20 years experience with GCLs in dams and dykes

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ABSTRACT

Although first applications of geosynthetic clay liners in hydraulic engineering are dated in 1989, the development of materials, systems and laboratory testing standards have been considered primarily on landfill applications during the recent decades. In comparison to landfill applications during the last 20 years, the acceptance of GCLs as sealing systems in hydraulic engineering applications increased more slowly. As lining elements for dams (with permanent hydraulic loads), levees (with temporary hydraulic loads) and coastal dykes (with wave pressure loads during wave run-up and overtopping) different requirements have to be taken into account. In all cases, GCLs provide significant functional advantages relating erosion stability in comparison to loose soil particles of compacted clay liners under hydraulic loads. During the last years, new recommendations for lining elements of river levees have been published by DWA. Further recommendations dealing with all systems of lining in hydraulic engineering – also including GCLs – will follow in 2010. The paper will focus on the experiences gained in hydraulic engineering applications during the last 20 years. Wet and dry installation methods are described in the paper and designs for dams and levees are presented. Excavations of samples taken from river levee lining applications after 12 years in service still show a high efficiency in sealing effectiveness. Moreover, the integration of such works into dyke rehabilitation works is pointed out. Latest investigations provide new solutions in stabilisation of sea dykes, which are forced by wave loads during tidal flood, so the extraction of natural clay in restricted coastal zones can be minimized. Furthermore, results from large scale physical model tests using GCLs as safe barrier against wave run-up and breaking waves are presented.

1. INTRODUCTION

Geosynthetic constructions are known in hydraulic engineering since approx. 1965. The first recommendations of the working group Ak14 "Synthetics in Earthworks and Hydraulic Engineering" of the German Geotechnical Society (DGGT e.V) founded in 1972 have been published together with the German Association for Water, Wastewater and Waste (former DVWK, today DWA) in the years 1975 "Basics", 1979 "Geomembranes" and 1982 "Geotextile Filters" and "Application Fields". In 1989 the DVWK for the first time edited a recommendation "Application and monitoring of synthetics in earthworks and hydraulic engineering" as recommended by Ak14, and the functions filtration, separation, drainage, protection, sealing, reinforcing and packing, including knowledge concerning raw materials, construction methods and testing methods are comprehensively and multidisciplinary discussed i. e. for applications in landfill technology, hydraulic engineering and traffic engineering (DVWK, 1989). In 1988 needle-punched geosynthetic clay liners have been developed introducing a high efficient sealing component bentonite in combination with geotextile components as carrier and cover layer. Since 1989, geosynthetics technology has rapidly developed as to construction methods and product technology. A large number of German recommendations, regulations, standards and guidelines for numerous requirements have been worked out and new fields of research have been developed. Today, numerous regulations for the use of GCLs are available for hydraulic engineering applications, amongst others the EAG-GTD (2002), DWA (2005) and the bulletins published by the BAW (EAO, 2002). The long-term stability of geosynthetics which was questioned in the past are these days confirmed and directly compared to the long-term stability of the structures which to be planned. Some GCLs are proven for use in landfills serviceability times of considerably more than 100 years under loads and are certified by the Federal Institute for Materials Research and Testing, BAM, Berlin. These tests are based on Arrhenius-Extrapolation and can confirm the internal shear strength of the GCL by conducting specially developed long-term shear box tests. In comparison to landfill requirements for GCL applications the Federal Waterways Engineering and Research Institute (BAW), Germany, is often involved in setting standards for the use of geosynthetics in hydraulic engineering applications besides the application for navigable channels.

During the recent years of GCL optimization needle-punched and shear-strength-transmitting GCLs are well established for dry installation. Nowadays further major specific requirements for hydraulic engineering applications have been met by smart product development:

- Underwater installation techniques,
- Robustness against stone dumping as an armour layer for bed and slope protection systems at navigable channels,
- Testing methods against bentonite wash-out under turbulent hydraulic conditions, and
- Stability against wave loads.

