O_{90,w}$ opening size criterion for NW-NP-SF-GTX filters by considering d_{50I} and U_I of the base soil (Fig. 7). Based on the diagram in Fig. 7 a range for selecting an acceptable opening size of a NW-NP-SF-GTX Filter can be determined. The upper limit for the range of $O_{90,w,D}$ is given by the design value itself and the lower limit by the "as coarse as possible" approach in analogy to grain filters, with $O_{90,w}$ selected $\geq 0.8\ O_{90,w,D}$. In addition, $O_{90,w,s} \geq 0.2\ O_{90,w,D}$ or $O_{90,w,s} \sim d_{50I}$ should be considered as lowest limits. If selecting corresponding small opening sizes additional investigations or calculations are strongly recommended to avoid clogging or blocking phenomena of the geotextile filter with the danger of filter cake formation.
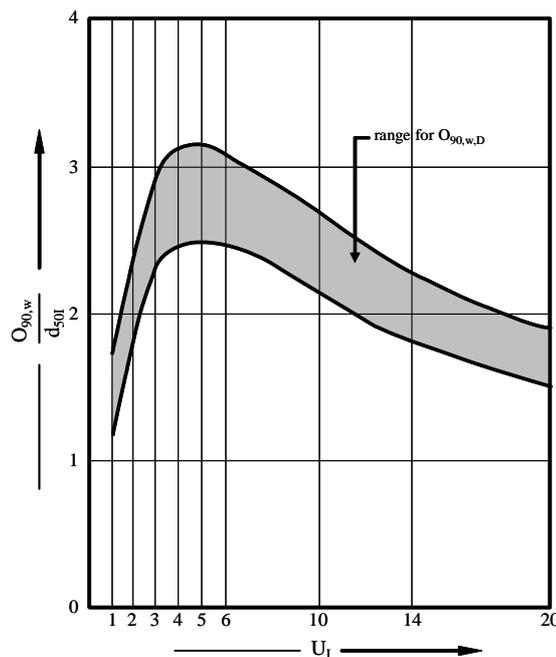

Fig. 7   Range of design values of $O_{90,w,D}$ as function of d_{50I} and U_I of the base soil

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The thickness analogy between required grain filter thickness and required geotextile filter thickness is based on the idea that <u>one</u> grain layer is one filtration slice for the grain filter and one opening size slice is one filtration slice for the NW-NP-SF-GTX filter. Therefore the grain filter thickness requirement of $t_F \geq 25 \cdot d_{50II}$ would lead to a geotextile filter requirement of $t_{GTX} \geq 25 \cdot O_{90,w,D}$. The investigation of several NW-NP-SF-GTX filters dug up out of hydraulic structures showed that the reduction of permeability of these geotextiles after long-term service in the structure was in the frame of permeability reduction known from grain filter design with the "as coarse as possible" approach (Heerten 1993). The thickness of these dug-up NW-NP-SF-GTX filters was in the range of $25 \cdot O_{90,w,D} < t_{GTX} < 50 \cdot O_{90,w,D}$.

Geotextile filter design

With the pore size and thickness analogies derived for grain filters and NW-NP-SF-GTX filters a very simple geotextile filter design is possible: With d_{50I} and U_I of the base soil out of Fig. 7 an opening size $O_{90,w,s}$ of a suitable product can be determined

$$O_{90,w,D} \leq O_{90,w,s} \leq 0.8\, O_{90,w,D}$$

and the thickness t_{GTX} of the geotextile filter should be limited by

$$25 \cdot O_{90,w,D} \leq t_{GTX} \leq 50 \cdot O_{90,w,D}$$

With these requirements regarding opening size and thickness of the NW-NP-SF-GTX filter a sufficient long-term permeability of the geotextile filter can be expected. Alternatively, a special permeability check is necessary for different geotextile parameters.

Survivability criteria to avoid puncturing of the geotextile filter

During installation a geotextile filter has to survive in the harsh environment of a construction site without puncturing. **With the risk of puncturing any effort with regard to a safe filter design is useless!**

The installation stresses can vary in a wide range from filling up and compacting a drainage trench wrapped with a geotextile layer to heavy stone dumping on top of the geotextiles in e.g. revetment or breakwater constructions. Only NW-NP-GTX have an ability to deform (high elongation at tensile test, usually > 40 %) and provide high robustness.