2. FIRST EXPERIENCES IN HYDRAULIC ENGINEERING (1989)

During the rehabilitation of the hydropower canal "Lech" in 1989, the state-of-the-art for available lining systems as well as environmental aspects were considered. The concept for the rehabilitation of the canal included a guarantee slope stability of the canal including a failure of the sealing system. During substantial preliminary investigations, solutions for the installation of a new sealing system in dry condition were considered. Alternative sealing systems under consideration of hydraulic binders and asphalt have been discussed as well as the use of GCLs. The clients i. e. electric power company (LEW) and the Water Management Authority of the Free State of Bavaria, finally specified and realised a complete rehabilitation of the section Meitingen with a controllable sealing system made of a GCL (first layer) and an asphaltic liner (second layer) with a monitoring drainage layer between both liners. Between the coffer dam at km 10.5 and the hydro-electric power station Meitingen at km 14.5, the following steps were carried out:

- Drying the canal: Installation of earth coffer dams by the use of GCLs as lining systems (see Figure 1)
- Removal of the existing gravel layer and clay layer
- Preparation and trimming of the new cross-section of the canal with intensive compaction of the canal slopes (trapezoidal canal cross-section)
- Installation of the GCLs providing a control for the efficiency of the asphaltic liner. The GBR-C from a receiving basin whose lateral height is restricted to the upper edge of the canal's lining invert.
- Installation and compaction of 50-cm-thick gravel for sealing and drainage purposes
- Installation of the asphaltic liner:

two layers at the slopes, that is 6-cm-thick asphalt drainage layer and 8-cm-thick asphalt concrete (permeability coefficient $k_f < 10^{-8}$ m/s)

two layers at the invert, that is 6-cm-thickk asphalt drainage layer and 8-cm-thick asphalt concrete

special ecological structure of the water exchange area

Figure 1: Rehabilitation of the hydropower canal Lech in 1989 – easy coffer dam lining with GCL

Eight pore water pressure gauges have been installed in the area of the concrete construction between the canal's asphalt liner and the concrete construction of the power station to ensure especially a careful control of the connecting areas. In addition, at a distance of approx. 500 m two seepage gauges and one groundwater gauge were installed in each canal dam. These facilities allow a perfect control of the seepage water level beneath the asphalt sealing. Deviations from normal operating conditions could be recognised at once and countermeasures could be taken.

At the beginning of November 1989 the section Meitingen of the canal Lech was ready for use and the hydro-electric power station was put into service again. At that moment the installed control gauges had to prove quality and efficiency of the lining. First measurements confirmed the efficiency of the installed asphalt liner and of the control system with the GCL in the receiving basin. In most sections of the lining no seepage water was registered. However, in one section shortly after beginning of flooding an increase of water level in the receiving basin occurred. Within approx. 20 days the water level fell to almost zero and did not rise again in the following days. The gauges in the dam did not show any influence of the groundwater level or any seepage lines in the canal dams. Thus, the serviceability of the GCL in its function as control sealing system and as second sealing element was completely given in the case of possibly occurring losses of sealing efficiency of the asphalt sealing (Heerten & List, 1990).

The gauges in the dam did not show any influence of the groundwater level or any seepage lines in the canal dams. Thus, the repair of the section Meitingen has been successfully completed and a further safe and long-term use of the canal Lech has been guaranteed in 1989.

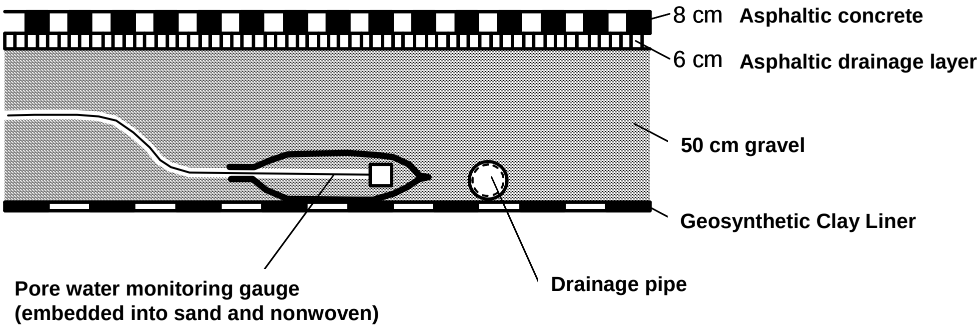

Figure 2. Cross-section of the sealing systems including pore water monitoring gauges in the supervision area of the section Meitingen of the hydropower canal Lech