High elongation behaviour provides the superior properties during the construction load case, which is determined as being the biggest risk for damaging the geotextiles. This requires minimum strength and minimum mass per unit area, but maximum elongation.

The impact test and the abrasion test will normally lead to nonwoven needle-punched geotextiles with $m_A \geq 600$ g/m² (Heerten 2007c). But even in drainage ditches or other geotechnical and hydraulic engineering structures it is recommended not to use geotextiles with mass per unit area ≤ 300 g/m² and elongation at break < 40 %.

Recently, the Federal Institute for Materials Research and Testing (BAM, Berlin) – in the frame of necessary BAM certifications of all geosynthetics being used in landfill application in Germany after the new German Landfill Directive (2009) – defined base requirements for filter geotextiles being used in landfill sealing systems with the demand of > 100 years functional effectiveness. The following requirements have to be fulfilled with the additional need of a state-of-the-art filter design (opening size / permeability / permittivity):

Mass per unit area:	$\geq$ 300 g/m²
Thickness:	$\geq$ 3 mm or at least 30 x characteristic opening size O_{90}
Puncture force:	$\geq$ 2.5 kN
Push-through displacement:	$\geq$ 50 mm

These requirements will only be fulfilled by NW-NP-GTX!

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OVERFLOW AND EROSION PROTECTION WITH GEOSYNTHETICS

Levee breaches caused by unintentional overflow, and consequential freeboard loss, inevitably represents a form of failure for levees ("unwanted polder") which are not secured. As floodwaters rise to the level of the levee's crown, emergency measures to shore up unsecured levee sections is a high-risk task for anyone involved with such efforts because a sudden breach of the levee must always be considered an imminent possibility. Particularly in areas with major damage potential, protective measures should be demanded which would significantly lower that damage risk.

There are numerous options to retrofit levees and dams with deliberate overflow features. DIN 19712 stipulates, *"Overflow segments are to be carefully planned, implemented and maintained. ... Where potential damage is not too critical, it is sufficient to reduce the grade of the land-side embankment within the range of 1:10 to 1:20 and provide a protected embankment footing."* The risk of a levee breach in combination with sudden flooding of the polder *"can be reduced by protecting the land-side embankment against erosion."* This type of improvement along entire stretches of levee *"was not previously an element of water engineering practice"* (DIN 19712/1997). The standard goes on to state, *"Every levee plan is to be reviewed for catastrophe-reducing potential through the implementation of erosion protected overflow segments at opportune points along the levee."* Under the expression "levee planning" all plans for levees, i.e. also those for levee improvement, are included. However, in practice these requirements are not generally being followed yet (Haselsteiner et al. 2007).

Deliberate overflow segments in levees offer the advantage that water quantities subsequently retained in the polders behind the levee at these points will reduce the floodwater hazard further downstream. But even in endangered areas with high damage potential it is recommended that protective measures be taken to preclude a complete levee breach. Because it is generally uneconomical to create very flat-sloped overflow segments for levees with concrete or grouted revetment – as, for example, is the case in the floodwater relief systems in dam structures (i.e. spillway chutes) – geosynthetics have been gaining acceptance for these applications. In the context of a "ground/geosynthetic composite system" it is possible to develop protective elements that will stabilize endangered inner embankments to prevent levee breaches and maintain levee cross-section integrity in the event of overload conditions. Potential protective methods (which can be combined with one another) employing ground/geosynthetic composite systems are:

(I)   surface erosion protection in combination with intact grass cover
(II)   near-surface erosion protection (if grass cover should be lost)
(III) integrated erosion protection (protecting the levee's cross-section)

Method (I) is accomplished by reinforcing the inner embankment with an armored grass cover. A three-dimensional erosion protection system is put into the upper layer of the topsoil layer. This protection system is formed by a matting of random array extruded synthetic fiber laid out onto the surface then subsequently filled with a topsoil/seed mixture. The growth of fine roots in the grass cover intertwine with the mat's random array to stabilize the grass cover which is so important for erosion protection. The overhead to realize this method is quite minimal because erosion protection is a consequence of the vegetation measures taken. Model experiments to test the effectiveness of armored grass cover for overflowed dam embankments were performed in Great Britain in 1987. These experiments proved the good functionality of the three-dimensional random array (CIRIA Report 1987). The effectiveness of non-armored grass cover and armored grass cover in comparison to systems with concrete construction are presented in Fig. 8.