3. NAVIGABLE CHANNELS

3.1 Requirements for lining systems

Traditionally, the critical value for water losses on German waterways is regarded as 15 litres/s/km. According to the "EAO – Recommendations for the use of lining systems on beds and banks of waterways (2002)" the critical value specified for clay liners is $k = 1x10^{-9}$ m/s. Thus the maximum mean permeation through a liner per unit area allowed in the basic test is $q = 2.5x10^{-8}$ m³/s/m², based on a minimum thickness of 20 cm. This applies to all lining systems. This corresponds to a permittivity of $\phi = 5x10^{-9}$ 1/s for a potential difference of 5 m. In on-site quality control tests, permeation (or a derived variable) shall not exceed a factor of 10. The volume of water permeating a liner at connections, joints and overlaps shall not exceed that permeating the surface. Lining systems are regarded as sufficiently flexible if they can adjust to subgrade deformations with an average side inclination of 1:10 or steeper (corresponding to a deflection with a height of at least 1/20 of the span). Flow velocities of up to 5 m/s in manoeuvring areas must not cause any erosion. Systems installed under water must satisfy special requirements as regards the overlaps and overall installation quality.

Among other alternative non-natural liner systems, e.g. cement-bonded or bituminous lining systems GCLs are introduced in EAO (2002) as sealing systems for navigable waterways within the liner group "natural lining system". According to the recommendations, GCLs shall have a maximum tensile strength of at least 12 kN/m. It is clear that GCLs possess good deformability characteristics and adjust well to existing deformations of the ground as well as to those occurring during installation and use. They are able to withstand tensile forces owing to the geosynthetics used. However, the tensile strength may only be exploited during placing, not during use. Owing to their tensile strength, geotextiles can span small voids beneath the liner without risk of rupture. Localised stressing of GCLs will occur when armour stones are dumped on them. Such stressing must not result in an increase in the permeability of the GCL due to local elongation or damage to the geosynthetic layers. A surcharge must be placed on GCLs immediately after installation as the liners will initially float owing to the air enclosed in them and to the fact that the bentonite has not yet hydrated. As a result, currents may cause the GCLs to turn over. A layer of small-sized material or a sand mat must therefore always be provided to act as a cushioning and surcharge layer. If layers of coarse grained material are used, it must be ensured that no material is allowed, under any circumstances, to become trapped between overlapping liners. The use of sand mats (geotextile filter layer as composite with a sand ballast filling of between 5 and 9 kg/m²) has been shown to eliminate such risks. Ideally, they should be placed at the same time as the GCLs, but installation may be staggered.

Connections under water can only be constructed by ensuring that overlaps are sufficiently wide. In most cases, a sealing wedge of treated natural clay or other suitable materials is required. The wedge must be in contact with the structural element over a length of at least 0.5 m and with the GCL over at least 0.8 m in the possible direction of flow. Joints in GCLs may only be executed as overlaps with a minimum width of 0.5 m. Sewing or gluing is not permitted at present. Horizontally placed overlaps are not permitted on slopes. Overlaps must prevent any water penetrating into the plane of the GCL (transmissivity). This must be achieved by the structure of the GCL as, in contrast to installation under dry conditions, it is not possible to carry out any subsequent treatment, such as strewing with bentonite powder and/or sealing with bentonite paste. A wider overlap length is required if the final overlap is only constructed a long time after installation of the GCL (e.g. in the centre of the canal if work is carried out one side at a time). An overlap width of 1.5 m is required at present. An overlap of around 1 m is adequate if the overlap area in the centre is covered temporarily with a strip of GCL and held firmly in place until the liners on the opposite side have been installed. Under dry situations the overlaps are generally done in lengths of only 30 cm to 50 cm.

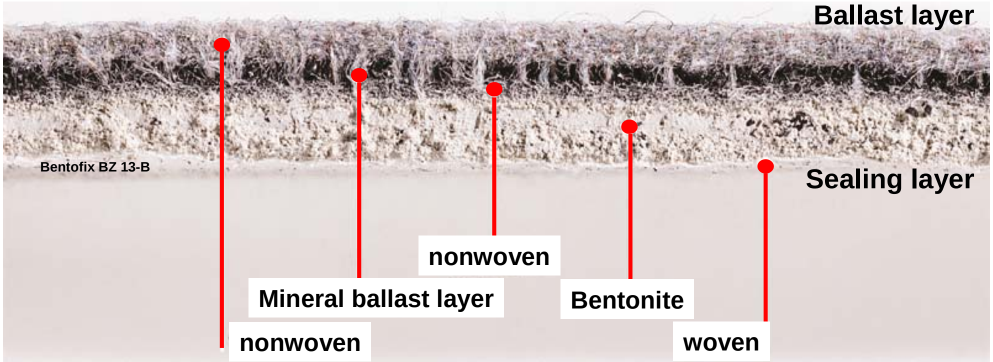

Figure 3: Cross-section of a heavy geosynthetic composite made from a sand mat and a GCL for underwater installation and as stable liner against wave loads (Heerten et al, 2008)

Based on EAO (2002), the sealing element GCL has - as a composite with a unit weight per area of 15 kg/m^2 made from a sand mat and a GCL - successfully been developed for underwater installation, so that rehabilitation measures of sealing systems under wet execution also can be carried out more easily incorporating specially developed safe overlap sections. The product cross-section design of such composite GCL is shown in figure 3. All components as shown in figure 3 are needle-punched for creating a shear strength transmitting GCL composite, which is introduced here as special GCL for hydraulic engineering applications with respect to underwater installation (sections 3.2 and 4) and also to high stability against wave loads (see section 5).

3.2 Experiences with underwater installation

In 1997/1998 near the turnout Eberswalde, Germany, for the first time in Germany, GCLs have been installed in a length of 500 m of a section of the Havel-Oder-Waterway (HOW) as lining in a waterway by means of underwater installation. At that time, the heavy composite GCL as shown in figure 3 was not developed yet. The installation was carried out by means of an overhead crane set up at the shore with a fixedly controlled, height adjustable installation cross-bar, which directly unrolls the clay liner on the base. In order to gain and document new experiences with this new sealing system in waterways, it was planned to monitor the sealing over a longer period of time. Fleischer & Heibaum (2002) reported on the first positive results after 3 years operation time. In order to be able to install the GCL which is thin compared to a traditional clay liner and to protect it in the case of rock rip-rap, a combination of a needle-punched GCL and a sand mat was rolled up the installation cross bar separately by leaving a space of 50-cm GCL overlapping length on the spreader bar (Figure 4).

Figure 4: GCL and sand mat separately enrolled on a spreader bar as lining system for underwater installation (Fleischer & Heibaum, 2002)

In the case of a second, 500-m long test section at the Dortmund-Ems-Canal (DEK), Germany, the GCL composite as shown in figure 3 was installed in 2000/2001. The overlapping areas are formed in such a way that a sealing efficient overlap bentonite on bentonite is achieved over length of 50 cm by leaving out the sand mat part on this length during the manufacture. The experiences gained, especially with the overhead crane and a fixedly controlled, height adjustable installation cross-bar used in Eberswalde, certify the qualified installation under water. However, the experiences gained at the Dortmund-Ems-Canal show that the installation appliances and installation procedures have to be adapted to the very heavy mat and that installation tests are required, especially if - like at the DEK - the equipment designed to install clay is also used for the installation of GCLs.