Method (II) is also an embankment-parallel protective mechanism but it is placed about 20 cm beneath the topsoil layer of the inner embankment. This technique produces a very high degree of protection even if the grass cover should be lost. High-tensile geogrid/nonwoven combinations (2-dimensional, like Combigrid®) are laid out contiguously over the surface of the levee's core and fixed in place with ground pins (Fig. 9). Thus a stabilized overflow bed remains even if the grass cover should be lost. A high degree of protection during overflow can be achieved with relatively low realization overhead (removal of the topsoil layer).

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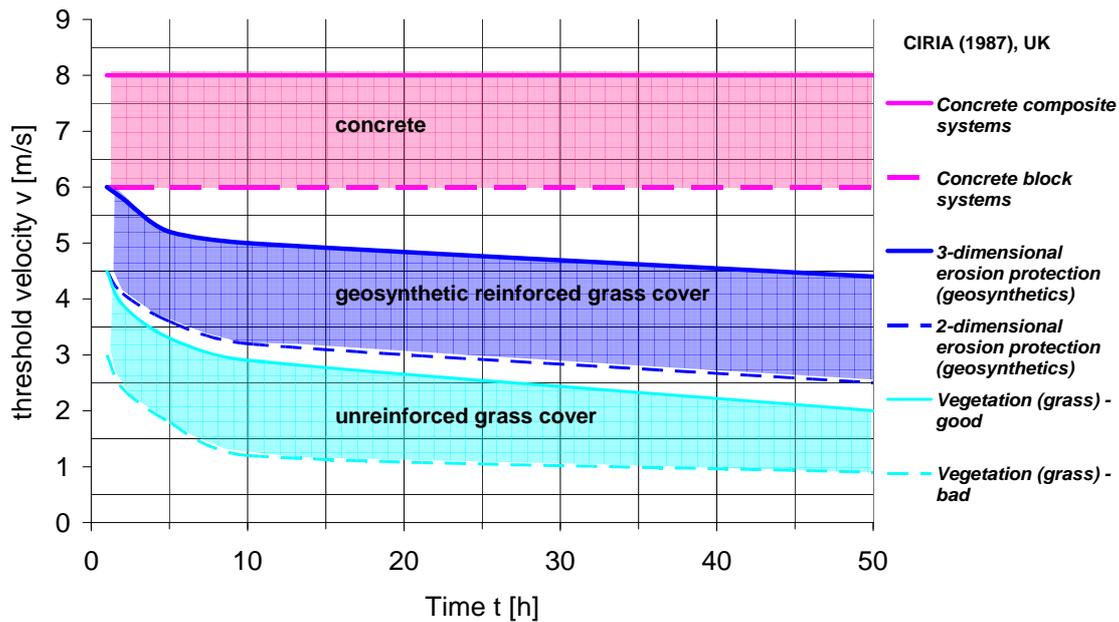*7 to 8 December 2010 | Bangkok, Thailand*

Fig. 8 Effectiveness of non-armored and armored grass covers on dam embankments during overflow (CIRIA 1987)
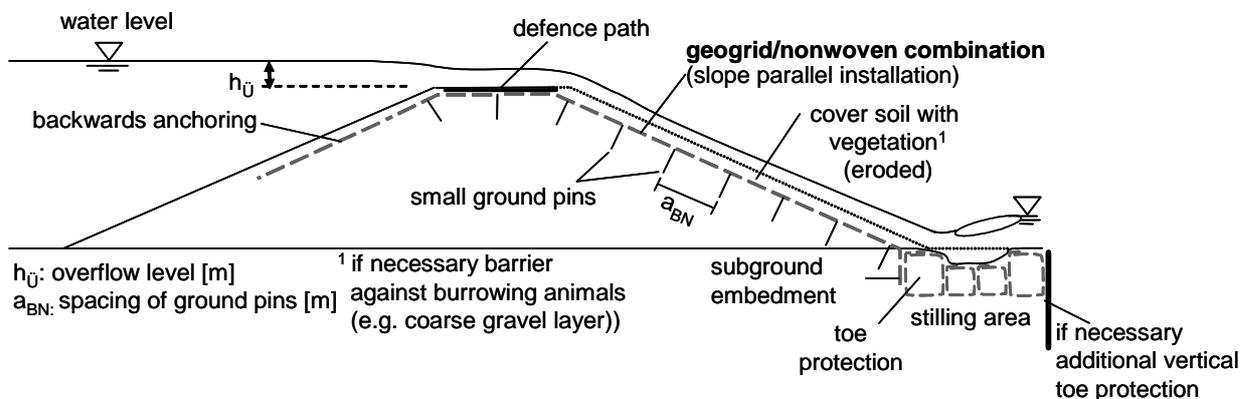

Fig. 9 Overflow protection per method (II), embankment parallel with geogrid/nonwoven combinations and ground pins (Haselsteiner et al. 2007)

As a protective measure built into the levee, method (III) offers the greatest protective functionality. A breach failure, as is possible in classic non-reinforced levee bodies, can be excluded entirely. The envelope method (wrap-around method) of layer-oriented encapsulation of earth in nonwovens, or preferably geogrids, is considered a standard procedure for forming earthwork and roadway reinforcement in steep embankments and support structures (slopes of 45° to 90°). Corresponding structures are known for their excellent stability under earthquake loading compared to traditional rigid structures of concrete. Though levees have comparably less embankment slope, this construction technique can be used to handle hydraulic overload conditions even for embankment slopes up to about 33°. Furthermore, when the inner embankment is designed according to Fig 10, a cascaded spill is produced that slows flow speed. The protection afforded by this construction technique can be classified exceptionally high. Implementation is quite simple but does require greater overhead in comparison to methods (I) and (II) due to the dimensioning of horizontal embedded lengths into the area of the levee's core. High earthquake resistance is an additional advantage in earthquake areas.

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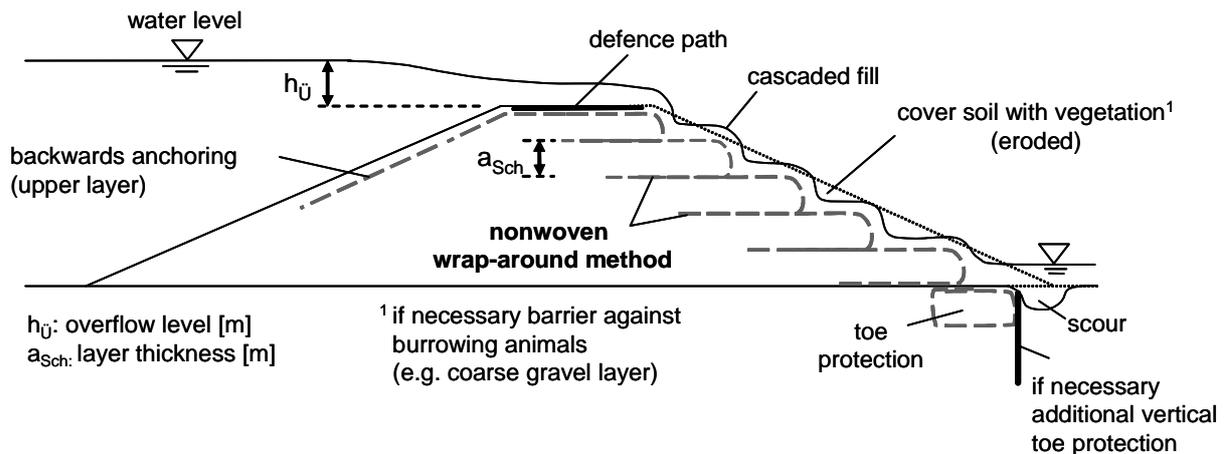*7 to 8 December 2010 | Bangkok, Thailand*

Fig. 10   Integrated overflow protection per method (III) in envelope method (Haselsteiner et al. 2007)