For the monitoring of the sealing performance and the long-term behaviour, fibre-optic cables have been installed in the test section below the sealing liners at the DEK in longitudinal direction of the channel. With these cables, possible leakages could be located via temperature measurements up to a precision of 0.5 m. Basic tests carried out by Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, Germany, preceded this construction. The results of these tests resulted in a general suitability of GCLs for use as sealing element in waterway constructions. The material properties were randomly monitored on site as to their mass per unit area, layer thickness, tensile strength and water permeability. Furthermore, during the construction process, check tests were carried out by means of divers of the Waterways and Shipping Administration as well as self-monitoring checks carried out by means of divers of the construction company as to the installation integrity (correct, wrinkle-free installation, sufficient overlaps, cleanliness of the overlap area and qualified joints to sheet pile walls).

In the meantime, samples were recovered from both test sections and tested by the BAW, Karlsruhe, Germany. The results confirm the general suitability of the bentonite alternative for sealing applications in waterways, but also the importance of an accurate, professional and monitored installation. The excavations by the BAW have shown that the armour layer dumping process onto the swollen GCL have to be done carefully especially on the slopes due to shear stresses (Fleischer & Heibaum, 2008). Until long-term experiences are available, the field of application in dams of navigable channels is restricted to water levels of max. 2 m above ground level area.

4. UNDERWATER INSTALLATION IN COMBINATION WITH CONCRETE FACING SLABS AS CANAL LINING SYSTEM

In the Ukraine, an open drinking water canal installed in 1958 and sealed with clay and concrete slabs with slopes having inclinations of V:H = 1:3 and a water depth of 6 m with flow rates of 0.40 m/s has successfully been rehabilitated in 2004 by means of underwater installation with the use of the geosynthetic composite made from sand mate and the GCL shown in Figure 3. The first 25000 m² was rehabilitated within a short construction time of only 12 weeks. The installation was carried out by the construction division of the operator of the canal in Donezk. The German company Colcrete von Essen Bau, which specializes in hydraulic engineering measures, was charged with the installation of the lining composite (Figure 5). They have special installation appliances that already have been successfully proven at the HOW (see section 3.2) in Germany. According to the construction schedule, after levelling of the surface (Figure 6.1) and installation of the bentonite/sand mat across the canal cross-section (Figure 6.2), installation of concrete slabs with reinforcing steel were planned as distance pieces as permanent formwork elements with concurrent protection capacity in the slope area (Figure 6.3). The pre-fabricated 0.5-m-wide overlapping areas were carried out for underwater installation measures according to the installation instructions of the manufacturer. Afterwards, the bottom was concreted (Figure 6.4) and the gap between concrete slabs and the GCL composite was filled with cast-in-place concrete (Figure 6.5), such that a homogeneous ballast and protection layer was achieved. Above the water level, the canal was coated with concrete. This procedure was developed by NAUE and could well be adapted to the available local parameters. The seepage rates of the old canal sealing system, which was in need of rehabilitation, were so high that the surrounding villages had an unscheduled, easy access to the drinking water because of high ground water levels. After rehabilitation of the canal, the seepage rates were reduced in such a way that complaints of a village chief near Donezk arrived due to the decreased ground-water level. He asked if water could be drawn from the water canal.

Figure 5: Underwater installation of the sand mat and GCL composite in a drinking water canal in the Ukraine, 2004