Model experiments were conducted on the above-referenced methods (I) through (III) in 2006 at Test Institute for Water Engineering and Water Management at the Technical University Munich to evaluate the resistance capability of levee inner embankments with geosynthetic reinforcements under overflow conditions. These investigations were initiated as a part of the "levee reconstruction" research and development program established by the Bavarian State Office for Water Management. The objective of these model experiments was to develop simple, cost-effective construction techniques employing geosynthetics which would inhibit the erosion of levee inner embankments under overflow conditions. Experiments which simulated the loss of vegetation layer (methods (II) and (III)) were carried out and evaluated. Systems with needle-punched nonwovens, sand mats and nonwoven/geogrid combinations were tested in conjunction with inner embankment installation variations: slope parallel, horizontal, with and without envelopes. A levee-integrated with an enveloped ground/geosynthetic composite system on a steep embankment slope of $1:n = 1:1.5$ and a near-surface system with needle-punched geogrid/nonwoven combination (Combigrid®) on a slope of $1:n = 1:2.5$ were overflowed. Systems with geosynthetics used in the envelope method (method III, Fig. 11) and embankment parallel nonwoven/geogrid combinations or sand mats with structural fixation (method II, Fig. 12) proved to be robust. The details of experiments performed are documented in Haselsteiner et al. (2007).

Fig. 11   Model experiments at the Technical University Munich,
Overflow of the inner embankment per method (III).
Left: before overflow, right: in overflow state with up to 130 l/m·s (Haselsteiner et al. 2007)

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Fig. 12   Model experiments at the Technical University Munich,
Overflow of the inner embankment per method (II)
Left: before overflow, right: in overflow state with up to 300 l/m·s (Haselsteiner et al. 2007)

SUMMARY

Fig. 13 depicts an improved levee cross-section optimally reinforced with geosynthetics. Its water-side has a surface seal of bentonite mats (preferably needle-punched GCL with powdered sodium bentonite and woven/nonwoven geotextile composite as carrier layer and nonwoven geotextile as cover layer). The levee's core has integrated erosion protection provided by encapsulating levee core material in nonwovens with the envelope method. A filter-effective configuration of air-side drainage is combined with a levee defense roadway. The levee's cross-section was implemented in Poland after the 1997 Oder River floodwater. It offers optimal prerequisites for a long-term, protective, stable and overflow-secure levee. Breach behavior, as would be exhibited by a levee with conventional cross-section consisting <u>only</u> of earthen materials, can be presumed eliminated. Additionally, a high resistance against earthquake loading can be expected which may be important in earthquake areas.
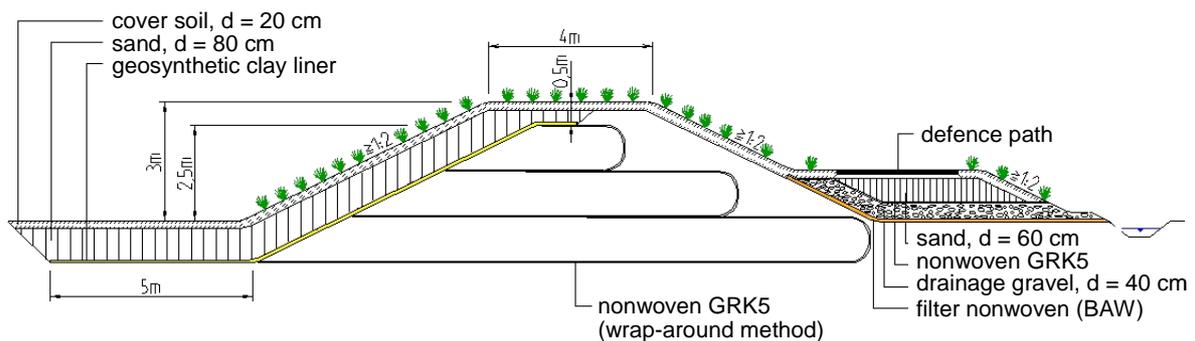

Fig. 13   Cross-section of a reconstructed Oder River levee in Poland (Heerten 1999)

Can we build safer levees? – Yes, we can!

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