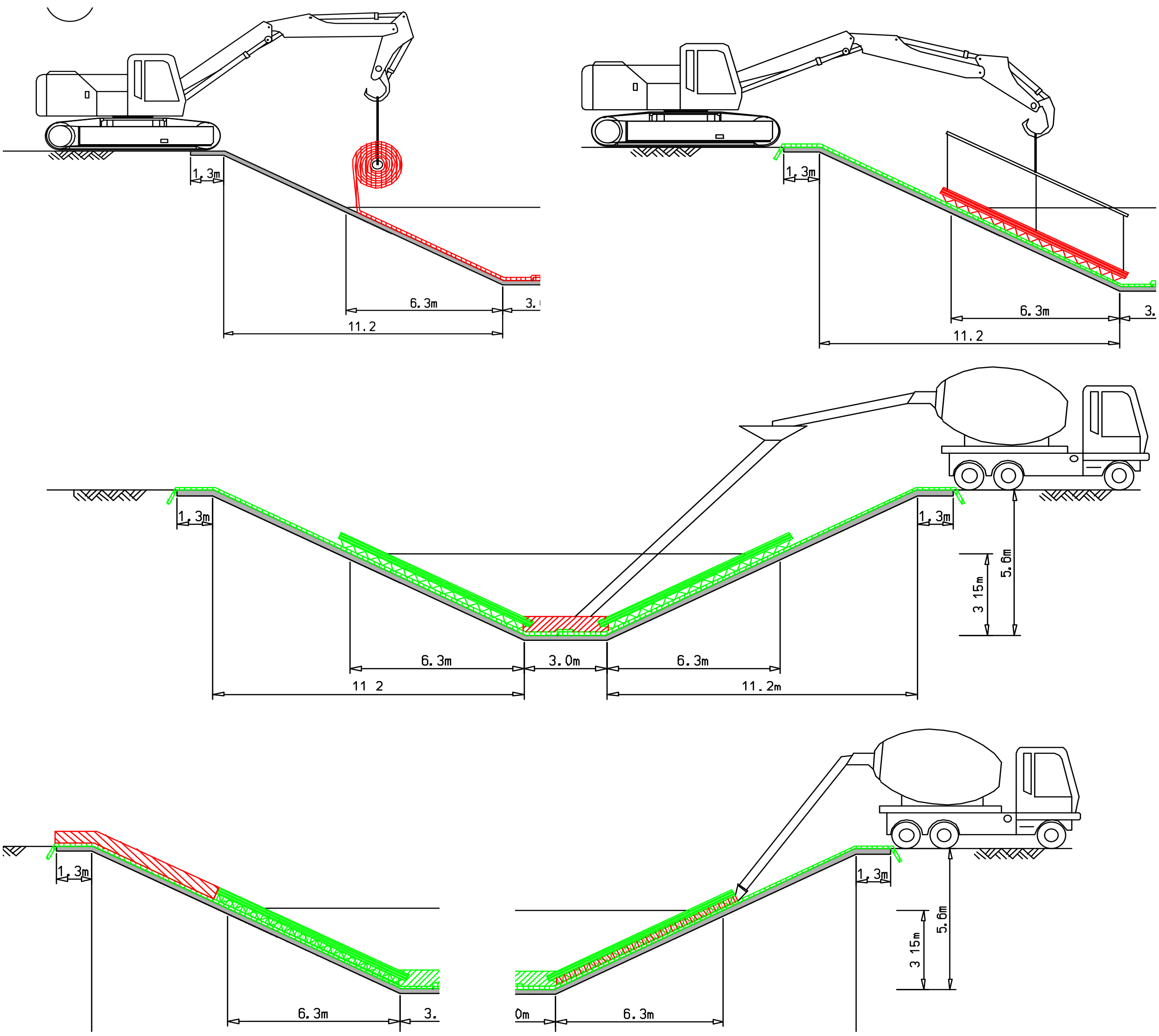

Figure 6: Underwater installation procedure with concrete slab facing (Ukraine, 2004)

5. DYKES AND LEVEES

5.1 River levees – safe protection against hydraulic infiltration

GCLs, in particular, have been frequently and successfully applied in dike refurbishment measures since 1995 in order to control seepage and to reduce water pressure in the levee core. They reflect an alternative to a thick compacted clay surface sealing system. The schematic application of GCLs as an inland levee sealing system against flooding from rivers is shown in Figure 7. Recommendations for design and installation of GCLs are given in DWA (2005), EAG-GTD (2002) and Heerten et al (2008).

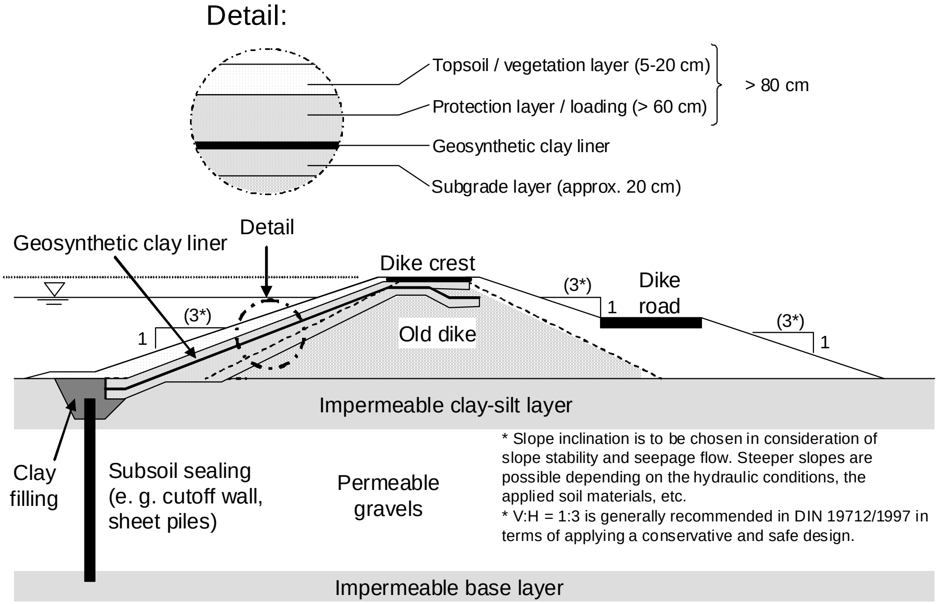

Figure 7: Application of a GCL in the course of dyke refurbishment works (Haselsteiner & Strobl, 2006)

Figure 8: Rehabilitation of the Kinzig river levee in 2001 with GCL - installation of non-cohesive river gravel as cover soil for the GCL (Heerten et al., 2008)

5.2 Costal dykes – stability against wave impact

For coastal dyke protection with tidal loads, the conventional cross-section requires a minimum 50-cm-thick clay layer on both slopes of the dyke (water side inclination of about H:V = 8:1 to 12:1), which is covered by a 20-cm-thick grass vegetation layer. These coastal dykes serve as barriers against tidal floods and are usually made of a highly erosion active sand core, which is protected conventionally by low erosion active cohesive compacted clay layer. Hydrodynamic loads as design loads have to be taken into account for coastal dykes, for which the compacted clay layer has to meet the following two functions:

- Erosion protection for dyke core made of sand, and
- Minimization of the infiltration of water into the dyke core. However, in contrast to river levees (flood levels can remain for weeks as load), coastal dykes are loaded to short-time tidal storm floods, which lead more to dynamic pressure impacts due to wave-run-up and risk of wave overtopping instead of water infiltration.

In coastal areas, where natural clay and loam is nowadays difficult to gain new alternatives for replacing the 50-cm-thick clay layer have to be determined with respect to high hydraulic stability against wave loads. Therefore for coastal dykes the stability of a GCL against wave loads has to be determined in order to replace a 50-cm-thick compacted clay. This load case assumes that the grass vegetation layer can be eroded due to the wave impact.

The investigated heavy composite made from sand mat and a GCL as shown in Figure 3 has been tested with focus on stability against wave loads by physical model tests in the Large Wave Flume at the Coastal Research Centre in Hannover, Germany (FZK, 2009). The aim was to investigate the GCL stability against potential movement and deformation under direct wave loads, if it must be assumed, that the grass cover layer is eroded in case of storm tides. Finally, the suitability of the heavy GCL composite as a coastal dyke sealing system with high erosion protection effectiveness should be determined. The hydraulic stability of this geocomposite as shown in figure 3 has been tested for a high water table of 4 m, which results in generated design wave heights of H_s = 1.10 m and peak wave periods of T_p = 8 s. In total, 1000 waves have been generated for different wave heights and wave periods. Figure 10 (left) shows the situation just before running the tests, Figure 10 (middle) shows the situation under wave run-up, and Figure 10 (right) shows the situation under wave run-down. The chosen hydraulic parameters are suitable as design wave parameters for applications at the Baltic Sea coastline. If it must be assumed that the grass vegetation layer is erodable for both systems - conventional with clay and alternative with the composite of GCL and sand mat - than the hydrodynamic impact on the exposed GCL composite is fully proven due to the test results. As a result, from the model tests, no movement or other remarkable deformations relating the GCL composite have been detected, so a high hydraulic stability has been confirmed by the Coastal Research Centre (FZK, 2009). This can be seen as large outcome to introduce a geosynthetic erosion protection element for coastal dykes.

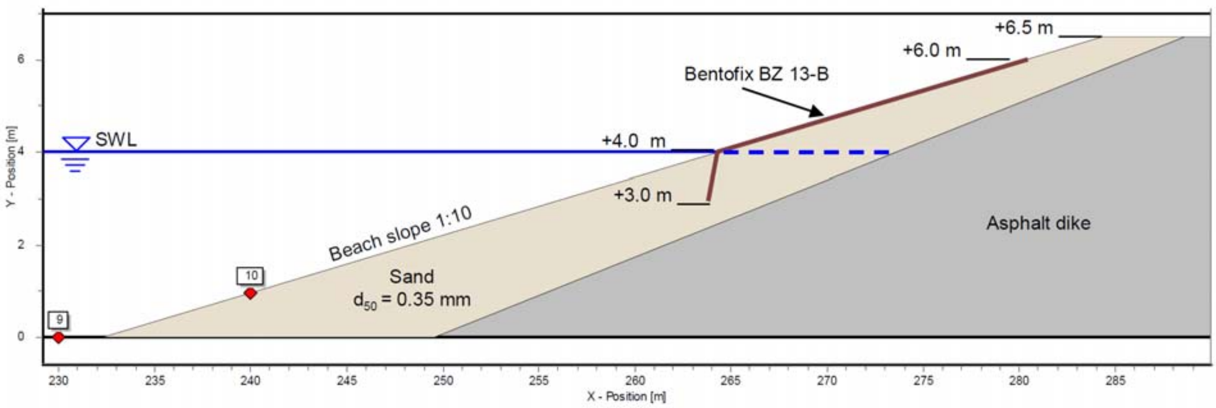

Figure 9: Cross-section of the model dyke by the use of a GCL and sand mat composite (FZK, 2009)

Figure 10: Physical model tests under wave loads – Hydraulic stability of the heavy composite GCL under wave loads (FZK, 2009)

6. SUMMARY

Although first applications of geosynthetic clay liners in hydraulic engineering are dated to 1989, the development of materials and systems have focussed primarily on landfill applications during the recent decades. In comparison to landfill applications during the last 20 years, the acceptance of GCLs as sealing systems in hydraulic engineering applications increased more slowly. As containment barriers, dams (with permanent hydraulic loads), levees (with temporary hydraulic loads) and sea dykes (with wave pressure loads during wave run-up and overtopping) have different requirements relative to landfills. In all cases, GCLs provide significant functional advantages relating erosion stability in comparison to loose soil particles of compacted clay liners under hydraulic loads. Wet and dry installation methods are available as well as experiences made from sample excavations taken from river levee lining applications after 12 years in service (Fleischer & Heibaum, 2008). Latest investigations provide new GCL product solutions in stabilisation of coastal dykes, which are subjected to wave loads during tidal flood (FZK, 2009). Finally, in hydraulic engineering applications where there are requirements for safe underwater installation techniques and for the demand of new coastal dyke cross-section designs, composites made of a sand mat and a GCL show a high effectiveness as alternative barrier against hydraulic loads.

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